Oxic and Anoxic Tailings Slurry Aging Studies for Environmental Assessment of a Proposed Mining and Processing Development with Emphasis on Cyanide Species

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Abstract

Modern metal mining and ore processing operations have to strive to meet high standards for discharge water quality, both during and after mining and processing. Pre-treatment of discharge water will have to be designed into the hydrometallurgical circuit, with the fate and transport of every contaminant carefully monitored, to obtain a permit to mine and process the ore. Experience has shown that there can be substantial changes in water quality as the tailings solids equilibrate with pore water, supernatant, and atmosphere during storage, and as residual cyanide and its degradation products react. Aging tests on two metallurgical testing product slurries that are bulk flotation tailings (BFT) mixed with cyanide tailings have given the first extensive determination of how cyanide species in the Hope Bay tailings could degrade when placed in a storage facility. During oxic aging, total cyanide, cyanate, and thiocyanate could degrade in eight weeks with an increase in the concentration of ammonia. In anoxic aging at 4 ^{o}C, total cyanide and cyanate degrade much more slowly in eight months. Ammonia does not increase from anoxic cyanide degradation in the Naartok West mixed tailings. However, ammonia does appear to be the product of anoxic cyanate degradation in the Doris Connector mixed tailings. Thiocyanate concentrations do not change during anoxic aging. Presently, it is not known what the cyanide degradation product is during anoxic aging.

Key Words: Hope Bay deposit, total cyanide, cyanate, thiocyanate, ammonia

Introduction

Newmont Mining Corporation is evaluating the Hope Bay project located in Nunavut Territory about 160 km southwest of Cambridge Bay. The Hope Bay deposits are located in an Archean greenstone gold belt that is up to 20 km wide and extends over a roughly 80 km strike length. Three significant areas with gold mineralization have been defined on the belt thus far: Doris (including the Doris North, Connector and Central deposits), Madrid (including the Suluk, Naartok East, Naartok West and Rand deposits), and Boston. A brief description of the deposits can be found in Murphey *et al.* (2009).

The Hope Bay Project is striving to meet high standards for discharge water quality, both during and after mining and processing in order to meet Canadian marine aquatic toxicity testing requirements. Pre-treatment of discharge water is being included in the hydrometallurgical circuit during bench scale metallurgical testing, and the fate and transport of every constituent of concern (COC) requires careful assessment. Experience has shown that there can be substantial changes in water quality as the tailings solids equilibrate with pore water, supernatant, and atmosphere during storage and as residual cyanide and its degradation products react. Aging tests on various types of metallurgical testing tailings slurries are being conducted to simulate these processes. This paper reports on an aging study conducted on Naartok West (NW) mixed tailings and on Doris Connector (DConn) mixed tailings. These tailings are a mix of bulk flotation tailings (BFT) and cyanide detoxified tailings (CNDT) in the proportion that is anticipated during processing based on the planned processing water balance and the actual flotation concentrate to tailings ratios obtained during flotation testing of the bulk ore samples.

The objective of this paper is to present, discuss and make conclusions on the fate of cyanide species and degradation products during the aging studies. During these bench-scale aging studies on NW and DConn

mixed tailings, analytical methods were used to determine, as best as possible, how cyanide and products of cyanide degradation such as cyanate and thiocyanate react under oxic and anoxic conditions. Such complete analyses are important for determining whether the cyanide degradation products themselves could be COCs for marine aquatic testing.

Methods

Sample preparation

For hydro-metallurgical pilot-scale and bench-scale testing of Hope Bay ores, sufficient sample was used so that complete environmental characterization of solutions, solids, and slurries could be performed as well as the usual beneficiation analyses. The metallurgical and geotechnical characterization studies required at least 30 liters of slurry, and the aging studies and environmental characterization required 20 liters of slurry.

The NW BFT slurry was generated in early 2009, in a pilot plant to simulate processing ore from an open pit mining scenario and the NW CNDT slurry was generated from a bulk flotation concentrate in early 2010. A concerted attempt was made to obtain the CNDT slurry as soon as possible after the cyanide leaching and detoxification tests were performed so that the mixed slurry was as fresh as possible. Untreated cyanidation solution was blended back with the cyanide detoxified solids and flotation tailings slurry to simulate weak and dissociable (WAD) cyanide detoxification to < 50 mg/L using counter current decant solution to meet International Cyanide Management Code (ICMI) requirements for protection of wildlife (see Time 0 Table 4). The mixed slurry contained 5 % by weight of CNDT tailings, 95% bulk flotation tailings and was approximately 30 to 40 % solids by weight. Cyanide detoxification on mixed tailings decant water was carried out using the INCO SO_2-air process with a copper catalyst (Devuyst et al., 1989) until the supernatant solution contained less than 0.1 mg/L in WAD cyanide. The decant solution was further treated by iron co-precipitation for arsenic removal and low pH reverse osmosis (RO). The RO permeate was conditioned to return the hardness with calcium and magnesium and submitted for and successfully passed freshwater acute toxicity testing (CCME 2007).

