CANMET Mining and Mineral Sciences Laboratories

Assessment of Chemical Stability of Impounded Tailings at Mount Nansen, Yukon Territory

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EXECUTIVE SUMMARY

To aid with decision-making on the final decommissioning of the Mount Nansen site, the Water Resources Division of Indian and Northern Affairs Canada (INAC), Whitehorse, approached CANMET/MMSL in September 2001 to design a detailed tailings characterization program and conduct relevant field and laboratory testing to assess the chemical stability of the impounded tailings. CANMET/MMSL responded with a proposal incorporating the following major components for investigation:

1. Review of historical monitoring data to identify trends in the evolution of tailings water chemistry;
2. Geochemical and mineralogical analyses to identify a) remnant metal values in the tailings: b) parameters of concern and their modes of occurrence; and, c) relative proportions of various tailings types, if proved different;
3. Short-term leach tests to identify immediate releases of contaminants upon disturbing the tailings;
4. Column testing and selective leaching to predict the long-term behaviour of the impounded tailings;
5. INCO SO_2/Air treatment of selected tailings followed by batch leaching to clarify the functionality of the treatment; and,
6. Investigation of the effect of multiple freeze-thaw cycles on the physical and chemical properties of the impounded tailings.

The acceptance of the proposal by INAC in October commenced an intensive field sampling campaign in mid-November. Nineteen boreholes were drilled systematically across the 200m by 200m impoundment to sample tailings for subsequent laboratory testing. Based on their observed contrasts in mineralogy, colour and texture during core logging, the tailings were divided into four categories, namely, oxide silt, oxide clay, sulfide silt and sulfide clay. The drilling program also revealed accelerated thawing of permafrost in the vicinity of the tailings seepage return located near the centre of the tailings dam.

Geochemical analyses show that the tailings solids, regardless of detailed type, contain anomalous contents of silver (Ag, up to 80 µg/g), arsenic (As, up to 0.6%), copper (Cu, up to 0.06%), lead (Pb, up to 0.6%), antimony (Sb, up to 0.1%) and zinc (Zn, up to 0.3%) and they are all potentially acid-generating to a small degree. The Ag content represents the only remnant metal value in the tailings and the other trace elements pose potential environmental liabilities. Depending on the tailings type, the tailings porewater contains on average 4-17 mg/L strong acid-dissociable cyanide (SAD CN or Total CN) and 3-5 mg/L weak acid-dissociable cyanide (WAD CN). Numerically these are about an order of magnitude lower than the same associated with the tailings solids (with the latter expressed in µg/g). The average concentrations of 0.5-2.3 mg/L As and 3.6-6.5 mg/L Cu are also observed in the porewater of the four types of tailings. Generally, there is a good correlation between dissolved Cu and WAD CN in the porewaters.

Mineralogical analyses reveal that the tailings are comprised predominantly of quartz with minor to subordinate amounts of sericite/illite, alkali feldspar, jarosite, kaolinite,

montmorillonite, goethite, and gypsum. Pyrite is the most common sulfide mineral observed. Arsenopyrite is typically replaced by scorodite.

Eight columns have been set up to simulate, in duplicate, the disposal of coarse, high- and low-sulfide tailings under a shallow water cover, a mixture of silty slurried tailings under a water cover and mixed tailings under flow through conditions. While rates of cyanide degradation and trace element releases cannot yet be established due to the short duration of the experiment, the column testing demonstrates that thiocyanate (CNS), ammonia (NH_4-N), As and possibly Sb may be mobilized in tailings porewater and the water cover at concentrations of concern. If the tailings were to be relocated to the open pit, moving the tailings in a relatively dry form would likely have a less significant impact on the resultant water cover quality than transferring the tailings as a slurry.

Sequential batch leach testing with clayey tailings also indicates that As and Sb are the only trace elements susceptible to significant leaching with intense perturbation of the tailings. Although the INCO SO_2/Air treatment is effective in destroying CN associated with the tailings solids, simultaneous releases of elevated concentrations of Total CN, CNS and NH_4-N to the liquid phase have been observed. The process also seems to affect the leaching of As, Cu, Sb and Zn to various extents.

Partial sequential extraction analyses were conducted on six typical tailings from Mount Nansen to investigate the impact of a changing environment on the behaviour of the trace elements occurring in anomalous amounts in the tailings. The results indicate that As and Zn are susceptible to remobilization under mildly acidic or reducing conditions. In comparison, Cu, Pb and Sb are less readily released. Freeze-thaw studies with the same six samples indicate that multiple freeze thaw events do not significantly affect the metal leachability of the test tailings. However, an increase in average grain size may occur in some samples resulting from the aggregation of clay particles in the freezing process.

Overall, the impounded tailings appear to represent a relatively stable system from a chemical perspective. Only the CNS and NH_4-N will remain parameters of major concern in the medium term. Although laboratory testing suggests potential As and Zn release with changing environmental conditions and tailings perturbation, such has not yet been observed to occur in any significant extent in the tailings impoundment. Elevated concentrations of dissolved As have been found only in tailings porewater (up to an average of 2.33 mg/L in the clayey oxide tailings), which has not escaped the impoundment. It is recommended that detailed information on mineral distribution, hydrology and hydrogeology be collected from the Brown-McDade open pit. This would provide relevant data to critically compare, preferably by using a risk assessment approach, the benefits of retaining the tailings in the existing impoundment versus relocation to the open pit. Meanwhile, a scaled model of the impoundment can be constructed to study water-tailings interaction under simulated field conditions. Further research on the treatment of CNS and NH_4-N are also desirable.

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INTRODUCTION

Project Background

The Mount Nansen Mine, hosting gold mineralization, was operated by BYG Natural Resources Inc. between November 1997 and February 1999. The operator went bankrupt and abandoned the mine site in July 1999, leaving significant environmental liabilities. Of particular concern is the chemical and physical stability of approximately 250,000 tonnes of impounded, cyanide- and arsenic-bearing tailings. Since mine abandonment, the Water Resources Division of Indian and Northern Affairs Canada (INAC), Whitehorse, has maintained operation of the effluent treatment system at the site to reduce the potential for serious environmental impacts resulting from tailings impoundment failure or uncontrolled discharge from the emergency spillway.

To facilitate decision-making with regard to long-term maintenance or decommissioning of the site, INAC requires the following information:

1. Metals and other contaminants occurring in the tailings and their response to long-term water contact and repeated wetting-drying cycles;
2. Long-term prognosis for treatability of thiocyanate generated by the modified INCO SO_2/Air water treatment system;
3. Cause of accelerated cyanide release from partially or completely drained tailings after a rainstorm event;
4. Proportion of sulfide versus oxide tailings in the impoundment and its impact on the long-term treatability of porewater which migrates to the collection pond; and,
5. Implications of moving the tailings and depositing them in the Brown-McDade Open Pit and the preferred means of transport.

To address the above issues, INAC approached CANMET/MMSL in September 2001 to design a detailed tailings characterization program and conduct relevant field and laboratory testing to acquire the necessary data. A draft research proposal was submitted to INAC in mid-September. After a preliminary visit to the Mount Nansen site followed by a meeting with INAC officials in early October, a formal proposal was prepared and approved by INAC in mid-October 2001. This started an intensive field and laboratory investigation program on the chemical stability of tailings impounded at the Mount Nansen tailings pond, the results of which are detailed in this report.

Scope of Work

All field and laboratory investigations were designed for completion by the end of March 2002. Because of the short time frame allowed for the research project, it is understood that not all of the questions raised by INAC may be fully answered at the end of the study. However, a comprehensive battery of test work has been incorporated to render sufficient data to reveal key issues related to the short- and long-term chemical stability of the impounded tailings and to evaluate the advantages and pitfalls of alternative decommissioning strategies for the site. Major components of the investigation include the following:

1. Review of historical monitoring data for trend identification;
2. Detailed tailings characterization to identify:
   a) if there are remnant metal values in the tailings;
   b) parameters of concern and their modes of occurrence where appropriate; and,
   c) relative proportions of various tailings types if proved different;
3. Short-term leach tests to identify immediate releases of contaminant, if any, upon disturbing the tailings;
4. Column testing and selective leaching to predict the long-term behaviour of the impounded tailings;
5. INCO SO_2/Air treatment of selected tailings followed by batch leaching to clarify the functionality of the treatment; and
6. Cursory investigation of the effect of multiple-freeze-thaw cycles on the physical and chemical properties of the impounded tailings.

Report Structure

This report contains ten sections. Section 1 briefly describes the project background, the scope of work and the organization of the subject report. Section 2 outlines the setting and general geology of the study site. Section 3 presents the physical characteristics of the tailings impoundment as revealed in the drilling program conducted to sample tailings for laboratory testing. Historic site monitoring data based on company and government records are also summarized. Section 4 deals with tailings chemistry and mineralogy. Various data including solids and water analyses rendered by inductively coupled plasma atomic emission spectrometry (ICPAES) and mass spectrometry (ICPMS), acid-base-accounting (ABA) characteristics and results of mineralogical analysis by petrography, X-ray diffraction (XRD) and scanning electron microscopy (SEM) supplemented with energy-dispersive X-ray (EDX) analysis are described. The analyses of grab samples from the Brown-McDade open pit, which is a candidate for long-term disposal of the tailings, are also included in this section.

Sections 5 through 7 document the results of various tests completed with the collected tailings. These include column testing of the coarser tails (Section 5), sequential batch testing of the fine tails, which also incorporates INCO SO_2/Air treatment in one of the tests (Section 6), and other test work with various leach media as well as the investigation of freeze-thaw effects (Section 7). The test results, especially with regard to their implications on the long-term chemical stability of the impounded tailings and appropriate decommissioning strategies, are discussed in Section 8. Section 9 summarizes conclusions drawn in the study and recommended further work is outlined in Section 10.

SITE SETTING AND GENERAL GEOLOGY

Site Location and General Setting

The abandoned Mount Nansen Mine previously operated by BYG Natural Resources Inc. is located about 60 km west of Carmacks and 180 km north of Whitehorse (Figure 1-Inset). The mine site lies in the Dawson Range consisting of rounded ridges and shallow valleys with elevations ranging from 945 to 1525 m. Drainage from the property flows through Nansen Creek to the west and Victoria Creek to the east (Figure 1) to the Nisling River, which in turn drains into the Yukon River system. Dome Creek, a tributary of Victoria Creek, is directly impacted by the Mount Nansen mine site, especially by historical underground mine workings, the mill facility and the tailings impoundment.

The average monthly temperature in the Mount Nansen area ranges from a high of about 15°C in July to a low of about -15°C in January. The average annual precipitation, which occurs mostly as rain in the summer months, is about 25 cm. The winter snow pack is typically 30 to 40 cm. Discontinuous permafrost ranging from 30 to 60 m thick occurs at a depth varying from 0.4 to 5 m depending on the nature of ground cover. The active layer is up to 1.5 m thick.

The mine site lies within the Dawson Range Ecosystem. Open stands of black spruce and white spruce occur in valley bottoms and benchlands near Dome Creek. While upper slopes are generally devoid of trees, lower slopes host stunted black spruce and trembling aspen. From valley bottoms to above the treeline, birch and willow shrubs form an extensive cover while Labrador tea is the dominant understorey and mosses and lichens constitute the common ground vegetation. Natural weathering of geologic materials including bedrock and surface sediments generates unstable upper slopes and secondary surficial sediments along the valley bottoms. Where surface and subsurface weathering is intense, bedrock can become friable and unstable.

General Geology

The Mount Nansen area lies within the Yukon-Tanana Terrane, the regional geology of which has recently been described in detail by Carlson (1987). Hart and Langdon (1997) as well as Andersen and Stroshein (1997) further discussed the local geology and mineral deposits of the Mount Nansen camp. A brief account of the property geology is furnished below, providing the background information against which later mineralogical analyses can be compared and discussed.

The Mount Nansen property is located in the eastern part of the Yukon Crystalline Terrane between the Coast Plutonic Complex to the southwest and the Yukon Cataclastic Terane to the northeast. The oldest rocks occurring in the area are Palezoic (early Mississippian) meta-sedimentary schists and gneisses, which were intruded by early Cretaceous plutons ranging from diorite, monzonite to syenite in composition. These felsic plutonic rocks were in turn intruded by and host younger mid-Cretaceous mafic to intermediate volcanic rocks of the Mount Nansen Volcanic Suite.

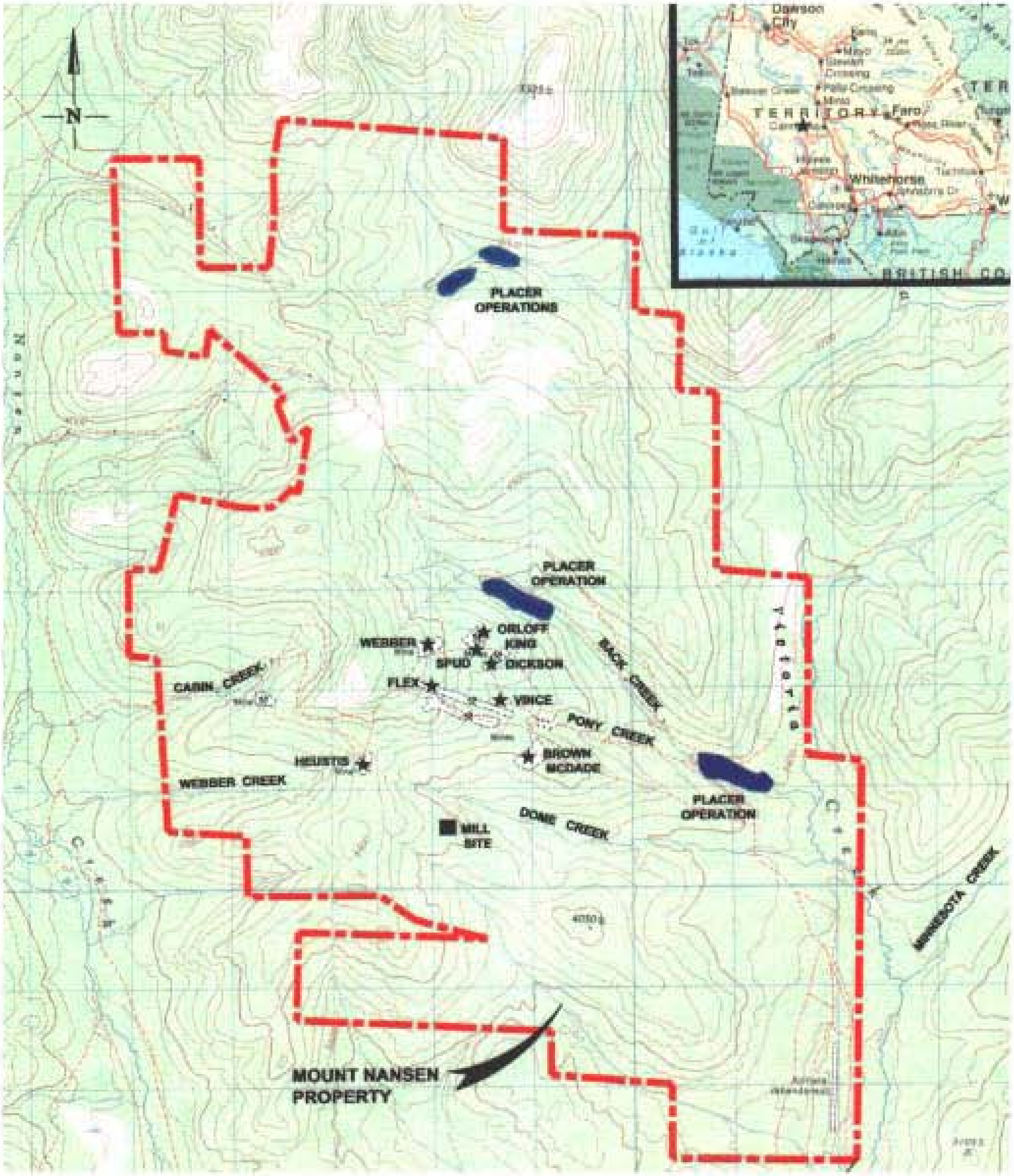


Figure 1. Location map of the Mount Nansen property. (Scale: each grid = 1 km)

Prior to abandoning the mine site, BYG Natural Resources Inc. had identified nine epithermal deposits at the Mount Nansen property (Figure 1). The three most westerly mineralized zones (i.e., Webber, Huestis and Flex) are hosted by older Paleozoic rocks dominated by strongly foliated, inter-layered quartz-feldspar-chlorite gneiss, quartzite, minor amphibolite and augen gneiss. Further southeast, the main mineralized zone named the Brown-McDade deposit is hosted by locally foliated, mid-Cretaceous granodiorite, quartz diorite and quartz monzonite. Occurring in the northern portion of the property is a large quartz-feldspar porphyry intrusive complex (the Mount Nansen porphyry complex) with flanking andesitic flow and tuff units. Within this intrusive complex, zones of small and silicified breccia pipes occur, locally with associated gold values. Propylitic alteration, characterized by the replacement of hornblende by epidote, calcite, pyrite and magnetite, is widespread peripheral to the Mount Nansen porphyry complex and has affected most rocks in the property.

Structurally, faulting is the main feature occurring in the Mount Nansen property. Two fault sets are prominent. One set trends north-northwest with dips varying from 50 to 70 degrees to the southwest. This fault set is parallel to the main vein direction at the Brown-McDade deposit and locally mineralized. The other set trends southeast with subvertical dips and locally cuts some of the mineralized zones. These faults form part of the larger regional structure known as the Mt. Nansen Trend (Hart and Langdon, 1997).

The property has not been affected by recent glacial activities. Consequently, weathering can reach depths in excess of 70 m from the surface. Generally, the depth of oxidation as evidenced by alteration of sulfides to limonite is variable throughout the property.

Modes of Mineralization

As reviewed by Strathcona Mineral Services Ltd. (2000), two forms of mineralization occur in the Mount Nansen property. The more common form occurs as structurally controlled planar veins consisting of quartz, carbonate and varying amounts of sulfides. The vein systems can occur as simple veins like those observed at the Huestis and Webber zones or as a complex anastomosing series of veins and veinlets prominent at the Brown-McDade deposit. Better gold values are generally restricted to steeply plunging shoots with a stronger vertical rather than horizontal continuity. The less common form of mineralization occurs as siliceous pipe-like structures, which may be sulfide-rich as observed at the north end of the Brown-McDade open pit or sulfide-poor as noted at the PPBX showing.

