MPERG Report 2010-4

Evalutation of the Effectiveness of Biological Treatment of Mine Waters

By

Laberge Environmental Services

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Evaluation of the Effectiveness of Biological Treatment of Mine Waters

For

Mine and Petroleum Environment Research Group

By
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March 31, 2010

Acknowledgment

Interviews with J.T. Chapman of SRK Consulting, Erin Clyde of Ecometrics, Andre Sobolewski of amec and Dylan Macgregor of SRK Consulting were very helpful and hereby gratefully acknowledged. The patience of Karen Pelletier, long-suffering chair of MPERG is acknowledged – thanks for all your help and advice Karen.

1.0 Project Background and Objective

Under the topic of information needs for mine closure and abandonment, the MPERG priorities for funding in 2009 included an investigation of the use of bioremediation as a treatment option for active and abandoned mine drainage. From the 2009 MPERG call for proposals: "The use of various "passive" treatment technologies is being proposed as a possible panacea to provide efficient, cost effective treatment of pit water and metal bearing water discharges. The long term effectiveness of these treatments in a northern environment needs to be investigated." Passive treatment of some kind has been considered for many years due to its appeal in comparison with mechanical-chemical treatment plants which are now required to operate almost in perpetuity at many closed mine sites. An observation that makes bioremediation so attractive are the many natural analogues observed around mine drainages that naturally attenuate or otherwise reduce metals burden in mine drainage without apparent harm to the host aquatic ecosystem. These include fen-bogs, swamps and other wetland structures which renovate mine drainage; effectively removing and in many cases sequestering contaminants. The original term "wetland treatment" has given way to "passive treatment" and/or "biological treatment" in recent years.

The objective of this report was to conduct a desktop review and communicate with practitioners and experts to generally evaluate its effectiveness and applicability to Yukon mine drainage applications. This report contains a bibliography of over thirty key reports, publications and papers on the topic. Since some of these document constitute reviews of the technology in themselves (e.g. Zagury, 2007), the reader is encouraged to obtain and review the document of most interest to them. In this way information is made available through MPERG to help the local regulatory and scientific community become more familiar with biological treatment strategies. For simplicity in the face of the enormous amount of information available on biological treatment, this report has focussed on passive bioreactors, passive wetlands and pit lake biological treatment programs. We have presented a brief synopsis of the methodology, history and current state of the art of bioremediation and have tried to answer some questions: does it work in the cold climates, is it dependable in the long term, is it environmentally sustainable and is it cost effective?

This report is organized into the following sections; overview of passive biological treatment processes, review of case studies, discussion and listing of key publications and papers.

2.0 Passive Biological Treatment Processes

Wastewater treatment using various biota is not new to North America. Historically, sewage treatment was the first to recruit bacteria and algae (a local example is the Teslin Wetland Sewage Treatment System), culminating in recent decades with passive wetland designs that use a combination of aquatic plants, phytoplankton and bacteria. Treatment of mine waste water including tailings ponds as well as acid and neutral mine drainage has traditionally been accomplished through conventional treatment using mechanical-chemical treatment plants.

Passive treatment of mine drainage falls into three main categories: anaerobic, limestone-based methods for treating acidic mine drainage; biological methods which pre-treat mine water for subsequent renovation usually by limestone; and enhanced biological treatment methods. Some biological methods don't need plants, such as biochemical reactors. Most passive systems in use today employ combinations of methods to suite the particular characteristics of the mine drainage in question.

Metals-laden water has been naturally renovated for eons; such as in bog iron ore. Wetlands have been long recognized as nature's kidneys, producing alkaline water by hydroxide and sulphide precipitation and pH adjustments among other bio-chemical processes. Early environmental investigations around mine sites revealed that natural wetlands receiving polluted mine water were showing excellent renovation of metals without apparent harm to the host ecosystem. Most of the early attempts to employ biological treatment mimicked natural shallow soil or wetland systems and were designed as engineered passive wetland treatment systems. Biological treatment utilizing wetlands really took off in the 1980s and early 1990s in the U.S. Appalachian coal mining region. Hundreds of constructed wetlands have been built since then. Early investigators of natural attenuation processes in the Yukon included Dr. John Kwong, G. Whitley, Environment Canada, Microbial Technologies Ltd. and Dylan Macgregor. Over the past fifteen years or so numerous experiments and full scale applications of passive biological treatment projects have been documented. Over the past decade biological treatment of inundated mined-out pits or pit lakes contaminated with metals and other pollutants has been extensively studied and applied. Using manipulation strategies such as addition of nutrients to create algal blooms, some pit lakes have been successfully treated to allow discharge to the environment. In recent years there has been a tremendous interest in biological treatment of mine drainage; depending on the search engine and criteria, literally hundreds of publications can be found.

Biological treatment can be separated into several classifications based on whether or not the process is aerobic or anaerobic, how much hands-on maintenance is required and which biological process dominates. Some classifications attempt to separate "passive" from "active" biological treatment based on the degree of intervention required to keep the system working and how much control can be achieved. The distinction between active and passive treatment will always be a bit unclear because even the simplest system requires upkeep and maintenance. An approach that seems to encapsulate passive biological treatment is that it doesn't require continuous mechanical-chemical inputs because the system mimics and enhances natural bio-chemical process. Of course, the perfect passive system would work indefinitely and need no maintenance. There are many applications of passive bioremediation including aerobic and anaerobic wetlands, sulphate reducing bioreactors, anoxic limestone drains, in-situ reduction fields, aerobic and anaerobic wetlands, limestone leach beds, open limestone channels and pit lake biological treatment systems. Clearly the use and enhancement of natural bio-geo-chemical forces to remove and sequester contaminants takes many forms. For the sake of simplicity we have narrowed the focus of this report to three main applications; engineered wetlands, passive bioreactors and biological treatment of pit lakes.

The main contaminants in mine drainage in the Yukon are metals and cyanide (the cyanide heap leach pad at Brewery Creek was successfully detoxified using biological treatment). A major generator of metals-laden mine drainage is Acid Rock, or Acid Mine Drainage commonly referred to as AMD, although Yukon sites predominantly present neutral pH metals-laden mine drainage. AMD happens when sulphide minerals, mainly pyrite and pyrrhotite are exposed to oxygen and water. It is a combination of chemical and biological processes that is greatly magnified if the reaction reaches low pH by bacteria such as Acidithiobacillus (formerly Thiobacillus) ferrooxidans. AMD is characterized by low pH, high sulphate and high dissolved metals. Much of the impetus for biological treatment was to find an effective economic means to treat AMD. AMD bacteria can be thought of as the "bad guys" of microbe community on mine sites while phytoplankton or algae, in combination with sulphate reducing bacteria (SRB) may be thought of as the "good guys". Sulphate-reducing bacteria are a group of anaerobic bacteria that use carbon to reduce sulphate to insoluble metal sulphides and produce bicarbonate ($HC0_3^-$) where an organic compound nutrient source is available. SRB use the organics as electron donors under anoxic and reducing conditions. The hydrogen sulphide generated forms insoluble metal precipitates thus removing metals from the water. The bicarbonate increases alkalinity. The process is very effective in removing metals such as

Cadmium, Copper, Lead, Mercury, Zinc and Iron (Kuyucak, 2002). SRB treatment processes have been applied in bioreactors, reactive barriers and constructed wetlands to treat seepage, sewage, and inundated mine pits. Following are overviews of three passive biological treatment technologies.

2.1 Constructed Wetlands

In wetland applications, donor species of water loving plants are transplanted in constructed impoundments rich in organic carbon substrate. Metals-laden water which is often the product of AMD but can easily be pH neutral, simply flows slowly through the substrate and root zone of the plants. The ways in which metals are removed include precipitation in the form of metal sulphides such as iron sulphide (Fe^{2+}) and zinc sulphides (Zn^{2+}). Iron and magnesium carbonates are also precipitated. Metals are also adsorbed onto organic substrate, onto the SRB and the precipitated metal sulphides. Finally, effluent quality is improved physically by filtration of suspended solids. Hundreds of engineered wetlands have been used to treat mine waste water for many years. Many applications can be found in the Appalachian Coal mining industry and were used primarily for pH adjustment and iron removal. Mine drainage was directed into a series of designed plant-based cells that included plants known for their ability to withstand the presence of heavy metals for both metal tolerance and sequestration potential. Many of the first US wetlands used Sphagnum and later Cattails. It was noticed early on that a good supply of organic carbon was needed in the substrate to feed the SRB. In the Yukon, experimentation with passive wetlands began in 1995 at the former United Keno Hill Mine (UKHM). Over the years investigators have documented wetlands and shallow soil metals removal mechanisms at UKHM (D. Macgregor, LES, and Microbial Technologies). The primary forces are metals uptake in plant material, co-precipitation of manganese with other metals, settling and adsorption.

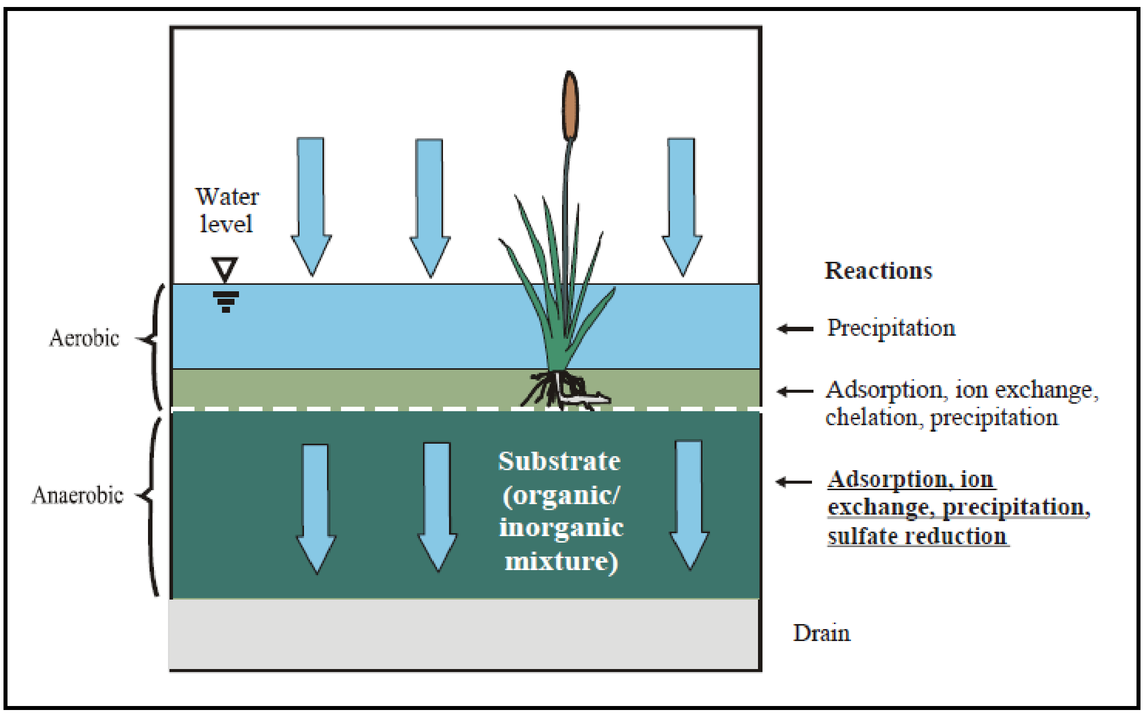

Figure 1 – typical wetland, from Eger and Wagner, see 5.1.18 below

How long can constructed wetlands be expected to perform? How long they last is a function of the treatment process and contaminant loading. Since the primary treatment mechanisms are more or less finite, metals removal should cease unless new micro-sites are generated to host the reaction. Fortunately, the annual growth cycle naturally process Most commonly, aerobic systems take out metals by adsorption, ion exchange and Practitioners have found that the rate of sulphate reduction goes down over time, but adequate treatment can be sustained for many years if additional carbon is added (Eger and Wagner, Zagury). Aerobic systems

2.2 Bioreactors

A bioreactor is some kind of flow-through structure; an above or below grade tank or above grade impermeable enclosure which has a layer of reactive mixture (usually some kind of carbon) with an input of contaminated mine drainage. The solid reactive mixture acts as a carbon source for SRB and also as a framework for microbial attachment and contaminant precipitation. There are two different types of bioreactors; active and passive systems. The active systems look like conventional treatment plants and are closer to chemical than biological engineering, but they use biological instead of chemical inputs. Active bioreactors feature careful system control over retention time, feed rate, pH balance and other parameters. Passive bioreactors are far simpler in design and may be as basic as a lined trench containing organic carbon substrate with a gravity feed of contaminated mine drainage. Bioreactors can take the form of permeable reactive barriers or even passive in-situ reactors.

Almost 20 years ago, SRK proposed using the underground adit in the Faro Pit as a big underground bioreactor which would have converted acid mine drainage to sulphate ions to hydrogen sulphide with zinc sulphides being precipitated. The concept would have used cattle manure as the bacteria source and some form of sugar as the energy source for the bacteria.

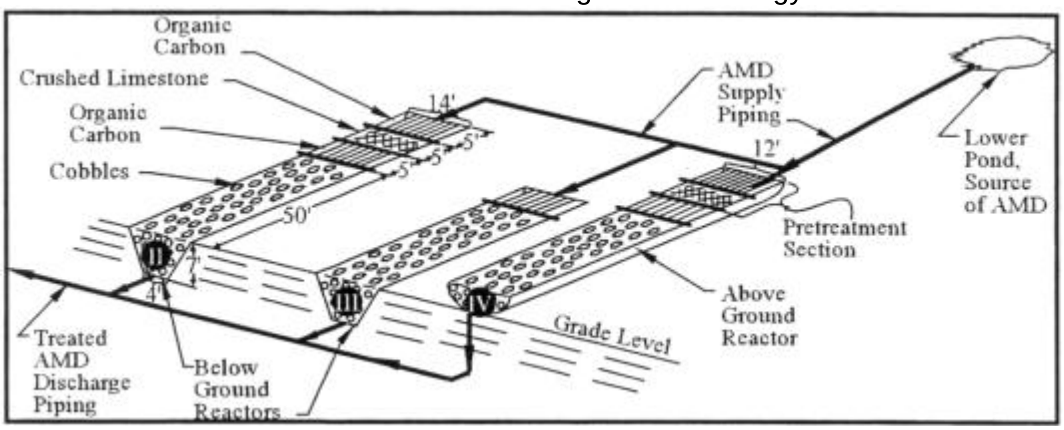

Figure 2 - example of an above ground bioreactor, from Andre Sobolewski – see 5.1.17

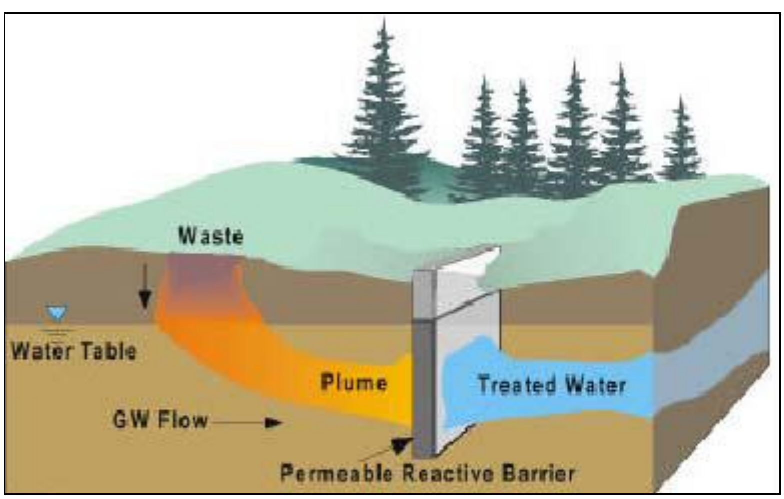

Figure 3 example of an underground bioreactor from Andre Sobolewski – see 5.1.17

Passive on-site bioreactors look very promising for treatment of mine drainage. They are simple, low cost technologies that work in the cold. Even though formation of metal sulphides is the preferred process, other mechanisms including adsorption and precipitation of metal carbonates and hydroxides occur in passive bioreactors (Zagury, 2007).