The DConn BFT slurry was prepared in early 2011 using batch flotation to simulate processing ore from an underground mining scenario and the CNDT slurry was generated in March of 2011 again using the INCO SO_2- air process to meet a <1 mg/L total cyanide tailings facility discharge requirement for the permitted mill and tailings site and <0.5 mg/L WAD cyanide to meet the (ICMC) requirements for the mill tailings disposal preliminary design. The mixed tailings were generated immediately after detoxification. Again, the mixed slurry contained 5 % by weight of CNDT tailings, 95% bulk flotation tailings. In this case Merrill-Crowe barren cyanidation solution was detoxified to meet <1 mg/L total cyanide by SO_2-air and blended back into the mixed slurry and thickened to 38 % solids to simulate the mixed tailings in the starter mill design. The resultant detoxified slurry was filtered, and the filtrate submitted for and successfully passed marine acute toxicity testing (CCME 2007).

Oxic and anoxic aging procedures

A complete description of preparation and execution of the aging procedures has been reported earlier in Murphey *et al.* (2009). At the time of preparation of the oxic and anoxic slurry aliquots, a time zero sample was taken. The oxic samples in 2.5 L narrow mouth bottles were set to age on a sunlit windowsill at room temperature in bottles with the caps propped open. Supernatant samples were taken at 1, 2, 4, and 8 weeks. The anoxic samples were prepared in 1250 mL zero head-space double sealed glass bottles in nitrogen purged glove bags and stored in nitrogen-purged, opaque anaerobic bags which were in continuously nitrogen purged glove bags in a refrigerator. Supernatant samples were taken at 1, 2, 4, and 8 months. The term anoxic is used here to imply that the atmosphere was kept devoid of oxygen as much as possible. No attempt was made to actively generate reducing conditions. Also, no attempt was made to generate sterile conditions and the slurries were not inoculated with any bacteria. Nevertheless, it is assumed that bacteria were present and mediated some reactions, particularly the cyanide decomposition

reactions. At no time during the aging were the samples shaken to re-suspend the tailings solids. Therefore mass transfer processes between the tailings porewater, tailings solids and tailings supernatant were limited by rates of diffusion.

General analytical procedures

The Canadian Council of Ministers of the Environment (CCME) water quality guidelines for the protection of aquatic life (CCME 2007) are quite stringent, extensive, and very useful for judging the potential for passing the marine aquatic toxicity test, which is required prior to discharging water under the preliminary permit to operate. An analytical program was instituted at Newmont Metallurgical Services (NMS) relying on inductively-coupled plasma atomic emission spectroscopy (ICP-AES), inductively-coupled plasma mass spectrometry (ICP-MS), and ion chromatography (IC) and has been effective at attaining detection limits below the CCME guidelines for most COCs. Hexavalent chromium [Cr(VI)], cadmium (Cd), and mercury (Hg), have caused analytical concerns, and the CCME guidelines and analytical procedures are summarized in Table 1.

Table 1 COCs that require special analytical considerations relative to the CCME guidelines

	CCME Guideline (µg/L)		
Constituent	Freshwater	Marine	Analytical Comments
Cr (VI)	1.0	1.5	Diluting sample for ICP-MS raises DL above guideline for dissolved chromium, no speciation method developed at NMS
Cd	0.017	0.12	Molybdenum interferes with ICP-MS analysis
Hg	0.026	0.016	Requires a trace analysis laboratory

Analytical procedures for cyanide species

Recently, standard procedures for free cyanide, total cyanide, and WAD cyanide have been developed by the American Society of Testing and Materials International (ASTM) (ASTM D7237, ASTM D 7511, and ASTM D6888). These new methods use the gas diffusion and amperometric detection method (Milosavljevic and Solujic, 1999), and are capable of detecting cyanide species to microgram/L concentrations and quantifying cyanide results in the range of 10 microgram/L. At NMS, these new cyanide analytical methods are performed using an OI Analytical FS3100 Cyanide Analyzer. In addition, IC methods have been developed for analyzing the degradation products of cyanide (CN^-) such as cyanate (OCN^-), thiocyanate (SCN^-), nitrate (NO_3^-), and nitrite (NO_2^-) and reduced sulfur species such as thiosulfate ($S_2O_3^=$).(Newmont 2009a, Newmont 2009b, 2010a). Table 2 summarizes cyanide species and degradation products that were analyzed, the detection limits, and the reference to the method.

Table 2. Summary of the analytical methods used for determining cyanide species and degradation products.