Sulfide minerals occurring in mineralization zones at the Mount Nansen property include pyrite, arsenopyrite and lesser amounts of galena, sphalerite, chalcopyrite, stibnite and various sulfosalts. Gold occurs as minute inclusions (5 to 40 μm across) in early pyrite and arsenopyrite, as peripheral infiltrations in several sulfide minerals and as "free gold" intergrown with galena, freibergite and other sulfosalts. Silver occurs mostly as inclusions in galena and sphalerite but freibergite and miargyrite have been identified from the property. Silver/gold ratios vary from 7/1 in the planar vein mineralization to 3/1 in the breccia pipe mineralization. The silver content appears to vary directly with the base metal content of the ore material (Strathcona Mineral Services Ltd., 2000).

In the Mount Nansen camp, Hart and Langdon (1997) recognized two types of epithermal veins. These are (1) an early, cherty quartz-sulfide vein with fine-grained pyrite and arsenopyrite; and, (2) a later coarse-grained quartz-sulfide vein with pyrite, galena and sphalerite and higher precious metal values. It is not clear if both vein types are prevalent in the two forms of mineralization described above.

Mineralization and Alteration at the Brown-McDade Open Pit

As the bulk of the tailings impounded at the Mount Nansen tailings pond is presumably derived from the processing of ore materials from the Brown-McDade open pit, it is instructive to review the mineralogy and alteration of the ore deposit. Moreover, transfer of impounded tailings to the Brown-McDade open pit has been considered as a long-term decommissioning option for the mine site (Strathcona Mineral Services Ltd., 2000). A better appreciation of alteration patterns prevailing at the open pit will aid with developing proper strategies for site closure.

In agreement with the general forms of mineralization reviewed above for the entire Mount Nansen camp, Conor Pacific Environmental Technologies Inc. (2000) also reported that open-pit mining of the Brown-McDade deposit revealed two separate ore mineralization types. These are (1) gold-silver vein mineralization forming a complex vein swarm hosted in a massive feldspar porphyry dike, and (2) a siliceous, sulfide-rich and gold-silver mineralized breccia in a pipe-like structure. The two mineralization types are separated by a complex, steeply dipping and north-easterly trending fault that crosscuts the open pit north of the Pony Creek adit. The gold-silver veins, which are largely planar in structure, are exposed in the southern two-thirds of the pit while the mineralized breccia zone is exposed in the northern one-third of the open pit. The latter is reportedly hosted by re-crystallized limestone, which has not been confirmed in the cursory examination of the open-pit during the course of this study.

Three main types of hydrothermal alteration, namely, silicification, argillic and phyllic alterations, have been reported by Conor Pacific Environmental Technologies Inc. (2000) in the Brown-McDade open pit. Silicification and bleached clay (argillic) alteration zones are commonly 1–3 m wide. Adjacent to veins and breccia zones, silicification usually occurs in vuggy form with yellow weathering and drusy quartz lining in the fine vug cavities. The silicified zone is usually enclosed by a phyllic alteration zone, in which the disseminated pyrite content increases away from the veins. The phyllic alteration consisting of sericite, pyrite and carbonates is in turn enveloped by argillic alteration which, within the feldspar porphyry, can be identified by the presence of kaolinite and montmorillonite. The argillic alteration can locally be so intense along vein contacts near the surface that the accumulation of clay has caused severe handling problems in the mining of the upper levels of the Brown-McDade deposit (Strathcona Mineral Services Ltd. 2000).

According to Conor Pacific Environmental Technologies Inc. (2000), near-surface oxide gold enrichment is well developed in the Brown-McDade mineralization. Within the oxide zone, gold has been liberated by the oxidation of sulfide minerals and cataclasis. In the subjacent sulfide zone, gold- and silver-bearing sulfides include pyrite, arsenopyrite, sphalerite, galena, sulfosalts, bornite, stibnite and chalcopyrite. Gold is apparently genetically related to an early phase of pyrite mineralization, occurring as 5-40 μm inclusions within pyrite.

CHARACTERIZATION OF THE MOUNT NANSEN TAILINGS POND

Field Investigation and Sampling

The primary purpose of the field program is to acquire adequate samples to determine the storage of remnant cyanide and potentially deleterious metals/trace elements in the tailings impoundment and for subsequent detailed characterization and water-tailings interaction studies. To plan field activities, a preliminary site visit was conducted on October 3, 2001 with INAC personnel to achieve the following goals:

1) Assess site conditions and finalize the field program;
2) Assess the nature and extent of chemical weathering in exposed tailings as well as geologic material in the pit area; and,
3) Sample pit water, tailings pond water and seepage for preliminary analysis.

The main sampling campaign took place on November 13-21, 2001. Assisted by two staff members each from Ace Drillings Services Ltd. and Laberge Environmental Services, 19 holes varying from 2.4 to 9.7 m deep were drilled using a sonic drill (Vibra-Corer) for systematic sampling of tailings in the impoundment (Figure 2). The sonic drill operates on the principle of drill-string oscillation. The drill head, which was powered by a 9-HP Honda engine, produced vibrations that were transferred to the drill string. The imparted vibrations essentially liquefied the surrounding material, allowing the drill rods to penetrate the tailings aided by the weight of the drill head and rod. A continuous tailings core was fed into the centre of the drill rod for later recovery. The drill cores were logged immediately upon retrieval and subdivided and sampled according to visible differences in composition and texture (Appendix A). A total of 132 samples including several overlying waters were collected. To aid classifying various types of tailings and to alleviate the complication of possible cyanide degradation during sample transport, the CANMET/MMSL team conducted 98 weak acid dissociable cyanide (WAD CN), 97 thiocyanate (CNS), 85 ammonia, 72 nitrite and 9 nitrate analyses on tailings pore and overlying water during the field campaign.

While the field sampling effort mainly focused on the tailings impoundment, the Brown-McDade open pit was also briefly examined. About 120 L of pit water was collected through the ice cover for subsequent column test work. Prominent alteration products were collected from the pit walls and two adits for mineralogical and geochemical analyses. An attempt was also made to secure a sample of the scarce sediments deposited at the bottom of the pit.

Classification of the Mount Nansen Tailings

Based on their apparent contrasts in mineralogy, colour and texture observed during field core logging, tailings impounded at Mount Nansen can be divided into four main types. These are (1) oxide-rich silt; (2) oxide-rich clayey silt; (3) sulfide-rich silt; and (4) sulfide-rich clayey silt. The oxide-rich varieties range from yellow-brown to light greyish brown in colour while the sulfide-rich varieties are typically greyish brown. The distribution of these four tailings types in the tailings impoundment are depicted in cross sections (Appendix B), two of which are illustrated in Figure 3.

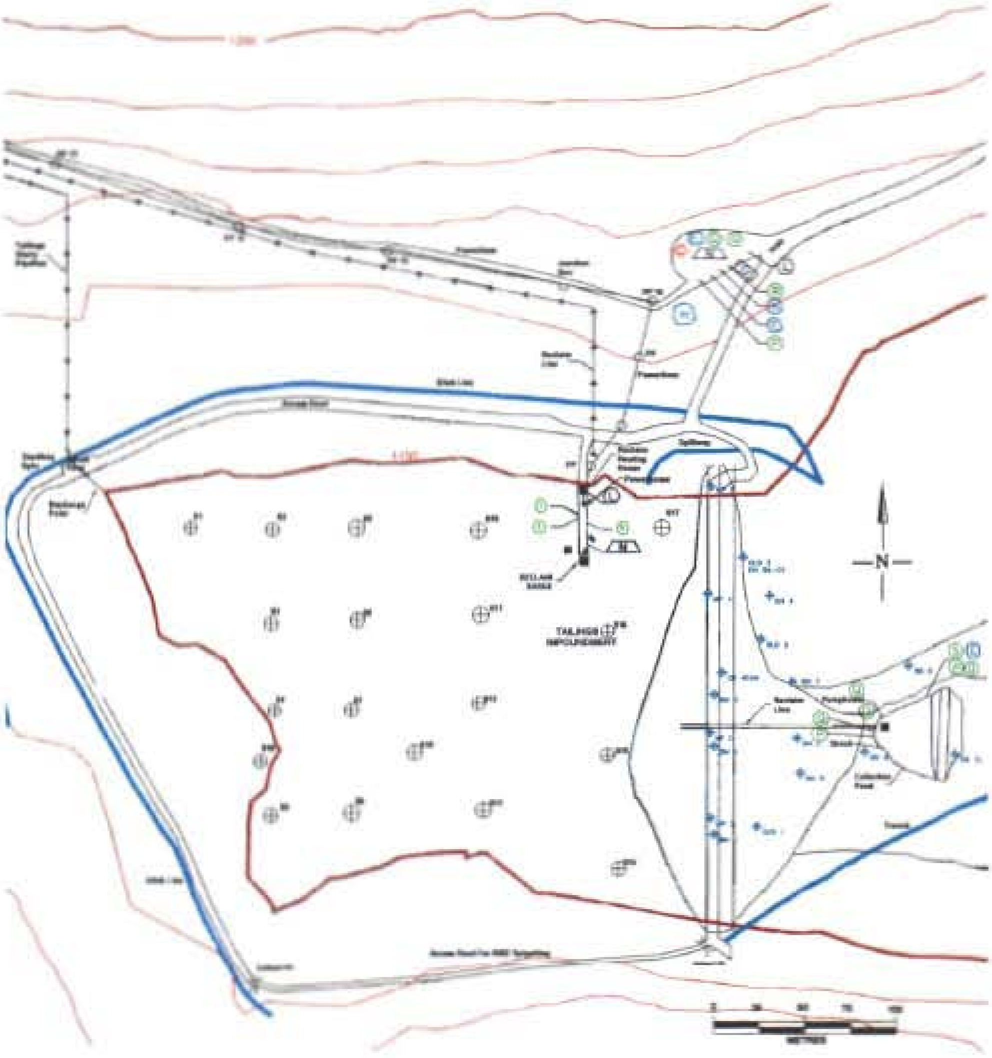


Figure 2. Map of tailings impoundment at Mount Nansen showing drill hole locations.

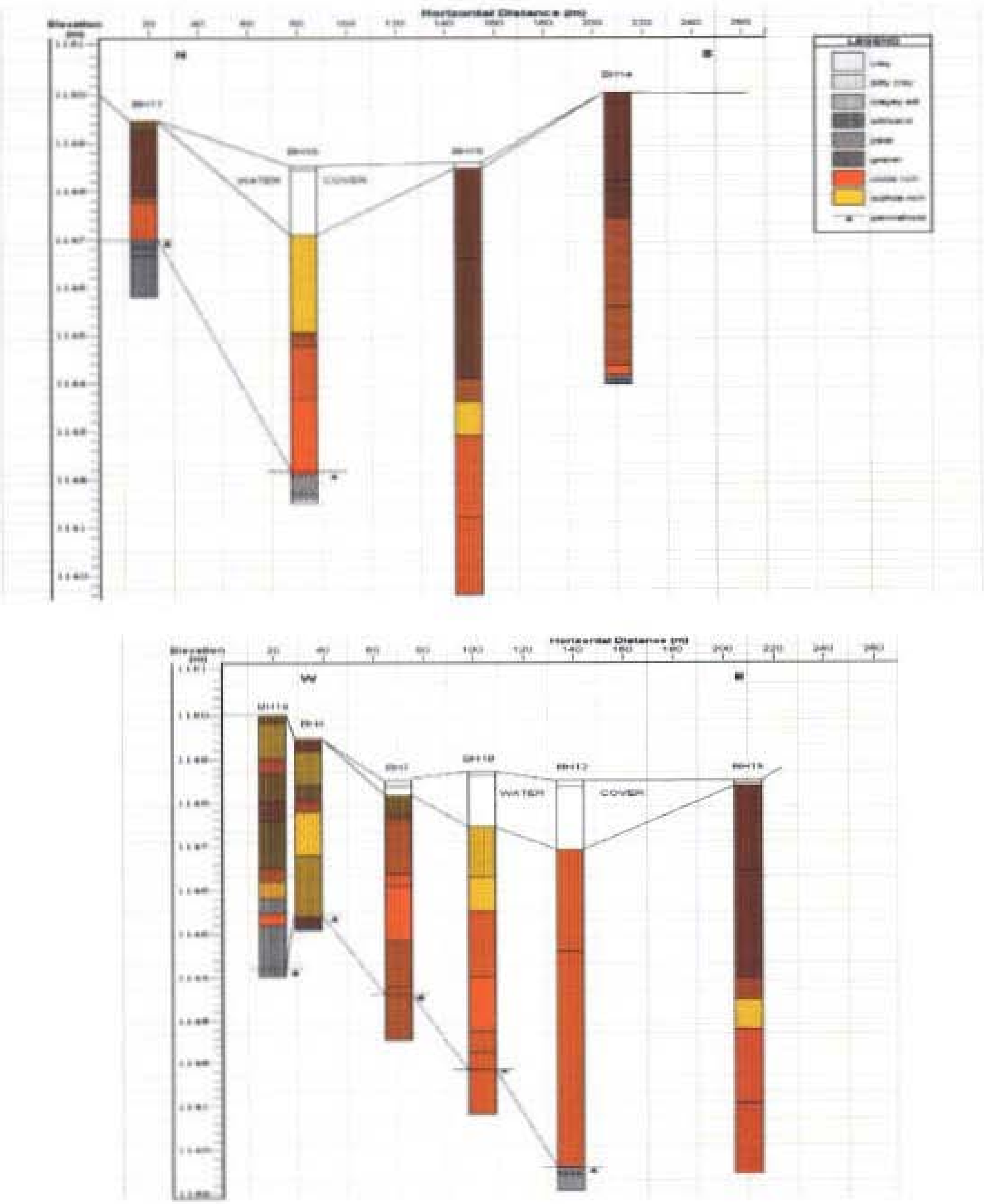


Figure 3. Selected N-S and W-E sections across the Mount Nansen tailings impoundment showing the distribution of various tailings types and the permafrost table.

Estimated from summing core lengths of similar materials, the impounded tailings are comprised of 35.0% oxide silt, 29.8% oxide clay, 16.5% sulfidic silt and 18.7% sulfidic clay. A perusal of a total of eight sections across the impoundment (Appendix B) leads to the following observations:

1. Sulfide-rich tailings are more widespread in the western half (particularly the southwestern quadrant) of the impoundment.
2. The fine tailings (silty clay instead of sandy silt) account for nearly half of the impounded tailings by volume. They are ubiquitous but more concentrated in the middle part of the tailings pond where a water cover usually exists.
3. Contrary to expectation, depth to permafrost is shallower towards the north side (3-4 m) instead of the south side (~7 m) of the impoundment. However, the greatest depth to permafrost is apparently near the seepage return to the pond such that at Hole Location B15 (Figures 2 and 3), no frozen ground has been detected at the drilled depth of 8.8 m.

To quantitatively measure the grain size distribution of the impounded tailings, seven selected samples including four composite and three individual samples were analyzed using a laser scattering particle size analyzer (Horiba LA-300). The detailed results are shown in Appendix C. The coarser tails (oxide and sulfide silts) typically show a trimodal distribution (Figure 4A) with mean particle size ranging from 30 to 119 μm and modes varying from 55-142, 6-7 and 0.4-0.5 μm, respectively. The fine tails (oxide and sulfide clayey silts) typically exhibit a bimodal distribution (Figure 4B) with mean grain size ranging from 4.8 to 13 μm and modes varying from 4-8 μm and 0.3-0.4 μm, respectively.

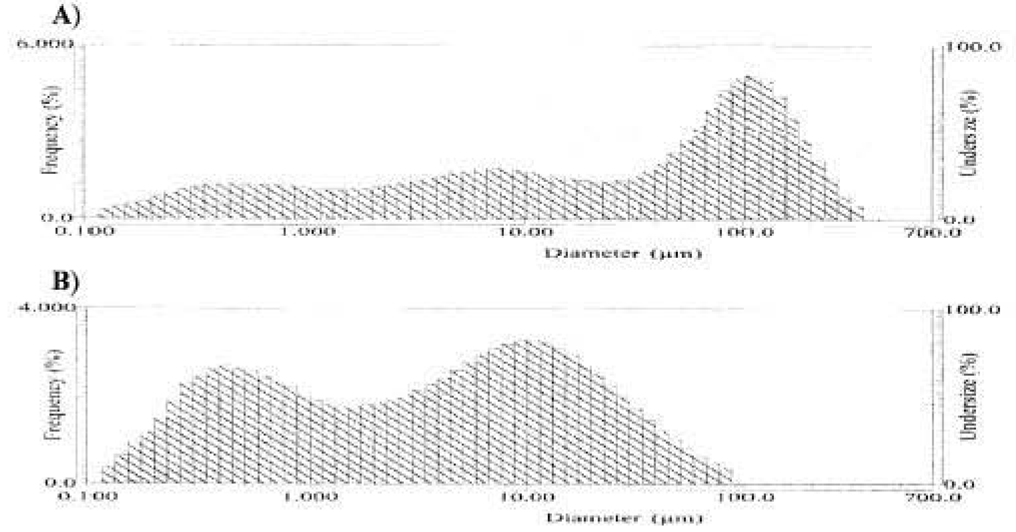


Figure 4. Typical grain size distribution in coarse silt tailings (A) and fine clayey silt tailings (B) at the Mount Nansen tailings impoundment.

Previous Monitoring Work at the Mount Nansen Tailings Pond and Brown-McDade Open Pit

Tailings impounded at Mount Nansen are presumably derived largely from the processing, by cyanidation, of oxidized ore originally containing gold-silver mineralization associated with pyrite and arsenopyrite. The tailings are thus relatively enriched in arsenic and cyanide. Since the commencement of mining operation in 1997, the tailings pond water and seepage return have been closely monitored by both the mine operator and government agencies. Since mine abandonment in 1999, INAC has continued the monitoring to ensure the discharge of effluents meet all water quality criteria stipulated in the expired BYG Natural Resources Inc. water licence, demonstrating INAC's commitment to the standards imposed on licensees. The monitoring data are useful in revealing trends in the evolution of water chemistry in the tailings impoundment. They are thus reviewed to help direct the focus of investigation in the subsequent laboratory test work.