2.3 Biological Treatment of Pit Lakes

In its simplest form, passive biological treatment of inundated mine pits (pit lakes) involves induced algal blooms which remove metals from the water column. Metals are scavenged by biogenic particles in the surface waters and are dragged down to the bottom with the settling dead plankton. Ideally, metal sulphides form in the bottom waters owing to the action of SRB. In some cases pit lakes slated for biological treatment have strong physical or chemical boundaries that keep them from mixing, forming a meromictic lake. Meromixis means the lake is permanently stratified and the layers are inhibited from mixing due to physical and/or chemical boundaries. In meromictic pit lake bioremediation it is sometimes possible to establish flow-through conditions where a clean layer of water meets discharge criteria while anoxic bottom waters host SRB that work to reduce metals under ice cover. Bioremediation involving algal blooms requires addition of specific mixtures of fertilizer to initiate and manage algal blooms so that excessive nutrients like phosphate do not build to unacceptable concentrations in the treated waters after the metals have been removed. In some cases sugar, ethyl alcohol or some other carbon source is added to bottom waters to induce anoxic conditions and SRB activity.

The function of the above passive biological treatment systems is best illustrated through descriptions of experiments and full-scale applications of the technology. Case studies most applicable to the Yukon are presented below.

3.0 Case Studies

Following are case studies that either represent direct Yukon applications of passive biological treatment or take place in areas with comparable conditions.

3.1 United Keno Hill Mines (UKHM)

In the 1970s and 1980s, DIAND and Environment Canada investigators began to document natural attenuation of metals in mine drainage from the UKHM mine openings which reported to natural wetlands and shallow surface soils (J. Kwong et al., 1984). Water and substrate samples collected along natural flow pathways which received metals laden water showed that metals concentrations were far reduced through natural processes but these were poorly understood. Passive wetlands had been in use for mine drainage but most applications were in temperate climates, so investigations turned to application of the technology in the Yukon. A passive wetland was designed and tested on a pilot scale by Dr. Andre Sobolewski in 1995. Native sedges (*Carex aquatilis*) were transplanted into a terraced slope with shallow impoundment walls and highly contaminated mine drainage was directed into the system after the plants were allowed to establish. Monitoring of the wetland continued for one season and results showed that treatment within the wetland reduced concentrations of zinc, cadmium, manganese and nickel. Sulphate reduction in the sediments and formation of insoluble metal sulphides appeared to be the main metal removal process.

Following up on this effort Laberge Environmental Services (LES) conducted a study of the remnant pilot wetland and natural wetlands receiving highly contaminated mine drainage in the UKHM area in 1999 (MERG Report 2000-3). This study found SRB was present in organic detritus and soil beneath the sedges. It also noted some differing metals removal processes; insoluble metal carbonates, metal sulphide precipitates, and iron and manganese oxides. The study found most of the contaminants of concern, zinc and cadmium, were bound onto iron and manganese oxides. Leach tests showed good prospects for long-term retention of zinc within the shallow black organic soils. Metals uptake was not an issue within the dominant sedges in the constructed and natural wetlands receiving metals-laden water. This study also found excellent colonization of the transplanted sedges in both the pilot wetland and within the old

UKHM tailings pond making the local sedge species excellent passive wetland candidates. The study concluded that passive wetland biological treatment appeared viable at UKHM.

In 2000 and 2001, Dylan Macgregor investigated metals attenuation in shallow soils in the UKHM study area, culminating in his Masters Thesis (and MERG Report 2003-5) Natural Attenuation of Aqueous Zinc Downstream of Galkeno 300 at UKHM, Central Yukon. The study field program was conducted in the summer of 2000 and was followed by a phase of laboratory testing. The field program demonstrated reduction of zinc concentrations from 150 mg/L at the Galkeno 300 adit to about 2 mg/L where the flow path entered Christal Creek. Upper organic and lower mineral soils were collected in and adjacent to the flow path. Zinc was found to be highly elevated in the upper organic soils. Physical characterization, batch absorption testing and column leaching with synthetic and natural mine drainage was conducted. It was observed that the organic soils had the highest attenuation capacity. It was also noted that the oxide fraction was holding most of the zinc and that a high concentration of manganese was removed simultaneously with the zinc. The study concluded that co-precipitation of zinc with manganese was the dominant process in the attenuation of metals in shallow soils in flow pathways from Galkeno 300.

While the above efforts have never resulted in a full-scale constructed wetland treatment system at UKHM, in 2009 a pilot scale passive bioreactor was activated at Galkeno 900 which employs some of the concepts noted in prior investigations, particularly utilization of SRB. So far the bioreactor has shown promising results and may be followed either by full-scale bioreactors or in-situ reduction fields at the other mine drainages on the property.

3.2 Faro Mine Complex

The Faro Mine Complex (FMC) was briefly the world's largest lead-zinc mine. After a series of closures and re-openings, the mine was declared abandoned and finally went into receivership in 1998. Since that time, numerous closure studies have been done to establish treatment strategies for contaminated mine drainage on the site. The three mine pits on site; the Faro Pit, Grum Pit and Vangorda Pit are inundated and receive metals-laden mine drainage. The Faro Pit Lake and Vangorda Pit Lake have been used as depositories for local contaminated runoff and seepage. Both of these pit lakes are pumped to mechanical-chemical treatment plants. In 2002 a study was undertaken to test the viability of using artificially induced algal blooms to treat contaminated water in the Little Creek Dam (LCD), an impoundment which captures AMD from the Vangorda waste rock piles (MERG Report 2003-1). The LCD was selected because it's zinc burden was in the range of 10 mg/L zinc – thought to be a manageable concentration for studying the effects of algal blooms. The LCD was fertilized using granular Potassium-Phosphate fertilizer from a small boat. A concurrent bench test was done at Microbial Technologies. Large volume samples were collected and tested by adding various fertilizers to induce algal blooms. Over the 56 days of the lab study, zinc was reduced from 58 to 3 mg/L. The field results were confounded by the onset of highly contaminated seepage reporting to the impoundment, dramatically raising the pond zinc level from a long term level of about 10 mg/L to over 300 mg/L. While algal growth was induced in the pond, it was not possible to differentiate any net zinc removal from the constantly increasing raw water zinc concentration. Important observations from this study were that; the lab work demonstrated potentially excellent zinc removal through algal adsorption and zinc removal was only successful if pond sediments were present. It was recommended that induced algal blooms be tested as a potentially inexpensive treatment alternative for the Grum, Vangorda and Faro pit lakes.

Figure 4 - Algae in Little Creek Pond

Pit lake water quality was assessed and reported by Gartner Lee Ltd. in 2003 and further investigated by SRK in 2004. Wall rock contributions to pit lake water quality were predicted (and later re-evaluated when it was found through seep surveys that the seeps were contributing far more metals than originally thought, particularly at the Grum Pit). Over the winter of 2003/2004 the mine operators, regulators and consultants carried out studies of post-closure conditions in the pit lakes and reviewed treatment options. Dr. Greg Lawrence and a team composed of UBC Earth and Ocean Sciences, SRK Consulting and Natural Resources Canada (NRCAN) studied and projected the mixing behaviour of the pit lakes under flow-through conditions and evaluated various treatment strategies including biological treatment. SRK compiled a report for Deloitte and Touche, the interim Receivers of the Anvil Range Mine. The scope of the report was to address water management and treatment strategies for the pit lakes at Faro and assess the potential for stratification (meromixis), look into in-situ treatment technologies and provide water quality prediction. The thinking at the time was to try and design a clean flow-through post closure pit lake system (SRK 2004). Dr. Lawrence's work was summarized by SRK; basically the lakes were apt to develop meroxisis only when water was diverted around them. If Faro, Vangorda and Grum Creeks were allowed to enter their respective pit lakes, it is likely that completely mixed conditions would develop in all the pit lakes. To confirm these projections, Dr. Lawrence recommended site specific under-ice and open season monitoring of the pit lakes. Meanwhile, Natural Resources Canada's CANMET was commissioned to look into the state of the art in pit lake treatment. They were tasked with addressing applicably, status of the technologies, effectiveness, costs and sustainability. CANMET found that there were several viable pit lake treatment technologies available and they fell into biological and chemical categories. After careful consideration, three methods were picked for further consideration; lime (or something else) to raise pH, sugar-alcohol amendments to make anoxic conditions to promote SRB and nutrient additions to create algal blooms (biological treatment). The review was encouraging; if waste rock sources could be controlled then water quality might be in the range where in-situ technologies would apply. Even though stratification would be partial at best and subject to uncertainties, flow-through options were still being considered as a post-closure strategy.

In the spring of 2004, Deloitte and Touche Ltd. Convened a workshop at SRK on pit lake biological treatment. Leading experts were invited (Microbial Technologies, Lorax Environmental Services, Rescan and Dr. Greg Lawrence). The result of the workshop was that Lorax was given the nod to experiment with nutrient amendments in the Faro Pit Lakes with Microbial Technologies to perform the pre-cursor bench testing. Lorax designed a system of mesocosms or limno-corrals to test various amendments that were deployed on an instrumentation raft in the Grum Pit Lake in June, 2004 with the assistance of Deloitte and Touche and LES. The results of the 2004 experiment with the Grum Pit Lake whole-lake fertilization were quite compelling; zinc was reduced in surface waters to less than 0.1 mg/L and sediment samples collected 12 m below surface contained around 2.5% zinc solids by weight. Detailed profiling and sampling of the Faro and Vangorda pit lakes was also conducted. Lorax found that; EDTA and fish fertilizer were not needed since excellent algal growth and zinc removal was obtained with conventional liquid fertilizer, conversion of dissolved to total zinc was most efficient when fresh algal growth was underway so pulsed eutrophication was seen as the best approach, Faro and Vangorda pit lakes also appeared to host the right conditions for bio-remediation. It was recommended that the program proceed with whole lake manipulations in Grum and Faro pit lakes in 2005.

Images from Grum Pit Lake June, 2004

The pit lake biological treatment experiment continued in 2005 under the direction of SRK, with the addition of whole-lake fertilization of the Faro Pit Lake. Although the Faro Pit Lake was only fertilized three times, a rapid and significant algal growth was achieved. The fertilization was halted at the direction of Deloitte because it was thought to be interfering with the operation of the lime treatment plant situated in the old converted mill. SRK estimated that the fertilization in the Faro Pit Lake resulted in the removal of between 45 and 60 tonnes of zinc at the rate of 0.48 to 0.80 g/m2/day, which compared favourably to the rate achieved in the Grum Pit Lake. Biological treatment of the Faro Pit appeared promising indeed. However, the plant proteins generated in the pit lake caused excess foaming in the treatment plant which in turn prevented effective settling of the hydroxide precipitates generated by lime treatment. It was suggested that simply deepening the withdrawal point to a different layer of the meromictic lake might alleviate the problem, but this was never pursued and experimentation with biological treatment of the Faro Pit Lake was abandoned. Likewise, the recommended fertilization of the Vangorda Pit Lake was halted.

Meanwhile, the fertilization of the Grum Pit Lake continued through 2005 to 2009 along with depth-integrated sampling and detailed profiling of all three pit lakes. Each year, SRK summarized the results in a series of reports submitted to the Receiver. Refinements were made to the fertilization program to end the algal blooms earlier in the season which had the desired affect of reducing residual nutrient concentrations in the surface waters. Each year the Grum Pit water responded well to fertilization and achieved excellent algal growth. The Grum fertilization appeared to be less effective in 2005 and 2006 until revised mass balance calculations revealed far more zinc was entering the pit than originally thought. Initially zinc loading to the Grum Pit Lake was estimated at only 350 kg per year but this was revised to 3,000 to 4,000 kg of zinc following detailed seep surveys undertaken by SRK. As it turns out, the biological removal effects a zinc reduction of about 4,500 kg per year. Results from 2007 and 2008 suggested that the treatment rate was starting to overtake the loading and that continued biological treatment will achieve even better results over the next few years. The weighted average zinc concentration in the Grum Pit Lake has been reduced from 10 to 12 mg/L to about 5 mg/L. SRK reported the results of the 2009 Grum Pit Lake fertilization program (SRK February 2010 draft report). The weighted average zinc concentration had been reduced to around 4 mg/L, and it appeared as though sulphate reducing bacteria were beginning to affect zinc removal in the bottom waters over the winter of 2009-2010. It is entirely possible that continued biological treatment of the Grum Pit Lake may lead to significant and sustainable improvements to the water quality in the pit lake. The effective control over residual phosphate and other nutrients in addition to continued decline in zinc makes continued biological treatment of the Grum Pit Lake imperative.

3.2 Colomac

The use of biological treatment in tailing ponds at the Colomac mine was reported by SRK (Water Treatment and Management during the Closure of the Colomac Mine, J.T. Chapman et al., 2003). Before it shut down in 1997 the Colomac Gold Mine, located about 220 km northwest of Yellowknife NWT had processed about 11 million tones of ore. The mine used the cyanide vat leaching process to recover gold and deposited tailings in two natural lakes, which in the original design were meant to become a single tailings containment area. This was to be a "zero discharge" facility so cyanide and other contaminants were not treated prior to discharge into the tailings facility. However, due to the premature shutdown of the mine, the final design configuration of the tailings containment and the goal of zero discharge was never achieved. Tailings were deposited to above the natural high water mark of the lake, and dams were built to contain seepage from topographic lows in strategic areas. As is often the case in permafrost dam construction, they leaked, causing the need for capture and return to the lake. The contaminated seepage water resembled the tailing pore water being very highly contaminated with cyanide, thiocyante and ammonia. In an "emergency" transfer, water was pumped to a mined-out pit on three occasions between 1998 and 2003 creating a second contaminated water body. A project team comprised of DIAND and SRK developed a remediation plan which included various treatment options to reduce cyanide compounds, ammonia and metals in the subject water bodies. A short list of treatment options included rotating biological contactors (RBCs) and alkaline breakpoint chlorination, which was selected because RBCs need too much heat. Meanwhile enhanced natural attenuation was being investigated at BC Research. What seemed to be the primary biological reactions in removal of Cyanide complexes were bacterially catalyzed reactions where Cyanide is converted to ammonia and direct uptake of some of the compounds into algae cells. It was found that the mine waters were deficient in phosphorus, so a program of bench tests were undertaken using differing additions of phosphorus to tailings water. Stimulated algal growth removed thiocyanate from 100 to less than .5 mg/L in 30 days. At that point it was decided to achieve a nominal concentration of about 1 mg/L Phosphorus in the tailings lake and the pit lake so as not to have residual concentrations of the nutrients after the biological treatment was finished. Thus, breakpoint chlorination was left as a back-up rather than a primary treatment option.

To start the program it was calculated that 12 tonnes of Mono Ammonium Phosphate (MAP) would be needed in the tailings lake and 24 tonnes of MAP for the pit lake. Since the granular MAP is less soluble than liquid fertilizer, it was dispersed over the ice just prior to break-up using a hopper suspended from a helicopter. This was done in February 2002 and followed by an additional 9 tonnes of MAP being added in May 2003. Following the fertilizer application, a program of depth profile water quality sampling, physical profiling and identification of algae and de-nitrification bacteria was conducted through subsequent years. This program discovered remarkable efficiency in removal of Cyanide, metal-cyanide complexes and ammonia without excess nutrient residues. The removal of cyanide and its associated compounds through enhanced natural removal proved to be a very cost effective mine water management strategy, saving millions compared with conventional treatment. The lakes treated with ENR have been discharging acceptable water for over two years.

