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Closure of the Colomac Mine tailings containment area

R. Breadmore *Contaminants and Remediation Directorate, Indian and Northern Affairs Canada, Canada*

W. Coedy *Contaminants and Remediation Directorate, Indian and Northern Affairs Canada, Canada*

Abstract

This paper presents the closure of the Colomac Mine tailings containment area (TCA). When the Colomac mine site reverted to Indian and Northern Affairs (INAC) in 1999, the Department faced significant environmental challenges, the most pressing of which were the management of contaminated water and tailings within the TCA. Emergency measures were required to protect local and downstream environments while suitable remediation technologies were developed. Additional controls were implemented to control windblown tailings and prevent direct exposure of tailings water and solids to caribou and moose. The paper will discuss the risks, remedial approaches and performance monitoring implemented over the project life.

1 Introduction

In 1999, INAC inherited the Colomac gold mine located approximately 220 km northeast of Yellowknife, Northwest Territories. The mine operated sporadically between 1990 and 1997, yielding approximately 535,000 troy oz of gold (Silke, 2009). Mill processing consisted of cyanide leaching with tailings deposition in a tailings containment area (TCA) consisting of three (3) natural lakes: Tailings, Spruce and Fuscum lakes, all of which were dewatered in preparation for mine operations. The TCA was permitted as a "zero discharge facility" (net inputs from processing and precipitation = losses from water reclamation and evaporation) and consequently, the tailings were not treated for cyanide removal. The tailings were deposited primarily in Spruce Lake and "stacked" behind an exfiltration structure known as "Dyke 7". Smaller volumes were deposited upstream of tailings dams to aid in water retention.

At mine closure, Tailings Lake levels began to rise steadily and, by 1998, began to encroach on freeboard limits at Dam 1. Because of unacceptable contaminant levels in the water an emergency transfer to Zone 2.0 Pit was carried out in 1999 under Section 39 of the *Northwest Territories Waters Act* which provided interim storage of the tailings water. Tailings Lake water contained elevated levels of cyanide, thiocyanate and ammonia, with ammonia proving to be acutely toxic in aquatic toxicity studies. Zone 2.0 Pit water quality resembled that of Tailings Lake but at lower contaminant concentration levels. Water balance calculations for Tailings Lake indicated that without further intervention, the lake would have reached freeboard by 2006. Tailings Lake limnology described a shallow water body with a warm active surface layer, cooler anoxic deeper layer and lake overturn prior to winter. Physical measurements of wind speed and temperature profiles determined that windstorm events could cause cold water upwelling and contaminant migration to the epilimnion (Pieters and Lawrence, 2006). By comparison, Zone 2.0 Pit was deep and did not mix beyond 20 per cent of its vertical depth, presenting an eventual constraint for Enhanced Natural Removal (ENR) treatment. Water treatment was also required before the pit reached equilibrium with adjacent Baton Lake.

The original Dam 1 in Tailings Lake was constructed on a geological fault and the dam began seeping significantly in 1996, with seepage releases increasing to about 1 m^3 per minute at mine closure. The seepage resembled tailings pore water and contained elevated concentrations of cyanide, thiocyanate, and ammonia and was continuously collected and returned to Tailings Lake. Flow rates and pump back volumes were tracked closely and reported daily. The construction of Dam 2 at the north end of Tailings Lake was incomplete at mine closure; the maintenance of freeboard levels at Dam 1 precluded any outflow at Dam 2. Dyke 7 was designed to contain mill tailings in Spruce Lake and allow the liquid fraction to exfiltrate through to Tailings Lake. Contrary to design however, a spillway at the east abutment was not constructed, resulting in tailings water and solids piping through the dyke at the west abutment and threatening the stability of the structure. The toe of the dyke was subsequently buttressed with waste rock and the upstream face reinforced with geotextile liner.