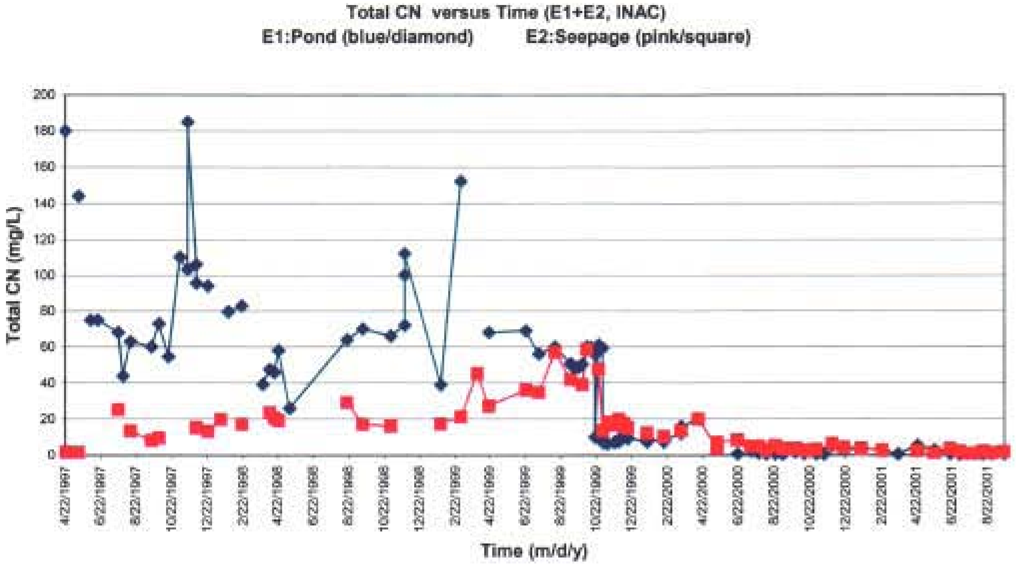
Figures 5 to 8 show time series plots of parameters of interest based on the review of a database containing monitoring data collected by INAC. Salient observations include the following:

1. Since the cessation of mining at Mount Nansen, Total CN (SAD CN) and WAD CN (Figure 5) as well as Total Cu (Figure 8) concentrations in both the tailings pond water and seepage return have continued to decrease with time but there appears to be insignificant attenuation so far for thiocyanate and ammonia (Figures 6 and 7).

2. Although both the cyanate (Figure 6) and Total As (Figure 7) concentrations in the tailings pond water appear to follow a decreasing trend with time, minor cyanate and As remobilization is suggested if the 2001 analyses are accurate.

3. It is intriguing to note that the Total Fe concentration in the seepage return has remained higher than that of the tailings pond water by an order of magnitude most of the time since mine operation (Figure 8).

In contrast to the large number of water monitoring data collected at the tailings impoundment, very few data are available to reveal the temporal evolution in composition for water accumulated in the Brown-McDade open pit since mine abandonment. Cu and Zn appear to be the main parameters of concern. Three samples collected by INAC personnel between March and August 2001 gave 0.06-0.12 mg/L total Cu, 1.6-3.7 mg/L total Zn and pH 7.2-7.8. A sample collected by Conor Pacific Environmental Technologies Inc. in September 1999 gave 0.08 mg/L total Cu, 15 mg/L total Zn and pH 7.5. In contrast, a sample collected by the Environmental Protection Service of Environment Canada in May the same year at presumably the same location rendered 4.9 mg/L dissolved Cu, 49 mg/L dissolved Zn and a pH value of 4.8. In all cases, however, the Zn analyses appear to correlate with dissolved Mn contents. The sparse data available also suggest that there are significant seasonal variations in the pit water chemistry.



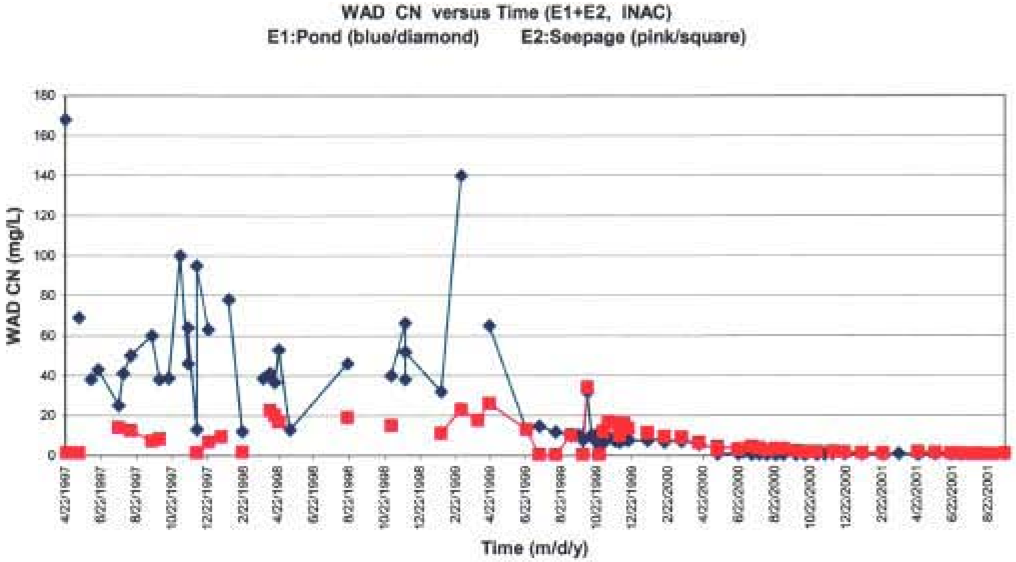


Figure 5. Temporal variation of total CN (upper plot) and WAD CN (lower plot) in the tailings pond water and seepage return based on INAC monitoring data.

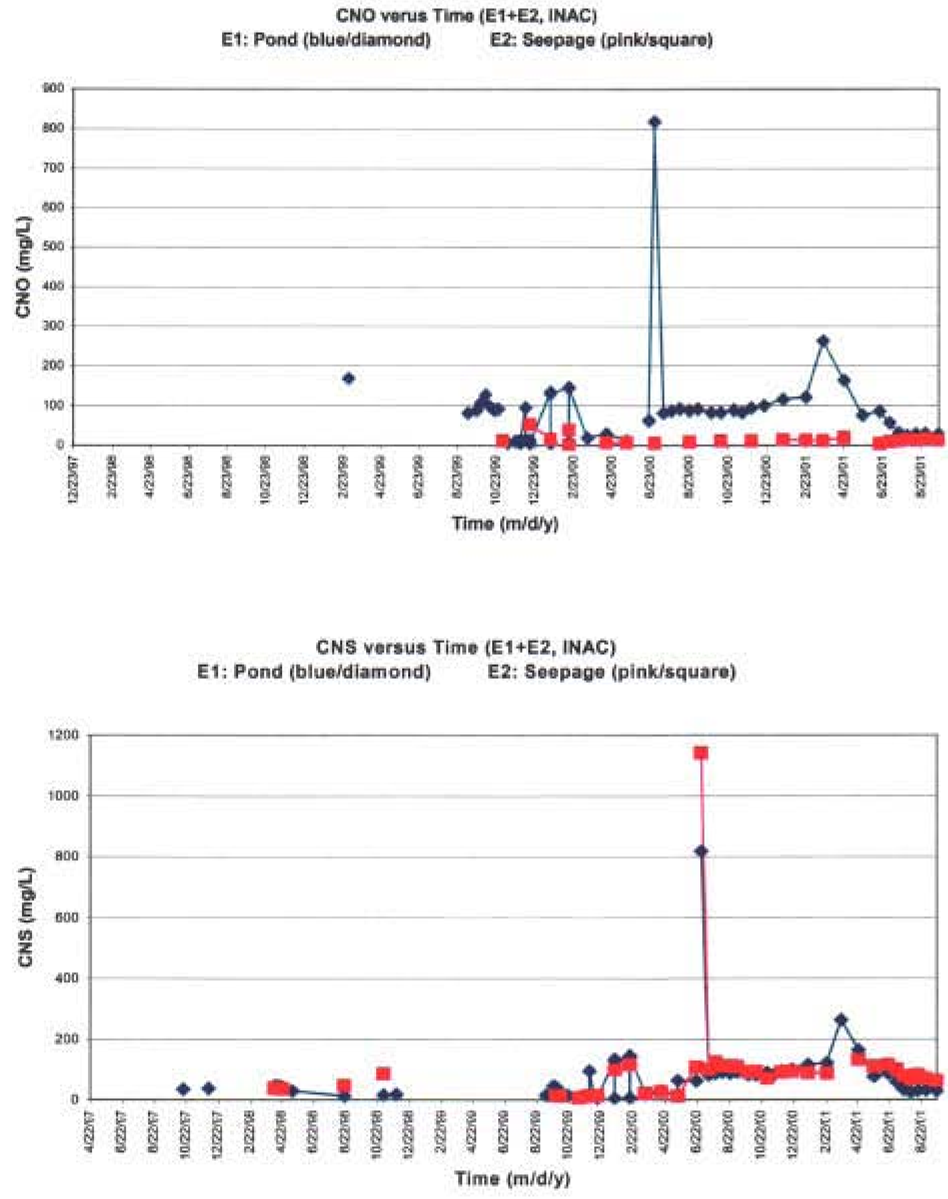


Figure 6. Temporal variation of cyanate (CNO, upper plot) and thiocyanate (CNS, lower plot) in the tailings pond water and seepage return based on INAC monitoring data.

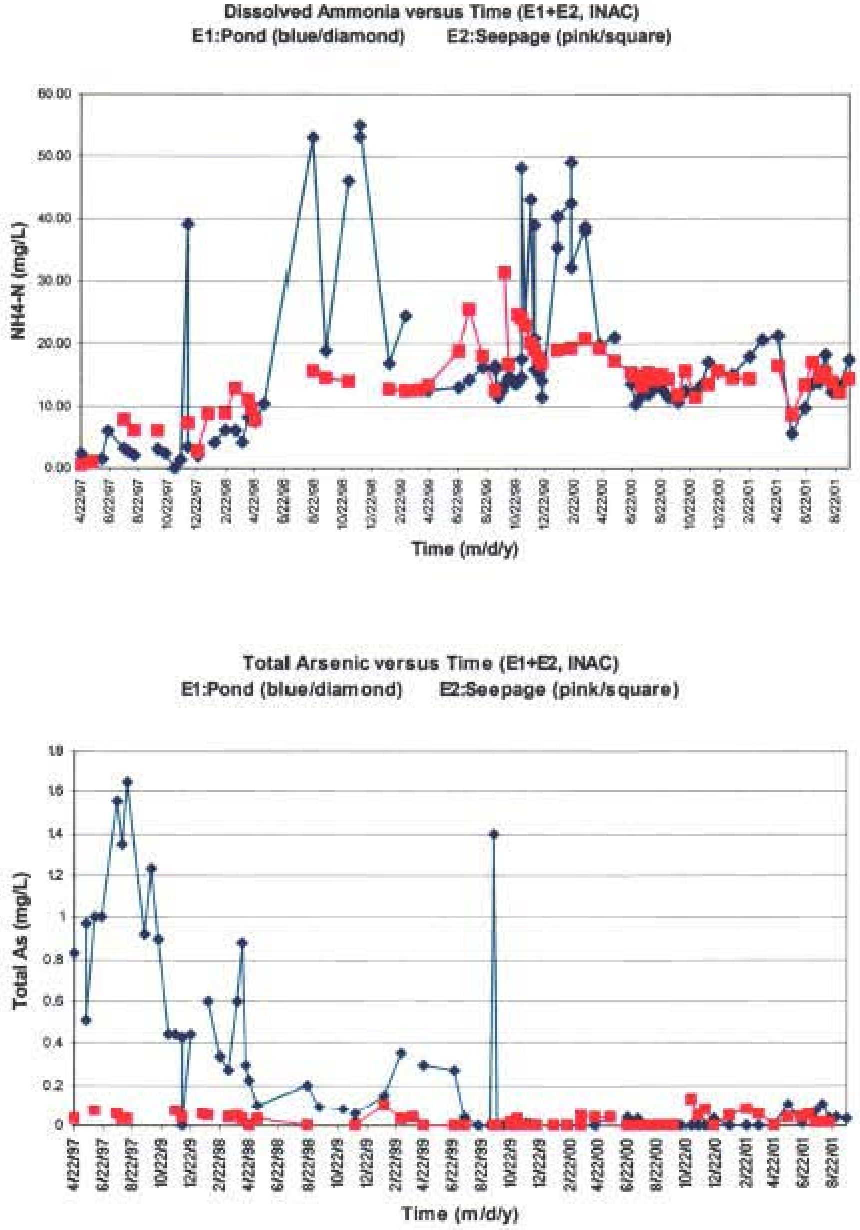


Figure 7. Temporal variation of dissolved ammonia (NH_4-N, upper plot) and total arsenic (Total As, lower plot) in the tailings pond water and seepage return based on INAC monitoring data.

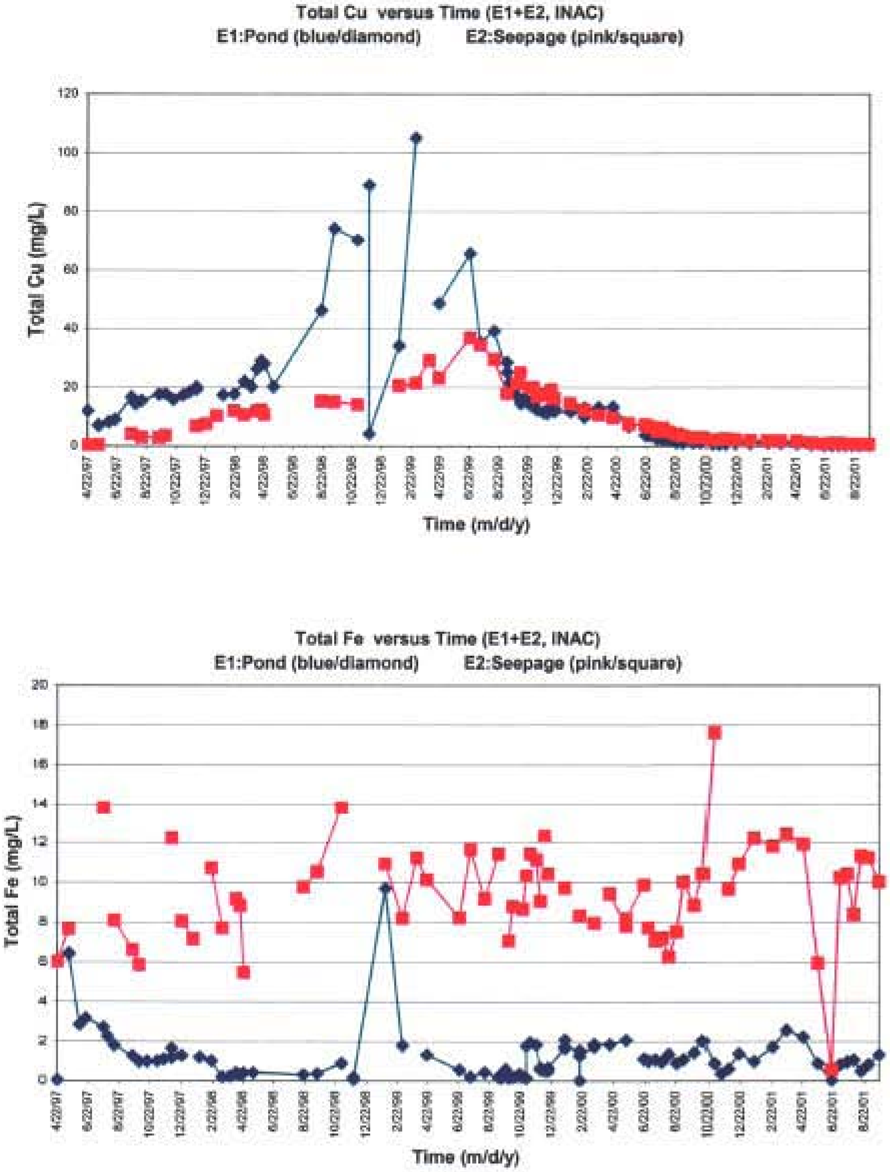


Figure 8. Temporal variations of total copper (Total Cu, upper plot) and total iron (Total Fe, lower plot) in the tailings pond water and seepage return based on INAC monitoring data.

GEOCHEMISTRY AND MINERALOGY

As described in the previous section, based on core logging in the field, tailings impounded at Mount Nansen can be divided into four categories according to apparent sulfide content and grain size variations. These are oxide silt (± sand), oxide clay (± silt), sulfidic silt (± sand) and sulfidic clay (± silt). To ascertain their mineralogical composition, 38 polished thin sections were prepared from individual or composite samples and examined with a petrographic microscope. Twelve of these were selected for further detailed analysis including point counting under a scanning electron microscope (SEM) equipped with an energy-dispersive X-ray (EDX) analyzer. In addition, 36 samples were analyzed by X-ray powder diffractometry (XRD). For geochemistry, 38 individual or composite samples were analyzed for ABA characteristics at BC Research Inc. and 110 for total metals content using four-acid digestion and ICP-AES scan at both CANMET/MMSL and BC Research Inc. Grab samples from the Brown-McDade pit were also subjected to similar analyses. In addition, 58 tailings solids resulting from the field analysis program were analyzed for Total CN. A lesser number of pond and porewater samples were also analyzed for various cyanide-related species and dissolved metals. Salient results and observations are presented below.

Tailings Geochemistry

Residual metals and parameters of environmental concern: The results of geochemical analysis of tailings solids from the impoundment and a few grab rock samples from the Brown-McDade open pit are tabulated in Appendix C. Generally, the tailings are heterogeneous in composition with anomalous contents of As (up to 0.6%), Cu (up to 0.06% and higher if contaminated by process chemicals), Pb (up to 0.6%), Sb (up to 0.1%) and Zn (up to 0.3%). The Ag content varies from 10 to 80 μg/g but Au is generally not detected (i.e., <4 μg/g). The Total CN content of selected samples analyzed ranges from 5 to 165 μg/g with most high values associated with the fine tails. From a geochemical perspective, the tailings can readily be differentiated from the underlying native sediments by an enrichment in Ag, As, Cu, Fe, Mn, Pb, Sb, Zn and Total S as well as a relative depletion in Na, Sr and, to a less extent, Ca and Mg. The contrast is best illustrated by comparing the chemical analyses of composite samples of the four tailings types with those of the native sediments (Table 1).