3.3 Island Copper

Island Copper was the site of a biological treatment process that involved flooding a mined out pit with sea water to create a meromictic lake, and has been reported in *Planning In-Perpetuity Mine Closure Costs*, G.L. Pierce and M.E. Wen 2006; and *Field Studies of Semi-Passive Biogeochemical Treatment of Acid Rock Drainage at the Island Copper Mine Pit Lake*, G.W. Poling et al., 2003. The aforementioned papers encapsulate the experience of the Island Copper Mine near Port Hardy, B.C. which closed in 1996. In a novel approach, the mine submerged tailings under sea water and when the pit was exhausted, it was flooded with sea water creating briefly, a spectacular waterfall. The flooding channel was closed and the lake was then capped with freshwater piped from a nearby river. The pit lake receives substantial AMD with elevated cadmium, copper and zinc from a collection system. Effective biological treatment of the surface waters is achieved through addition of liquid fertilizer. Treatment is accomplished by two mechanisms; semi passive treatment in the top layer of the lake, and passive treatment in the middle layer of the lake. The top layer treatment is by means of fertilizer induced phytoplankton growth. The abundant microscopic phytoplankton provides adsorption surfaces for metals that, once adsorbed, sink to the bottom where they are sequestered in the anoxic sediment. The pit lake system treats annually approximately 3.5 million cubic m of AMD.

An optimisation program was undertaken in 2004 to increase the life of the top layer treatment system through a method called Middle Layer Lifting. This system uses a gravity feed of AMD to drive a Venturi system that mechanically lifts water from the middle layer to the surface to thicken the top layer over time. The thickening of the top layer is integral to meeting discharge criteria of water that exfiltrates to Rupert Inlet, and it will allow the pit lake biological treatment to function for 30 to 50 years, after which some kind of active treatment will be needed. (Wen and Pierce, 2006)

3.4 Equity Silver

The Main Zone and Waterline pit lakes at the Equity Silver Mine near Houston, BC were subjected to a research program which assessed various bio-remediation strategies through field-scale manipulations with enclosed mesocosms (limnocorrals). (*A Tale of Two Pit Lakes: Initial results of a three year study of the Main Zone and Waterline pit lakes near Houston, B.C., Canada*, L. Crusius, R. Pieters, A. Leung, P. Whittle, T. Pederson, G. Lawrence and J.J. Mcnee, and *Field Scale Assessment of Bioremediation Strategies for Two Pit Lakes Using Limnocorrals*, AJ Martin, J Crusius, JJ McNee, P Whittle, R Pieters, and T Pedersen., 2003). Manipulation strategies included addition of algal nutrients and dissolved organic carbon. The amendments resulted in the effective removal of metals from surface waters. The removal mechanism is a two-stage process, in which metals are first sequestered to biogenic particles, followed by export from the surface layer via particle settling. In particular, fertilisation appears to have considerable benefit with respect to Zn, Cu and Cd, all of which have a strong affinity for biological particles. The increased production of H_2S in the bottom waters of Waterline Pit fostered by the addition of dissolved organic carbon (ethanol) resulted in the enhanced removal of Zn and Cd as sulphide minerals (ie ZnS, CdS). This passive form of bio-remediation is utilised in other forms of anaerobic wastewater treatment which utilise sulphate reducing bacteria, including bio-reactors (Zaluski et al, 2000), wetlands (Sobolewski, 1999) and reactive walls (Benner et al, 2002). The results from the limnocorral experiments have relevance to pit lake management at Equity and elsewhere. First, both metal sorption to particles and particle settling act to reduce the bioavailability (and hence toxicity) of metals to aquatic organisms. The export of particulates (via settling) from surface waters removes metals from the available pool, while the sorption of metals to particulates reduces their bioavailability (Campbell, 1995). Both of these processes also have relevance within the regulatory framework. Mining effluents are typically regulated with respect to both water quality parameters such as metals concentrations and toxicity to aquatic organisms. The results also indicate that significant improvements to surface-water quality can be achieved within a two-month fertilisation period. Similarly, the results indicate that sulphide removal mechanisms can be enhanced within weeks via the addition of ethanol (A.J. Martin et al,. 2003)

4.0 Discussion

Bioremediation and passive treatment of mine drainage may not be a panacea to solving the Yukon's mine drainage treatment issues but this technology certainly offers a viable alternative to existing mechanical-chemical treatment. During the review of scientific papers and reports and in discussions with experts a common theme emerges; that passive biological treatment approaches are better understood and more predictable all the time.

Passive wetlands appear to have the most potential as tertiary treatment, although there may be cases where enough space is available to use them as full-scale treatment options such as the valley bottoms around Galena Hill at the former UKHM.

Biological treatment of pit lakes appears to be a cost-effective treatment approach to Yukon situations, especially remote sites. The approach to each pit lake would depend on site-specific conditions and the design of the treatment system might vary from straightforward application of algal and bacterial nutrients to combined biological-chemical treatments. It all comes down to loading vs. treatment requirements. Several examples exist where biological treatment has effectively overcome loading (Grum Pit Lake, Island Copper, Colomac).

Passive bioreactors designed for site specific conditions seem very promising for Yukon applications. A passive system was successfully implemented in northern Quebec (*Successful Implementation and Operation of a Passive Treatment System in an Extremely Cold Climate, Northern Quebec, Canada*, Nural Kuyucak, Francois Chabot and John Martschuk, 7th ICARD, 2006). In this case a remote site, the Cadillac Mine, was provided with a passive treatment facility including anaerobic and aerobic cells, seepage collection and a limestone filter. Locally available materials were used for organic nutrients and the system produced water quality acceptable for discharge. Findings of a detailed evaluation of passive bioreactors shows that the technology may well be applicable to Yukon settings (*Passive Treatment of Acid Mine Drainage in Bioreactors using Sulfate-Reducing Bacteria Critical Review and Research Needs* by : Carmen-Mihaela Neculitaa, Gérald J. Zagury and Bruno Bussièreb Dep. of Civil, Geological, and Mining Engineering, École Polytechnique de Montréal, Montreal, QC, Canada, Dep. of Applied Sciences, Univ. du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, QC, Corresponding author (**gerald.zagury@polymtl.ca**). Drawbacks to bioreactors noted in pilot and field studies are short-circuiting, plugging, compacting, overloading, and exhausting of carbon available to SRB. Bioreactor technology continues to be successfully applied by the private sector in proprietary designs of treatment systems.

It is possible that the cost of passive treatment may have been exaggerated by the requirement for detailed scientific study. Bioremediation and passive treatment are terms that still suffer from the perception of incomprehensible "black box" technology, and because they involve life sciences are inherently unpredictable. As a consequence passive treatment must prove itself through years of research. Rigorous experimentation and study continues in most passive biological treatment options. Sceptics may eventually yield to a preponderance of defensible data as each successful application shows the efficacy and economy of biological treatment strategies. There is no doubt that bioremediation can be cost effective especially when the cost of studying them is factored out.

Passive in-situ treatment approaches can be sustained in the long term (Island Copper, Colomac) and can even utilize locally available materials (Cadillac Mine, northern Quebec), offering a potentially viable and environmentally sustainable alternative to mechanical-chemical treatment technology.

Over the past two decades significant research has been directed to passive biological treatment by academics, government and the private sector. Numerous academic papers document passive biological treatment proof of concept and research findings. In government, Natural Resources Canada's CANMET Mining and Mineral Resources Laboratories have conducted research into both passive biological treatment and passive bioreactors. Also the private sector has implemented many successful biological treatment applications. While the latter tend to be proprietary or withheld from publication for the purpose of commercial advantage, the overwhelming results of published work are positive about biological treatment technologies. The working hypothesis over the years has been that passive treatment can be very efficient in metals removal; can sequester metals in dense chemically stable sludge; can be far less expensive in operating and maintenance costs; can reduce or eliminate the use of hazardous chemicals; uses less energy; and has the potential to regenerate itself. This review found that those hypotheses have been proven in many cases.

Is the technology applicable to the Yukon? Doubts about the effectiveness of biological treatment approaches include the issues of whether or not they can work in cold climates, if they can continue to yield good results in the long term, if they are cost-effective and if they can meet stringent discharge criteria. The examples of the Cadillac Mine, Island Copper and Colomac show that biological treatment can be effectively applied and can overcome the aforementioned limitations.

Researchers and Practitioners of passive treatment have identified some research and design criteria needs to advance the application in Northern settings. Additional work needs to be done to properly assess the long-term efficiency of reactive mixtures and the metal removal mechanisms. Furthermore, metal speciation and ecotoxicological assessment of treated effluent from on-site passive bioreactors have yet to be performed (Zugury, 2007). It behoves everyone engaged in mine drainage management to better understand the processes involved and continue to seek sustainable alternatives to conventional chemical-mechanical treatment.

5.0 Technical Reports, Publications and Papers

Following is a list of key technical reports and articles on passive biological treatment organized into two categories; wetland treatment/bioreactors and pit lake treatment.

5.1 Reports on Passive Wetland Treatment and Bio-reactors

5.1.1 A Review of Passive Systems for the Treatment of Acid Mine Drainage

Authors: B. Gazea, K. Adam and A. Kontopoulos 1996 Laboratory of Metallurgy, Department of Mining and Metallurgical Engineering, National Technical University of Athens, GR-157 80 Zografos, Athens, Greece

Abstract

This review presents the current state of development of the passive mine water treatment technologies. The background of passive treatment is reviewed and the chemical and biological processes involved in metals removal and acidity neutralization are detailed. The types of currently existing passive treatment technologies and their applicability range as defined by the mine water chemistry are presented. Finally, the performance of passive systems constructed for the treatment of acid mine drainage from both coal and sulphide metal mines is summarized.

Author Keywords: Acid rock drainage; bacteria; environmental; pollution

5.1.2 A Review of Processes Responsible for Metal Removal in Wetlands Treating Contaminated Mine Drainage

Author: André Sobolewski, Microbial Technologies Inc., Gibsons, B.C., Canada

DOI: 10.1080/15226519908500003

Abstract

Many reports have documented wetlands removing a wide variety of contaminants in mine drainage, including aluminium, arsenic, cadmium, cobalt, copper, cyanide, iron, lead, manganese, nickel, selenium, uranium, and zinc. This article reviews biogeochemical processes responsible for their ability to transform and retain metals into insoluble forms. Shallow depth and large inputs of organic matter are key characteristics of wetlands that promote chemical and biological processes effecting metal removal. Aquatic macrophytes play an essential role in creating and maintaining this environment, but their uptake of metals usually accounts for a minor proportion of the total mass removed. Sorption onto organic matter is important in metal removal, particularly for copper, nickel, and uranium. Aluminium, iron, and manganese are often removed by hydrolysis, with the resulting acidification of water buffered by alkalinity produced in wetland sediments by anaerobic bacteria. Bacterial sulphate reduction accounts for much of this alkalinity. It can also contribute significantly to metal removal by formation of insoluble sulphides. Other important processes include the formation of insoluble carbonates, reduction to non-mobile forms, and adsorption onto iron oxides and hydroxides. Examples from field studies are presented throughout the review to illustrate these processes.

5.1.3 Investigations Into Passive Wetlands Treatment of Mine Drainage to Remove Heavy Metals at Various Sites at UKHM

Author: Bonnie Burns, Laberge Environmental Services. MERG Report 2000-3

Executive Summary

Wetlands have been used for decades in the treatment of municipal wastewater (sewage) in many parts of the world. Since the 1980s wetlands have been used in the treatment of acid mine drainage, usually resulting from coal mining. Recently, natural and constructed wetlands have been researched and utilized for the removal of metals from mine drainage. Most of these wetland treatment systems have been designed and used in temperate climatic areas where permafrost, extreme minimum temperatures, and limited plant productivity is not a great concern, There is interest in northern regions on the possibility of the application of wetlands as a passive treatment system for metal contaminated mine drainage.

A research program investigating this possibility was initiated in the summer of 1995 in the vicinity of the United Keno Hill Mine property in central Yukon. A pilot wetland treatment system was constructed in May 1995 near the Galkeno 900 adit to determine whether it could improve the quality of its discharge. Sedges (Caex aouat#&) were obtained from a local natural wetland unaffected by any mine drainage and planted in the plot. After the plants were allowed to establish, untreated mine drainage was introduced to the wetland. Monitoring of the wetland continued for one season. Initial results showed that treatment within the wetland reduced concentrations of zinc, cadmium, manganese and nickel. Sulphate reduction in the sediments and formation of insoluble metal sulphides appeared to be the primary process responsible for their removal.

In 1999, further investigations were completed on this pilot project and on some of the natural wetlands which receive untreated mine drainage. Due to insufficient volumes of water flowing through the examined wetlands, they could not be fully evaluated as to their performance in the

treatment of waste water. However sediment analyses showed that metals had been attenuated. The colonization of the transplanted sedges (*Carex aquatilis*) in the constructed wetland was evaluated. Successful growth and propagation was apparent. These local sedges appear to be a hardy species capable of withstanding transplanting, and appear to thrive with a minimum of effort.

Metal uptake in plant tissues was also examined. Low levels were documented throughout the study area with the exception of high zinc concentration in sedges that were collected from the No Cash wetland. As *Carex aquatdis*, the dominant sedge found in the local wetlands, is generally unpalatable to herbivores, the low and incidental levels of metals found within the tissue of the sedges poses little environmental concern.

Overall, the preliminary results indicate that there is good potential for the use of wetlands to treat metal contaminated mine drainage.

5.1.4 Natural Attenuation of Aqueous Zinc in Shallow Soil over Permafrost Downslope of Galkeno 300 Mine Adit, United Keno Hill Mines Central Yukon

Author: Dylan B. Macgregor, Master's Thesis and MERG Report

Abstract

This study investigated the natural attenuation of zinc in mine drainage at Galkeno 300 mine site, located at the northern limit of discontinuous permafrost zone in central Yukon Territory. The mine drainage contains about 150 mg/L zinc where it exits the mine; where these same waters enter the receiving environment of Chrystal Creek, zinc concentrations have been reduced to 2 mg/L. This study was conducted in two phases; a site investigation and laboratory characterization.

The co precipitation of Manganese and Zinc oxides appears to be the dominant process of natural attenuation of zinc at the Galkeno 300 mine site.

5.1.5 Multi-stage Biological Treatment System for Removal of Heavy Metal Contaminants

Authors: Mattes A. W.D. Gould B Duncan Nature Works, Trail, BC CANMET, Ottawa, ON Teck Cominco, Trail, BC almattes@rogers.com dgould@nrcan.gc.ca, bill.duncan@teckcominco.com

Abstract:

A multi-stage treatment system to treat landfill leachate containing high levels of heavy metals has been constructed in Trail, British Columbia. The site is in close proximity to the Teck Cominco lead zinc smelter and treats 12-15,000 L a day of landfill leachate emanating from a

historic capped landfill site. Zinc levels as high as 651 ppm, As levels to 285 ppm and Cd to 1 ppm are each reduced to levels of <0.5 ppm (<0.02 ppm for Cd). The treatment system includes a two-stage anaerobic digestion system that includes an anoxic limestone drain configuration to assist in pH elevation. The two anaerobic digesters are constructed using vertical sub-surface wetlands design criteria.

Following the bacterial-based treatment system the partially treated leachate flows into a series of plant-based cells that includes a number of plants known for their ability to withstand the presence of heavy metals for both metal tolerance and sequestration potential. Detailed measurement of plant uptake over a 3-year period demonstrates both metal tolerance and limited sequestration potential.

The system was originally designed as a prototype system capable of treating metals during the summer growing season but it has been upgraded and is currently operating year-round. Results from wintertime operations indicate that removal efficiencies remain as high for Cd and As but fall for Zn. For best removal of Zn as a sulphide a pH of between 7.2 and 7.6 is required. When our system failed to do this the levels of Zn concentration in the final effluent rose dramatically. Ensuring appropriate pH levels is, therefore, of prime concern when complete Zn removal is required. The critical micro organisms in successful operation of the system are sulphate-reducing bacteria (SRB), which produce alkalinity and precipitate metals as their sulphides. Three groups of bacteria were enumerated at various points within the treatment system, the SRB, iron reducing bacteria (IRB) and fermentative bacteria which provide the carbon substrates (simple organic acids and alcohols) that are used by the SRB. The highest numbers of bacteria were found in the lower anaerobic cell with SRB numbers as high as 10^7 bacteria/g of the pulp mill biosolids. The lower cell was the first to be constructed and has had time for bacterial populations to develop. The role of the IRB in this particular system is unclear. Future work will be directed towards characterizing the reactions of As in anaerobic cells.