Constituent	Analytical Method	DL (mg/L)	Reference
Free CN	Flow Injection Amperometric	0.005	ASTM D7237 Proposed revision to the Interlaboratory Quantitation Estimate at 10% RSD
WAD CN	Flow Injection Amperometric	0.002	ASTM D6888
Total CN	Flow Injection Amperometric	0.002	ASTM D7284
OCN^-	Ion Chromatography	1.0	Newmont 2010a
SCN^-	Ion Chromatography	0.02	Newmont 2009b
$S_2O_3^=$	Ion Chromatography	1.0	Newmont 2009a
NO_3^-	Ion Chromatography	0.02	ASTM D5542
NO_2^-	Ion Chromatography	0.002	ASTM D5542
NH_3	Colorimetric	0.01	ASTM D1426

Results

General Results

To provide a geochemical context, a description of the general chemistry of the two supernatants of these two mixed tailings follows. The results are similar to the chemistry of bulk flotation slurries reported in previous studies (Murphey et al. 2009, Newmont Mining 2010b). Results that follow trends seen in previous studies follow.

- As in previous studies, the pH remained at 8.0 or above and, although the alkalinity dropped over time, it remained above 100 mg $CaCO_3$/L for both the oxic and anoxic studies. This provides significant buffering capacity for the slurries. There is no apparent tendency for the solutions to turn acidic; the Naartok West mixed tailings are classified as highly basic and Doris Connector mixed tailings are classified as basic, according to the acid-base characteristics based on pyrolysis loss sulphur and acid neutralization potential with metal acidity correction (Bucknam 2011). For both mixed slurries and for both oxic and anoxic aging, the alkalinities have dropped. For the DConn Mixed oxic slurry this drop has been from 370 to 150 mg $CaCO_3$/L.
- With respect to major constituents, the balance between cations and anions is within 15 %. Sulfate is the major anion and magnesium, calcium, and sodium are the major cations. With the exception of sodium coming from the addition of NaCN, this is comparable to the results seen for previous aging studies (see Figure 1).
- In the oxic study, the concentrations of magnesium and sulfate increase, whereas in the anoxic study, these constituents remain constant. Figure 1 shows the concentration changes for the major ions in the NW mixed oxic aging study. This trend was also seen in the previous BFT studies (Murphey et al. 2009).
- In the NW mixed slurries for both the oxic and anoxic studies, the Eh values remained between 250 and 350 millivolts. At a pH of 8.0, this is in the range where iron would be present predominantly as ferric hydroxides. However, in the DConn mixed slurries, the Eh dropped significantly from 210 mV to 45 mV for the 8 week oxic sample and to 22mV for the 8 month anoxic sample. For the anoxic samples, care is taken to measure the Eh while the slurry is still under a nitrogen atmosphere.