Nine individual native sediments sampled in the tailings coring program were analyzed to arrive at the average composition given in Table 1. A few other samples collected near the tailings contact and thus contaminated by the tailings to a varied extent were deliberately excluded. The four tailings composite samples were comprised of several samples (5 to 10) of the same type mixed together and subsequently homogenized to give a large bulk sample for various laboratory testing. For two reasons, the clayey composites were analyzed more often. First, the clayey tailings were more difficult to mix than the silty tailings, multiple analyses are required to demonstrate their homogeneity. Second, the two sets of samples have been used as inter-laboratory check samples. The mean and standard deviation shown in Table 1 are derived from analyses produced by both the CANMET-MMSL Analytical Services and BC Research Inc.

Table 1. A comparison of chemistry of the four tailings types and the underlying native sediments at the Mount Nansen tailings impoundment

Parameters	Oxide Silt Composite (MNOMIX)	Sulfidic Silt Composite (MNSMIX)	Oxide Clay Composite (BATCHO)	Sulfidic Clay Composite (BATCHS)	Native Sediments (9 samples)
Samples analysed	1	1	6	4	1 (each)
Ag (μg/g)	36	42	56 ± 3	44 ± 3	2 ± 2
As (μg/g)	2800	2270	4930 ± 383	3590 ± 166	99 ± 94
Ca (%)	0.77	1.43	1.04 ± 0.05	1.36 ± 0.10	2.50 ± 0.64
Cu (μg/g)	290	365	483 ± 225	356 ± 20	42 ± 62
Fe (%)	4.85	5.02	6.66 ± 0.04	6.06 ± 0.17	2.1 ± 0.4
K (%)	1.79	2.02	2.49 ± 0.09	2.28 ± 0.15	1.70 ± 0.18
Mg (%)	0.24	0.37	0.27 ± 0.01	0.33 ± 0.01	0.70 ± 0.18
Mn (μg/g)	1330	2380	1680 ± 94	2250 ± 155	510 ± 100
Na (%)	0.10	0.16	0.13 ± 0.01	0.13 ± 0.01	2.30 ± 0.20
Pb (μg/g)	1470	1800	4510 ± 149	2750 ± 96	49 ± 37
Sb (μg/g)	386	433	847 ± 104	443 ± 55	7 ± 6
Sr (μg/g)	96	125	131 ± 2	127 ± 1	448 ± 47
Zn (μg/g)	1020	1940	1590 ±120	1920 ± 56	92 ± 53
Total S (%)	2.30	2.36	1.38 ± 0.05	1.96 ± 0.16	0.05 ± 0.04

In addition to demonstrating the compositional differences between the tailings and the native sediments, the data shown in Table 1 lead to the following observations with regard to the geochemistry of the four tailings types:

1. The clayey tailings are more enriched in As, Mn, Pb, Zn and, to a lesser extent, in Fe and K as well as slightly impoverished in Total S than the silty varieties.
2. The sulfidic tailings are only marginally higher in Total S content than the oxide tailings regardless of grain size.
3. The oxide clayey tailings appear to be preferentially enriched in Ag, As, Pb and Sb while the oxide silt tailings are apparently depleted in Zn and, to a lesser extent, in Ca and Sr.
4. Regardless of grain size and sulfide content, Mn appears to correlate with Zn.

An odd observation regarding the tailings analyses is that the variation of Cu is significantly higher than those of the other elements. As explained later, this appears to be related to both the mode of occurrence of the prevalent Cu-containing minerals and contamination from process chemicals, especially during water treatment using the INCO-SO_2/Air process.

ABA Characteristics: Forty selected samples were analyzed for various ABA parameters using the modified ABA procedure (MEND, 2001) at BC Research Inc. The detailed data acquired are given in Appendix C. A brief perusal of the appended data readily reveals that the impounded tailings are potentially acid-generating. However, the sulfide-sulfur content does not exceed 4 wt.% in any of the analyzed samples. Thus, the worst net neutralization potential

(NNP) measured is only -82 kg $CaCO_3$/tonne. Although the inorganic carbon analyses indicate the presence of carbonate minerals in most tailings, the fact that the Carbonate NP is often lower than the sample neutralization potential (NP, determined by back titration) suggests that some of the carbonates are Fe- or Mn-bearing. Table 2 summarizes selected ABA parameters of the impounded tailings and the underlying native sediments. These data demonstrate that there are large variations in ABA properties within each tailings grouping such that the four types of tailings are not, statistically speaking, significantly different. However, it is apparent that the oxide tailings, regardless of grain size, are relatively depleted of carbonates while the fine tails, especially the oxide clay tailings, are relatively impoverished in sulfide-S.

In contrast to the tailings, native sediments underlying the impoundment appear to have some inherent acid buffering capacity. This is reflected by the positive NNP values (up to 20 kg $CaCO_3$/tonne) of the few samples analyzed.

Table 2. Summary ABA characteristics of tailings and native sediments sampled from the Mount Nansen tailings impoundment.

Sample Type	Paste pH	Carbonate-NP*	MPA*	NP*	NNP*
Oxide silt tails:					
Composite	7.7	13.2	62.8	11.1	-51.7
8 more samples	7.5 ± 0.5	29.1 ± 20.2	66.6 ±30.7	24.1 ±13.6	-42.6 ± 25.7
Sulfide silt tails:					
Composite	8.0	29.7	58.1	24.9	-33.2
10 more samples	7.9 ± 0.5	29.6 ± 15.9	63.2 ± 31.0	24.1 ± 9.8	-39.1 ± 23.1
Oxide clay tails:					
Composite	8.6	11.6	25.9	14.1	-11.8
3 more samples	8.9 ± 0.3	12.0 ± 2.9	39.2 ± 1.5	16.3 ±1.9	-22.8 ± 1.8
Sulfide clay tails	8.3	21.6	40.6	18.8	-21.8
6 native sediments	7.5 ± 0.8	12.2 ± 10.5	0.4 ± 0.6	12.9 ±11.4	12.6 ± 11.1

*Carbonate-NP=carbonate neutralization potential based on inorganic-C, MPA=maximum potential acidity based on sulfide-S, NP=neutralization potential and NNP=net neutralization potential, all measured in kg $CaCO_3$/tonne.

Tailings Mineralogy

To determine the tailings mineralogy, polished thin sections were made from 36 selected individual and composite tailings samples for petrographic examination. Portions of the same samples were also analyzed by XRD. Based on the results obtained, 12 selected polished thin sections were examined in detail under a SEM equipped with an EDX analyzer to reveal the mineral associations and composition. Salient observations are presented below.

Petrography: Largely due to the fine grain size of the tailings samples, not much detailed mineralogical identification and decipher of textural relationships can be achieved by examination under the petrographic microscope. However, even from a cursory examination of the polished thin sections, it is evident that quartz is the dominant mineral in all of the tailings samples. Alkali feldspar appears to be a subordinate phase in many sections but it is often intensively replaced by sericite ± carbonate ± clay ± epidote. Gypsum or a similar sulfate appears to be a common accessory mineral. Pyrite, generally amounting to less than 5 modal %, is the dominant sulfide identified. While many of the pyrite grains show an oxide rim, the majority of them are fresh, fully liberated grains up to about 100 μm across. In contrast, arsenopyrite is only rarely observed, mostly embedded in larger quartz grains.

XRD results: The analysis of the 36 selected tailings samples confirms that quartz is the dominant mineral in all four tailings types. In addition, muscovite ± illite, gypsum, kaolinite and jarosite are the ubiquitous accessory minerals. Montmorillonite and small amounts of pyrite, alkali feldspar and calcite are also positively identified in some of the samples. Largely due to overlapping reflection peaks, minerals occurring in less than about 5 wt.% cannot be always confirmed by XRD. Based on the XRD analysis, the clayey tails can readily be differentiated from the silty tails by the presence of a greater abundance of clay minerals (Figure 9). The oxide and sulfide varieties of the same grain size group, however, cannot be differentiated based on XRD evidence alone. Additional X-ray diffractograms of representative samples in each tailings type are appended (Appendix D-1).

SEM/EDX analysis: With the supplementary capability of an EDX analyzer for chemical analysis in situ, mineral identification can be performed in the examination of polished thin sections of tailings samples under a SEM. By setting up a grid across the thin section, the traditional point counting technique can be applied to ascertain mineral abundance. This procedure was applied in the examination of 12 selected polished thin sections. The results (Appendix D-2) show that, similar to bulk geochemistry, the tailings are heterogeneous in mineralogical make-up. However, the coarser tails generally contain more quartz (58-69 versus 41-51 modal %) and less sericite (>20 versus <16 modal %) than the fine tails. Alkali feldspar occurs in subordinate amounts (up to 17 modal %), which tends to be more concentrated in the sulfidic tails. The most abundant sulfide mineral observed in the tailings is pyrite (0.2-5 modal %). Most arsenopyrite has been altered to scorodite (Figure 10). Because of the common occurrence of encapsulation of sulfides in coarse quartz particles in all the tailings types (e.g., Figures 10 and 11) the sulfidic tailings show only marginally more sulfides than the oxide tails. In addition to iron oxyhydroxide (3-6 modal %), a common secondary mineral found in the tailings is jarosite (1-7 modal %). Other minor to trace minerals identified in the tailings include kaolinite, gypsum, calcite, ankerite, Mn-rich carbonate, manganese oxide, albite, sphalerite, galena, chalcopyrite, covellite, argentite, bournonite, rutile, ilmenite, apatite, epidote, monazite, zircon and a couple of sulfosalts enriched in Fe and Sb and Pb and Sb, respectively.

Although amorphous iron oxyhydroxide, loosely called goethite in this report, constitutes only a minor component of the tailing solids, it plays a significant role in attenuating the transport of some potentially deleterious metals and trace elements. The sorption of Zn in goethite enriched in Mn is demonstrated by a series of X-ray maps in Figure 11. Other examples of textural features of interest observed during the SEM analysis as well as chemical analyses of rare minerals are illustrated in Appendix D-2.

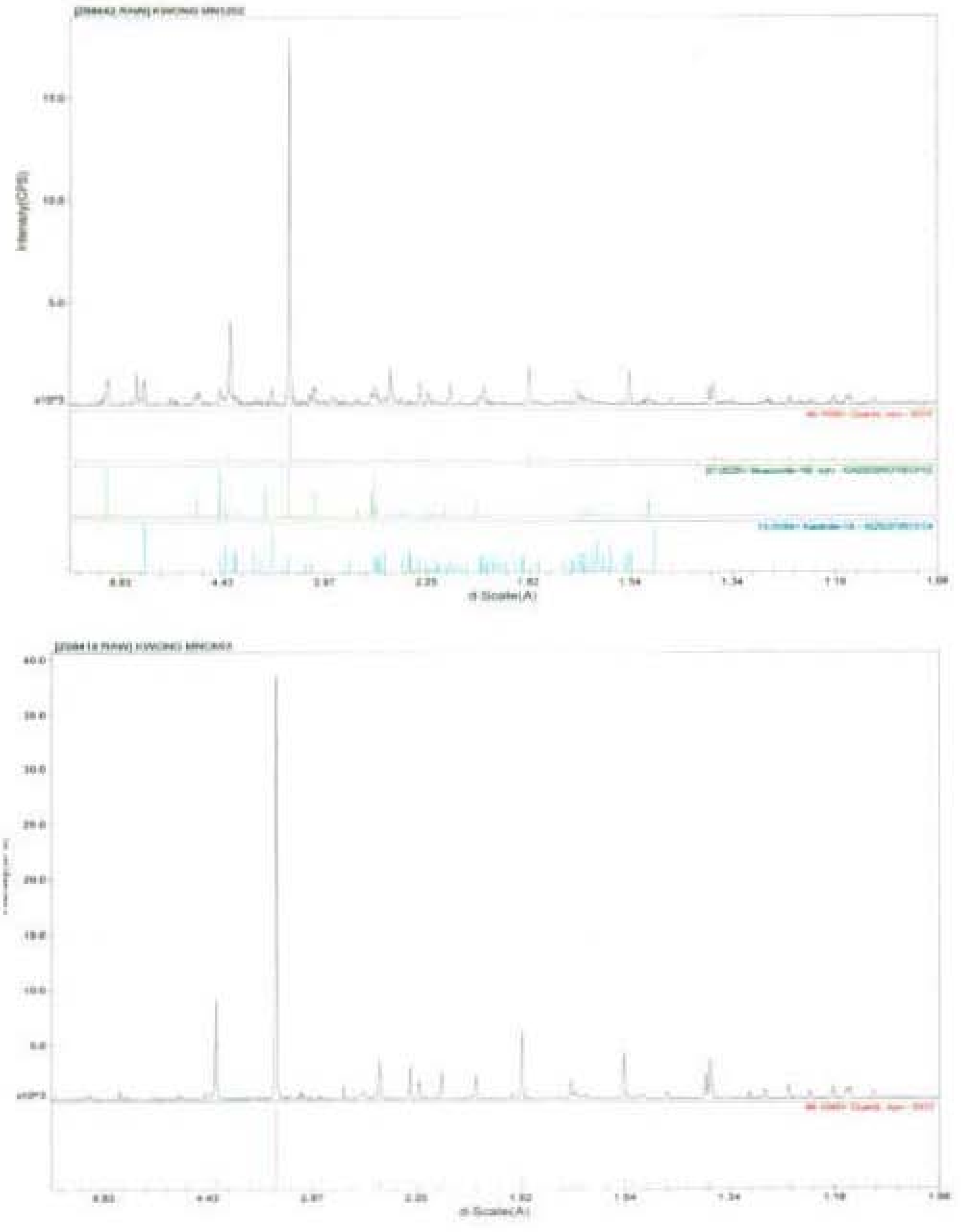


Figure 9. A pair of X-ray diffractograms illustrating that clayey tailings (above) differ from silty tailings (below) by the amount of clay minerals present regardless of sulfide content. Reference XRD patterns of relevant minerals are provided below each diffractogram to demonstrate positive identification.

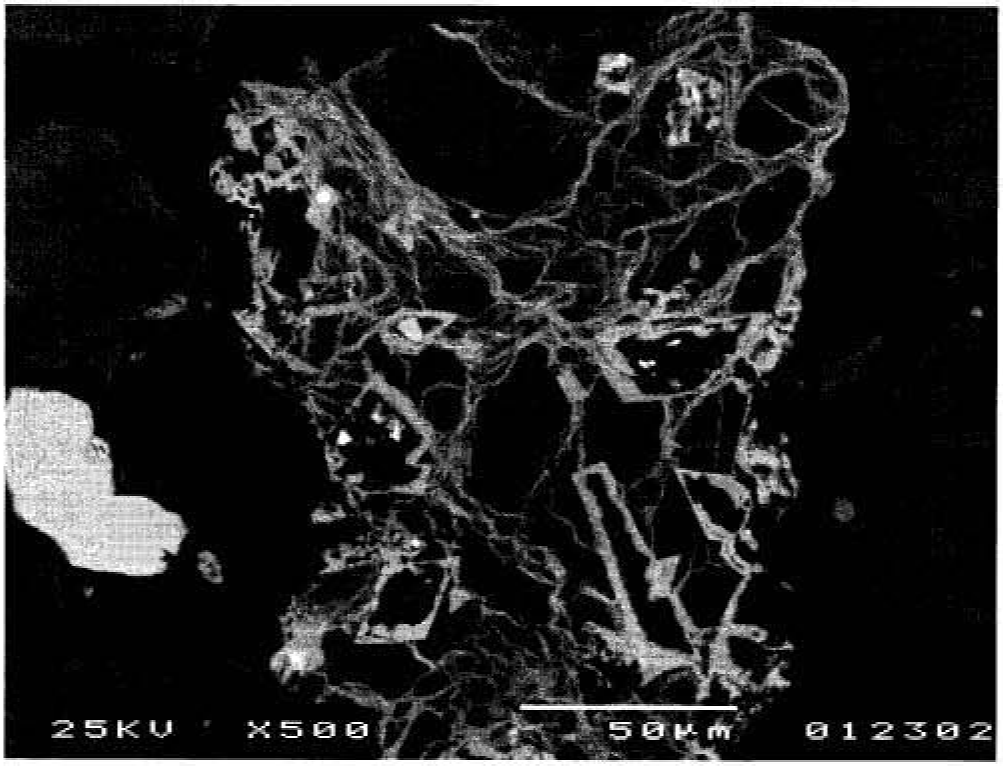


Figure 10. A backscattered electron photomicrograph illustrating complete replacement of arsenopyrite (angular grains with apparent voids in the centre and embedded in a composite grain of quartz) by scorodite. A subhedral pyrite grain (light grey, left edge of picture) is totally devoid of alteration. The small white grain inside one of the weathered-out arsenopyrite is bournonite, a lead antimony sulfide.