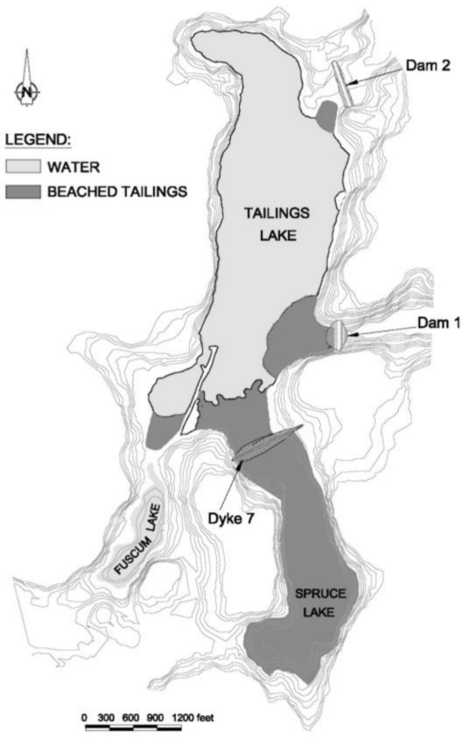

Figure 1 Map of Colomac tailings containment area

In addition to the water management and treatment challenges at mine closure, windblown tailings from exposed tailings on Spruce Lake and tailings beaches within Tailings Lake were impacting on the local environment. Caribou and moose were being directly exposed via consumption of tailings and tailings water (mineral salt attraction) as well as contaminated vegetation.

2 Methodology

The remedial measures associated with the closure of the Colomac TCA were a combination of scientific and engineering methodologies, involving water management, water treatment and wildlife management which had to be executed in parallel due to the tight water treatment timeline.

2.1 Water management

The investigation into viable water treatment options began in 2001. The uncertainty associated with water treatment in a northern climate, combined with the potential effects of consecutive wetter than average years on the overall water balance, required the implementation of contingencies for water management. Water balance calculations for Tailings Lake indicated that without further intervention, the lake would have reached freeboard by 2006. Tailings Lake limnology described a shallow water body with a warm active surface layer, cooler anoxic deeper layer and lake overturn prior to winter.

The mine shutdown created a strongly positive water balance in the TCA and additional transfers of water from Tailings Lake to Zone 2.0 Pit were required between 2000 and 2002, amounting to approximately 3.4 million m^3. In addition to the water transfers, a system of diversion ditches and deep collection sumps were constructed around the TCA to divert surface runoff outside of the TCA catchment. Fuscum Lake was an important reservoir representing approximately 8 per cent capacity of total Tailings Lake volume; however, with ammonia levels above criteria in 2001, Fuscum Lake had to be treated prior to discharge using a high efficiency turbo mist evaporator and circulation pump. Annual spring discharges from Fuscum Lake and the diversion ditch/sump system occurred between 2002 and 2007. Water balance modelling included variables such as a “wetter than average year” as well as losses due to wind and sun and indicated that Tailings Lake discharge could be extended by up to four years, depending on the collection efficiencies of the ditches and sumps. The success of the ENR program led to the completion of the diversion ditch program in 2007.

2.2 Water treatment in the TCA

Physical measurements of wind speed and temperature profiles determined that windstorm events in Tailings Lake during the spring could cause cold water upwelling and contaminant migration to the epilimnion (Pieters and Lawrence, 2006). By comparison, Zone 2.0 Pit was deep and did not mix beyond 20 per cent of its vertical depth, presenting an eventual constraint for Enhanced Natural Treatment.

Tailings Lake monitoring between 1998 and 2001 indicated that natural degradation of cyanide, thiocyanate and ammonia had occurred since mine shutdown; however, no significant concentrations of nitrate or nitrite were detected. This suggested that the cyanide and thiocyanate were being converted primarily to ammonia. Total cyanide concentrations decreased from 38 mg/l in 1998 to 1.0 mg/l in 2001; Thiocyanate decreased from 228 mg/l in 1999 to 119 mg/l in 2001 while ammonia increased from 23 mg/l to 48 mg/l for the same period. The change in the thiocyanate concentration with time is illustrated in Figure 2. The dashed line represents an estimation of the change in the concentration of thiocyanate naturally without any phosphorus addition. The benefits of enhanced attenuation on thiocyanate degradation are illustrated with the solid line and would allow for acceptable discharge at or before 2009.