5.1.6 Natural Attenuation Of Heavy Metals in Shallow Subsurface Soils Over Permafrost Downslope of Galkeno 300 Mine Adit, United Keno Hill Mines, Central Yukon - Literature Review

Author: Dylan Macgregor MERG Report 2000-6

INTRODUCTION

Mining of metallic ores exposes metal-bearing minerals in wall rock, tailings and waste rock to accelerated rates of weathering; this can lead to increased metal loading to the environment. Waters draining natural exposures of metalliferous rocks and rocks exposed through mining or mineral exploration commonly contain high concentrations of metals. The aquatic environment downstream from these sites can be negatively impacted by the resulting high metal flux. Natural processes that act to reduce metal concentrations in these waters help to mitigate the effects of water-borne metals on the receiving environment. A number of natural soil processes can act to remove metal species from metal-bearing water; in many situations, metal-bearing waters flow through soil before joining a surface water body, in which case soil processes may reduce metal loading to downstream aquatic communities. These processes can be important

at a number of sites: at the base of waste rock dumps, where uncontrolled drainage seeps into the subsurface; at the mouths of adits discharging metalliferous waters which then seep into the ground; down gradient of tailings dams, where metal-bearing seepage flows through soils; at active or abandoned exploration sites, where waters draining recent exposures of metalliferous rocks percolate into the subsurface; at natural metalliferous rock exposures, where drainage waters subsequently flow through the soil; and, on the perimeter of stream channels, where metal-bearing waters contact or flow through soils. The northern climate influences soil properties, geochemical processes and the ways in which water-borne metals move through soils. The presence of permafrost impacts site hydrology on a spatial and on a seasonal basis, and permafrost processes have potential implications for metal behaviour in soils.

5.1.7 The importance of biological oxidation of iron in the aerobic cells of the Wheal Jane pilot passive treatment system

Authors: G. Hall[a, ,] , P. Swash[b] and S. Kotilainen[b] [a]Centre for Ecology and Hydrology, The Ferry House, Far Sawrey, Ambleside, Cumbria, LA22 0LP, UK [b]Department Earth Science and Engineering, Imperial College, London, UK

Abstract

The passive treatment system designed to treat the mine water discharge of the abandoned Wheal Jane tin mine in Cornwall consisted of a sequence of artificial wetland cells, an anaerobic cell and a final series of rock filters. Three systems were operated which differed only in the pre-treatment of the mine water before discharge to the aerobic wetland cells. The aerobic cells were designed to promote aerobic oxidation and precipitation of iron which could exceed a concentration of 100 mg/l in the raw mine water discharge. The largest investment of land area was to the artificial wetland cells and it was important to understand the processes of oxidation and precipitation of iron so that the performance of this aspect the pilot passive treatment plant (PPTP) could be managed as efficiently as possible. The generally low pH of the influent mine water and inevitable trend of decreasing pH due to hydrolysis of Fe(III) meant that distinguishing between biotic and abiotic mechanisms was fundamental for further design planning of passive treatment systems. This paper describes these observations.

5.1.8 Passive Treatment of Acid Mine Drainage in Bioreactors using Sulfate-Reducing Bacteria Critical Review and Research Needs

Authors: Carmen-Mihaela Neculitaa, Gérald J. Zagurya,* and Bruno Bussièreb Dep. of Civil, Geological, and Mining Engineering, École Polytechnique de Montréal, Montreal, QC, Canada, Dep. of Applied Sciences, Univ. du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, QC, Corresponding author (gerald.zagury@polymtl.ca)

http://jeq.scijournals.org/cgi/content/full/36/1/1

Abstract

Acid mine drainage (AMD), characterized by low pH and high concentrations of sulfate and heavy metals, is an important and widespread environmental problem related to the mining industry. Sulfate-reducing passive bioreactors have received much attention lately as promising biotechnologies for AMD treatment. They offer advantages such as high metal removal at low pH, stable sludge, very low operation costs, and minimal energy consumption. Sulfide precipitation is the desired mechanism of contaminant removal; however, many mechanisms including adsorption and precipitation of metal carbonates and hydroxides occur in passive bioreactors. The efficiency of sulfate-reducing passive bioreactors is sometimes limited because they rely on the activity of an anaerobic microflora [including sulfate-reducing bacteria (SRB)] which is controlled primarily by the reactive mixture composition. The most important mixture component is the organic carbon source. The performance of field bioreactors can also be limited by AMD load and metal toxicity. Several studies conducted to find the best mixture of natural organic substrates for SRB are reviewed. Moreover, critical parameters for design and long-term operation are discussed. Additional work needs to be done to properly assess the long-term efficiency of reactive mixtures and the metal removal mechanisms. Furthermore, metal speciation and ecotoxicological assessment of treated effluent from on-site passive bioreactors have yet to be performed.

5.1.9 Long Term Performance of Passive Acid Mine Drainage Treatment Systems

Authors: P. F. Ziemkiewicz1, J. G. Skousen2 and J. Simmons1

National Mine Land Reclamation Ctr, WV

1)

Div of Plant and Soil Sciences, West Virginia Univ, Morgantown, WV

2)

Abstract.

State and federal reclamation programs, mining operators, and citizen-based watershed organizations have constructed hundreds of passive systems in the eastern U. S. over the past 20 years to provide reliable, low cost, low maintenance mine water treatment in remote locations. While performance has been reported for individual systems, there has not been a comprehensive evaluation of the performance of each treatment type for a wide variety of conditions. We evaluated 83 systems; five types in eight states. Each system was monitored for influent and effluent flow, ph, net acidity, and metal concentrations. Performance was normalized among types by calclating acid loading reductions and removals, and by converting construction cost, projected service life, and metric tonnes of acid load treated into cost per tonne of acid treated. Of the 83 systems, 82 reduced acid load. Average acid load reductions were 9.9 t/yr for open limestone channels (OLC), 10.1 t/yr for vertical flow wetland (VFW), 11.9 t/yr for anaerobic wetlands (AnW), 16.6 t/yr for limestone leach beds (LSB), and 22.2 t/yr for anoxic limestone drains (ALD). Average costs for acid removal varied from $83/t/yr for ALDs to $527 for AnWs. Average acid removals were 25 g/m2/day for AnWs, 62 g/m2/day for VFWs, 22 g/day/t for OLCs, 28 g/day/t for LSBs, and 56 g/day/t for ALDs. It appears that the majority of passive systems are effective but there was wide variation within each system type, so improved reliability and efficiency are needed. This report is an initial step in determining passive treatment system performance; additional work is needed to refine system designs and monitoring.

Key words: acidity - acid load - aerobic wetlands - anaerobic wetlands - anoxic limestone drains - limestone leach beds - open limestone channels - slag leach beds - successive alkalinity producing systems - vertical flow wetlands

5.1.10 Performance of 116 Passive Treatment Systems for Acid Mine Drainage

1 Jeff Skousen2 and Paul Ziemkiewicz3

Abstract:

State and federal reclamation programs, mining operators, and citizen-based watershed organizations have constructed hundreds of passive systems in the eastern United States over the past 20 years to provide reliable, low cost, low maintenance mine water treatment in remote locations. In 2000, we evaluated 116 systems comprised of eight system types in eight states. We revisited 14 of these sites in 2004 to confirm results from the earlier study. Each system was monitored for influent and effluent flow, pH, net acidity, and metal concentrations. Performance was normalized among types by calculating acid load removed, and also by converting construction cost, projected service life, and metric tonnes of acid load treated into cost per tonne of acid treated. Of the 116 systems, 105 reduced acid load (90%). Average acid load reductions were 0.8 t/yr for Ponds; about 9 t/yr for open limestone channels (OLC), anaerobic wetlands (AnW), aerobic wetlands (AeW), and vertical flow wetlands (VFW); 76 t/yr for slag leach beds (SLB), and about 15 t/yr for limestone leach beds (LSB) and anoxic limestone drains (ALD). Average removal rates ranged from 18 to 2,334 g/day/t for the limestone systems, and 1.7 to 87 g/m2/day for the Ponds and wetlands. Average costs for acid removal varied from $36/t/yr for SLB to $1,468/t/yr for Ponds. The 2004 data showed slightly greater removal efficiencies for two Ponds, two VFWs, and one LSB. Large declines in removal were found for one AnW, two VFWs, one ALD, and one OLC. Two OLCs greatly increased efficiency. Most passive systems were effective for >5 yrs, yet there was wide variation in performance within each system type.

Additional Key words: acidity; acid load; aerobic wetlands; anaerobic wetlands; anoxic limestone drains; limestone leach beds; open limestone channels; Ponds, slag leach beds; successive alkalinity producing systems; vertical flow wetlands.

1 Paper was presented at the 2005 National Meeting of the American Society of Mining and Reclamation, Breckenridge CO, June, 19-23 2005. Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

2Jeff Skousen, Division of Plant and Soil Sciences and Paul Ziemkiewicz, National Mine Land Reclamation Center; West Virginia University, Morgantown, WV; e-mail: jskousen@wvu.edu

5.1.11 Case Studies of Passive Treatment Systems: Vertical Flow Systems

Authors: Arthur W. Rose and Jonathan M. Dietz

Abstract. As part of the Acid Drainage Technology Initiative (ADTI), case studies of 30 vertical flow systems (VFS or SAPS) have been compiled. Data includes inflow and outflow chemistry, flow rates, dimensions, design features and problems encountered. The increase in net alkalinity ranges widely, from 7 to 686 mg/L CaCO3 (median 160 mg/L), but is positive for all systems. Systems having low influent acidity added little net alkalinity compared to units with high influent acidity. Increased retention time shows a correlation with increase in net alkalinity, suggesting that a standAMD retention time is not necessarily optimum. A regression of influent acidity loading vs. effluent alkalinity indicates that an acidity loading less than 40 g/m2/d, on average, produces net alkaline effluent (r2=0.55, p=0.0002). Similarly, 12 of the VFS had net acid effluent and are interpreted to be at the limit of VFS effectiveness. Most of the 12 units decrease acidity by between 25 and 50 g/m2/d. These values are similar to the 25 g/m2/d determined by Dietz and Stidinger (1996). A value of 25 g/m2/d is suggested as a design criterion for VFS, in place of retention time. Results for several units suggest that this loading may be increased by addition of fine limestone to the compost layer, and multiple regressions suggest that pH and acidity may modify the expected effectiveness.

Multiple regressions show that net added alkalinity depends positively on influent Fe and negatively on Mn, as found by Jage et al. (2001), but also on H+ (antilog pH) and retention time in compost. Many units have operated satisfactorily for 5 to 10 years, but regular inspections are desirable to correct minor problems. Thin spots in compost are deleterious because of channeling, and high-Fe inflows may suffer from accumulation of Fe precipitates in the VFS pond.

Additional key words: Acid mine drainage, SAPS, vertical flow wetlands.

5.1.12 Long-term Performance of Vertical Flow Ponds – An Update

Author: Arthur W. Rose

Abstract. Some vertical flow ponds (VFP's, SAPS) are performing less well than expected. This paper compiles quantitative data on performance and problems to extend previous evaluations in 2002 and 2004.

Of 40 sites, about half are performing entirely satisfactorily. Six sites have essentially ceased to treat. Most of the remainder are treating at a moderate level, but not up to original expectations, which in some cases were unrealistic. Problems include overflow because of plugging by Fe precipitate on top of compost or by Al precipitate in limestone, leakage, decreased treatment because of short-circuiting or Al coating, or inadequate size for the acidity loading. Low-cost rebuilding has restored several systems. Some problems result from inadequate preconstruction flow and chemical data.

The evaluation shows that vertical flow ponds are an effective method for treatment of most net-acid discharges if the ponds are properly designed and constructed. Improved designs such as bioreactors or automatic flushers may be needed for systems with influent Al exceeding about 20 mg/L.

This Paper was presented at the 7th International Conference on Acid Rock Drainage (ICAMD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

Arthur W. Rose is Professor Emeritus of Geochemistry, Pennsylvania State University, University Park, PA 16802.

5.1.13 A Continuous Process for the Biological Treatment of Heavy Metal Contaminated Acid Mine Water

Authors: R. P. Van Hille, G. A. Boshoff, P. D. Rose and J. R. Duncan

Abstract

Alkaline precipitation of heavy metals from acidic water streams is a popular and long standing treatment process. While this process is efficient it requires the continuous addition of an alkaline material, such as lime. In the long term or when treating large volumes of effluent this process becomes expensive, with costs in the mining sector routinely exceeding millions of rands annually. The process described below utilises alkalinity generated by the alga Spirulina sp., in a continuous system to precipitate heavy metals. The design of the system separates the algal component from the metal containing stream to overcome metal toxicity. The primary treatment process consistently removed over 99% of the iron (98.9 mg/l) and between 80 and 95% of the zinc (7.16 mg/l) and lead (2.35 mg/l) over a 14-day period (20 l effluent treated). In addition the pH of the raw effluent was increased from 1.8 to over 7 in the post-treatment stream. Secondary treatment and polishing steps depend on the nature of the effluent treated. In the case of the high sulphate effluent the treated stream was passed into an anaerobic digester at a rate of 4 l/day. The combination of the primary and secondary treatments effected a removal of over 95% of all metals tested for as well as a 90% reduction in the sulphate load. The running cost of such a process would be low as the salinity and nutrient requirements for the algal culture could be provided by using tannery effluent or a combination of saline water and sewage. This would have the additional benefit of treating either a tannery or sewage effluent as part of an integrated process.

5.1.14 Successful Implementation and Operation of a Passive Treatment System in an Extremely Cold Climate, Northern Quebec, Canada[1]

Authors: Nural Kuyucak, Francois Chabot and John Martschuk[2]

Abstract:

Seepage from tailings stockpiles at a decommissioned mine site in northern Quebec, Canada showed typical characteristics of acid rock drainage, requiring collection and treatment to be completed within a few months. The site is remote and without power, making the application of a chemical (active) treatment unfeasible due to significant required resources in both capital and time. Passive treatment systems are a reasonable alternative, despite the extreme winter conditions prevalent at the site, and were implemented at the site in 2004.

During site clean up and preparation, a site-specific passive treatment facility was designed based on available data; it included a seepage collection system, anaerobic and aerobic cells, and a limestone filter. Organic nutrients required for the anaerobic fermentation and cultivation of sulphate reducing bacteria were selected from locally available materials. A suitable mixture was prepared and preconditioned. The treatment facility was installed and commissioned in October 2004. The results to date indicate that a properly designed passive system can produce water quality in compliance with the provincial government regulations. Experience gained from the work is discussed.

This Paper was presented at the 7th International Conference on Acid Rock Drainage (ICAMD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

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Martschuk, Director of Environmental Services, Barrick Gold Corporation, Toronto, ON M5J 2S1 Canada

5.1.16 Biological Detoxification of Cyanide in Northern Environments

A Project Report submitted to: Viceroy Mineral Corporation and Mining Environment Research Group MERG Report 2000-1 Prepared by Microbial Technologies, Inc.

Executive Summary

Microbial Technologies investigated the technical feasibility of using cyanide-degrading bacteria to destroy cyanide associated with ore from a spent heap using bacteria native to the Yukon Territory. A microbiological analysis of samples collected in the vicinity of the Brewery Creek Mine showed that bacteria degrading metal-cyanide complexes (nickel-cyanide, ferrous and ferriccyanide complexes), thiocyanate are widely distributed, even in environments known not to be exposed to (anthropogenic) cyanide. Interestingly, most iron-cyanide degrading isolates also degraded thiocyanate. Ammonia oxidizing bacteria and nitrate-reducing bacteria were also common at the site. Three columns received different treatments during a three months period: a control (water rinse) column, a peroxide treatment column, and a biological treatment column. Column effluents were monitored weekly for changes in pH, conductivity, redox potential and WAD cyanide concentrations. After the treatments, for Total and WAD cyanide and ammonia remaining on the spent ore were analyzed.