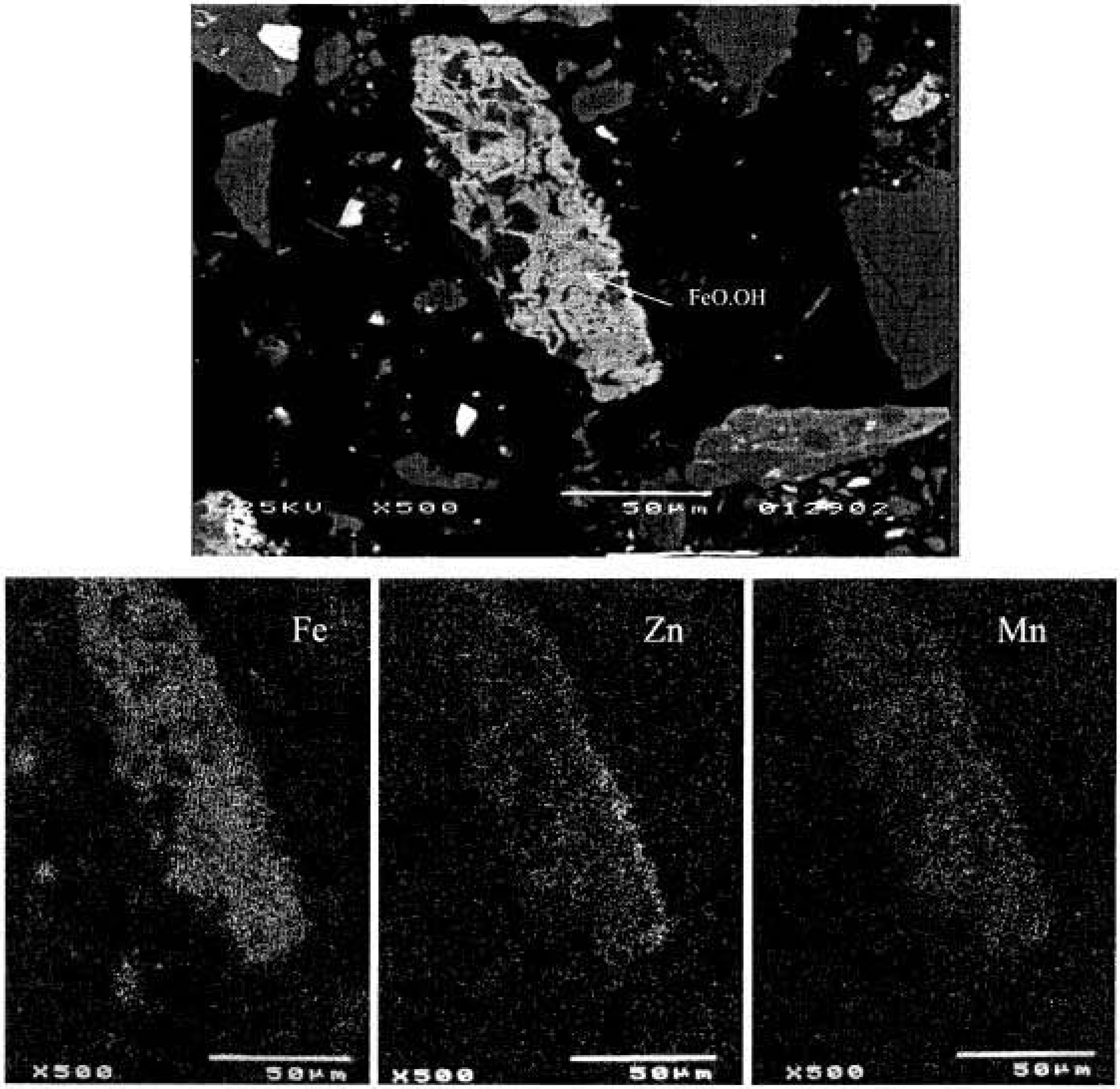


Figure 11. Top: Secondary electron photomicrograph of an aggregated grain of goethite (FeO.OH) with included quartz (dark grey). Bottom: X-ray maps of Fe, Zn and Mn of the aggregated grain above illustrating the sorption of Zn with the iron oxyhydroxide enriched in Mn content. Note also the partial encapsulation of pyrite in quartz (upper left corner in the secondary electron photomicrograph) that has hampered its oxidation to goethite.

Tailings Porewater Chemistry

Most of the core samples acquired in the drill program were saturated tailings. Upon transport from the tailings pond to the field laboratory, compaction often led to the bleeding of porewater to the surface of the tailings in a sample bag. Such porewater was carefully decanted and filtered (0.45 µm) for various analyses. For clayey tailings that did not readily bleed water, centrifuging was required to extract any porewater. Frozen tailings were allowed to thaw before porewater extraction. For samples that did not yield any porewater, leaching with de-ionized distilled water at a 1:1 liquid to solid ratio was conducted to provide a leach water (simulated porewater) for field analysis of cyanide-related species only.

The porewater samples were analyzed for pH, weak acid dissociable cyanide (WAD CN), thiocyanate (CNS), ammonia (NH_4-N), nitrite (NO_2-N) and nitrate (NO_3-N). In the field, WAD CN was measured using a Perstorp analyzer obtained from INAC. The analysis of NH_4-N, NO_3-N, NO_2-N and CNS was conducted using a Hach DR 2010 analyzer. Upon completion of the field analyses, excess porewater samples were preserved and shipped to CANMET/MMSL, Ottawa for further analysis. An aliquot of each sample (~25 mL) was preserved with concentrated nitric acid (one drop per 20 mL of sample) for ICP/MS metal scan and sulfate. The remainder was preserved using 1.0M NaOH (to pH >12) for the analysis of various CN species.

The detailed porewater analyses on each sample and a summary of the CN-related parameters and selected metals are tabulated in Appendix C-3 on a hole-by-hole basis. Briefly, the porewater Total-CN concentration ranged from 0.1 to 65.3 mg/L while the Total CN content of tailings solids ranged from 53 to 145 µg/g. The maximum porewater WAD CN concentration measured, which appeared to be strongly related to dissolved Cu, was 38.3 mg/L. The total CN and WAD CN concentrations increased with depth in Bore Holes 2, 3 and 4 while in the majority of other holes they did not follow any specific pattern with either increasing or decreasing depths. For nine porewater samples the WAD CN values obtained in field were higher than the Total-CN concentrations determined at the CANMET/MMSL laboratory. The Total CN concentration in the majority of these samples was lower than 1 mg/L. The total CN analysis was conducted in Ottawa about two weeks after the field program. Given the low initial concentrations, the time delay and the impact of NaOH addition (for sample preservation) on a variety of metal-CN complexes may have contributed to the observed discrepancies.

While the sulfidic clays contained a higher average amount of Total CN (72.7 µg/g), the oxide tailings, regardless of grain size, were more enriched in both porewater Total CN and WAD CN (Figure 12). Incidentally, the oxide tailings (both silt and clay) were also observed to have the higher average dissolved Cu and Fe concentrations in their porewater samples.

Porewater CNS concentrations ranged from <2 mg/L to a maximum of 315 mg/L. They generally did not show any relationship with either porewater Total CN or WAD CN. The CNS concentration reached 100 mg/L even for porewater samples with Total CN and WAD CN concentrations of less than 1 mg/L. The average CNS concentration for sulfide clay, sulfide silt, oxide clay and oxide silt samples were 168, 104, 118 and 140 mg/L, respectively (Figure 12). Thus sulfide clay tailings are apparently most enriched in CNS.

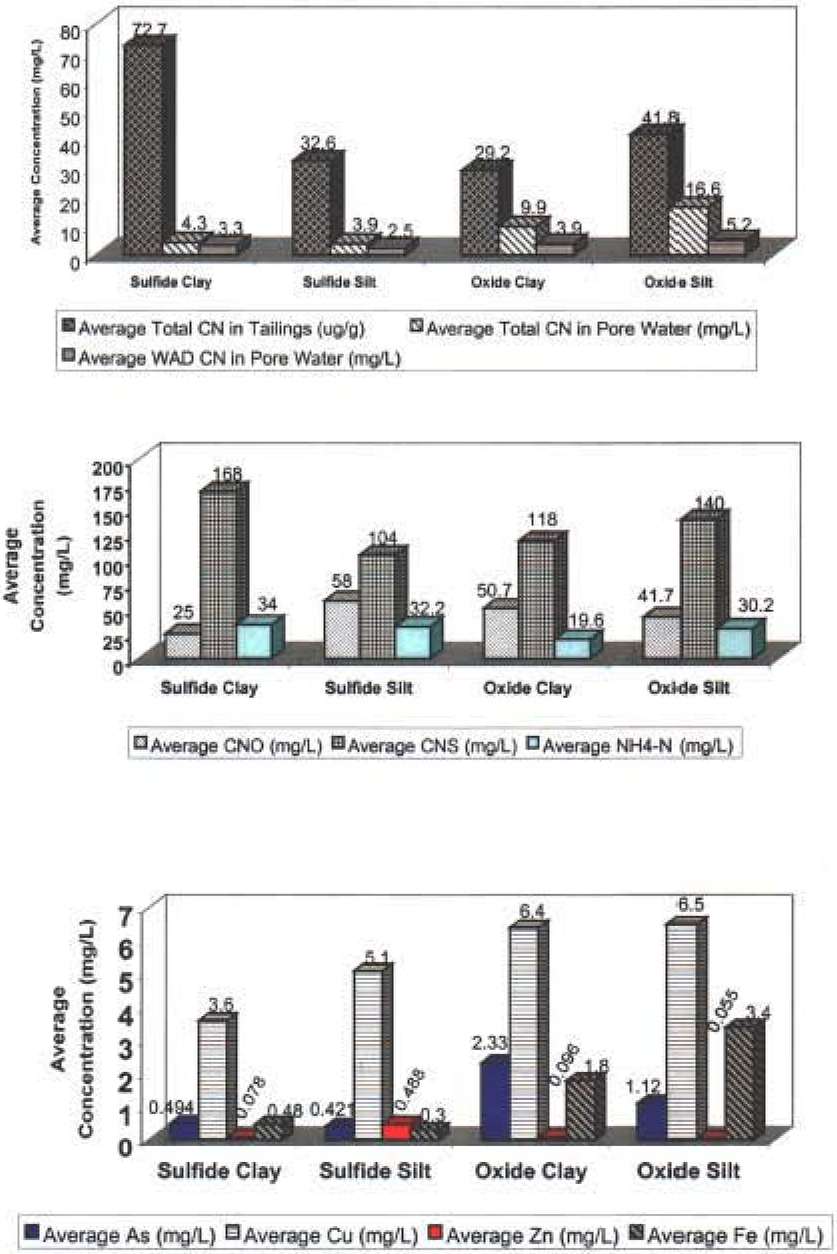


Figure 12. Average concentration of Total CN in tailings solids and various CN-related species and selected metals in porewaters of the four types of tailings identified in the Mount Nansen tailings impoundment.

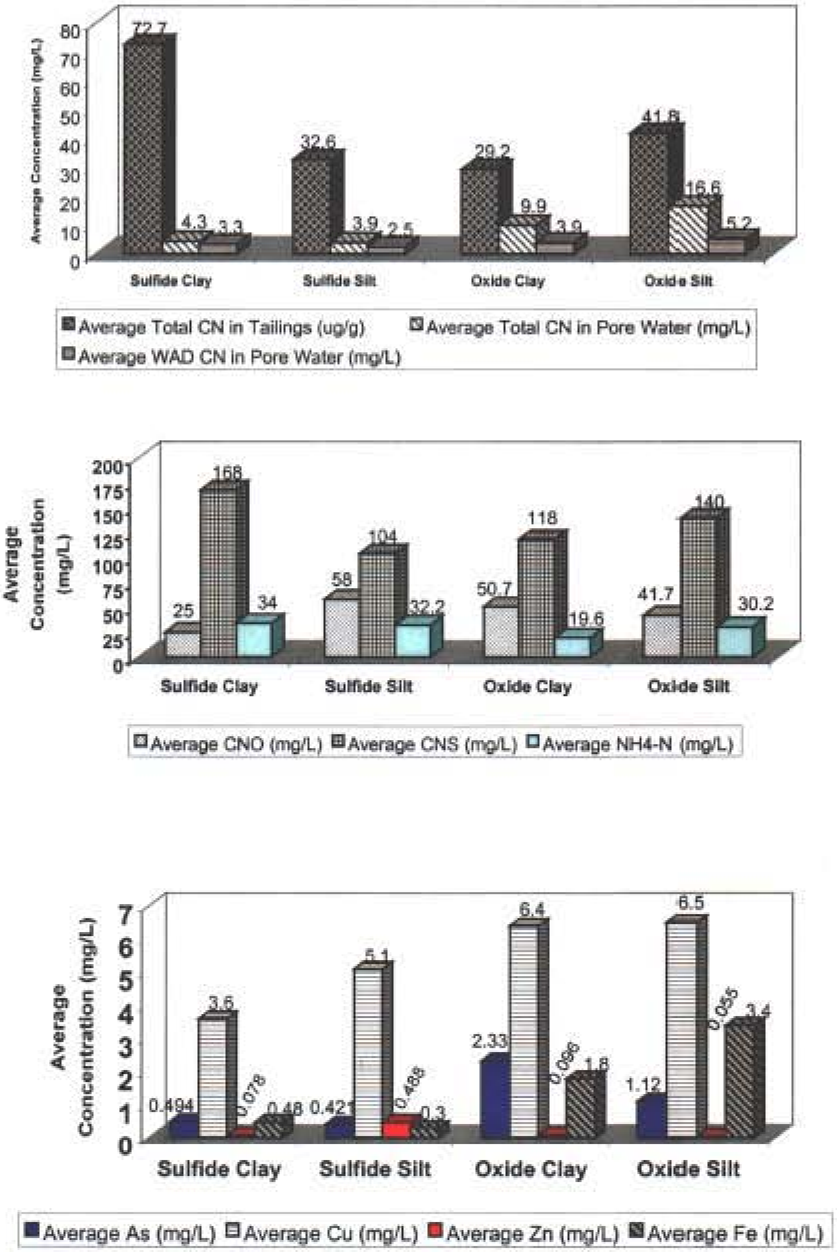


Figure 12. Average concentration of Total CN in tailings solids and various CN-related species and selected metals in porewaters of the four types of tailings identified in the Mount Nansen tailings impoundment.

Porewater CNO values in the Mount Nansen tailings ranged from 3 mg/L to 153 mg/L. Porewater samples with Total CN and WAD CN below 1 mg/L had CNO concentration below 20 mg/L. The thermodynamics of the cyanide-cyanate reaction indicates that cyanate should be the predominant species under natural conditions. However only strong oxidants are capable of directly oxidizing cyanide. Under natural conditions microbial enzymatic reactions and catalytic surfaces of minerals are able to promote this oxidization. Cyanate is also generated by the hydrolysis of thiocyanate. The average CNO concentrations in porewaters associated with the sulfide clay, sulfide silt, oxide clay and oxide silt tailings are shown in Figure 12.

The ammonia concentration in the porewater samples ranged from 1 mg/L to 59 mg/L. Ammonia concentrations in general were higher for samples containing higher amounts of CNS. In the leach water samples (mainly on BH 5 cores that yielded no porewater) the WAD CN, CNS and NH_4-N concentrations were <0.2, 10 and 10 mg/L, respectively. The analysis of frozen ice samples below the snow cover gave <0.1 mg/L WAD CN but the CNS concentrations were between 50 to 65 mg/L and ammonia in the 20 to 25 mg/L range. The variation of average NH_4-N in porewaters of the different tailings types is also shown in Figure 12.

As expected, the average Total S concentration in the porewaters was higher in sulfide silt/clay cores than in oxide clay/silt cores. The dissolved As concentration in porewaters ranged from as low as 1 µg/L to as high as 5,620 µg/L. The maximum Zn concentration in the porewater samples was 5,774 µg/L. The Cu concentration ranged from 0.01 mg/L to 27.7 mg/L. In general, samples with a higher Cu concentration also showed higher WAD CN. The average porewater Zn concentration was higher for sulfide silt cores (Figure 12). The average As concentration in porewater samples was higher for oxide cores than for sulfide cores. The Cu concentration in general was higher in oxide silt (6.5 mg/L) and oxide clay (6.4 mg/L) than in sulfide silt (5.09 mg/L) and sulfide clay (3.6 mg/L). The average porewater Fe concentration in the oxide silt/clay cores was higher than that in the sulfide clay/silt cores.

Analyses of Grab Samples from the Brown-McDade Pit

Samples collected during a brief examination of alteration and remnant mineralization at the Brown-McDade pit and subjected to detailed analysis include the following:

1. Four grab samples of intense alteration at the two adits and a breccia zone in the north wall near the middle of the pit;
2. Two pit water samples from the top and bottom of the pit pond, respectively; and
3. A small sample of sediments accumulated at the bottom of the pit.

The results of XRD, SEM/EDX and geochemical analyses of the grab alteration samples confirm the presence of pyrite as the dominant sulfide and gypsum, jarosite, muscovite/illite and kaolinite the common crystalline alteration products. Two samples submitted for ABA characterization are shown to be potentially acid-generating with NNP values of -92 and -147 kg $CaCO_3$/tonne, respectively. X-Ray diffraction analysis of the pit sediment reveals that it differs from the impounded tailings by the presence of a significant amount of montmorillonite and the absence of gypsum. Quartz, muscovite/illite and kaolinite are the other constituents identified.

The analysis of the pit waters by ICPAES reveals the presence of chemical stratification in the pit pond. The sample collected from just beneath the ice cover, which was used in the column and leaching studies, contained significantly less dissolved metals than the sample collected near the bottom of the pit. Notable contrasts include 0.04 versus 0.35 mg/L Al; 127 versus 426 mg/L Ca; 0.05 versus 0.86 mg/L Fe; 1.25 versus 5.99 mg/L K, 29.0 versus 397 mg/L Mg; <0.006 versus 0.025 mg/L Mn; 7.99 versus 15.8 mg/L Na; 81.7 versus 899 mg/L total S; and, 0.82 versus 1.74 mg/L Zn. Dissolved Si, however, was enriched near the top of the pit (9.84 versus 3.72 mg/L). Dissolved As, Cu, Pb and Sb in both of the water samples were below the ICPAES quantification limits (which is defined as 10X the detection limits) of 0.55, 0.018, 0.52 and 0.32 mg/L, respectively. Supplementary ICPMS analyses gave 0.024 mg/L As and 0.060 mg/L Sb in the surface pit water, 0.014 mg/L As and 0.022 mg/L Sb in the bottom water and <0.020 mg/L Pb in either water. The pit surface water gave a field pH measurement of 7.1 while that of the pit bottom water was pH 7.5. It thus appears that both As and Sb are more soluble in a higher pH medium.

COLUMN TESTING

Purpose of Study

To investigate possible interactions of the impounded tailings with water accumulated in the Brown-McDade pit, eight columns were set up to simulate four disposal scenarios in duplicate (Figure 13). The scenarios are:

1. High sulfide tailings under a water cover;
2. Low sulfide tailing under a water cover;
3. Mixed (high and low sulfide) tailings slurried and placed under a water cover; and
4. Mixed tailings under flow-through conditions.