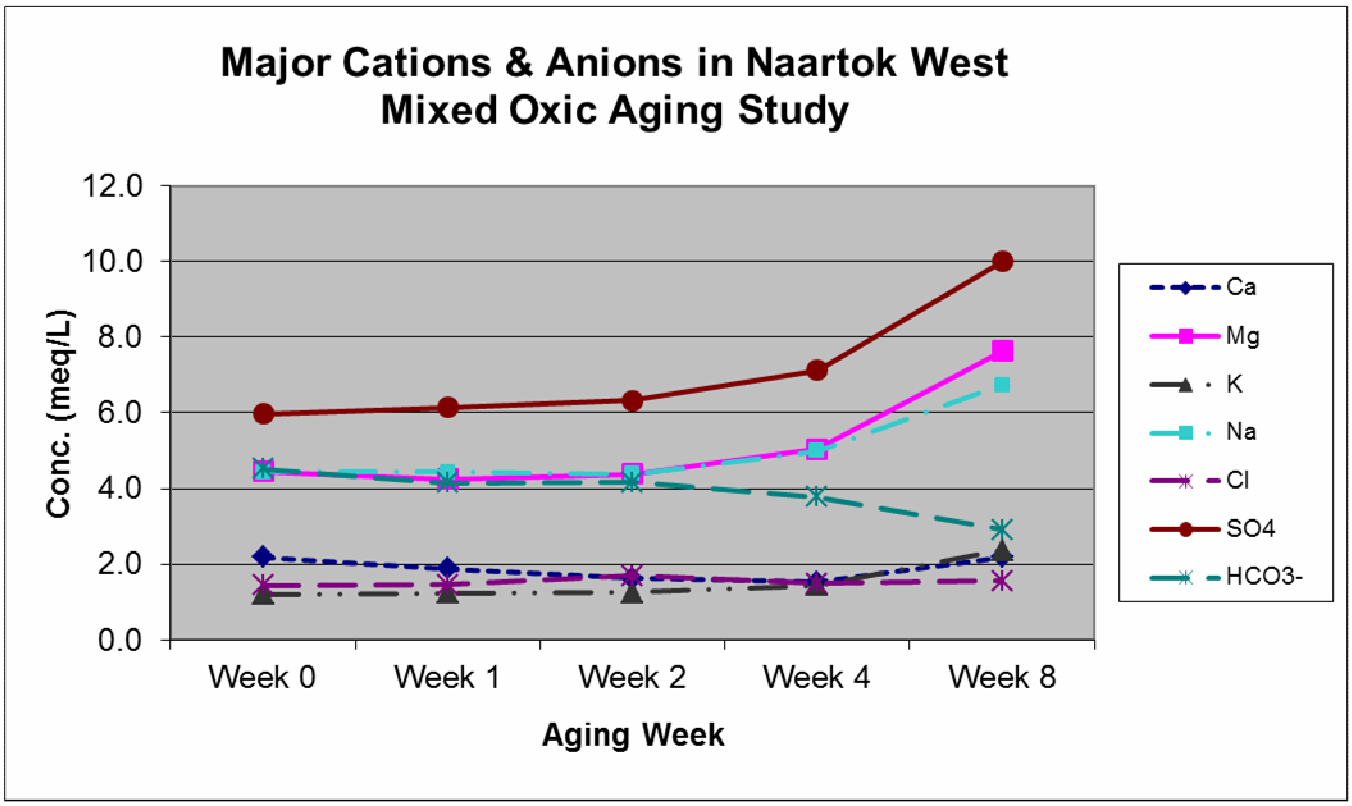

Figure 1. The concentration changes for the major ions in the NW mixed oxic aging study. The concentration units are in milliequivalents/L (meq/L), which is determined by dividing the molarity by ionic charge and multiplying by 1,000.

Results for cyanide species

Tables 3 and 4 show the results for the cyanide species for the NW mixed and the DConn mixed tailings slurries. For the NW slurry, a barren cyanide solution from simulated counter-current decantation (CCD) was blended into the BFT slurry to make the mixed slurry that was <50 mg/L WAD cyanide for the open pit mining and decant water treatment scenario. In the DConn mixed tailings slurry, the barren cyanide solution was detoxified to <1 mg/L total cyanide and that solution was blended back into the DConn BFT tailings. The differences in the slurry mixes is seen in the time zero concentration of cyanide constituents and degradation products. Also, all the cyanide degradation products have their concentrations given in mg/L as N. For example the actual OCN^- concentration was divided by 14/42 to calculate OCN^- as N. Making this adjustment allows the concentration values to be directly compared.

Discussion of Cyanide Results

We believe that these two tailings aging studies are the first in which a consistent set of cyanide species were analyzed by the new methods summarized in Table 2. As such, they provide an interesting picture of how low concentrations of cyanide species could change over time in tailings storage facilities, recognizing that actual rates of change will vary depending on temperature, light, and other specific conditions.. Many of the changes that do occur are catalyzed by bacteria. In this context, it is useful to refer to a review article by Ebbs (2004) to determine what the products are in biologically mitigated cyanide degradation reaction chains.

Table 3. NW mixed slurries cyanide, degradation products and reduced sulfur species concentrations in mg/L[b].

Parameter NW Mixed	NH_3 Tot as N	OCN^- as N	CN^- as N Free	CN^- as N Total	CN^- as N WAD	NO_3^- as N	NO_2^- as N	SCN^- as N	$S_2O_3^=$
Units	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
Fresh Water	**a**		**0.0027**			**2.9**	**0.06**		
Marine						**3.6**			
Time 0	0.78	0.4	1.5	5.3	2.3	<0.05	0.05	2.4	NA
Oxic 1 wk.	0.97	1.0	1.3	2.8	2.1	<0.05	0.05	2.9	NA
Oxic 2 wk.	0.42	1.0	1.1	1.4	1.2	<0.05	0.03	3.0	NA
Oxic 4 wk.	2.61	1.7	<0.01	<0.01	<0.05	<0.05	0.02	0.4	NA
Oxic 8 wk.	2.97	<0.3	<0.01	<0.01	<0.05	<0.05	<0.02	<0.01	NA
Anoxic 1 mo.	0.45	0.6	0.6	2.1	1.0	1.03	0.14	2.8	NA
Anoxic 2 mo.	0.42	<0.3	0.2	2.1	0.6	<0.05	0.02	3.1	NA
Anoxic 4 mo.	0.48	<0.3	<0.01	1.0	0.3	<0.01	<0.01	3.3	5.8
Anoxic 8 mo.	0.5	<0.3	0.0	0.8	0.0	<0.50	<0.01	3.0	<1

a. The CCME guideline varies with pH and temperature. At pH=8 and 5 °C, the value is 1.27 mg/L.
b. For the NH_3, OCN^-, NO_3^-, NO_2^-, and SCN^-, the concentrations are in mg/L as N so that concentrations can be directly compared. The freshwater and marine rows are the CCME guidelines for freshwater and marine organisms (CCME 2007).

Table 4. DConn mixed slurries cyanide, degradation products and reduced sulfur species concentrations in mg/L[b].