A number of treatment alternatives were evaluated at desk top and pilot scale, including carbon adsorption, biological nitrification and de-nitrification using Rotating Biological Contactors (RBCs) and breakpoint alkaline chlorination. A pilot plant was erected at the south end of the TCA in 2002 to contain the pilot scale chemical treatment plant and the RBCs. Tailings water was tested by both systems over a 6 month period. Because of the heating requirements for the RBC system, alkaline chlorination was selected as the preferred technology (Botz and Mudder, 2003). In parallel, natural degradation enhancement via phosphorus addition was also assessed at bench scale tests at BC Research in Vancouver (Akcil and Mudder, 2003). BC Research reported that the addition of phosphorus to Tailings Lake water at concentrations ranging from 0.6 and 7.3 mg/l as total phosphorus stimulated algal growth and resulted in the removal of thiocyanate in excess of 100 mg/l to less than 0.5 mg/L in a 30 day period. Furthermore, ammonia produced as a by-product could be attenuated provided there were sufficient phosphorus levels to sustain algae growth. Based on these results and discussions with the Tlicho and Colomac Technical Advisory Committee (TAC), it was decided that phosphorus would be added to both Tailings Lake and the Zone 2 Pit Lake to achieve a nominal concentration of about 1 mg/l. It was anticipated this would be sufficient to sustain algal populations for an entire summer season, without leaving residual phosphorus which could lead to eutrophic conditions.

In 2002, ENR was selected as the preferred treatment option due to its simplicity in implementation and considerable cost savings. ENR would not require a treatment plant, operators training, annual re-stocking of chemicals and heating fuel on the winter road nor produce any residual by-products. However, the Best Available Technology using alkaline chlorination proved equally successful at removing cyanide, ammonia and metals. This technique was selected as a contingency should the actual rates of ENR be lower than those achieved in the laboratory tests.

2.2.1 Application of phosphorus

Mono-ammonium phosphate (MAP-$NH_4H_2PO_4$) was selected as a readily available granular source of phosphorus and was distributed on the ice surface of each water body in early spring, using a helicopter mounted hopper to ensure uniform phosphorus release. Initially, to achieve 1 mg/l total phosphorus, 12 tonnes of MAP were required for Tailings Lake (volume approx. 3.1 million m^3) and 24 tonnes for Zone 2 Pit Lake (volume approx. 6.4 million m^3). The ammonia content in the fertilizer was insignificant to existing ammonia levels in the water bodies. After a season of monitoring, the TAC decided to add another 9 tonnes of MAP in 2003 to raise phosphorus levels to 1 mg/l. No additional phosphorus was required after 2003.

2.2.2 Aeration system for Zone 2 Pit

An artificial circulation system for the de-stratification and aeration of Zone 2 Pit was designed by Ken Ashley (Ashley, 2005). It included two high output air compressors supplying two raft-mounted diffuser manifolds (stainless steel, 180 x 1.5 mm drilled holes) via 75 cm HP flexihose which was floated to rafts.

A fabricated pontoon boat was used to lower the diffusers to a depth of 60 m to ensure deep mixing. A total of 1.4 M m^3 of air was injected into the pit in 2006 and 2007 (equivalent to approx. 800 tonnes of oxygen).

2.2.3 ENR monitoring

The Technical Advisory Committee (TAC) oversaw the ENR monitoring program (which included physical limnology, water chemistry and biological analysis) over a five year period in both water bodies. Membership of the TAC consisted of public and private sector and academia to ensure all regulatory and technical aspects were adequately addressed. The TAC met annually and reported Surveillance Network Program (SNP) and ENR results to the Mackenzie Valley Land and Water Board (MVLWB). A Microsoft Access database was customised for the monitoring data by Wildrose Consulting and has served as the reporting mechanism for performance assessment and regulatory compliance. Two sampling stations were established for each water body with sampling campaigns commenced in 2002 and were conducted monthly during open water from June to September and twice under-ice in December, March or April. With discharge criteria achieved by 2007, SNP and ENR monitoring were reduced accordingly.

2.2.3.1 Monitoring - physical

To better understand the limnology of the lake systems, in-situ depth profiles of temperature, pH, conductivity, dissolved oxygen and redox potential (ORP) were measured with a Hydrolab Mini-Sonde-4. A physical lake mixing study was conducted by the Department of Ocean Sciences of UBC in Vancouver (Pieters and Lawrence, 2006). A mixture of Hobo Temp Pros and Brancker TR1040s (internally recording temperature loggers recording at 30 sec. intervals) were attached to a line at discreet depths to provide year round depth profiles and uploaded each spring and fall. A second profiler owned by UBC (Seabird SBE19plus CTD profiler) provided high accuracy temperature (+0.002C) and conductivity (+1 uS/cm). Meteorological data was collected (Davis Vantage Pro weather station) located at each lake for wind speed/direction, air temperature, relative humidity and solar radiation every two hours between August 2004 and 2007 for the interpretation of lake mixing and biomass growth cycles. Beginning in 2003, water elevation surveys were performed each spring and fall in conjunction with snow pack–water equivalent surveys each spring for the purpose of water balance calculations.