Biological destruction was more successful at removing cyanide than was peroxide treatment. WAD cyanide associated with the spent ore was reduced from an initial value of 2.10 mg/kg to 1.01 mg/kg in the biological column, compared with 1.60 mg/kg in the peroxide column. Spent ore in the control column had 1.92 mg/kg WAD cyanide at the end of the study. Ammonia concentrations were significantly higher in the peroxide column than in either the control or the biological columns. The biological treatment produced much lower ammonia concentrations. The biological column also had high levels of nitrate, indicating that bacteria in the column were oxidizing ammonia as well as the cyanide.

The successful removal of cyanide in the biological column provides a proof-of-concept for the biological detoxification of cyanide in spent heaps in Northern environments. The results indicate that a biological treatment can attain cyanide removal rates superior to a peroxide treatment. The bacterial oxidation of ammonia is a further, considerable benefit of a biological approach.

5.1.17 Evaluation of Treatment Options to Reduce Water-Borne Selenium at Coal Mines in West-Central Alberta

Author: Andre Sobolewski, Microbial Technologies, for Alberta Environment

Executive Summary

Microbial Technologies, Inc. reviewed the environmental chemistry of selenium and technologies for its treatment at three mountain coal mines in West-Central Alberta. These mines have recently been shown to release selenium to adjacent water bodies, resulting in its uptake into the food chain. Based on limited data from the Alberta mines, selenium is found in the dissolved form (mostly as selenate) in surface waters, a form that from a chemical perspective is relatively unreactive. Selanate can be reduced to selenite, a form more readily removed (chemically) from solution, or (biologically) to elemental selenium, an insoluble form. Currently, the expected duration of selenium release at the Alberta coal mines is not known. Notwithstanding the advantages or disadvantages of treatment technologies, preventative measures such as submerging seleniferous sulphides or covering waste rock are recognized as an integral component of any management plan for selenium at coal mines in West-Central Alberta. These measures are not fully reviewed in this document. However, a manual of Best

Management Practices for seleniferous mining wastes is currently being developed in Idaho and is expected to provide practical guidance with regAMDs to such preventative measures.

Eleven technologies were reviewed in detail. These include physically-based technologies (reverse osmosis, nanofiltration, and ion exchange), chemically-based technologies (iron precipitation and catalyzed cementation), and biologically-based technologies (algal volatilization, biological treatment plant, in-situ treatment, Biopass and other passive treatment systems, treatment wetlands, and evaporation ponds). Several of these technologies have been tested at a pilot-scale or implemented as treatment facilities.

The above technologies varied considerably with regAMDs to their ability to remove selenate from solution cost-effectively. Several of them could not meet a treatment objective of 5 µg/L. Treatment costs ranged from less than USD$1.00/1,000 gallons for in-situ treatment to over $10.00/1,000 gallons for reverse osmosis and iron precipitation. Some technologies employ very straightforwAMD processes, with simple process flowsheets (e.g., in-situ treatment or constructed wetlands), whereas others rely on more complex processes (e.g., iron precipitation). In addition, some technologies are handicapped by the necessity to manage residues from treatment, such as brines or wash solutions for membrane filtration and ion exchange, or sludges resulting from iron precipitation.

These different technologies were evaluated using a scoring system based on nine separate factors relevant to coal mines in West-Central Alberta. Two technologies stood out from the others as being most suited: in-situ treatment and bioreactors (biological treatment plant). Four other technologies might possibly be appropriate to some of the sites if favoured by some site-specific factors: reverse osmosis, nanofiltration, the Biopass/passive treatment systems and treatment wetlands. The other technologies were deemed too underdeveloped or inappropriate for application at coal mines in West-Central Alberta.

5.1.18 Wetland Treatment Systems – How Long Will They Really Work?

Paul Eger and Jon Wager, Minnesota Department of Natural Resources

Abstract:

The use of wetlands to treat mine drainage has become increasingly common; particularly as more information is available on their operation and construction. However, the lifetime of each system is still, at best, an estimate.

Treatment lifetime depends on the types of processes that provide the majority of the metal removal. Anaerobic systems (vertical flow systems) rely primarily on sulfate reducing bacteria, which reduce sulfate to sulfide and generate alkalinity. Metals can be precipitated as sulfides, and acidity is neutralized. These systems can remove over 90% of the metals and increase pH from around 4 to over 7. The bacteria will remain active as long as the system remains anaerobic and contains an adequate supply of sulfate and small chain organics. Although estimates of lifetime made on the total carbon in the system suggest that lifetime should exceed 20 years, data from field and laboratory studies show that the rate of sulfate reaction decreases with time, and that after several years rates decreased substantially. To maintain acceptable treatment, either additional organic material must be added or the total metal and acid load to the system would need to be reduced substantially.

Aerobic systems (overland flow wetlands) can effectively remove metals from neutral mine drainage by reactions with organic material in the substrate. Over 90% of the copper and nickel have been removed in aerobic systems treating mine drainage in Minnesota. The primary removal processes in these systems include adsorption, ion exchange and complexation, which are finite; removal will cease unless new removal sites are generated. At one wetland in northeastern Minnesota, the annual production of new removal sites has been estimated to be equal to the annual metal input, and, as a result, metal removal should theoretically continue indefinitely.

5.1.19 The Applicability of Passive Treatment Systems for the Mitigation of Acid Mine Drainage at the Williams Brothers Mine, Mariposa County, California: Bench and Pilot-Scale Studies

Author: Erin Jane Clyde

Abstract:

The Williams Brothers Mine is located in Mariposa County, California. Surface waters from the ite drain into the south fork of the Merced River and the San Joaquin River Basin. The mine was developed in the 1980s and mined intermittently until 1996. In 1998, concerns of acidic drainage at the site arose. Effluent sampling by Engineering Remediation Resources Group (ERRG) found acid mine drainage (AMD) characterized by a pH of 3.9, sulphate concentrations of 100 mg/L and low metal concentrations of 0.074, 4.60, 1.23, 0.047 and 0.133 mg/L for Cu, Fe, Mn, Ni and Zn, respectively. The aim of this research was to evaluate passive treatment system alternatives for the mitigation of the AMD to meet water quality objectives for the San Joaquin River Basin.

A bench-scale study was undertaken which consisted of 3 systems treating synthetic AMD: (1) a peat biofilter to remove dissolved metals followed by an anoxic limestone drain (ALD) to increase alkalinity and pH; (2) a sulfate reducing bacteria (SRB) bioreactor followed by an ALD, in which SRB reduce sulphate to sulfides, generating alkalinity and decreasing metal concentrations via metal sulfide precipitation; and (3) a SRB bioreactor.

Synthetic AMD was produced to represent AMD characteristics observed at the site. The peat- ALD system effluent pH was 6.9 and concentrations of Fe and Cu decreased to below water quality objectives with concentrations of 0.008 and 0.06, respectively. The SRB-ALD and SRB system effluents met water quality objectives for pH and Cu, Ni and Zn metal concentrations. The effluent pH for both systems was 6.5. The SRB-ALD system reduced Cu, Ni and Zn to concentrations of 0.004, 0.016 and 0.025 mg/L, respectively. The SRB system reduced metal concentrations for Cu, Ni and Zn 0.006, 0.010 and 0.027 mg/L, respectively.

Based on the bench-scale study, the pilot-scale system consisted of a combined passive treatment system containing a peat biofilter, SRB bioreactor and a limestone drain. Pilot-scale testing commenced on May 23rd, 2007. To date, some metal attenuation has been observed, with average effluent concentrations of Cu, Fe, Mn, Ni and Zn equal to <0.005, 0.92, 0.45, <0.005 and 0.049 mg/L, respectively.

5.1.20 A Periodic Table of Passive Treatment for Mining Influenced Water

Author: James J. Gusek, P.E.

Abstract:

The technical community of regulators and engineers that specializes in passive water treatment should be familiar with the passive treatment “decision tree” that was published by the former US Bureau of Mines about 14 years ago. The decision tree was originally intended to address mining influenced water (MIW) from coal mines. But since then, the breadth of passive treatment has expanded to embrace precious and base metal mines, uranium mines, and even gravel pits. Each MIW has its unique signature, either imposed by the natural geochemical conditions of the ore body and surrounding mine waste, or by resource recovery processes that may include heap leaching or traditional hydrometallurgical technologies. In the context of the elements of the periodic table, the decision tree certainly could be improved as it was originally developed to focus on coal geology derived MIW which typically contains acidity/alkalinity, iron, aluminum and manganese. For example, the expanded decision tree could consider residual ammonia or nitrates from blasting, cyanide from heap leach pad rinsing, trace amounts of selenium, or other parameters that may require passive treatment at a given mine, coal or otherwise. However, developing an individual decision tree for each MIW element or suite of

elements and their species would be a daunting task and would probably introduce more confusion where simplicity is desired.

With apologies to Dmitri Ivanovich Mendeleev, a "Periodic Table of Passive Treatment" could become a useful design tool to satisfy the need to embrace a larger range of MIW chemistries. The revised, color-coded table presented in this paper focuses on identifying passive treatment methods that have been observed to work on specific elements or species of elements typically found in MIW that is based on the author's experience or other practitioner's of the technology. The author offers it as a starting point that could be enhanced with further study, to include geochemical modeling and speciation investigations in existing passive treatment systems.

5.1.21 Sulfate-Reducing Bioreactor Design and Operating Issues: Is This The Treatment Technology For Your Mine Drainage?

Author: James J. Gusek, P.E.

Abstract:

There are basically two kinds of biological passive treatment cells for treating mine drainage. ***Aerobic Cells,*** containing cattails and other plants, are typically applicable to coal mine drainage where iron and manganese and mild acidity are problematic. ***Anaerobic Cells*** or ***Sulfate- Reducing Bioreactors*** are typically applicable to metal mine drainage with high acidity and a wide range of metals. Most passive treatment systems employ one or both of these cell types. The track record of aerobic cells in treating coal mine drainage is impressive, especially in the eastern coalfields. Sulfate-reducing bioreactors have tremendous potential at metal mines and coal mines, but have not seen as wide an application.

This paper presents the advantages of sulfate-reducing bioreactors in treating mine drainage, including: the ability to work in cold, high altitude environments, handle high flow rates of mildly affected ARD in moderate acreage footprints, treat low pH acid drainage with a wide range of metals and anions including uranium, selenium, and sulfate, accept acid drainage containing dissolved aluminum without clogging with hydroxide sludge, have life-cycle costs on the order of $0.50 per thousand gallons, and be integrated into "semi-passive" systems that might be powered by liquid organic wastes.

Sulfate reducing bioreactors might not be applicable in every abandoned mine situation. However a phased design program of laboratory, bench, and pilot scale testing has been shown to increase the likelihood of a successful design. Additional Key Words: Constructed wetlands, acid mine drainage, heavy metals, sulfate reduction

5.1.22 Role of Microorganisms in Mining: Generation of Acid Rock Drainage and its Mitigation and Treatment

Author: N. Kuyucak, Golder Associates Ltd. October, 2002

Abstract:

As a group of microorganisms may contribute to the generation of ARD, different types of microorganisms may play a vital role in the development of microbiological prevention, control and treatment technologies. The role of microorganisms in the generation of ARD and their role in the methods used for prevention, control and treatment are discussed in this paper. Benefits, limitations and design criteria for passive biological processes are presented using examples of passive and biological treatment processes that have been developed recently and implemented to mine sites.

5.2 Pit Lake Biological Treatment

5.2.1 The Physical, Chemical and Biological Dynamics of Two Contrasting Pit Lakes: Implications for Pit Lake Bio-Remediation

Authors: J. Jay McNee, John Crusius, Alan J. Martin, Phil Whittle, Roger Pieters, Tom F. Pedersen, Lorax Environmental Services, University of British Columbia, Department of Earth and Ocean Sciences, Vancouver, Canada, School of Earth and Ocean Sciences, University of Victoria, Victoria, B.C., Canada.

Abstract:

The Main Zone and Waterline pit lakes at the Equity Silver Mine near Houston, BC (Canada) are the sites of an ongoing 3-yr government- and industry-funded research program. The pits exhibit considerable contrasts in their physical, chemical and biological limnology. The Main Zone pit is deep (~120 m), maintains permanently oxygenated bottom waters, and hosts a modest level of phytoplankton productivity. In contrast, the Waterline pit is shallow (~40 m), exhibits negligible plankton productivity, and is characterized by permanent stratification and bottom water suboxia below a water depth of ~10 m. In order to assess the feasibility of various bio-remediation strategies, field-scale manipulations were conducted using limnocorrals. Two manipulation strategies were tested: 1) addition of algal nutrients (phosphate and nitrate) to Main Zone Pit surface waters; and 2) addition of nutrients (surface waters) and dissolved organic carbon (deep waters) to the Waterline Pit. Nutrient addition was conducted in order to stimulate algal production and enhance metal scavenging by biogenic particles, while dissolved organic carbon (ethanol) was added to increase oxygen demand and foster the development of sulphate reduction in pit bottom waters. In the Main Zone Pit, the stimulation of algal growth resulted in the pronounced removal of both dissolved and total metals (Zn, Cu and Cd) from surface waters, with higher rates of metal removal being observed at higher nutrient additions. Metal removal could be attributed to the scavenging of dissolved metals by biogenic particles and subsequent particle settling. A similar pattern of removal from surface waters was observed in Waterline Pit (Zn and Cd). The addition of ethanol to deep waters in Waterline Pit was effective in promoting sulphate reduction in the lower layer. The development of reducing conditions resulted in near-quantitative removal of dissolved Zn and Cd, presumably as secondary metal sulphides. Collectively, the results demonstrate that the passive forms of bioremediation tested in these pit lakes may be effective for whole pit-lake remediation.

KEY WORDS: Pit lake, Remediation, Mining

5.2.2 Detoxifying Pit Lakes by Controlled Algal Blooms: Laboratory Test and Pilot Phytoremediation Trail at Little Creek Pond at Vangorda Pit near Faro, Yukon Territory, Canada

By Dr. Andre Sobolewski Microbial Technologies March 2003 MERG Report 2003-1

Executive Summary

When a mine closes, the open pit left behind often fills with water that washes metals from the pit walls. This water may be toxic and cannot be discharged without further treatment. This study evaluated the feasibility of using algal blooms to remove toxic metals from pit lakes. The study had two components: laboratory tests and pit lake fertilization trials. The site for the field trial was Little Creek Pond, a small collection pond located at Vangorda Pit, near Faro, Yukon Territory. The pond receives zinc-contaminated leachate form a waste rock dump and seepage from Vangorda Pit.

The laboratory study, using Little Creek Pond, demonstrated that zinc could be removed by promoting an algal bloom. Its concentrations were decreased dramatically during the 56-day study, from starting concentrations of 55 mg/L down to 3 mg/L. An interesting finding was that zinc was removed if pond sediments were present, but not if they were absent. The high initial zinc concentrations may have been too toxic to allow the development of a strong algal bloom in

the absence of sediments. This idea is supported by other recent studies, which reported that zinc could be removed from the water column at lower initial concentrations.

During the short field season at Little Creek Pond, good algal growth was promoted on pond sediments by addition of fertilizer. This is remarkable, considering that pond water contained over 200 mg/L, a highly toxic level. Nevertheless, zinc removal was not shown in the field trial. This may be partially explained by the short time available to produce the algal blooms and the fact that metal laden waters were continuously seeping into Little Creek Pond during the study. Our attempt to determine if zinc removal still occurred was frustrated by our inability to calculate an accurate water balance. This was due to a lack of reliable data on seepage flows and zinc concentrations, on water volumes in the pond, and on other possible inputs into the pond from groundwater.

A single measurement of zinc content in harvested algae (over 12g per kg wet weight – Appendix G) indicates that zinc was successfully absorbed by algae growing on sediments. However, this provides insufficient information to conclude that significant zinc removal occurred.