Parameter Dconn	NH_3 Tot as N	OCN- as N	CN^- as N Free	CN^- as N Total	CN^- as N WAD	NO_3^- as N	NO_2^- as N	SCN^- as N	$S_2O_3^=$
Units	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
Fresh Water	**a**		**0.0027**			**2.9**	**0.060**		
Marine						**3.6**			
Time 0	4.7	19	<0.01	0.86	<0.01	0.92	<0.01	3.2	6.9
Oxic 1 wk.	12.4	20	<0.01	0.00	<0.01	0.24	<0.01	3.5	<1
Oxic 2 wk.	6.1	20	<0.01	0.14	<0.01	0.32	0.01	3.7	<1
Oxic 4 wk.	15.9	12	<0.01	0.05	<0.01	0.11	<0.01	0.1	<1
Oxic 8 wk.	20	<0.3	0.02	0.00	<0.01	0.17	<0.01	<0.01	14
Anoxic 1 mo.	3.47	25	<0.01	0.95	<0.01	<0.01	<0.01	3.4	
Anoxic 2 mo.	6.4	18	0.02	0.74	<0.01	<0.01	<0.01	3.3	26
Anoxic 4 mo.	9	14	<0.01	0.29	0.01	<0.01	<0.01	3.8	<1
Anoxic 8 mo.	15.5	<0.3	<0.01	0.07	<0.01	<0.05	<0.02	3.5	<1

a. The CCME guideline varies with pH and temperature. At pH=8 and 5 °C, the value is 1.27 mg/L.
b. For the NH_3, OCN^-, NO_3^-, NO_2^-, and SCN^-, the concentrations are in mg/L as N so that concentrations can be directly compared. The freshwater and marine rows are the CCME guidelines for freshwater and marine organisms (CCME 2007).

Oxic aging slurries

For oxic situations, all cyanide degradation pathways lead to ammonia (Ebbs 2004). The overall reaction is:

$$2\,H_2O + 2\,HCN + O_2 \rightarrow 2\,NH_3 + 2\,CO_2 \quad (1)$$

The degradation of cyanide is shown in Table 3 for the NW mixed oxic aging study where the ammonia-nitrogen concentration builds up at the expense of total cyanide, cyanate, and thiocyanate. At time zero in the NW mixed slurry, the WAD cyanide is less than the total cyanide but more than the free cyanide, suggesting the presence of some WAD and strong cyanide complexes. Indeed there are 2 mg/L of copper (WAD) and 1.3 mg/L of iron (strong) in the supernatant solution of NW mixed tails even though the pH is 8.0. These concentrations of copper and iron would account for 2.8 mg/L of cyanide as N tied up in metal complexes. However, at the end of 8 weeks all cyanide species are below the detection limit and the copper and iron concentrations have decreased to 0.016 and 0.06 mg/L respectively. Thus it appears that these WAD and strong cyanide complexes are also broken down to ammonia in the oxic aging process with the precipitation of iron and copper. Ebbs(2004), states that biodegradation of metal cyanide complexes readily occurs in the presence of sunlight.

The conclusion that all cyanide degradation in oxic situations leads to ammonia would be stronger if the total NH_3-N concentration in week 8 matched the total concentration of cyanide species at time zero. As N, the total cyanide concentration at time zero is 5.3 mg/L. Combining this concentration with OCN^--N, SCN^--N, and NH_3-N at time zero gives a combined concentration of cyanide species at time zero of 8.9 mg/L as N. This should result in 8.9 mg/l of NH_3 as N at week 8; there is only 3.0 mg/L. At pH 8.0, the ratio of NH_3 to NH_4^+ is 0.056. Because the oxic slurry bottles are open to the atmosphere and are expected to breathe, some molecular ammonia could vaporize and escape from the system. Oxidation to nitrate is possible, however the concentrations of nitrate and nitrite remain at or below the detection limit throughout oxic aging. Despite this lack of closure on the oxic degradation of cyanide in the NW slurries, it is clear that oxic cyanide degradation will generate another COC, that being ammonia-nitrogen.

For the DConn mixed slurry, mixed cyanide detoxified slurry and cyanide detoxified barren solution was blended into the BFT slurry. Thus, as seen in Table 4, the time zero concentration of total cyanide is 0.86 mg/L as N. However, the concentration of cyanate is 19 mg/L as N. The oxic degradation of cyanate is more complex. Ebbs (2004) suggested that cyanate is an intermediate in the oxic biodegradation of HCN and it biodegrades in the presence of bicarbonate by the following reaction:

$$OCN^- + 3\,H^+ + HCO_3^- \rightarrow NH_4^+ + 2\,CO_2 \quad (2)$$

This reaction is essentially an hydrolysis and no electron transfer is involved. Flynn and Haslem (1995) suggest that oxidation of cyanate requires a stronger oxidizing agent than O_2 and the product is N_2, molecular nitrogen. For the oxic degradation of cyanide species in the DConn mixed slurries, the balance of cyanide species at time zero reacting to ammonia-nitrogen at 8 weeks is much better than for the NW mixed slurry. Using the calculation methods given above for the NW mixed slurry, the total of OCN^--N, NH_3-N, SCN^--N, and Total CN^--N is 27.8 mg/L as N, and 68 % of this is cyanate. At week 8, NH_3-N is the only species present, and its concentration is 20 mg/L as N. The only way that the ammonia-nitrogen could be this high at week 8 is by the majority of the cyanate degrading by the pathway given in reaction (2). Thus these oxic aging results for the DConn mixed slurry confirm that cyanate also degrades to ammonium ion under natural oxic conditions.