Figure 13. Eight columns set up to study four disposal scenarios for the Mount Nansen tailings

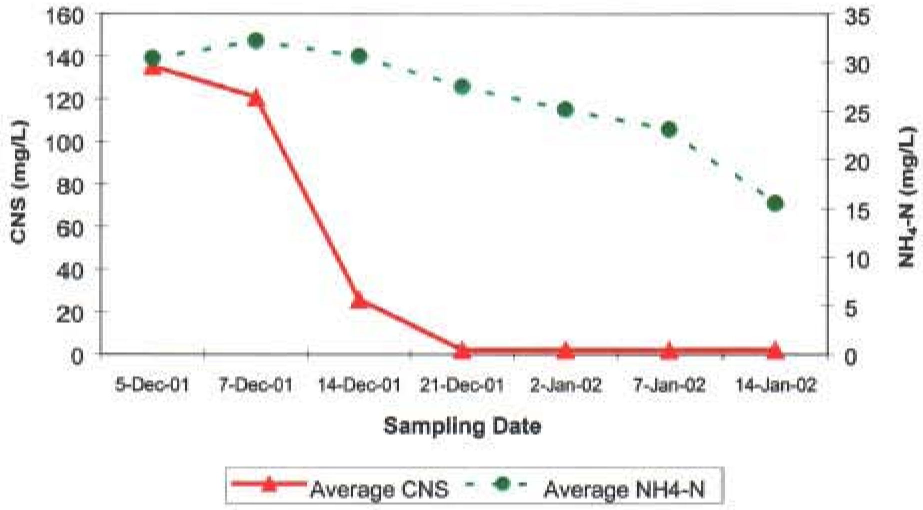
Scenarios 1 and 2 simulate the transfer of tailings with relatively little water followed by placement under a shallow water cover. Scenario 3 simulates transfer of mixed coarse tailings as a slurry, followed by settling under a shallow water cover. Scenario 4 (flow through) simulates leaching of exposed tailings by natural precipitation. For practical reasons (time and permeability of the test solids), only composite samples of the coarser tailings (sulfide and oxide silts) were used in the column testing. The column configuration and set up, test procedures and monitoring data acquired to date are detailed in Appendix E. Between December 2001 and February 2002, the columns with a water cover were sampled four times and the flow-through columns ten times. For the former, samples of the overlying water and porewater at 5 cm below the water/tailings interface were collected in addition to one drawn from the base of the columns. For the latter, sampling was done only from the base of the columns. Salient observations on the water analyses are presented and discussed below.

Results and Observations

Since the commencement of the column testing in December 2001, Total and WAD CN have not been released into the water to any significant degree in all the disposal scenarios studied. Total CN in concentrations ranging from 0.05 to 0.07 mg/L were observed in the last two sampling events at the base of the columns with tailings under a water cover (Scenarios 1 and 2). The high-sulfide columns had the higher CNS concentrations in porewater and at the base of the column. The average CNS concentrations in the porewater and at the base of the high-sulfide column were 39 and 131 mg/L, respectively, at the last sampling event conducted on February 11, 2002. In the low-sulfide columns, CNS was detected only at the base of the columns during the last two sampling events with a concentration range of 9.9 to 12 mg/L. Ammonia was detected in all columns. The NH_4-N concentration in the high-sulfide columns ranged from a minimum of 3.75 mg/L in the water cover to a maximum of 35 mg/L in the porewater. In the low-sulfide columns, the NH_4-N concentration ranged from a minimum of 0.54 mg/L in water cover to a maximum of 24.7 mg/L at the base of the column. The water cover of the mixed slurry columns in general had higher NH_4-N compared to the low- and high-sulfide columns, with a maximum NH_4-N concentration of 21.4 mg/L at the start of the column study. For the columns with a water cover, NH_4-N at the base of the columns was observed to increase with time, whereas porewater NH_4-N was observed to decrease with time. A similar trend was observed for CNS and SO_4 concentrations in the porewater and at the base of the columns with a water cover. The flushing of porewater from the upper regions of the columns through extraction of water samples at the base of the column may have contributed to the observed increase in the NH_4-N at the base of the columns. As ammonia is a degradation product of CN and CNS, its presence indicates that CN/CNS degradation reactions were taking place. Since the column testing is conducted at room temperature (considerably higher than that under field conditions) the CN/CNS degradation rates may have been enhanced. Cyanate was not observed in the columns with the water cover during the first two sampling events. In the high-sulfide tailings, a maximum CNO concentration of 25 mg/L was observed in the tailings porewater and at the base of the columns. Lower CNO concentrations were observed in the low-sulfide, mixed slurried tailings and flow-through columns. The presence of CNO also confirms that CN/CNS degradation reactions were taking place in the columns and possibly the reactions rates were enhanced towards the last two sampling events. It is thus desirable to continue the column testing for at least three additional sampling events to clarify the evolution trends. The oxidation of ammonia to nitrite and nitrate was not observed to any significant levels in any of the columns. The only other ammonia removal mechanisms from water would be by volatilization and/or by ion exchange/sorption with the clay particles in the tailings. Since the pH in the columns was generally below 9.5, ammonia removal by volatilization would not be significant.

Arsenic was observed in the water cover, porewater and base flow of all the columns. The dissolved arsenic concentration in the water cover, porewater and at the base of the high-sulfide and mixed slurry tailings columns increased with time and appeared to have stabilized at concentrations of 1.5 ± 0.2 mg/L. A maximum arsenic concentration of 2.58 mg/L was observed at the base of the low-sulfide columns at the last sampling event. Dissolved zinc in the porewater and at the base of the columns decreased with time to concentrations of less than 0.038 mg/L at the last sampling event. However, zinc was generally present in higher concentrations (0.08 to 0.62 mg/L) in the water cover compared to porewater and at the base of the columns. This can readily be explained by the higher Zn concentration (0.74 mg/L) in the pit water, which was used in the column testing. Lower dissolved Zn in the porewater and at the base of the columns suggests that Zn was removed by precipitation/sorption on mineral surfaces as overlying water was drawn downward during sample collection. A maximum dissolved Cu concentration of 0.194 mg/L was observed at the start of the testing in the flow-through columns. Generally, the dissolved Cu concentrations in the water cover, porewater and at the base of the columns have decreased to levels ranging from 0.03 to 0.05 mg/L by the last sampling event. Dissolved Cu at much higher concentrations was observed in porewater samples collected from the tailings pond. Here the porewater results indicate a strong relationship between Cu and WAD CN concentrations. Dissolved Cu, Total and WAD CN were not found in the column samples at concentrations comparable to the tailings pond porewater results. It is possible that WAD CN (predominantly as copper-cyanide complex) degraded between the time the core samples were extracted from the tailing pond and the set up of the columns. The Cu released from WAD CN degradation could have precipitated or sorbed onto mineral surfaces and the CN could have either volatilized, degraded or formed complexes with Fe and also precipitated among the tailings solids. It is also possible that redox-potential changes and other secondary reactions may have led to the formation of a variety of precipitates such as Cu (I, II) and ferri/ferro cyanide complexes, which are highly insoluble and can remain inert (Smith and Mudder, 1991). Compounds such as hexacyanoferrates are usually tightly bound to the tailings solids. They are thermodynamically stable and do not dissociate readily. In an iron-rich medium containing excess ferric, ferrous and copper ions, an insoluble metal hexacyanoferrate often forms and precipitates out from solution. This could also explain why total CN was not released to any significant degree in the column testing.

While the column test work to date indicated that tailings might not release significant amounts of Total CN and WAD CN to the water cover and base flow, seepage water collected during the drilling program had Total CN and WAD CN contents of approximately 0.3 mg/L. The tailings seepage at the site has been continuously pumped back to the tailing pond. The CNS and NH_4-N concentrations in the tailings pond seepage water were 60 mg/L and 17 mg/L, respectively. The average CNS and NH_4-N concentrations observed in the last sampling event at the base of the mixed slurried tailing columns were 58 mg/L and 21.7 mg/L, respectively. However, in the flow-through columns (simulating a storm accelerated flushing scenario) CNS was no longer detectable at the base approximately two weeks after the column set up. Instead, its degradation product NH_4-N was observed at an average concentration of 15.5 mg/L during the last sampling event. Thiocyanate was present in the base flow of the columns with a water cover at the last sampling event. The average CNS concentrations ranged from 11.5 mg/L in the low-sulfide columns to 131 mg/L in the high-sulfide columns. Figure 14 shows time-series plots of CNS, NH_4-N, SO_4, As and Sb observed at the base of the flow-through columns. The flow-through column results to date show that the release of NH_4-N from the tailings will likely continue to decrease with time in concentration. The concentration of As initially increased and now appears to have stabilized at a concentration of approximately 0.9 mg/L. The leaching of Cu, Zn and Sb appears to have stabilized at approximately <0.03 mg/L, 0.03 mg/L and 0.08 mg/L, respectively. The average dissolved As concentration in the base flow samples of columns with a water cover was approximately 1.6 mg/L in the high-sulfide and mixed slurry tailings columns and 2.58 mg/L in the low-sulfide columns.



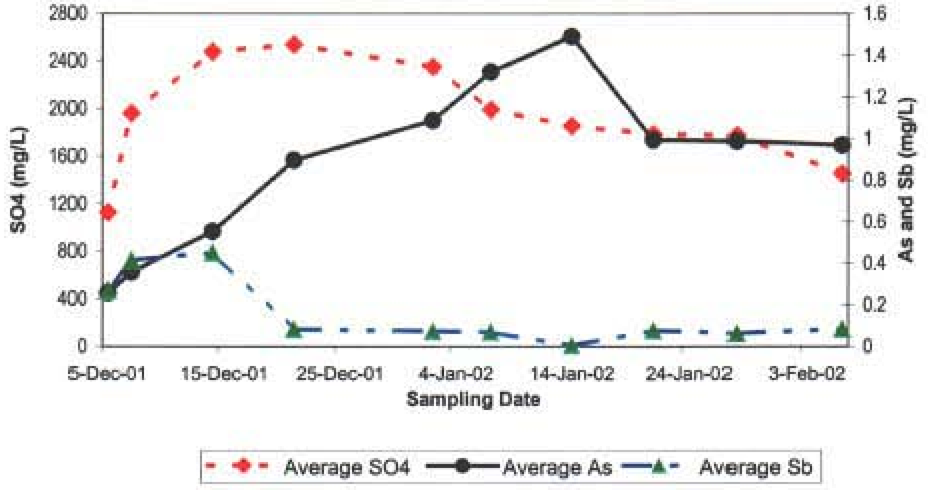


Figure 14. The average concentration of CNS, NH_4-N, SO_4, As and Sb in samples collected at the base of the flow-through columns.

Based on observations made to date in the column study, the method used for moving the tailings from the present location to the pit could also impact the water quality of the resultant water cover and seepage water. The tailings, if slurried and then pumped to the pit, will initially generate higher concentrations of CNS, SO_4, NH_4-N, As and Sb in the water cover. Moving the tailings in a relatively dry form may not have as significant an impact on the water cover quality. At the time of the field sampling campaign, the tailing pond seepage water had dissolved As, Cu, Sb and Zn concentrations of 0.037, 0.389, 0.004 and 0.643 mg/L respectively. In the flow-through columns after approximately three months of pit water application the average concentrations of dissolved As, Cu, Sb, and Zn in the collected samples were 0.969 mg/L, 0.029 mg/L, 0.084 and 0.013 mg/L, respectively. In all of the columns, the base flow samples in general had higher concentrations of dissolved As and Sb and lower concentrations of dissolved Cu and Zn than those measured in the tailings pond seepage return water. The column testing to date shows that, with the exception of overlying water in the low-sulfide columns, dissolved As levels in most samples were higher than the 0.5 mg/L limit of maximum acceptable monthly mean value indicated in the Environment Canada's Metal Mining Liquid Effluent Regulations and Guidelines (1977). Total CN and WAD CN were below the detection limit of 0.05 mg/L in the majority of samples collected. The maximum Total CN and WAD CN concentrations observed in the column study were 0.10 and 0.17 mg/L, respectively. It appears that to date Total CN associated with the tailings in the columns did not leach into the water as Total CN or WAD CN to any significant degree.

SEQUENTIAL BATCH LEACH TESTS

Because of the fine grain size of the clayey tailings and consequently their inherently low permeability, it is not practical to run column testing with them. Instead, the sequential batch test as described by Filipek (1999) is adopted to investigate the impact of varying water to solid ratios on the leaching behaviour of the fine tailings. Two tests were conducted, one on untreated tailings and the other on tailings after treatment with the INCO-SO_2 process. The focus of the former was on metal releases and the latter on the behaviour of CN-related species.

Test with Untreated Tailings

The test procedure is schematically illustrated in Figure 15. The experiment was started with 100 g of fine tailings shaken overnight with 100 mL of the Brown-McDade pit water as the leach medium. An aliquot of the filtered leachate was advanced successively through a new, smaller batch of fresh tailings from left to right while keeping the same liquid to solid ratio. From top to bottom, the residue from the previous leaching step was successively leached with an increasing amount of pit water. In other words, going from left to right, the same batch of pit water encountered more and more fresh tailings while from top to bottom, the same batch of tailings was subjected to repeated leaching by new batches of pit water. Consequently, although the liquid to solid ratio was maintained the same along a horizontal series of batch leaching, the effective liquid to solid ratio at each leach step varied. The latter was calculated and shown in each box pertaining to an individual step in the batch test procedure. Note that there are built-in redundancies in the test procedure such that Leachates A1 and B3 have the same effective liquid to solid ratio and so do Leachates B1 and C2. The agreement between the analyses of a particular constituent in these corresponding leachates indicates if sorption and rapid dissolution control the behaviour of the constituent, or if errors have been made in the test work or in the subsequent chemical analysis.

The ICP-AES analyses of the leachate samples show that As and Sb are the only trace elements that were significantly leached from the tailings. The test results are illustrated in a plot of amount of elements released versus the effective liquid to solid ratio in each leach step (Figure 16). The major cations, K and Ca, are also included in the diagram to illustrate the different processes that could have occurred during the batch leach testing.

Of the four elements depicted, K shows the most significant and consistent decrease in concentration with increasing effective liquid to solid ratio. This reflects that the release of K into the leachates was indeed controlled by sorption or rapid dissolution reactions. The dissolved Ca concentration in the leachates does not appear to vary at all with the effective liquid to solid ratio except for the leaching of the oxide clayey tailings at high dilution. This suggests a solubility control on the Ca release throughout most of the sequential batch testing. Given the notable presence of gypsum in the tailings, it is likely that rapid dissolution of gypsum had maintained a constant Ca concentration in the leachates until it was totally depleted. In other words, the leachates were in equilibrium with gypsum except at very high dilutions. A perusal of the associated sulfate data (Appendix F) provides additional support for the gypsum dissolution hypothesis. Since the oxide tailings contain less gypsum than the sulfide tails, it is logical to expect that gypsum will be depleted sooner in the former, leading to the observed drop in dissolved Ca concentration when the effective liquid to solid ratio approached 6 (Figure 16).

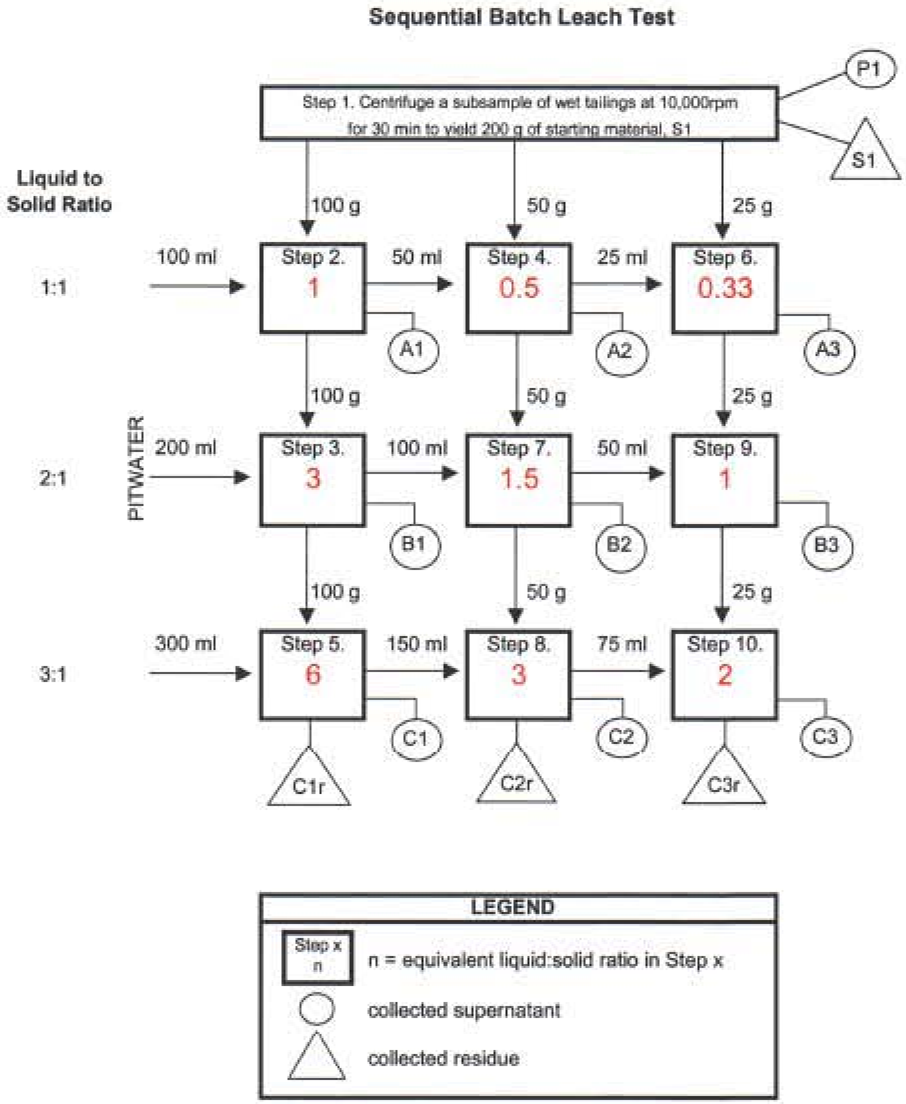

Sequential Batch Leach Test

Figure 15. A schematic diagram showing the test procedure for the sequential batch test.