Despite these qualified results, aquatic phytoremediation appears to be a promising, low cost alternative to conventional lime treatment. We recommend that further studies be undertaken in pit lakes that contain lower zinc concentrations, such as the Grum pit, near Faro, Yukon.

5.2.3 Biological Treatment of Acid Mine Drainage at the Island Copper Mine Pit Lake: Results From an Enclosure Study[1]

Authors: M.E. Wen, G.W. Poling, C.A. Pelletier, J. Chapman, E.L.J. Bingham

Abstract

The Island Copper Mine near Port HAMDy, British Columbia, closed in 1996. The open pit was flooded with seawater by temporarily connecting the pit with adjacent Rupert Inlet. The flooding channel was then closed and the lake was then capped with freshwater piped from the Marble River to create a stable meromictic lake. Waste rock dumps generate Acid Mine Drainage (AMD) with elevated cadmium, copper and zinc that drains to the pit lake. The lake receives some 3M m3/year of AMD (Zn 3 mg/L) directly on the surface and an additional 1M m3/year of AMD (Zn 8 mg/L) injected at depth. Biologically mediated metal removal in the surface layer has been optimized through the surface application of a 6N:1P (by weight) liquid fertilizer. Concentrations of dissolved metals in the surface layer have been low (Zn <0.2 mg/L) since year round fertilization of the lake began in 2001. The treated water drains slowly through a porous, and mostly submarine, shoreline fill to the marine receiving environment of Rupert Inlet.

A pilot test facility was recently constructed in the pit lake to assure the effectiveness of AMD treatment for Island Copper in the long term. The test facility included two 90 m diameter floating rings supporting an 11 m deep polyethylene barrier curtain, head tanks, pipe works, valves and a control system to manipulate the chemistry in the two enclosures. By manipulating the flow of feed water from two distinct AMD sources into the enclosures, we tested two very different approaches to treating water in the pit lake. We present results from this experiment and discuss their use in the design of a novel full-scale AMD treatment system for Island Copper.

[1] Poster paper presented at the 7th International Conference on Acid Rock Drainage (ICAMD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

Marc E. Wen, Rescan Environmental Services Ltd, Vancouver, BC, V6E 2J3, Canada, SRK Consulting, Vancouver, BC, V6E 3X2, Canada and BHP Billiton, Miami, Arizona 85539.

5.2.4 The Evolution of the Island Copper Mine Pit Lake

Authors Mike J. Wilton; Greg A. Lawrence. P.Eng. UBC

Abstract:

The seawater flooded open pit at Island Copper near Port HAMDy is used as a passive treatment system for acid mine drainage (AMD). The pit has evolved into three distinct layers: a brackish upper layer, well mixed intermediate layer extending down to the depth of the AMD discharge and a quiescent lower layer. Temperature, salinity and dissolved oxygen profiles have been measured and a layered model developed to predict long term evolution of water quality in the pit lake and the wind speed that would be needed to cause upwelling of the intermediate layer.

5.2.5 Planning for In-Perpetuity Mine Closure Costs

Authors: G.L, Pierce BHP Billiton, Base Metals, Canada
M, E, Wen Rescan Environmental Services Ltd, Canada

INTRODUCTION

The Island Copper Mine was closed in December 1995. Reclamation of the site began in 1996 based on a closure plan approved by regulatory agencies. In 1994, when the Island Copper closure plan was submitted to government for approval the estimated closure costs were C$15 million, for environmental mitigation arid monitoring with other money set aside for severance packages and decommissioning. The monitoring was planned for 10 years, with the latter five years at a significantly reduced level of effort. The company view at the time was that after five to ten years, the water quality at the site would meet regulatory standards and allow the company to return the land to the government. This did not happen. To date well in excess of this provision has been spent with additional expenditures planned to deal with the in-perpetuity obligation.

After about five years, post-closure monitoring regulators requested the company to undertake studies to improve the understanding of the closed site. The company responded by undertaking comprehensive studies of the site, of which a main focus was on the pit lake semi-passive treatment system. This type of treatment was at the time untested in the world and Island Copper was the first site to treat its acid mine drainage by fertilizing and using a pit lake as a treatment system. The studies lead to improvement in the underlying science behind this unique treatment system, and ultimately lead to improvements to the system and to an updated closure plan.

The closure plan was assessed for post-closure residual risks, which are those risks that remain alter closure and reclamation activities have been executed. For each risk, the timing and probability of the risk eventuating were evaluated. The consequence of each risk, should it eventuate, was considered and the associated activities and costs were estimated.

It became apparent through this closure planning process that that the care and maintenance, monitoring and management of the site would be required in-perpetuity because of the risks associated with the evolving nature of the mine drainage and the long-term requirement to treat this drainage. A discounted cash flow model captured the estimated costs for closure, with any cashflows after 50 years assumed to be incurred in perpetuity. This in-perpetuity cost estimate is fully risked and can help estimate long-term liability at the site. For companies with a number of closed mines, this risk can be further managed through a portfolio

5.2.6 Field Studies of Semi-Passive Biogeochemical Treatment of Acid Rock Drainage at the Island Copper Mine Pit Lake

Authors: G W Poling, C A Pelletier, D Muggli, M Wen, J Gerits, C Hanks and K Black (Rescan Environmental Services Ltd.)

Abstract:

On-land waste rock dumps at BHP Billiton Base Metals' Island Copper Mine (ICM) near the northern end of Vancouver Island, B.C. continue to discharge AMD. These waters, which amount to approximately five million cubic metres each year, are injected into a three-layer, meromictic pit lake for treatment. The top layer is brackish water, replenished by each year's rainfall (amounting to nearly 2 m/year). This top layer of water must meet effluent permit limits for heavy metals. This water eventually exfiltrates through a 'beach' waste rock dump, which is 93 per cent submerged along the north shore of Rupert Inlet. The middle and dissolved oxygen) and anoxic (0.03 mg/L dissolved oxygen), respectively. Spreading of a liquid fertilizer every ten days throughout the top layer results in plankton and bacterial blooms that scavenge zinc, copper and cadmium out of this layer eventually to become mineral sediment in the bottom of the pit lake. Adsorption on planktonic skeletons and mineral precipitates also scavenges these dissolved metals from the middle and bottom layers to form bottom sediment. Sulfate reduction has recently begun in the bottom sediments. Diagenetic processes in the bottom sediments will eventually transform most of the dissolved heavy metals into insoluble sulfides. Cycling of ferric iron between the sediment and the water column and back seems to contribute dramatically to the biogeochemical metal removal processes. This biogeochemical system serves to maintain the top-layer water well within permit limits for discharge to the environment.

5.2.7 Assessment of Biological Treatment of Faro, Grum and Vangorda Pit Lakes

Author: J.J. McNee, Lorax Environmental Services for SRK October, 2004

Abstract:

In support of closure planning for the Anvil Range Mine site near Faro, Yukon an assessment of bio-remediation was conducted in 2004. In addition to whole lake fertilization of Grum Lake, alternative manipulations using EDTA and fish fertilizer were tested in a mesocosm (limnocorrals) with one corral serving as a control. Physical and geochemical properties were surveyed in all three pits. Resident algae facilitated rapid growth of algae using liquid fertilizer applied top the whole of Grum Lake. It was observed that fresh micro sites supplied by new algal growth were important in converting dissolved zinc to particulate form. By the end of the season, up to 3 meters of water met criteria for discharge if this were required, and the lowest value achieved was 0.1mg/L in the surface waters. Pulsed eutrophication was found to be the most effective. Faro and Vangorda pit lakes appeared to host conditions favorable to bio-remediation in addition to Grum Lake. Amendments using EDTA (to mitigate toxicity) and fish fertilizer (for added micro nutrients) were not required. Prodigious growth as measured by Chlorophyll was achieved and was responsible for converting dissolved to total particulate zinc. Zinc solids reached 2.5% by weight in sediment traps at 12 m depth. It was concluded that remediation of the Grum Pit Lake was feasible and that Faro and Vangorda would also be good candidates for biological treatment.

5.2.8 Anvil Range Pit Lakes 2007 Evaluation of In-Situ Treatment 2007/08 Task 39

Author: J. Chapman SRK for Deloitte and Touche Inc.

Executive Summary

Investigations undertaken in 2004 concluded that biological treatment should be continued in the Grum Pit and tested in the Faro Pit. The 2005 investigations in the Grum Pit concluded that biological treatment should be continued there. However, the 2005 fertilization program in the Faro Pit interfered with the performance of the Faro Mill water treatment system, and biological treatment in the Faro Pit was discontinued. In 2007, continued water quality and physical limnological monitoring were recommended in the Faro and Vangorda Pits. Additionally, consistent with 2006, the rate of fertilization was reduced to ensure that nutrient concentrations are essentially depleted at the end of the season. This report provides presents and discusses the results from the 2007 biological treatment program in the Grum Pit and the monitoring of the Faro and Vangorda Pits.

The monitoring results indicated that nutrient concentrations of phosphate species have essentially been depleted from the surface water in the Faro Pit. An assessment of the annual contaminant loadings indicate that the annual zinc loading to the Faro Pit is about 20 tonnes per year, of which about 5 tonnes originates from the Zone II Pit. The sulphate loading is about 735 tonnes with about 129 tonnes originating from the Zone II Pit.

The Grum Pit water responded well again to fertilization and achieved excellent algal growth. Revised mass balance calculations for the surface layer indicated that 3000 to 4000 kg of zinc enters the pit lake annually. Initial estimates placed the zinc loading to the Grum Pit lake at only 350 kg per annum. The biological removal effects a zinc reduction of about 4,500 kg per annum. It is because the total loadings to the pit lake had been underestimated that the biological treatment did not appear to perform as predicted. Nevertheless, the most recent results suggest that the treatment rate is starting to overtake the loading and that continued biological treatment will significantly improve the water quality in the pit lake over the next two to three years. The reason that the loadings to the pit lake have been underestimated appears to have been to due to inadequately estimating the loading that would be released from the talus as it is inundated due to rises in the water level. The 2007 results further demonstrated that the residual level of phosphate and other nutrients in the water column can be controlled effectively by ceasing fertilizer applications in mid to late summer.

Monitoring in the Vangorda Pit indicates increasing zinc concentrations at depth, suggesting that zinc is being dissolved from treatment sludges that were previously deposited in the pit. This explanation is supported by pH values of less than 6 observed at depth.

It is recommended that monitoring of both the Faro and Vangorda Pits be continued in 2008. Mass balance calculations should be carried forward to verify the current estimates of metal loadings to each pit.

Based on the zinc removal rates observed for the Grum Pit and the level of control established in 2007, it is recommended that the fertilization program be continued in 2008.

5.2.9 Field-Scale Assessment of Bioremediation Strategies for Two Pit Lakes Using Limnocorrals

A J Martin, J Crusius, J J McNee, P Whittle, R Pieters and T F Pedersen

Abstract:

The Main Zone and Waterline pit lakes at the Equity Silver Mine near Houston, BC (Canada) are the sites of an ongoing three-year government- and industry-funded research program. In order to assess the feasibility of various bio-remediation strategies, field-scale manipulations were conducted using enclosed mesocosms (limnocorrals).

Two manipulation strategies were tested:

1. addition of algal nutrients (phosphate and nitrate) to Main Zone Pit

surface waters; and

2. addition of algal nutrients (surface waters) and dissolved organic Nutrient addition was conducted in order to stimulate algal production and enhance metal scavenging by biogenic particles, while dissolved organic carbon (ethanol) was added to increase oxygen demand and

foster the development of sulfate reduction in pit bottom waters. Fertilisation resulted in rapid growth of natural phytoplankton populations in the surface waters of both pits. In the Main Zone Pit, the stimulation of algal growth resulted in the pronounced removal of both dissolved and total metals (Zn and Cu) from surface waters, with higher rates of metal removal being observed at higher nutrient additions. Metal removal could be attributed to the scavenging of dissolved metals by biogenic particles and subsequent particle settling. A similar pattern of removal from surface waters was observed in Waterline Pit (Zn and Cd). The addition of ethanol to deep waters in Waterline Pit was effective in promoting sulfate reduction in the lower layer. The development of reducing conditions resulted in near-quantitative removal of dissolved Zn and Cd, presumably as secondary metal sulfides. Iron, As and Ni profiles in Waterline Pit exhibited no evidence of removal from either surface waters or bottom waters. Collectively, the

results demonstrate that the passive forms of bioremediation tested in these pit lakes may be effective for whole pit-lake remediation.

5.2.10 Tale of two pit lakes: Initial results of a three-year study of the Main Zone and Waterline pit lakes near Houston, British Columbia, Canada

Authors J. Crusius, R. Pieters, A. Leung, P. Whittle, T. Pedersen, G. Lawrence and J.J. Mcnee

Abstract

The Main Zone and Waterline pit lakes at the Equity Silver Mine near Houston, BC, Canada, are the sites of a three-year research program. Its primary goals are to understand the controls on metal concentrations in the lakes. The program used mesocosms to test a variety of remediation strategies and verify and improve an existing coupled physical-geochemical model to improve predictions of pit lake water quality. Initial data from two summer surveys in the Main Zone pit lake reveal elevated dissolved metal concentrations (Zn as high as 800 µg/L) in a 2-m-(6.6-ft-) deep mixed layer and reveal elevated particulate metal concentrations towards the bottom of the water column. Hydroxide sludge, a byproduct of acid rock drainage (AMD) treatment, is being discharged to the surface waters of the Main Zone pit lake. The sludge sinks rapidly to the lake bottom, which leads to deep waters with elevated levels of dissolved O2 and total metals. By contrast, the deep waters of the proximal Waterline pit lake are mildly reducing, manifested by depletion of O2 and elevated levels of dissolved Fe. These reducing conditions have led to elevated levels of As (up to 1,500 µg/L) in Waterline pit deep waters. The contrasting behaviour of these two pit lakes, as well as the processes controlling metal concentrations in the lakes, is discussed.

5.2.11 Water Treatment and Management during the Closure of the Colomac Mine

Authors: J.T. Chapman SRK Consulting(Australasia)

W. Coedy Technical Advisor for Colomac Site Remediation, Contaminants & Remediation Directorate/DIAND, Yellowknife, NT

S. Schultz SRK Consulting (Canada)

M. Rykaart SRK Consulting (Canada)

Abstract:

In 1999 the Department of Indian and Northern Affairs (Canada) inherited the abandoned Colomac gold mine located in the remote boreal forest about 220 km northeast of Yellowknife, NT. Gold was recovered by a conventional vat cyanide leaching and carbon adsorption process. The cyanide leach tailings were deposited in the tailings containment area (TCA) constructed within the Tailings Lake and Spruce Lake basins. The TCA had been permitted as a zero discharge facility and consequently the tailings were not treated for cyanide removal during operations. At the end of operations, TCA basin contained about 2 million cubic meters of water at elevated concentrations of cyanide complexes and related degradation compounds (thiocyanate and ammonia). An emergency transfer of water to Zone 2 Pit was conducted when the water level in Tailings Lake first reached its capacity limit in 1998. A remediation plan has been developed for the site and was approved in 2004. As part of developing the remediation plan various treatment options were assessed to reduce the cyanide compounds, ammonia and metals in Tailings Lake and the Zone 2 Pit lake.

Enhanced Natural Removal (ENR) was selected as the preferred treatment method. In combination with water management measures designed to minimize natural inflow to the TCA basin, predictions indicated that the water quality objectives for Tailings Lake could be achieved by first discharge anticipated for 2009.

Since implementation of the ENR program in 2002 cyanide and thiocyanate concentrations in the Tailings Lake TCA have been reduced from highs of 1 mg/L and 120 mg/L respectively in 2001, to less than the constituent detection limits of 0.05 mg/L and 0.5 mg/L respectively. Ammonia has been reduced from 50 mg/L to less than 5 mg/L well in advance of original predictions and the water quality in Tailings Lake is suitable for discharge. Unlike Tailings Lake, the depth of mixing in the deeper Zone 2 Pit pit-lake has been limited to the top 25 m of the 110 m deep lake which limited the oxidation reactions. Consequently in 2006 air was injected at depth to promote mixing of the water column and introduce oxygen to promote the reactions to convert the cyanide, thiocyanate and ammonia to nitrate. Monitoring indicated that mixing of the water column was effective and that due to enhanced oxygen transfer the thiocyanate had been removed from the water column.