2.2.3.2 Monitoring - water chemistry

Water samples were collected at depth using a 4.2 l Kemmener water sampler, with water depth being adjusted for the thermocline; consequently, the depth varied from one sampling event to the next. On-site tests for orthophosphate, thiocyanate and ammonia were conducted immediately at the Colomac site laboratory using a Hach spectrophotometer (Dillon Consulting Ltd., 2010). A wide suite of water quality parameters were analysed by ALS Environmental Laboratory in Vancouver which included the major contaminants of concern. A quality assurance and quality control plan was prepared for the ENR Monitoring Program and evaluated each year. The Hydrolab used to collect in-situ measurements, was calibrated annually and checked against an in-house standard prior to each event. Quality control in the field involved the inclusion of field blanks, filter blanks for dissolved metals, nutrients and chlorophyll ‘a’. Certified Reference Materials “SPEX” were prepared and submitted with samples to the laboratory to assess accuracy. Precision was assessed through the degree of agreement between replicates collected at various depths and at different stations. On occasion, inter-laboratory studies were conducted to verify accuracy split samples were sent to another laboratory and the results compared for agreement.

2.2.3.3 Monitoring - biological

Identification and population estimates of cyanobacteria, denitrifying and nitrifying bacteria were based on “BART” culture test kits. Algal taxonomy and biomass were determined from an integrated surface depth sample representing the Euphotic Zone. A Secchi disk was used to determine the depth of light penetration of the Euphotic Zone. Chlorophyll “a” was measured in the euphotic zone to estimate the biomass productivity levels. An integrated depth sample from the Euphotic Zone was preserved with Lugol’s solution and shipped to the Freshwater Institute laboratory in Winnipeg for algal taxonomic composition, biomass and spatial/temporal distribution from 2003 to 2005. Phytoplankton and protozoan composition was analysed using an M40 Wild Inverted Optical Microscope at 320X magnification according to Standard Environmental Monitoring Methods (Kling, 2006).

2.2.3.4 Monitoring - air quality

Hi-Vol dust collector samplers were operated at the TCA dam beaches to determine worker exposure, while passive dust collectors were placed strategically in vegetated areas around TCA to measure wind- blown dust to the environment. Particulate matter and metal analysis were determined from dust capture in air filters.

2.3 TCA remediation and risk management

The traditional land users – the Tlicho People – indicated concerns over caribou and moose exposure to the contaminated tailings and tailings water in the TCA early during the remediation planning phase. Soil and vegetation surveys were conducted within the TCA in 2003–2004 to determine exposure risks. By the end of 2003, an 8 km fence was constructed around the TCA perimeter to prevent direct exposure to caribou and moose. During final remediation planning in 2008, INAC notified the Tlicho Government of its plans to bring down the Caribou Fence and the Tlicho requested that confirmatory sampling be carried out to determine residual contaminant levels and risk. A comprehensive survey, analysis and risk assessment was completed during the summer of 2008 which confirmed that metals in the TCA soils and vegetation had declined by up to 60–70 per cent between 2003 and 2008 (Obst, 2008) and risk to caribou and moose had been sufficiently reduced (MacDonald, 2008). The fence was decommissioned in late 2008.

At mine closure, the wind-blown fraction of the tailings were migrating outside of the TCA footprint, requiring the implementation of a dust management program. The program included initial application of various cellulose-based dust suppressants, eventual large-scale irrigation system utilising water from Tailings Lake and comprehensive dust monitoring. The exposed tailings were ultimately addressed through the placement of a tailings cap in 2006. Cap options were evaluated with the Tlicho (waste rock, waste rock + soil amendment, waste rock + amendment + re-vegetation) with the preferred option being a straight waste rock cap. It was felt that the cap would provide a physical barrier to caribou and moose and limit natural re-vegetation, based on concerns for contaminant update and root disturbance of cap. Additionally, the tailings cap would serve to reduce surface water infiltration and subsequent pore water migration to Tailings Lake. The capping involved the placement of clean waste rock (mined from the North Waste Rock Dump) to a depth of 0.8 m on all exposed tailings in Spruce and Tailings Lake. Along the eastern shore of Spruce Lake (where surface run-off was greatest and tailings saturation was highest) and along the shoreline of Tailings Lake, geotextile cloth had to be placed over the tailings to prevent loss of rock fill.