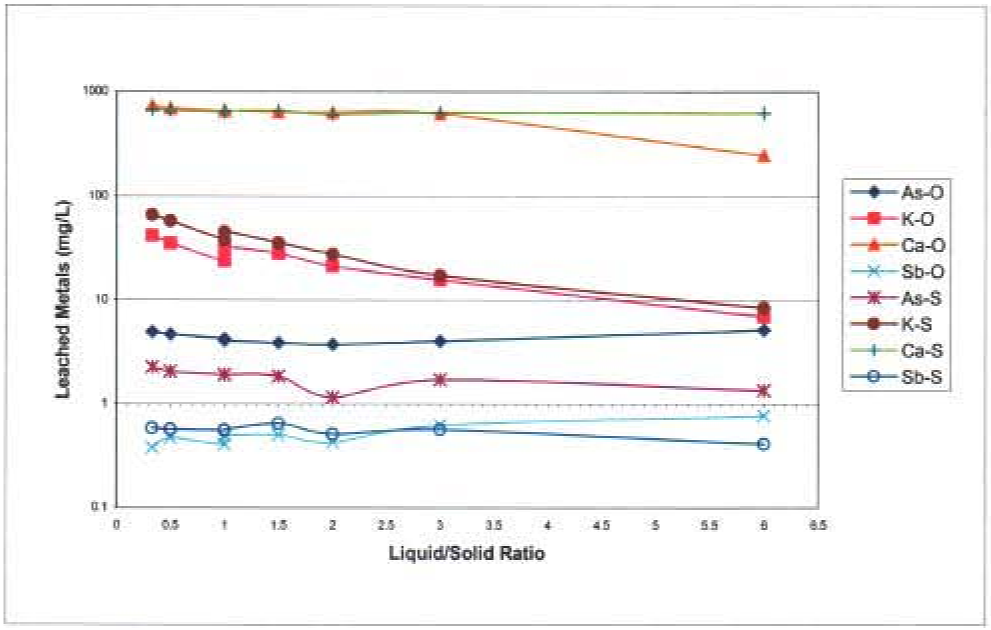


Figure 16. Variation of elements released with effective liquid to solid ratio in a sequential batch leach of clayey tailings with the Brown-McDade pit water. (O in the legend refers to oxide tails and S to sulfide tails.)

The leaching of As and Sb apparently followed a different path depending on the composition of the tailings tested. With the clayey sulfide tailings, both the As and Sb concentrations in the leachates slightly decreased with an increasing effective liquid to solid ratio in the leaching process. With the clayey oxide tailings, however, the leachate Sb concentration showed a slight increasing trend at higher dilution. The leachate As concentration first decreased and then increased with an increasing liquid to solid ratio. These observations suggest that the leaching of As and Sb from the sulfide tails was controlled by slow desorption and dilution reactions. In contrast, ionic exchange probably dominated the As and Sb release from the oxide tailings, especially under high dilution conditions.

Test with INCO SO_2/Air Treated Tailings

The INCO SO_2/Air treatment process is commonly used for the removal of free and complexed cyanide from water and tailings. The process uses a combination of SO_2 plus oxygen in air as an oxidizing agent in the presence of copper as a catalyst. The reaction is normally completed in 5 to 60 minutes. This process has been widely used in the gold mining industry.

The INCO SO_2/Air treatment of the fine sulfide and oxide tailings was conducted separately in a 2 L reaction vessel. Prior to treatment, the tailings were vacuum-filtered to remove the associated porewater. One kg of tailings were thoroughly mixed with 1.5 L of deionized water using a magnetic stirrer bar. One hundred mg of copper sulfate was also added to the reactor. Sulfur dioxide and air were then introduced into the tailings slurry at a flow rate of 20 mL/min and 110 mL/min, respectively. The slurry was continuously mixed and lime was added to maintain the pH at 9.5. The tests were conducted for 45 minutes. In total, 50 g of lime was added during the treatment of the tailings.

The total CN of 63 µg/g in the sulfide tailings solids was reduced to less than 0.2 µg/g after the treatment. The total CN in the oxide tailings solids was reduced from 47 µg/g to <0.2 µg/g. Thus the INCO SO_2/Air treatment was effective in removing the Total CN associated with the tailings. The Total CN concentration in the INCO SO_2/Air process water was detected at 4.05 and 1.0 mg/L for the sulfide and oxide tailings, respectively. The WAD CN, CNS, NH_4-N and SO_4 concentrations in the process water for the sulfide tailings were <0.05, 15, 10.4 and 1,630 mg/L, respectively. The corresponding values for the oxide tailings were <0.05, 22, 6.3 and 494 mg/L, respectively. The dissolved As, Cu, Zn and Sb concentrations in the INCO SO_2/Air process water for the oxide tailings were 1.34, 0.043, 0.016, and 0.260 mg/L, respectively. For the sulfide tailings, the corresponding analyses were 0.438 mg/L As, 0.043 mg/L Cu, 0.052 mg/L Zn, and 0.128 mg/L Sb. Higher concentrations of As and Sb were released during the INCO SO_2/Air treatment of the oxide tailings compared to treating the sulfide tailings.

The tailings after INCO SO_2/Air treatment were subjected to the sequential batch test. The results are shown in Table 3 for the sulfide tailings and in Table 4 for the oxide tailings according to effective liquid to solid ratios. A high degree of variability in the concentration of the measured parameters was observed. In the leaching of the two tailings composites, the maximum concentrations of Total CN, WAD CN, CNS, and NH_4-N released into the water were 3.8, 0.09, 7 and 9.8 mg/L, respectively. Arsenic, Cu, Zn and Sb released into water at maximum concentrations of 3.86, 0.069, 0.187 and 0.403 mg/L, respectively, were also observed.

Table 3. Results of sequential batch test conducted for sulfide tailings after INCO SO_2/Air treatment.

Parameter	Effective Liquid Solid Ratio								
	0.33 (A3)	0.5 (A2)	1 (A1/B3)		1.5 (B2)	2 (C3)	3 (B1/C2)		6 (C1)
pH	8.87	8.16	8.34	9.08	8.42	8.41	8.06	8.34	8.07
Conductivity (µS/cm)	-	2650	2870	2420	2600	2910	2500	2520	2010
Total CN (mg/L)	3.40	<0.05	<0.05	1.50	<0.05	0.50	<0.05	0.06	0.10
WAD CN (mg/L)	<0.05	0.07	<0.05	0.06	0.09	0.05	0.09	0.06	<0.05
CNS (mg/L)	7	6	<1	<1	<1	<1	<1	<1	<1
NH_4-N (mg/L)	1.7	12	8.1	-	6.3	2.9	2.3	2.4	<1
As (mg/L)	3.12	1.10	1.07	2.98	1.06	2.98	0.934	3.83	1.02
Cu (mg/L)	0.063	0.063	0.033	0.035	0.032	0.036	0.069	0.033	0.025
Zn (mg/L)	0.164	0.110	0.034	0.012	0.025	0.026	0.187	0.021	0.017
Sb (mg/L)	0.324	0.242	0.272	0.305	0.233	0.334	0.233	0.240	0.185

Table 4. Results of sequential batch test conducted for oxide tailings after INCO SO_2/Air treatment.

Parameter	Effective Liquid Solid Ratio							
	0.33 (A3)	1 (A1/B3)		1.5 (B2)	2 (C3)	3 (B1/C2)		6 (C1)
pH	8.31	9.50	8.70	9.24	8.4	8.77	8.62	
Conductivity (µS/cm)	2710	1131	2450	1809	2470	1725	2020	1602
Total CN (mg/L)	0.3	3.8	0.2	2.2	0.2	1.5	1.0	0.6
WAD CN (mg/L)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
CNS (mg/L)	<1	5	<1	<1	<1	<1	<1	<1
NH_4-N (mg/L)	9.8	2.0	4.1	1.4	2.3	1.4	1.0	<1
As (mg/L)	1.18	3.58	1.08	3.86	1.25	3.44	1.32	3.57
Cu (mg/L)	0.046	0.035	0.032	0.030	0.033	0.032	0.033	0.030
Zn (mg/L)	0.040	<0.005	0.024	<0.005	0.020	0.070	0.009	0.009
Sb (mg/L)	0.403	0.263	0.249	0.311	0.309	0.357	0.397	0.312

These results show that treating the tailings with the INCO SO_2/Air process could remove the Total CN associated with the tailings. However, CNS, NH_4-N and sulfate will be generated during the process. Arsenic and antimony will also be released from the tailings into the water during the INCO SO_2/Air treatment. Much of the Total CN released into the process water during the treatment could have been further eliminated by increasing the reaction time from 45 minutes to 60 minutes.

SELECTIVE LEACHING AND FREEZE THAW STUDIES

To complement the column testing and sequential batch leach test work, customized leach tests and freeze thaw studies were conducted on samples representative of the four tailings types to elucidate the impact of changing environmental conditions on the tailings chemical stability. Salient results and observations are presented below.

Selective Leach Tests

a) Partial sequential extraction analysis: The potential for remobilization and hence the bioavailability of trace elements associated with geologic materials like tailings depends on how the elements are distributed among the different components in a typical sample. Hall et al. (1997) have furnished a sequential extraction scheme involving a series of successive chemical treatments of a sample, each being more drastic in nature than the previous step, to determine the relative mobility of trace elements associated with five common components of a geological sample. Exchangeable and adsorbed trace elements and those coprecipitated with carbonates (collectively known as the AEC component) can readily be leached by subtle changes in the composition of a circulating fluid. Trace elements associated with hydrous oxides of Mn and Fe (abbreviated as the amorphous FeO fraction) can readily be remobilized under mildly reducing conditions. Trace elements associated with the other components that can be released with increasing difficulty include those bound by crystalline FeO, sulfides and organics, and a residual fraction usually locked in silicate minerals. The AEC and amorphous FeO bound trace elements thus represent the more readily remobilized and bioavailable fractions in a geologic sample while those bound in other components can only be leached under conditions not readily reached in a natural setting.

To determine the mobile metals and trace elements associated with the impounded tailings at Mount Nansen, a partial sequential extraction procedure of Hall et al. (1997) was adopted. The AEC fraction was determined by extraction with a sodium acetate solution buffered at pH 5.0. Metals and trace elements associated with amorphous and hydrous Fe and Mn oxides (i.e., the amorphous FeO fraction) were extracted with a solution of 0.25 M $NH_2OH.HCl$ in 0.05 M HCl. Six samples of different tailings types were tested. The raw data are tabulated in Appendix F and the derived fractionation results are summarized in Table 5.

Several observations can readily be made from a perusal of the data shown in Table 5. These include the following:

1. Amorphous Fe±Mn oxyhydroxides are a significant host for Cu, Pb, Zn and, to a lesser extent, As, in the Mount Nansen tailings.
2. With about 40% of the total concentration associated with the AEC and amorphous Fe-Mn oxyhydroxides, Zn is understandably the metal most susceptible to remobilization in the impounded tailings.
3. A relatively high proportion (average about 20%) of Cu and Pb in the tailings, regardless of grain size and composition, also occur in readily releasable forms. However, the total Cu concentration in the tailings solids is relatively low and thus

will not give rise to highly concentrated leachates. For Pb, a greater proportion of the releasable component is associated with the amorphous oxyhydroxide. It can be remobilized only under reducing conditions where the oxyhydroxides are no longer stable.

4. The clayey tailings apparently host more AEC As than their silty counterparts. The relatively low proportion of amorphous oxide-bound As in the silty oxide tails suggests that sorption with clay minerals is an important mechanism for attenuating transport of As in the impoundment.
5. With less than 5% of the total concentration occurring in readily releasable forms, most Sb in the Mount Nansen tailings is likely locked up in sulfosalts as observed during SEM examination of selected tailings.

Table 5. Proportion of easily releasable As, Cu, Pb, Sb and Zn in the Mount Nansen tailings as derived from sequential extraction analysis.

Sample Description	*As*	*Cu*	*Pb*	*Sb*	*Zn*
Oxide clay BATCHO					
Total concentration, µg/g	4926	483	4514	847	1588
% AEC	11.4	3.3	4.5	2.0	11.4
% Amorphous FeO-bound	6.5	8.4	20.5	<1	28.3
Sulfide clay BATCHS					
Total concentration, µg/g	3589	356	2745	443	1916
% AEC	10.0	12.3	3.7	2.6	12.0
% amorphous FeO-bound	9.8	14.6	19.6	<2.2	34.4
Sulfide clay MN1102					
Total concentration, µg/g	4070	630	3750	571	2440
% AEC	8.5	6.9	5.0	<1.7	12.0
% amorphous FeO-bound	10.3	10.0	17.5	<1.7	31.7
Oxide silt MN1401					
Total concentration, µg/g	4442	338	2270	460	2100
% AEC	3.5	10.2	5.3	2.2	11.5
% amorphous FeO-bound	3.0	15.1	19.6	<2.1	25.9
Sulfide-Oxide silt (SOMIX)					
Total concentration, µg/g	2468	285	1758	375	1525
% AEC	5.5	11.1	5.0	<2.6	13.3
% amorphous FeO-bound	3.5	11.1	13.2	<2.6	25.5
Sulfide-Oxide silt (Slurry)					
Total concentration, µg/g	2473	312	1644	375	1525
% AEC	5.4	8.0	4.3	<2.6	12.1
% amorphous FeO-bound	3.5	11.8	14.4	<2.6	27.7

It should be noted that the extraction analysis was conducted with vigorous agitation and aggressive digestion. The analyses would thus reflect the worst-case remobilization for the elements analyzed. Under normal field conditions, the release of these elements is expected to occur to a much smaller extent. Leachates obtained at each step of the sequential extraction analysis were also analyzed for Total CN. However, all analyses were below the detection limit of 0.05 mg/L. Therefore WAD CN was not analyzed for these samples.

b) Controlled lime leach: Since both As and CN are parameters of concern at Mount Nansen and the mobility of which are known to vary with pH, it was decided to leach the same selected tailings samples used in the sequential extraction analysis with a 0.1M lime solution. A standard leach protocol with a modified liquid to solid ratio of 5:1 was used as the test procedure. A controlled experiment was also conducted with distilled water as the leach medium. The test results are summarized in Table 6.

A perusal of the data shown in Table 6 reveals a few surprises. Arsenic and antimony were not leached by the lime solution in all samples but were released at low concentration with the distilled water leach. In contrast, the lime leach appeared to have mobilized Pb, Zn and CN in most samples while the control showed insignificant leaching of these species by distilled water. The leaching of CNS is apparently independent of leach media but controlled by the composition of tailings. The mobilization of Pb and Zn appears to be related to the instability of iron oxyhydroxide at very high pH. Further work will be required to fully explain the observed behaviour of the other species analyzed.

Table 6. A comparison of the results of leaching selected tailings with a lime solution and distilled water (control)

Sample	*pH*	*As*	*Pb*	*Sb*	*Zn*	*Total CN*	*CNS*
BATCHO							
Lime	12.3	<0.55	<0.52	<0.32	0.027	2.3	7
Control	8.6	3.22	<0.45	0.36	<0.05	0.60	5
BATCHS							
Lime	12.2	<0.55	<0.52	<0.32	0.137	4.7	6
Control	8.0	1.18	<0.45	0.45	<0.075	0.09	<1
MN1102							
Lime	12.1	<0.55	1.00	<0.32	0.132	4.2	12
Control	8.0	<0.49	<0.45	0.57	<0.075	0.05	11
MN1401							
Lime	12.2	<0.55	1.04	<0.32	0.067	2.5	<1
Control	7.6	<0.49	<0.45	0.69	<0.075	<0.05	<1
SOMIX							
Lime	12.3	<0.55	0.69	<0.32	0.062	2.1	<1
Control	7.8	<0.49	<0.45	0.57	<0.075	<0.05	<1
SLURRY							
Lime	12.2	<0.55	0.57	<0.32	0.204	1.5	<1
Control	7.7	<0.49	<0.45	0.62	<0.075	<0.05	<1

Note: All values in mg/L except for pH.

Freeze Thaw Study

The objective of the freeze-thaw study was to assess the effects of repeated freezing and thawing on the physical and chemical properties (especially grain size distribution and chemical leachability) of the tailings impounded at Mount Nansen. For the study, five different tailings samples or composites representative of the range of tailings found at the site were subjected to three cycles of freezing and thawing from -20°C to 20°C and vice versa at a rate of 2°C/hour.

Leach testing of the tailings with distilled water was conducted both prior to and after the freeze-thaw cycles. The detailed method of investigation and data acquired are described in Appendix G. Salient observations are summarized as follows.

In the study, no trends or major differences were noted in the samples with regard to metal mobility. The liquid to solid ratio used for the leaching test prior to and post-freeze-thaw was 5:1 and the samples were agitated at 150 rpm for 24h to allow the tailings to equilibrate with the leach medium. After the freeze-thaw cycles, the arsenic release slightly decreased for all the samples. Leaching of Ca, Mg and Na was observed but varied in extent among the samples. Overall, the metal leachability remained more or less the same before and after the freeze-thaw study.

Cyanide concentrations measured were usually below the limit of quantification except for the clayey oxide tailings sample (BatchO). As the final leachate pH was below 9.0 after the leaching test, cyanide may have been leached from the solid and then converted into the gaseous form (i.e., HCN). This hypothesis is supported by the test results obtained using a lime solution as the leachant. As described above, the lime leach gave rise to measured cyanide concentrations of between 1.0 and 3.0 mg/L in the leachate.

The initial concentration of cyanide (Total CN) in the sample BatchO was 47 µg/g and only a small fraction of the cyanide was leached from the sample. Before the freeze-thaw study, the leachate pH was above 9.0. Consequently all the cyanide leached from the sample would have remained in solution. The total cyanide concentration in the leachate of the clayey oxide tails was reduced by more than 50% after the freeze-thaw step. However, the final leachate pH measured then was below 9.0. Part of the cyanide released could have been converted to HCN. Thus the reduction in the leachate cyanide concentration is probably not directly related to the effect of freeze-thaw but is most probably pH-dependent. For the other samples, no cyanide was measured in the leachate probably because the leachate pH was below 9.0.

The particle size distribution was different after the freeze-thaw treatment for the clayey sulfide tails (BatchS) and the silty oxide tails (MN1401). The mean diameter increased from 6.21 to 17.32 µm for BatchS and from 29.14 to 64.10 µm for MN1401. Several researchers (Ahukrichs and White, 1962; Anderson and Hoekstra, 1965; Rowell and Dillon, 1972) found that clay aggregates were produced during freezing, resulting in an increase in overall grain size. Further mineralogical analysis should provide more information about the consolidation of the BatchS and MN1401 samples.