This paper presents and discusses the closure measures implemented at the site with particular emphasis on cyanide, thiocyanate and ammonia removal, nutrient sequestration and recycle, and the effectiveness of the aeration system implemented within the Zone 2 Pit.

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Personal Communications: J.T. Chapman, SRK Consulting; Andre Sobelewski, amec; Dylan Macgregor, SRK Consulting; Erin Clyde, Ecometrics;

Water Treatment and Management during the Closure of the Colomac Mine

J.T. Chapman *SRK Consulting(Australasia)*

W. Coedy *Technical Advisor for Colomac Site Remediation, Contaminants & Remediation Directorate/ DIAND, Yellowknife, NT*

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Abstract

In 1999 the Department of Indian and Northern Affairs (Canada) inherited the abandoned Colomac gold mine located in the remote boreal forest about 220 km northeast of Yellowknife, NT. Gold was recovered by a conventional vat cyanide leaching and carbon adsorption process. The cyanide leach tailings were deposited in the tailings containment area (TCA) constructed within the Tailings Lake and Spruce Lake basins. The TCA had been permitted as a zero discharge facility and consequently the tailings were not treated for cyanide removal during operations. At the end of operations, TCA basin contained about 2 million cubic meters of water at elevated concentrations of cyanide complexes and related degradation compounds (thiocyanate and ammonia). An emergency transfer of water to Zone 2 Pit was conducted when the water level in Tailings Lake first reached its capacity limit in 1998. A remediation plan has been developed for the site and was approved in 2004. As part of developing the remediation plan various treatment options were assessed to reduce the cyanide compounds, ammonia and metals in Tailings Lake and the Zone 2 Pit lake.

Enhanced Natural Removal (ENR) was selected as the preferred treatment method. In combination with water management measures designed to minimize natural inflow to the TCA basin, predictions indicated that the water quality objectives for Tailings Lake could be achieved by first discharge anticipated for 2009.

Since implementation of the ENR program in 2002 cyanide and thiocyanate concentrations in the Tailings Lake TCA have been reduced from highs of 1 mg/L and 120 mg/L respectively in 2001, to less than the constituent detection limits of 0.05 mg/L and 0.5 mg/L respectively. Ammonia has been reduced from 50 mg/L to less than 5 mg/L well in advance of original predictions and the water quality in Tailings Lake is suitable for discharge.

Unlike Tailings Lake, the depth of mixing in the deeper Zone 2 Pit pit-lake has been limited to the top 25 m of the 110 m deep lake which limited the oxidation reactions. Consequently in 2006 air was injected at depth to promote mixing of the water column and introduce oxygen to promote the reactions to convert the cyanide, thiocyanate and ammonia to nitrate. Monitoring indicated that mixing of the water column was effective and that due to enhanced oxygen transfer the thiocyanate had been removed from the water column.

This paper presents and discusses the closure measures implemented at the site with particular emphasis on cyanide, thiocyanate and ammonia removal, nutrient sequestration and recycle, and the effectiveness of the aeration system implemented within the Zone 2 Pit.

1 Introduction

The Colomac Gold Mine, located about 220 km northwest of Yellowknife, ceased processing ore in December of 1997 due to a low gold price, increasing operating costs and depletion of ore reserves. Approximately 11.2 million tonnes of ore was mined by open pit mining methods, and an estimated 16.7 tonnes gold recovered using conventional cyanide vat leaching and carbon adsorption.

Tailings were deposited in two lakes, Spruce Lake and Tailings Lake, which in the original design would have become a single tailings containment area (TCA) as shown in Figure 1. The TCA was intended to be operated as a ‘zero discharge facility’. The tailings water was therefore not treated to remove cyanide from the process water prior to tailings deposition. However, early shutdown of the project meant that the final configuration of the TCA was not established and that a zero discharge water balance could not be attained.

Tailings were deposited in Spruce Lake to above the original lake elevation. Tailings Lake was partially filled, and a large water body is contained by a dam (Dam 1) and a tailings beach area. The dam was designed to minimise seepage losses. However, due to discontinuity in the foundation permafrost and a geological fault beneath the structure, seepage was being released under or around the dam. The seepage, which represents tailings porewater, contains elevated concentrations of cyanide, thiocyanate, and ammonia. The seepage is being collected at the toe of the dam and pumped back to the lake.

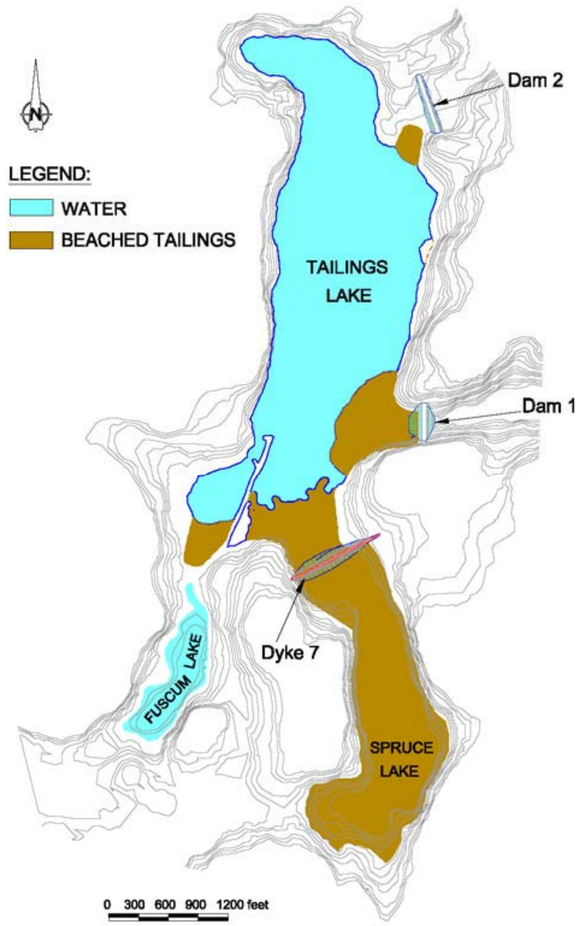

Figure 1 Colomac Tailings Containment Area

As part of the water management strategy at the site, water from Tailings Lake was transferred to the Zone 2 Pit to extend the period within which the TCA water level would remain below the permitted freeboard level. Approximately half the volume of water contained in the pit in 2004 was from three transfers between 1999 and 2003. Consequently, the pit lake was contaminated and resembled the water quality of Tailings Lake, but generally with lower contaminant concentrations.

Water balance calculations for Tailings Lake indicated that, without further intervention, the lake would likely reach the minimum freeboard limit for the dam by 2006 or 2007 at which time it would have been necessary to discharge some water to maintain the water balance.

Monitoring of both water bodies indicated that degradation of cyanide, and its related compounds, had occurred in the period since mine shutdown. A summary of historic water monitoring results contained in Table 1 illustrates the degradation of the cyanide, thiocyanate and ammonia for Tailings Lake. No significant concentrations of nitrate or nitrite were detected, which suggests that the cyanide and thiocyanate are being converted primarily to ammonium.

Table 1. Historical Water Quality Monitoring at Tailings Lake

Date	Total Cyanide (mg/L)	Thiocyanate (mg/L)	Ammonia-N (mg/L)
17-Sep-98	38.0	-	-
28-Nov-99	11.9	228	23
28-Jun-00	5.5	185	26
4-Oct-00	4.5	173	30
16-Jul-01	1.3	128	28
27-Sep-01	1.0	119	48

Based on the anticipated requirement to discharge water by 2006 and the observed rate of degradation, it was concluded that water treatment would be required to meet discharge water quality objectives.

2 Water Treatment Options

A number of treatment alternatives were evaluated at desk top and pilot scale, including biological nitrification and de-nitrification using rotating biological contactors (RBCs) and alkaline breakpoint chlorination. Because of the heating requirements for the RBC system, alkaline breakpoint chlorination was selected as the preferred technology.

In parallel the potential for enhancing the natural removal processes was also assessed. The modelling of o natural attenuation has been updated over the last two decades to allow evaluation at different geographical locations around the world (Akcil and Mudder, 2003). The processes that may be contributing to the natural degradation of the cyanide and its related compounds include bacterially catalysed reactions in which cyanide compounds are converted to ammonia and, possibly, direct uptake of some of the compounds by one or more by algal species. The rate of biological processes relies on the availability of nutrients for bacterial and algal growth. An assessment of algal growth and nutrient analysis indicated that the water bodies were deficient in phosphorus. Tailings water from the site was therefore tested at bench scale tests at BC Research, Vancouver, to assess cyanide compound removal using phosphorus as a nutrient source. The addition of phosphorus to tailings 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 from concentrations in excess of 100 mg/L to less than 0.5 mg/L in a 30 day period.

Based on these results 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 that this concentration would be sufficient to promote and sustain adequate algal populations for the entire summer season, without leaving undesirable residual concentrations of phosphorus.

Because of its cost advantages and simplicity to implement, enhanced natural removal (ENR) was selected as the preferred water treatment strategy. Alkaline breakpoint chlorination was selected as a contingency strategy should the actual rates of removal be lower than those achieved in the laboratory tests.

3 Water Management

Because of the uncertainty associated with the water treatment performance combined with the potential effects of consecutive wetter than average years on the overall water balance, a contingency water management strategy was implemented. The water management strategy entailed the installation of various diversion ditches to capture natural runoff within the catchment of the TCA and discharging the clean runoff. Figure 2 shows the locations of the diversions that were installed. Modelling of the effect of the diversions indicated that the period before discharge would be required could be extended by up to 4 years, as shown in Figure 3, depending on the collection efficiency that could be achieved for freshet and rainfall runoff.

Current indications are that discharge from the TCA will occur only by 2009 and that the diversions have been effective at limiting inflow to the TCA.

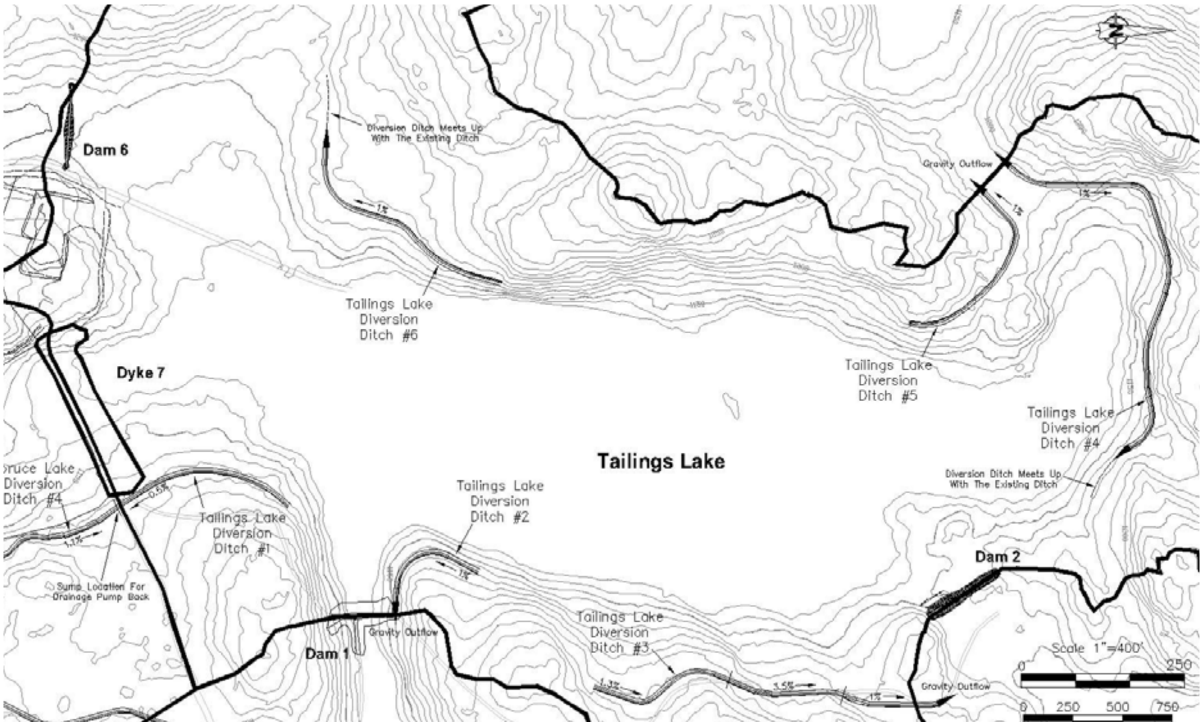

Figure 2 Colomac Tailings Containment Area Freshwater Diversions

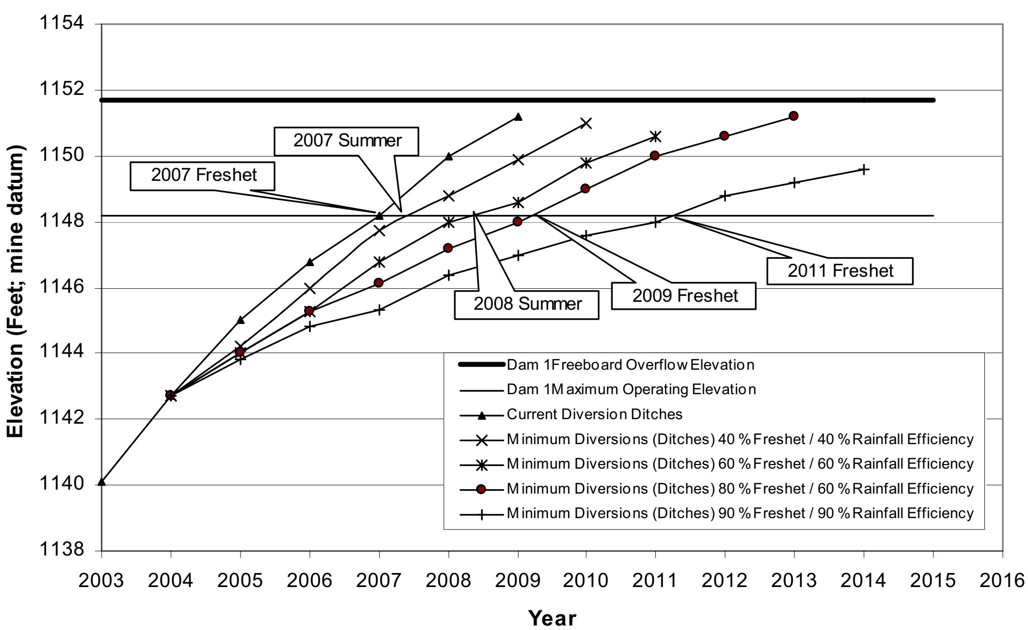

Figure 3 Colomac Tailings Containment Area Freshwater Diversion Performance Estimates

3 Enhanced Natural Removal

3.1 Source of Phosphorus

A readily available source of phosphorus is mono-ammonium phosphate, or MAP ($NH_4H_2PO_4$). MAP is an inexpensive soil fertilizer which yields about 1 gram of total phosphorus for every 3.7 grams of fertilizer. It is supplied as brown granular slightly soluble solid.

3.2 Application of MAP

Initially, to achieve a 1 mg/L P concentration in the two water bodies, 12 tonnes of MAP were required for Tailings Lake with a volume of about 3.12 million m^3 and 24 tonnes were required for the Zone 2 Pit lake with a volume of about 6.44 million m^3.

Because of the relatively insoluble nature of the MAP, to maximize phosphorus release it was necessary to contact it with water for as long as possible before releasing it to the water bodies. Hence, the MAP was dispersed on the ice surface of each water body shortly before ice break-up was expected.