It has been suggested that in mill process streams HCN oxidation may possibly generate NO_3^--N or NO_2^--N (Flynn and Haslem 1995, Milosavljevic and Solujic 1999). The concentrations of nitrate-nitrogen and nitrite-nitrogen in Tables 3 and 4 show that only in the DConn mixed slurry at time zero is nitrate-nitrogen present and this nitrate-nitrogen decreases through the aging time. In the other situations, no NO_3^--N or NO_2^--N are present and none is generated during aging. It appears that in these mixed systems, the generation of nitrate or nitrite through cyanide degradation is not an issue.

In the oxic aging systems, thiocyanate also degrades. The overall reaction is:

$$SCN^- + 2\,H_2O + 2\,O_2 \rightarrow SO_4^{=} + NH_4^+ + CO_2 \qquad (3)$$

Ebbs (2004) suggested that there are multiple pathways for reaction (3) and cyanate does not necessarily have to be an intermediate product. Because thiocyanate is not the primary species at time zero in either of the mixed slurries, it is hard to tell the pathway for thiocyanate degradation. In both oxic aging studies sulfate does increase from time zero to week 8. However, as seen in Figure 1, the increase is too large to be attributed to only thiocyanate degradation.

Anoxic Aging Slurries

The picture for anoxic aging of cyanide species is less clear. It should be kept in mind that the anoxic aging samples are in sealed bottles with no headspace and the bottles are placed in sealed, non-transparent anaerobic bags. Hence, photolysis induced reactions should be minimized and all degradation products, particularly ammonia-nitrogen, should be retained in the system. Ebbs (2004) suggested cyanide biodegradation through hydrolysis of HCN by the following reaction to produce ammonium formate:

$$HCN + 2\,H_2O \rightarrow HCOO^- + NH_4^+ \qquad (4)$$

Cyanate is not an intermediate in this hydrolysis pathway. Fallon et al. (1991) reported that the anaerobic degradation of cyanide produces methane and ammonia-nitrogen. Ebbs (2004) also suggested the possibility of methanogenesis, which also generates ammonia-nitrogen:

$$HCN + 6\,H^+ + 6\,e^- \rightarrow CH_4 + NH_3 \qquad (5)$$

However the Eh of the slurry only reaches 22 mV by month 8, a value that is too high for methanogenesis. In order for the reduction reaction (5) to proceed, the oxidation of an organic substrate is a prerequisite. Fallon (1991) used a number of organic feeds to effect this anaerobic degradation. The problem is that in the NW anoxic aging system, total cyanide does significantly degrade but ammonia-nitrogen concentration remains constant. Figure 2 depicts concentration changes in cyanide-nitrogen species in the anoxic aging of the NW mixed slurry. The concentrations are given as N in mg/L so that direct comparisons can be made.

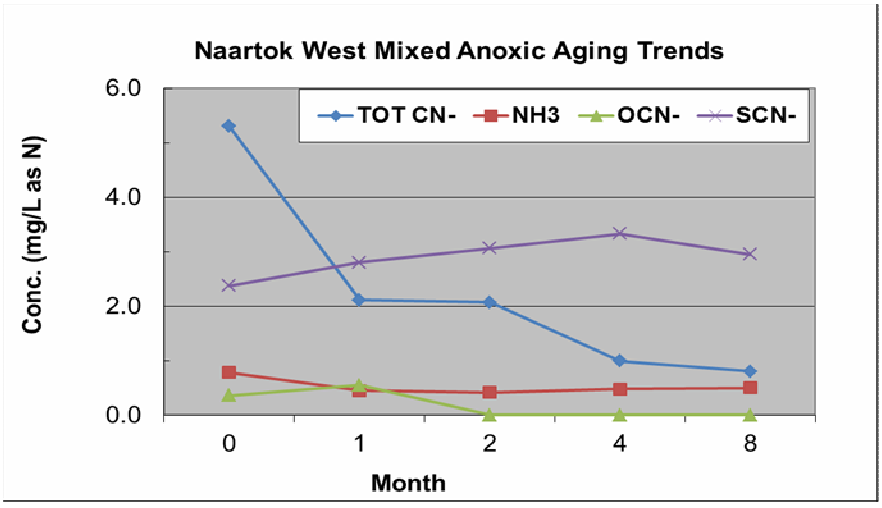

Figure 2. NW anoxic aging trends for cyanide compounds and degradation products. Concentrations are given in mg/L as N

The graph clearly shows that total cyanide-nitrogen decreases, but ammonia-nitrogen remains constant. Also, cyanate-nitrogen degrades, but thiocyanate-nitrogen does not. The overall mass balance for the N-species consistently indicate a loss from 13.5 mg/L at time zero to 8.9,7.4, 5.6, and 5.0 mg/L after months 1, 2, 4, and 8 respectively. Because molecular nitrogen (N_2) generation could not be analyzed, its formation could also account for the net loss of nitrogen.