Overall, the freeze-thaw cycles did not significantly change the metal leachability of the test samples. The main factor controlling metal leachability appeared to be the pH of the leachate. Samples collected from Mount Nansen might have already been subjected to many freeze-thaw cycles. Consequently, the impact of incremental freezing action is expected to be very small. Results may have been different if fresh tailings that have never been subjected to cold climates were tested. Multiple freeze-thaw cycles seemed to modify the final leachate pH. After freezing and thawing, the pH was systematically lower. The pH decrease could be related to Fe(II) oxidation; the hydrolysis of the Fe(III) ion produced could depress the pH of the solution.

DISCUSSION

In response to the request from INAC, the comprehensive tailings characterization and testing program described in earlier sections was designed to achieve the following two primary objectives:

1. to evaluate the short- and long-term chemical stability of the impounded tailings at Mount Nansen; and,
2. to provide scientific data to aid with making appropriate decisions for the permanent disposal of the problematic tailings.

The ensuing discussion intends to reflect on the implications of the research findings with regard to the chemical stability of the impounded tailings and to suggest how the acquired information may help to develop a proper strategy for final decommissioning of the site.

Tailings Chemical Stability

Geochemical analyses of the tailings solids reveal their anomalous contents of Ag, As, Cu, Pb, Sb, Zn and a few CN-related species. The average Ag content of about 45 µg/g represents the only metal value remaining in the tailings. The other anomalous trace elements and chemical compounds pose potential short- and long-term liabilities, some of which are well reflected by the poor water quality observed in the tailings pond water, tailings porewater and leachates of various laboratory testing. The extent of environmental impacts that the tailings may potentially exert on the local ecosystem depends, in the short term, on the concentrations and rates of release of the contaminants identified and, in the long term, on the mode of occurrence and quantity of the contaminants in the system as well. These are briefly discussed below, taking the observed trends of chemical evolution into consideration.

Although neither the tailings pond water nor the seepage water currently shows excessive dissolved As, both the field porewater chemistry and laboratory leachate analyses suggest potential As mobility. However, the As content in the Mount Nansen tailings is relatively low (on the order of tenths of a per cent) compared to many other gold mines with similar mineralization. With only 10 to 20 per cent of the arsenic occurring in readily releasable forms and the low net acid-generating potential of the impounded tailings, it appears that the threat for long-term As hazard is not significant if the tailings are properly contained. Geochemically, antimony behaves in a similar way as arsenic. In the Mount Nansen tailings, the Sb content is an order of magnitude lower than that of As. Dissolved Sb is rarely detected in the tailings pond water and porewater. Results of the leaching experiments suggest that it may be released only at a limited range of liquid to solid ratio. Consequently, Sb leaching is unlikely to become a significant environmental issue at Mount Nansen.

Among the three base metals occurring in anomalous amounts in the impounded tailings, copper is the least abundant. Its presence in the tailings pond water, porewater and leachates appear to correlate with the WAD CN content. Thus, aqueous Cu in the impounded tailings may have been largely derived from mineral processing and subsequent (including post-mine) water treatment. The decreasing trend in dissolved Cu concentration in the tailings pond water and the seepage return since mine closure supports such a hypothesis. Results of the partial sequential extraction analysis indicate that more than 80% of the Cu in the tailings occurs in less readily leachable forms (mostly as liberated sulfides and sulfosalts or the same minerals encapsulated in quartz). This coupled with its relatively low abundance (a few hundred μg/g Cu) suggest that copper leaching is and will not be a serious threat at Mount Nansen.

Although lead occurs in comparable concentrations in the Mount Nansen tailings as arsenic, dissolved Pb has not been detected in most liquid samples analyzed, except at low concentrations (≤ 1 mg/L) in the lime leachates. Up to about 20% of Pb in the tailings solids are associated with amorphous oxyhydroxides. These are susceptible to remobilization with the dissolution of oxyhydroxides under either acidic or reducing conditions. However, this is unlikely to occur if similar environmental conditions as currently prevailing at the impoundment are maintained. Consequently, the likelihood of Pb leaching is considered as remote for the impounded tailings.

For zinc, about 30% of the average content of approximately 2,000 μg/g in the tailings are found to be associated with the oxyhydroxides and another 10% as sorbed ions and/or carbonate-bound. Results of both the geochemical and SEM analyses have demonstrated the close association of Zn with Mn-rich phases. Therefore, Zn can be more readily mobilized than Pb with slight changes in environmental setting. This is supported in part by the elevated Zn content in water samples of the Brown-McDade pit, where there is evidence of local acid generation during the dry seasons. However, results of the sequential batch leach of the tailings with pit water indicate no significant Zn leaching and those of the column studies show that the tailings serve as a sink to dissolved Zn in the overlying water. These observations suggest that Zn is stabilized in the tailings. Unless acidic or reducing conditions are generated with changes in the disposal settings, Zn leaching from the tailings is unlikely to be significant.

The occurrence of CN and its derivatives (in particular CNO, CNS and ammonia) often at anomalous levels in the tailings pond water and seepage has been a concern and necessitates continuing water treatment since the cessation of mining at Mount Nansen (Higgs, 2000). Chemical analyses of pond and porewater and tailings solids as well as the results of the column and other leach test work suggest strong sorption of the bulk of these CN species with the clay fraction of the tailings. Only a small percentage of the residual CN from milling is partitioned into the liquid phase (i.e., porewater) in the tailings pond. Various CN-related species in the porewater are susceptible to degradation as is evidenced by the observed trend of decreasing concentrations of Total and WAD CN and the abundance of ammonia in the tailings pond water and seepage return. Sorbed CN and related species with the tailings solids are, however, difficult to remove and only decay very slowly as is evident from the column and leach test results. Thus it is expected that as long as there is seepage from the tailings impoundment, the site will see anomalous CNS and NH_4-N until all the CN species in the tailings are degraded. Unfortunately, the short duration of the column testing and the complication of a higher temperature setting in the laboratory experiments have precluded an accurate prediction of when the potentially hazardous products of CN degradation will be reduced to sufficiently low levels to allow direct discharge of excess water from the tailings impoundment.

Results of the cursory freeze-thaw study suggest that multiple cycles of freezing and thawing may lead to some aggregation of fine particles in the tailings but generally do not affect the release of most trace elements. Some CN, however, has apparently been desorbed from the tailings particles in the process. In many ways, the wetting and drying process is similar to freeze thaw and can be expected to affect CN release from the tailings to a limited extent. If the released CN ends up in a liquid phase with pH <9, it is susceptible to loss by volatilization with vigorous agitation. This was observed in the freeze thaw study. Released CN ended up in a quiescent system such as impounded tailings will likely stay in the porewater. This could explain the detected increase in CN concentrations in the tailings seepage following an antecedent drying period produced by drawing down the water level in the tailings pond.

In short, although water treatment is currently required for the discharge of effluents from the tailings impoundment at Mount Nansen because of elevated levels of CN and related species, the tailings contain relatively low concentrations of mobile trace elements. Only As and Zn may be susceptible to remobilization in moderate concentrations with changing environmental settings. Given the relatively small size of the impoundment (about 200x200 m^2) and the amount of contained tailings (~ 250,000 tonnes), it is tempting to devise a one-time solution that will eliminate the need to maintain the site for an extended period of time. Implications of the research findings to the possible options are discussed below.

Decommissioning Options for the Impounded Tailings

As reviewed by Strathcona Mineral Services Ltd. (2000), dictated by the setting of the minesite, there are only two possible options for long-term disposal of the impounded tailings at Mount Nansen. These are (1) retain them at the current impoundment with improvements made to the facility; and, (2) transfer and re-deposit them in the Brown-McDade open pit. Based on the findings of the field and laboratory investigations conducted in this study, the advantages and drawbacks of the two options are discussed. Additional measures that may enhance the performance or functionality of each of the options are also suggested.

Retention in the current impoundment: Largely contained by permafrost except near portions of the tailings dam, the tailings impoundment is apparently isolated from the regional groundwater flow system. Contaminant transport from the impounded tailings is dominated by surface runoff, controlled discharge and limited local seepage. Although anomalous levels of ammonia and thiocyanate in the tailings pond water and seepage currently pose toxicity concerns, historic and on-going monitoring data collecting at the impoundment and the results of various laboratory testing indicate that the system is chemically stable and improving. Concentrations of Total and WAD CN as well as dissolved Cu are decreasing with time. For the two relatively mobile elements, As and Zn, occurring in the tailings based on the laboratory test work, elevated dissolved As concentrations are restricted to tailings porewaters and there is insignificant leaching of Zn in the existing impoundment. If means can be devised to reduce ammonia and CNS to acceptable levels in the tailings seepage, leaving the impounded tailings in place may avoid the risks of contaminant releases resulting from exposing the tailings to significant changes in environmental conditions in a new disposal setting.

The two main concerns with regard to sustaining the existing impoundment are the physical stability of the tailings containment dam and the impact of erosion on the maintenance of the associated diversion ditches (D. Sherstone and B. MacAlpine, personal communication, October 2001). The tailings dam is a compacted earth dam keyed into the underlying frozen ground. To ensure its physical integrity, original design requirements include: initial placement of tailings to press against the low-permeability geomembrane near the centre of the dam, and no water rests directly against the dam structure for 50 m upstream of the dam (Klohn Crippen Consultants Ltd., 1995). Both design criteria were apparently ignored when the tailings were first disposed in the impoundment, leading to partial thawing of permafrost beneath the dam. Nonetheless, recent geotechnical reassessments of the conditions of the tailings dam have suggested that the tailings dam is still safe, except possibly during severe seismic events, if the designed width of the tailing beach is maintained (EBA Engineering Consultants Ltd., 1999; Klohn Crippen Consultants Ltd., 2000). Strathcona Mineral Services Ltd. (2000) suggested redistribution of tailings within the impoundment to achieve the purpose, which might possibly alleviate the extent of diversion ditch maintenance. It may be worthwhile to investigate if the physical integrity of the dam can be improved by installing some sort of reinforcement structure at the downstream base of the dam.

If decisions were made to retain the tailings in the existing impoundment, restoring permafrost in the impoundment area should perhaps be considered to further ensure the chemical stability of the impounded tailings and the physical stability of the impoundment infrastructure. Admittedly, given the partially thawed, relatively "warm" permafrost apparently occurring at the site at present, it may not be easy to kick start the permafrost progradation process. However, if it can be done at all, increasing the permafrost depth in the tailings pond will not only prevent trace element leaching, it may also slow down the CN degradation process and thus the production of ammonia and CNS at acceptable levels. Relocating the seepage return pipe farther upstream of the containment dam may also help to arrest thawing at its base. The eventual conversion of the tailings pond to an oxic, boreal wetland by incorporating native sand and local ground cover into the impoundment may further enhance both the chemical and physical stability of the system.

Transfer of impounded tailings to the Brown-McDade open pit: Relocating the impounded tailings with final deposition in the open pit will obviously eliminate the problem of a potentially unsafe tailings containment dam. The transferred tailings may cover some of the exposed mineralization and alteration in the pit floor and pit walls, thereby reducing the extent of metal leaching (e.g., Zn mobilization) and local acid generation. During tailings transport, agitation and exposure of the tailings to a more oxidizing environment may enhance volatilization and degradation of some of the CN and related species. Other than that, placement of tailings in the open pit will certainly be beset with challenges, some of which are briefly discussed below.

Both the column studies with coarse tailings and batch leach tests with fine clayey tails have demonstrated potential mobilization of As, Sb and selected sorbed CN species with disturbance of the tailings and interaction with the pit water. While some free CN and WAD CN may be eliminated during tailings transport, additional loads of CNS and NH_4-N are likely to be generated at the same time. If the transport medium is eventually contaminated with excessive trace elements and potentially hazardous CN-related compounds and their derivatives, the medium has to be impounded and treated before discharge. Transfer of tailings in a relatively dry form will impose a less significant impact on the quality of the subsequent water cover, if one develops. However, given the fine grain size of the tailings and elevation difference between the tailings impoundment and the open pit, transport of tailings by truck may be challenging.

In the absence of detailed information on the local hydrology and hydrogeology of the open pit, the post-deposition environmental setting for the transferred tailings is largely unknown. If a deep water cover eventually forms on the tailings, reducing conditions will develop in the tailings, leading to potential dissolution of amorphous Fe and Mn oxyhydroxides and the release of the associated trace elements. If unsaturated conditions develop, oxidation of the remnant sulfides may occur, leading to acid generation and metal leaching. In contrast to the tailings impoundment, the open pit appears to be connected to the regional groundwater flow system. The observed seasonal variation in the monitored pit water chemistry appears to have derived from a fluctuating water table. Unless major conduits are somehow blocked, contamination of groundwater with trace metals and CN-related species in the tailings porewater is highly probable. The Total CN occurring in the tailings can effectively be destroyed using the INCO SO_2/Air process prior to transfer to the open pit. However, as mentioned before, this will result in a simultaneous release of significant doses of As, Sb and ammonia. The requirement for treatment of the resultant effluent seems inevitable.

A variation in the theme of transferring the tailings to the Brown-McDade pit is to mix the tailings with cement and dispose of them in a paste form that does not bleed water. This will eliminate the problem of potential flushing of contaminated tailings porewater to the regional groundwater system and also help to reduce the likelihood of acid generation. However, since both arsenic and antimony are mobile under both acidic and alkaline conditions, the effect of lime addition (in the form of cement) on the long-term chemical stability of As- and Sb-containing minerals is uncertain. Although the overnight leach testing with a lime solution conducted in the current study did not yield evidence of significant arsenic leaching, there are indications from other mine sites that elevated calcium, bicarbonate and lime contents in a tailings system reduce the long-term stability of As-containing minerals (Kwong et al., 2000; Soprovich, 2000). In addition, the same leach test with a lime solution gave rise to cyanide release. The results of the freeze-thaw experiments also suggested alkaline condition would enhance the persistence of CN. Furthermore, whether or not the entire tailings mass can be used in paste making with cement is not known. Therefore, much research remains to be done if the paste option is to be pursued further.

Concluding remarks: From the perspective of tailings chemical stability, among the two options considered for permanent disposal of the problematic tailings, retaining the tailings in the existing impoundment appears to be associated with fewer unknown factors than transferring the tailings to the Brown-McDade open pit. To fully evaluate the latter option, a detailed study of the pit hydrology and hydrogeology as well as the distribution of minerals and alteration along the pit walls should be conducted. This will provide the necessary information to compare and contrast the two options, including their variations, using a risk assessment approach. Based on the assessment results, the more cost-effective and environmentally friendly option can be adopted.

CONCLUSIONS

The Mount Nansen tailings chemical stability project aims to characterize the impounded tailings with regard to their chemical and mineralogical composition and assess their short- and long-term behaviour so as to provide scientific data for making decisions on their permanent disposal. Based on observations made and test results obtained in field and laboratory investigations conducted for this project, the following conclusions can be drawn:

1. Tailings impounded in the Mount Nansen tailings pond can be divided into four main types according to grain size and composition, namely, oxide silt, oxide clay, sulfide silt and sulfide clay. The combined sulfide varieties make up about 30% by volume of the impounded tailings and the combined fine-grained varieties slightly less than 50%.

2. Regardless of the detailed type, the impounded tailings are generally enriched in Ag, As, Cu, CN, Pb, Sb and Zn and show a moderate acid-generating potential.

3. Column testing simulating four tailings disposal scenarios demonstrates potential mobilization of CNS, NH_4-N and As in the tailings porewater and overlying water at undesirable concentrations. If the impounded tailings were to be relocated to the open pit, moving the tailings in a relatively dry form will lead to reduced impacts on the water cover quality.

4. The sequential batch leach tests showed that As and Sb are susceptible to leaching from the tailings by the pit water.

5. The INCO SO_2/Air treatment is effective in destroying CN associated with the tailings solids but releases significant amounts of Total CN, CNS, NH_4-N as well as possibly As and Sb to the process water at the same time.

6. The results of partial sequential extraction analysis on selected tailings indicated that As and Zn are the most readily releasable trace elements occurring in the tailings.

7. Multiple freeze-thaw cycles do not generally affect the metal leachability of the test tailings. However, an increase in average grain size may result from the aggregation of clay particles during freezing.

8. The impounded tailings represent a relatively stable chemical system the quality of which is expected to improve with time. However, CNS and NH_4-N levels in tailings pond water and porewater may remain a concern for the medium term unless appropriate technology can be devised to efficiently enhance their removal.

RECOMMENDATIONS FOR FURTHER WORK

Constrained by the limited time frame allowed for this project, both field and laboratory investigations have been designed to render the most useful data in the shortest time possible to aid decision making on developing an appropriate strategy for the long-term disposal of the arsenic- and cyanide-bearing tailings at Mount Nansen. Details are often sacrificed for variety and information gaps are frequently identified upon interpreting the acquired data. To fully address the issues raised by INAC with regard to the tailings behaviour and disposal options, further work in the following areas is recommended.

1. Three months of column testing have proved to be inadequate to render sufficient data to establish the rates of metal leaching and cyanide degradation. Depending on the selection of the preferred long-term disposal option, the corresponding columns, if not the entire column test work, should be run for another three to six months to acquire the relevant rate data.

2. The column test work has been conducted at room temperature; therefore the rate data obtained may not be truly representative of those taking place in the field. If it is decided to retain the tailings in the existing impoundment, it will be instructive to experiment with a scaled model of the impoundment constructed with the remainder of the tailings and native sediments collected. The model would incorporate a frozen layer at depth and a partially thawed tailings dam on one side. The model would be closely monitored for a year for the transfer of trace elements and CN species across the porewater-tailings solids interface as well as the generation and movement of ammonia and thiocyanate in the tailings porewater. Such a model experiment will give a more realistic picture of the water-tailings interactions occurring under field conditions.

3. Regardless of the final option chosen for long-term disposal of the problematic tailings, the generation of ammonia and thiocyanate is likely to continue for some time. It is worthwhile to review and develop new technologies for treating water containing excessive amounts of such potentially toxic, CN degradation products.

4. Insufficient information on the detailed distribution of minerals, hydrology and hydrogeology of the Brown-McDade pit is currently available to fully predict the potential consequences of disposing the impounded tailings there. Efforts should be made to acquire such information and then a risk assessment can be performed and the procedure applied to select the most appropriate long-term disposal options for the impounded tailings.

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