The original remediation design objectives for the TCA required re-contour of the Dyke 7 and a new discharge location by 2006. The Dyke 7 spillway serves to shed surface water off the Spruce Lake tailings cap and prevent erosion and subsidence to Tailings Lake; The new Discharge Channel at the Dam 2 location serves as a stable spillway to the north wetland and will maintain static water level in Tailings Lake.

Construction of Dam 1 B (just downstream of the original Dam 1) commenced in November 2006 and was completed by April 2007. The dam design was very robust, with the base keyed into permafrost and thermosyphon loops placed in the dam key and at each abutment. The upstream face of the dam was protected with polypropylene liner as well as geo-synthetic clay liner. Over the winter of 2009 a “controlled fill” was conducted to test the new dam and create an ice plug upstream of the dam face, using water from the upper strata of Tailings Lake. Thermistor monitoring and thermosyphon testing confirm that the dam is performing as per design and the seepage collection system was decommissioned in May 2009.

3 Data

The following figures describe the thiocyanate decay in Tailings Lake (Figure 2) and the Zone 2.0 Pit Lake temperature de-stratification (Figure 3).

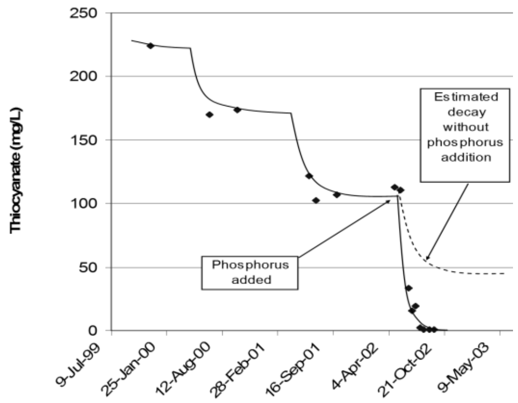

Figure 2 Thiocyanate concentrations in Tailings Lake – actual historic and prediction

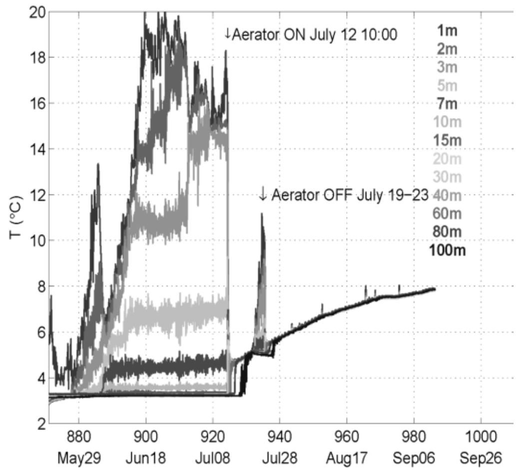

Figure 3 Temperature depth profiles indicating de-stratification of Zone 2 Pit at aeration start up (Source: Pieters and Lawrence, 2006)

Tables 1 and 2 summarise the water quality for Tailings Lake (TLK) and Zone 2.0 Pit (Z2P).

Table 1 Water quality data for Tailings Lake; average concentrations (mg/l) at turn over

TLK	2001 1st MAP	2002 2nd MAP	2003	2006	2008 Discharge	2010	Water Licence Criteria
SCN	119	<0.5	<0.5	<0.5	0.7	0.7	3.00
TCN	1.0	<0.01	<0.01	<0.01	<0.05	<0.05	0.10
NH_3-N	48	42	20.9	2.1	1.2	0.12	5.00
NO_3-N	NA	NA	6.49	1.2	1.2	0.24	5.00
NO_2-N	NA	NA	0.08	0.10	0.52	NA	0.40
TP	0.04	0.11	0.48	0.119	0.047	0.028	0.220
TCu	0.06	0.010	0.013	0.018	0.015	0.014	0.010

Table 2 Water quality data for Zone 2 Pit; all average concentrations (mg/l)

Z2P	2003 After MAP	2006 1st Aeration	2007 2nd Aeration	2008	2010
SCN	18	<0.5	<0.5	0.5	0.6
NH_3-N	22	12.4	0.4	0.3	0.5
NO_3-N	<0.1	7.6	13.4	11.7	9.1
NO_2-N	<0.1	0.5	0.28	0.63	0.09
TP	0.480	0.358	0.180	0.082	0.10

NA = Not Available.