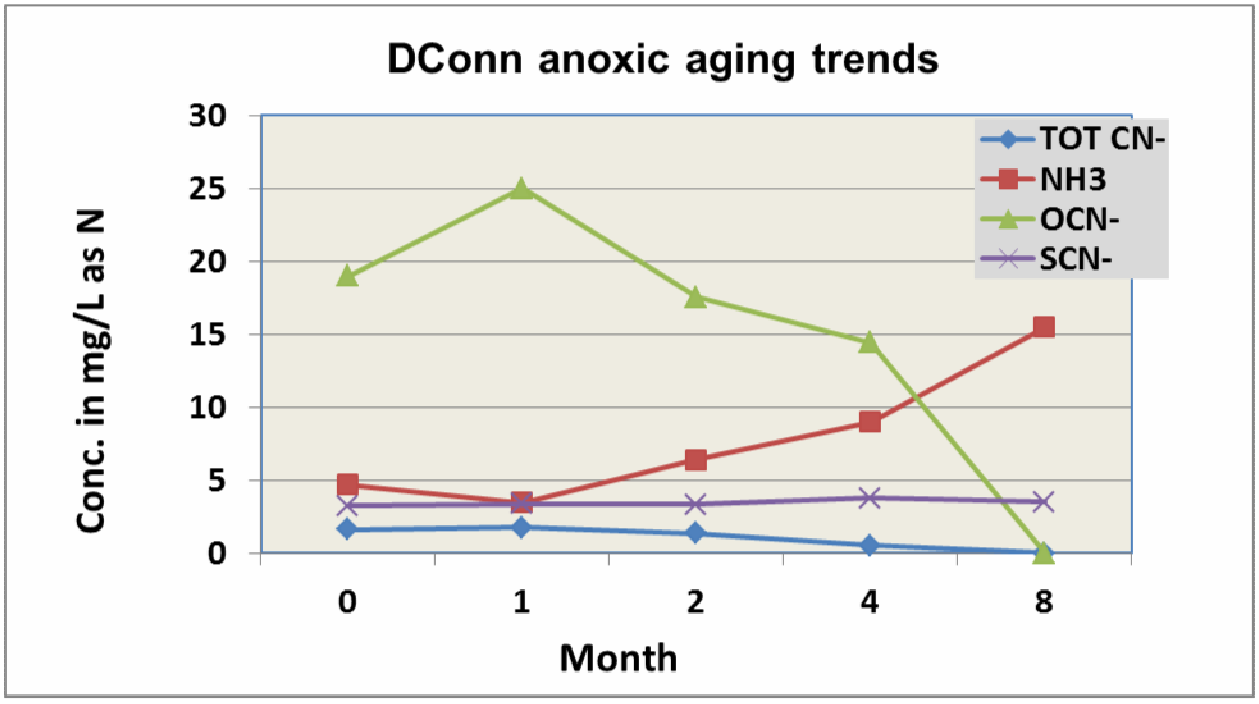

Figure 3. DConn mixed anoxic aging trends for cyanide compounds and degradation products. Concentrations are given in mg/L as N.

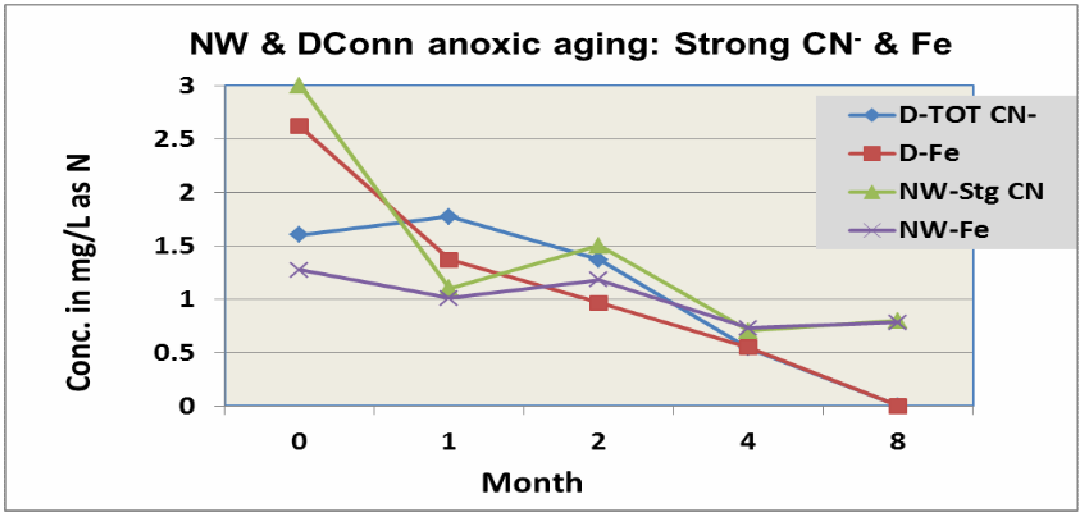

Figure 4. NW and DConn mixed anoxic aging trends for strong cyanide complexes and Fe. Concentrations for cyanide are given in mg/L as N.

For the DConn mixed slurry, the picture shown in Figure 3 is different than for NW mixed anoxic aging. The primary cyanide species is OCN^-, and it appears to degrade to NH_3-N. Because reaction 2 is by hydrolysis, no oxidation or reduction is necessary. While the overall balance shows a net loss of nitrogen, the loss is less pronounced than for the NW mixed results. Because OCN^- is the predominant cyanide degradation species, the ammonia-nitrogen can only be produced by cyanate. The nitrate-nitrogen present at time zero was removed by month 1 suggesting that denitrification is occurring. Again, it appears that thiocyanate-nitrogen is not degrading.

For the DConn mixed anoxic study, the 0.86 mg/L as N of total cyanide that is residual from the detoxification slowly degrades. This same degradation is seen in the NW mixed anoxic study. Figure 4 compares the degradation of strongly complexed cyanide as N with the disappearance of iron from the supernatant solution of the slurry. For the NW solutions the concentration of strong complexes was estimated by subtracting WAD CN^- from total CN^-. Two possibilities can account for the trend that is seen. Biodegradation of the iron cyanide complex can occur. If biodegradation is the cause for the disappearance, then the product is not ammonia- perhaps it is N_2 or it is incorporated into biomass. Also, the iron cyanide complexes can be immobilized through the precipitation metal/iron cyanide salts or through adsorption of complexes onto metal oxyhydroxides (Milosavljevic, 2012).

Conclusions

Oxic and anoxic aging studies on metallurgical testing tailings that are a mixture of BFT and cyanide detoxified residue and barren slurries reveal that for a relatively clean ore with respect to soluble metals, such as that coming from the Doris Connector deposit, attaining CCME goals for marine organisms can be met and only a few COCs are above the CCME goals for freshwater organisms. Keep in mind that the CCME values are goals and permission to discharge depends upon aquatic toxicity testing, which are often reflected in site specific water license requirements and in the Metal Mining Effluent Regulations (MMERs). The oxic and anoxic aging of cyanide species reveals the following:

- For oxic aging with sunlight, total cyanide, cyanate, and thiocyanate degrade to below detection limits and a primary degradation product is ammonia-nitrogen.
- In the DConn mixed tailings that contained detoxified cyanide tailings slurry and detoxified Merrill-Crowe barren, the primary detoxification product in oxic aging of cyanate is ammonia-nitrogen and this leads to a significant concentration of total ammonia–nitrogen.
- For the anoxic aging of the NW carbon-in-leach mixed tailings, the degradation of total cyanide is slower and not quite complete after 8 months. The product of anoxic aging does not appear to be ammonia-nitrogen, and it is not clear from the analyses of cyanide species just what the product of anoxic degradation is, since it is not measured. It could be the precipitation of iron cyanide complexes, the formation of molecular N_2 or possibly incorporated into biomass, if biodegradation is occurring.
- For the anoxic aging of the DConn slurry, OCN^- slowly degrades and primarily ammonia-nitrogen is formed. However, it appears that the total cyanide disappears in the same manner as in the NW mixed anoxic study.
- For both slurries during anoxic aging, thiocyanate does not degrade.

It is noted that the processes examined in this paper were limited to the reactions that were occurring in the tailings supernatant, and that mass transfer processes, including precipitation and/or dissolution of solutes to or from the tailings solids have not been considered. These would require additional analyses of the solids and specific tests such as peepers to examine mass transfer processes occurring across the tailings/water interface.

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Acronyms

ASTM	American Society of Testing and Materials
BFT	Bulk flotation tailings
CCME	Canadian Council of Ministers of the Environment
Cd	Cadmium
CN^-	Cyanide
CNDT	Cyanide detoxified tailings
OCN^-	Cyanate
COC	Constituent of concern
Cr	Chromium
Cr(VI)	Hexavalent chromium
DConn	Doris Connector ore deposit
HCN	Hydrogen cyanide
Hg	Mercury
IC	Ion chromatography
ICP-AES	Inductively-coupled plasma atomic emission spectroscopy
ICP-MS	Inductively-coupled plasma mass spectrometry
ICMC	International Cyanide Management Code
MMERs	Metal Mining Effluent Regulations
NH_3-N	Ammonia-nitrogen
NMS	Newmont Metallurgical Services
NO_3^--N	Nitrate-nitrogen
NO_2^--N	Nitrite-nitrogen
NW	Naartok West ore deposit
SCN^-	Thiocyanate
$S_2O_3^=$	Thiosulfate
WAD	Weak and dissociable