4 Results

4.1 Water quality in Tailings Lake and Zone 2.0 Pit

4.1.1 Physical and chemistry

Physical measurements in Tailings Lake showed consistent annual thermal stratification to about 5 m, leading to the development of a warmer, oxygenated surface layer (epilimnion), and cooler anoxic deeper layer of water. With gradual warming during summer, the thermocline migrates to the bottom and lake turn over occurs in late September. Greatest contaminant removal was consistent with the peak algal growth and active epilimnion.

Total cyanide (TCN) and weak acid dissociable cyanide (WAD CN) were rapidly removed in Tailings Lake. Since 2004, the cyanide concentrations have remained well below the discharge water licence limits of 0.1 mg/l TCN and 0.025 mg/l WAD CN. Similarly, thiocyanate (SCN) decreased rapidly after initial phosphorus addition in 2002, with concentrations being reduced from 119 mg/l to less than 0.5 mg/l (Chapman et al., 2003). Degradation of cyanide complexes also resulted in the removal of copper, cobalt, iron, nickel and silver by biomass adsorption. The biological oxidation of cyanide to produce ammonia and metals is well known (Sharer et al., 1999; Botz and Mudder, 2000). The ammonia generated in Tailings Lake had increased to 48 mg/l in 2002 but was degraded to less than 5 mg/l by 2006.

The generation of ammonia from the biological oxidation of TCN and WAD complexes in Tailings Lake and Zone 2.0 Pit was found to be relatively insignificant in comparison to the thiocyanate degradation. Analytical results for one of the formation products, sulphate, determined that the primary mechanism for thiocyanate removal was oxidation. The stoichiometry of the degradation reaction indicated that approximately 0.24 mg/l of ammonia would have been formed for every 1.00 mg/l of thiocyanate oxidised; however, a corresponding increase in the ammonia did not materialise due to the removal mechanisms of ammonia. The removal rates of thiocyanate and ammonia were examined to verify that the ENR process could remove both elevated levels of thiocyanate and ammonia (Chapman et al., 2007). Rates of removal were dependent on nutrient concentrations as well as temperature and solar conditions at the site.

In October 2000, the concentration of thiocyanate in Zone 2.0 Pit was 64 mg/l and ammonia (NH_3) was 16 mg/l. These concentration levels were a result of Tailings Lake transfers. Zone 2.0 Pit had received phosphorus additions to yield 1 mg/l and 0.3 mg/l in 2002 and 2003 respectively. Although surface concentrations of SCN decreased every summer, the concentrations below the 15 m mixed layer remained between 10–20 mg/l. A similar pattern was observed for ammonia. Water quality monitoring in Tailings Lake has confirmed no increases in NH_3 or TCN concentrations, suggesting that the tailings cap on Spruce Lake was reducing pore water migration and functioning as per design. Additionally, with the cessation of seepage pumpback in 2009, there was no further loading (recycling) of SCN back to Tailings Lake.

Zone 2.0 Pit mixing extended only to 20 m of the total depth of 100 m and therefore it was classified as weakly merometic. As was learned from Tailings Lake, mixing provided a source of phosphorus to the surface layer which was needed for continued growth of algae, biological oxidation of thiocyanate and uptake of ammonia. The ENR process was constrained by the depth of the pit lake, and until 2006, natural removal was limited to the surface layer. Removal predictions indicated that thiocyanate and ammonia would persist in the deep water for many years beyond the anticipated discharge and remediation closure in 2010. During the monitoring period, the groundwater inflow rate to the pit was about 1m/year but would become slower with time. The pit lake was expected to reach freeboard limit by 2010 and be in equilibrium with adjacent Baton Lake in 2017.

In order to speed up the process the TAC approved the business case to de-stratify the pit lake with an aeration system. The aerators were suspended at 60 m below the surface to avoid mixing of any sediments or solids by the aeration plume. Within minutes after start-up, a large dark upwelling of deep stagnant water broke the surface. Hydrogen sulphide gas was detectable by smell but not by instrumentation. Visual observation of the surface from the boat indicated that large bubble bursts were domed shaped up to 10 cm over a region of 2 m. The bubbles spread in a radial pattern, (20–30 m diameter) around the raft.

Temperature change was captured every half-hour by the string of depth sensors moored from the Z 2.0 Pit NW raft. Figure 3 illustrates the rapid de-stratification of the pit lake by the aeration system on July 12, 2006. The top 60 m was mixed by the bubble plume within 24 hours. Complete mixing of the pit lake to a depth of 100 m was accomplished within 4 days of aeration. A temporary shut-down period on July 19 allowed the pit lake to re-stratify with surface temps reaching 10°C after 4 days. While the aerator was operational, the temperature of the water column was uniform to within 0.2°C. Over the operational period the pit lake had warmed from 5°C in mid-July to 8°C by mid September.

Dissolved oxygen depth profiles for 2006 indicated the change in oxygen content before and after aeration. Before aeration, the pit-lake was essentially anoxic below the surface. After aeration, the entire pit-lake was oxygenated to near saturation. After shut-down in September 2006, the pit-lake resorted back to anoxic conditions because of the high oxygen demand from the microbiological conversion of ammonia and organic matter. The biological oxidation processes had been accelerated as a result of aeration and thiocyanate was completely removed from the water column during the first year of operation. In order to achieve complete oxidation of ammonia, the aeration system was re-installed and operated between June and September 2007.

4.1.2 Nutrients

Biological nitrification of ammonia nitrogen is a two-step process (Takahashi and Saijo,1981). Ammonia is oxidised to nitrite (mediated by Nitrosomonas spp); nitrite is then converted to nitrate (mediated by Nitrobacter spp). The monitoring results for Tailings Lake suggested that only a small proportion of ammonia was converted to nitrite, and little to no free nitrate was formed. These results suggested that the major mechanism of ammonia removal in Tailings Lake was algal assimilation (Rees et al., 1998).

Mass balance calculations were completed annually using the average mixed concentrations for nutrients in Tailings Lake and Zone 2 Pit to estimate the total mass of phosphorus, nitrite and nitrate. The calculations indicated net removals of the nitrogen compounds, but a small net gain was observed for orthophosphate and total phosphate during 2006. The source of nutrient into the Tailings Lake system after 2003 was investigated and determined to be related to sediments release, especially during anoxic winter conditions. The under-ice investigations in 2004–2005 tracked ammonia and ortho-phosphate contributions. Recycle release rates had peaked in 2004 and results indicate a decreasing trend. Sediment traps were used to confirm the removal of nitrogen and phosphorus from the water column by the algae through sedimentation. Fractionation analysis of the top sediment layer indicated that about 50 per cent of the phosphorus was organically bound and associated with iron and aluminium. When associated with iron, phosphorus becomes available under reducing conditions. Over the tailings capping period (2006), slight increases in copper and manganese were observed in the water column, likely the result of porewater migration from Spruce Lake. Water quality monitoring has indicated that metals in Tailings Lake are in a decreasing trend.

By 2006, ENR had reduced contaminant levels in Tailings Lake to the discharge limits set out in the water licence and by August 2008, Tailings Lake water began to flow to the receiving environment through the discharge channel. Water quality in Tailings Lake, and downstream along the discharge pathway, is currently monitored monthly during open water season and once through the winter.

Ammonia removal mechanisms in Zone 2 Pit included direct uptake by algae and nitrification to nitrite and nitrate. Once the thiocyanate had been removed from the water column in 2006, ammonia removal progressed at rates comparable to those observed in Tailings Lake. Nitrite, an intermediary product of the oxidation reaction, was also formed during this period. Nitrate was generated at a similar rate to ammonia removal, suggesting most of the ammonia was being oxidised to nitrate. The complete removal of ammonia generated high nitrate levels which have decreased annually to acceptable water quality levels by 2010.

4.1.3 Phytoplankton

Algal response to phosphorus additions was immediate for both water bodies. The taxonomy of the dense biomass surface bloom indicated Chlorophytes typical of wastewater assemblages. Chlorophyll “a” was measured in the euphotic zone to estimate the biomass productivity levels. Particular emphasis was placed on the phytoplankton, which was analysed for taxonomic composition, biomass and spatial/temporal distribution from 2003 to 2005. Phytoplankton was represented by small Chlorophyta and large heterotrophic flagellates.

Major changes in the abundance and composition of the algal and zooplankton in Tailings Lake were observed for the period 2003 to 2005 with average biomass of 9,485 µg/l and 15,681 µg/l in Z 2.0 Pit in 2005 (Watson and Kling, 2006). Phytoplankton biomass <1,000 µg/l generally indicate low nutrient conditions (oligotrophy) typical of the lakes around Colomac, while biomass levels >10,000 µg/l indicate high nutrients or eutrophy. Both Tailings Lake and Zone 2 Pit were in a state of eutrophy for a brief period of time following the first addition of MAP. In 2006, average biomass had decreased about 5 times in Tailings Lake with the most dramatic drops seen in the chlorophytes and cryptophytes; in Zone 2.0 Pit, decreases in chlorophytes and dinoflagellates were observed. In 2005, there was a seasonal succession shift in Tailings Lake towards Crytophyte flagellate and a diversity shift to zooplankton *Cyclops vernalis* and Daphnia species. Reasons for the shifts were likely food related (Kling, 2006). A plausible explanation is that *Daphnia pulex* can reduce algae as well as rotifer populations rather quickly as they interfere with rotifer feeding behaviour and compete for the same food. With the improvement in water quality, the decrease in algal biomass and the appearance of zooplankton in 2005, Tailings Lake was in a state of recovery. Total Phosphorus levels have continually decreased since discharge to approximately less than 0.1 mg/l in 2010.

Following the installation of the artificial de-stratification system in Z2P, a dramatic drop in biomass (about 4 times lower) was observed; this was most likely attributed to light limitation from mixing and temperature cooling. Higher trophic levels of phytoplankton have been observed in the water column of the pit lake since 2008. Total phosphorus levels (post-aeration) have decreased from 0.4 mg/l to less than 0.1 mg/l in 2010.

5 Conclusions

Water management activities, designed to minimise natural inflow to the TCA basin were used in combination with ENR water treatment. The addition of phosphorus, as the preferred treatment process, was shown to enhance the removal of cyanide compounds and ammonia. In combination with the water transfers to Zone 2 Pit, the diversion ditches were found to be an effective water management strategy to extend time for ENR process. Water quality objectives for Tailings Lake discharge were met in 2006 well in advance of original predictions. Since implementation of the ENR program in 2002, thiocyanate and ammonia concentrations in the TCA have been reduced from highs of 120 mg/l and 50 mg/l respectively to 0.05 mg/l and 0.5 mg/l. Since discharge commenced in 2008 water quality in Tailings Lake continues to meet water licence criteria set for the compliance point downstream.

The ENR processes in the Zone 2.0 Pit Lake were hampered by meromixis. An innovative artificial aeration system was used to enhance the mixing in 2006 and 2007. Aeration of the pit lake effectively mixed the entire water column and promoted the removal of thiocyanate and the biological oxidation of ammonia to nitrate. Water quality objects were achieved in 2007 and in advance of predicted passive discharge in 2010. The use of ENR for removal of cyanide and associated compounds, combined with water management, proved to be very cost effective for managing contaminated water in the TCA and Zone 2.0 Pit.

The exposed tailings, a health concern for workers and wildlife and a source of contaminated pore water migration into the treated Tailings Lake, were ultimately addressed through the placement of a tailings cap over all exposed tailings. The construction of the Dyke 7 spillway allowed for ponded water to flow from

Spruce Lake to Tailings Lake and the Discharge Channel allowed Tailings Lake water levels to reach a static level. To address seepage loss to the environment, Dam 1B was constructed using a robust design (keyed into permafrost, thermosyphon loops in dam key and abutments, geomembrane liner coupled with a geosynthetic clay liner) and an ice plug upstream as added assurance (SRK, 2008).

A number of activities were associated with the remediation of the Colomac TCA. Performance measures were used to evaluate the success of each implemented activity and included: diversion ditch efficiencies, reduced dam seepage, water licence criteria achieved, dust monitoring, caribou and moose diverted from TCA, reduction of porewater from Spruce Lake to Tailings Lake. The performance measure confirmed the success of the remediation and permitted the ultimate closure of the TCA. Long term monitoring at project closure will ensure that the Colomac TCA remediation technologies will perform as designed.

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