In late February 2002, 36 tonnes of MAP were transported to the mine site on a temporary winter ice road used to haul fuel and equipment into the site. The granular fertilizer was distributed as evenly as possible across the surface of the ice on each waterbody using a hopper attached to a Bell 206 helicopter. The hopper held about 250 kg of fertilizer and was recharged at a near-by staging area using a dump truck with a modified tailgate.

In May 2003 an additional 9 tonnes of MAP was again added to each water body to raise the phosphorus level. Since then no additional phosphorus additions had been made.

3.3 Water Quality Monitoring

Detailed monitoring programs were implemented by the Colomac Technical Advisory Committee for both Tailings Lake and the Zone 2 Pit lake. Three sampling stations were established in each of the waterbodies and GPS latitude and longitude coordinates were obtained for each. The monitoring programs were similar for both water bodies and comprised:

- In-situ depth profiles were obtained using a Hydrolab Surveyor 4a and DataSonde 4 to measure temperature, pH, conductivity, dissolved oxygen, redox potential (ORP) and ionized ammonia.
- Depth profile water samples for water chemistry were taken with a 4.2 liter Kemmener sampler.
- Depth profile sampling for biological identification and population estimates of algal growth, which included a bottom sample to determine the presence of denitrifying bacteria.

Typically two sampling campaigns were conducted each month during the open water season from June to September. Sampling under ice was performed twice before ice breakup. The depths of water sample collection were adjusted for the thermocline and consequently varied from one sampling event to the next. A wide suite of water quality parameters were analyzed, which included the major cyanide compounds, nutrients, major cations and anions and trace elements of concern. A Secchi disk was used to determine the depth of light penetration. Water samples were also collected at various depths for algal identification and cell counts.

Algal cell counts were conducted for Phytoflagellates (colonial algae and diatoms) with an optical microscope at 320X magnification. Identification and population estimates of cyanobacteria, denitrifying and nitrifying bacteria were based on "Bart" culture test kits.

Quality control in the field involved the inclusion of field blanks, filter blanks for dissolved metals and chlorophyll'a', and replicates collected at various depths and at different stations (DIAND, 2002). On occasion, split samples were sent to another laboratory and the results compared for agreement.

4 Results and Discussion

4.1 Tailings Lake

Annually, thermal stratification to a depth of about 5 m led to the development of a warmer, oxygenated surface layer (epilimnion), and cooler anoxic deeper layer of water. Physical measurements of wind speed and temperature profiles have determined that windstorm events can cause cold water up-welling and bring contaminants to the epilimnion (Pieters and Lawrence 2006). Algal growth occurred in the surface layer and most of the removal processes that relied on oxidation occurred within this layer. The stratification together with the solute concentration profiles in the water column were used to estimate average concentrations in the epilimnion (warmer surface layer) and the hypolimnion (colder deeper layer) to assess changes in the water quality over time and to calculate overall mass balances for Tailings Lake. The results are discussed briefly in the following sections.

4.1.1 Cyanide Compounds

Total cyanide and week acid dissociable cyanide were rapidly removed. Since 2004, cyanide concentrations have remained well below the discharge water licence limits of 0.1 mg/L and 0.025 mg/L (WAD-CN) respectively for total (T-CN) and weak acid dissociable (WAD-CN). Thiocyanate concentrations, as shown in Figure 4, decreased rapidly after the initial phosphorus addition and consistently measure below detection and are well below the water licence limit of 3 mg/L.

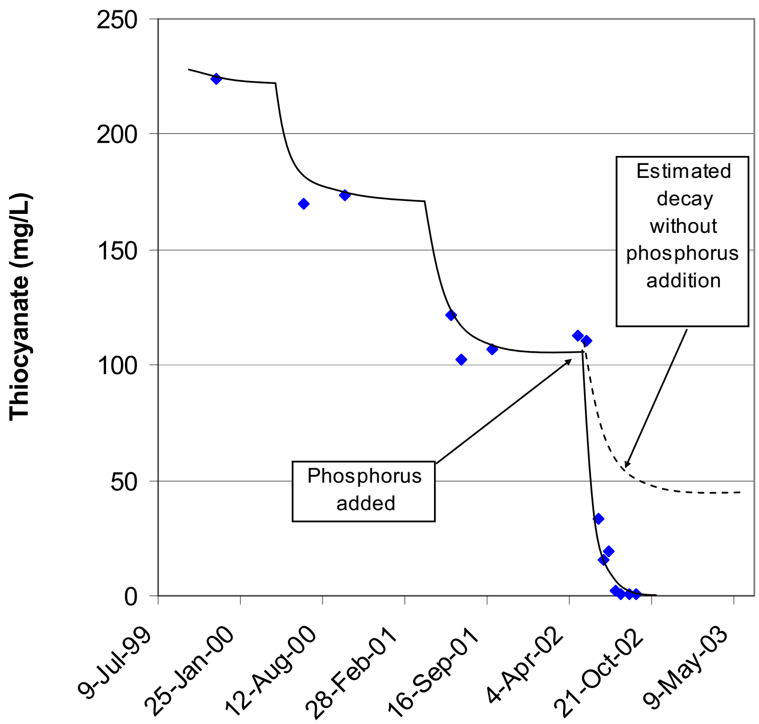

Figure 4 Thiocyanate Concentrations in Tailings Lake

4.1.2 Nutrients

Table 2 provides a summary of the average mixed nutrient concentrations in Tailings Lake at the end of each season. Using these concentrations, mass balance calculations were completed to estimate the total mass of each nutrient contained in the Tailings lake water body, and to estimate net removals or gains for each year. By considering the entire year the calculations provide estimates of the net changes (i.e. inclusive of removal and recycle) occurring in the lake.

The calculations indicate net removals of the nitrogen compounds; however a net gain was indicated for orthophosphate and total phosphate-P during 2006. The net gain however is very small and is likely indicative of hypolimnion recycling. Sediment traps were used to confirm nutrient removal from the water column.

Winter recycling was estimated independently from the changes in nutrient concentrations that were observed during the winter periods. The results are summarised in Table 3. The table also shows the corresponding potential range of incremental concentrations that may result from winter recycling. As shown, the incremental concentrations that may result are relatively small and are below the respective water licence limits.

Table 4 compares the estimated recycle rates with values reported in the literature. As shown the results compare favourably with those reported elsewhere.

Table 2 Summary of Nutrient Concentrations, Inventories and Calculated Net Gain/Loss in Tailings Lake

Date	NH3-N	NO3-N	NO2-N	Ortho PO4-P	Total-P
Concentration (mg/L)					
Sept. 2003	20.9	6.49	0.081	0.275	0.455
Sept. 2004	12.5	2.14	0.02	0.22	0.29
Sept. 2005	4.4	1.9	0.38	0.007	0.045
Sept 2006	2.1	1.2	0.09	0.042	0.093
Inventory (tonnes)					
Sept. 2003	64.6	20.1	0.25	0.85	1.41
Sept. 2004	42.5	6.8	0.06	0.68	0.91
Sept. 2005	14.9	6.4	1.3	0.024	0.15
Sept. 2006	7.9	4.5	0.35	0.16	0.35
Gain (+) or Loss(-) (tonnes)					
Sept 2003 to Sept 2004	-22.1	-13.3 to -28	-0.19	-0.16	-0.49
Sept 2004 to Sept 2005	-27.6	-0.40 to -19	1.23	-0.68	-0.76
Sept 2005 to Sept 2006	-7.0	-1.9 to -6.5	-0.95	+0.14	+0.20

Table 3 Summary of Net Nutrient Winter Recycle in Tailings Lake

Winter	**Recycle (tonnes)**		
	NH3-N	**Total-P**	**Ortho-P**
2002/03	8.5	0.37	0.11
2003/04	11.0	0.21	0.60
2004/05	5.5	-0.05	0.12
2005/06	5.8	0.29	0.29
Average	7.7	0.21	0.28
Average Conc. (mg/L)	2.3	0.06	0.08

Table 4 Comparison of Tailings Lake Winter Nutrient Recycle Rates with Data Reported in the Literature

Winter	Recycle Rates (mg/m2/day)		
	NH3-N	**Total-P**	**Ortho-P**
2002/03	109	4.8	1.4
2003/04	150	2.2	6.3
2004/05	75	-0.6	3.3
2005/06	58	2.9	2.9
Literature	0.8 to 61	-2.96 to 11	-2.96 to 11

4.2 Zone 2 Pit Lake

Zone 2 Pit is an 860 m long basin with a surface area of 17 ha, a depth of 105 m and is sheltered by 30 to 50m vertical walls. During the monitoring period, the pit inflow rate was equivalent to a rise of about 1m/year. The water elevation was about 4 to 5 m below the adjacent lake, Baton Lake. The pit lake is expected to be in equilibrium with Baton Lake in 2017.

As observed for Tailings Lake, thermal stratification within the Zone 2 Pit lake formed a warmer surface layer that supported algal growth during the summer months. However, unlike Tailings Lake (which is shallow), the much deeper Zone 2 Pit lake did not turn over during fall to completely mix the water column. The depth of mixing in the Zone 2 Pit was observed to occur to a depth of about 15 to 20 m, which represents a small proportion of the 100 m deep pit lake. Up until 2006 natural removal of thiocyanate and other compounds was therefore limited only to the upper 15 or 20 m of the water column. Rates of removal in this layer were similar to those observed for the TCA.

To de-stratify the meromixis that had established in the pit lake, during 2006 circulation was induced using compressed air injected at depth (Ashley, 2005). The purpose of the aeration program was to fully mix the water column, introduce oxygen to the deeper water and promote the oxidation of thiocyanate contained in the deeper stagnant water.

Complete mixing of the pit lake was accomplished within 4 days of commencing aeration. However, aeration led to the disruption of the ENR process. Therefore, rather than discussing in detail concentrations in the water column, the overall changes in contained contaminants that occurred during 2006 and how they may relate to the implementation of the aeration process are discussed below.

4.2.1 Thiocyanate, Ammonia and Nitrate/Nitrite

Figure 5 illustrates the total inventory of thiocyanate, ammonia-N and nitrate-N contained in the Zone 2 Pit Lake historically through to the end of 2006. The vertical dashed line indicates the approximate start date for aeration. Total cyanide and weak acid dissociable cyanide were below detection.

As shown, thiocyanate has been completely removed from the water column. Compared to previous trends, the net removal has been accelerated as a result of aeration. Initially ammonia-N is shown to increase. While ammonia was being removed from the water column (through volatilization, oxidation, or algal uptake) the initial rate of thiocyanate removal exceeded the rate at which ammonia-N was removed and hence the increase was observed. Once the thiocyanate had been removed from the water column, ammonia removal progressed at rates comparable to those observed in preceding years. Concurrently nitrate-N was generated at a similar rate to ammonia-N removal, suggesting most of the ammonia was being oxidized to nitrate. Nitrite, an intermediary product of the oxidation reaction, was also formed during this period.

4.2.2 Oxygen Uptake and Demand

The total oxygen that had been consumed subsequent to the initiation of aeration was estimated based on the overall change in inventory and associated reaction stoichiometry.

As shown in Table 5, the reactions that occurred in the pit lake consumed about 300 tonnes of oxygen. The calculations however neglect any consumption that may have occurred due to the oxidation of organic matter. On the same basis the remaining oxygen demand for the complete oxidation of ammonia-N to nitrate-N was calculated as shown in Table 6. The results indicate that a further 433 tonnes of oxygen would be required to achieve complete oxidation. Assuming oxygen delivery occurs at the same rates as during 2006, aeration for up to 140 days could be required to achieve complete oxidation of the ammonia. Once completely oxidized, the nitrate concentration could increase to about 20 mg/L assuming little or no de-nitrification occurs in the interim.

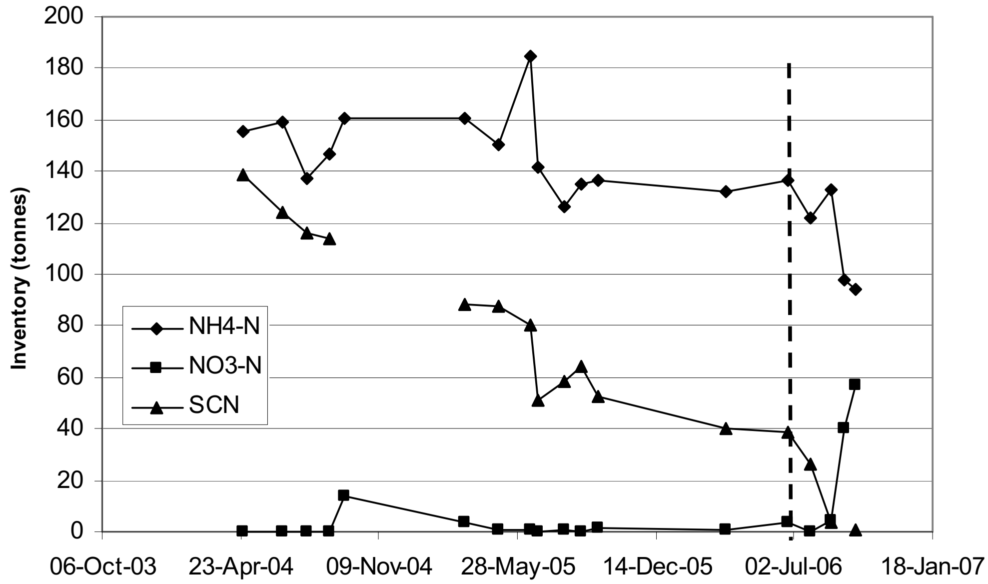

Figure 5 Total Thiocyanate, Ammonia-N and Nitrate-N Inventories in Zone 2 Pit Lake

Table 5 Estimated Oxygen Consumed in the Zone 2 Pit Lake

Reaction	Removed (tonne)	O_2 Consumed (tonne)
SCN -> NH3	38.0	52
NH3->NO3	53.6	245
23 Jun 06 to 29 Sep 06		297

Table 6 Estimated Oxygen Demand Remaining in the Zone 2 Pit Lake

Reaction	Nitrogen Eq. (tonne)	O_2 Demand (tonne)
NH3->NO3	93.9	429
NO2->NO3	3.4	3.9
Remaining Oxygen Demand		433

5 Fate of Cyanide and its Related Compounds

5.1 Total Cyanide and Metals

Total cyanide comprises free cyanide (CN^-; HCN), weak complexes with metals (e.g. zinc ($Zn(CN)_4^{-2}$)), moderately strong complexes (e.g. copper ($Cu(CN)_2^-$;$Cu(CN)_3^{-2}$), nickel ($Ni(CN)_2^{-2}$) and silver ($Ag(CN)_2^-$) and strong complexes (e.g. with iron ($Fe(CN)_6^{-4}$), and cobalt ($Co(CN)_6^{-4}$)).

In excess of 85% of the total cyanide was removed from the Tailings Lake water during the summer of 2002. The biological oxidation of cyanide can be described by the following reaction:

$$M_x(CN)_y + 2yH_2O + ½y\ O_2 \rightarrow xM^{+(y/x)} + yHCO_3^- + yNH_3 \quad (1)$$

Where M = Fe; Cu; Ni; Zn

Overall, because the total cyanide was at a low initial concentration, ammonia–N generated by this mechanism would be insignificant. However, the effect on metals concentrations is pronounced. Cobalt, copper, iron, nickel, and silver all were observed to decrease significantly. These metals were likely present as dissolved cyanide complexes, and with the removal of cyanide, they were either precipitated (as hydroxides) or sorbed onto biomass that was formed.

5.2 Thiocyanate

Effectively all of the thiocyanate was removed from the lake water. The biological oxidation of thiocyanate can be described by the following reaction:

$$SCN^- + 2H_2O + 5/2O_2 \rightarrow SO_4^{-2} + HCO_3^- + NH_3 \quad (2)$$

From April 2002 to end of September 2002, the thiocyanate concentration in Tailings Lake decreased from about 110 mg/L to less than 0.7 mg/L, i.e. a decrease of about 1.93 mmol/L. Over the same timeframe, the sulphate concentration increased by about 1.87 mmol/L. Given that this is in reasonable agreement with the stoichiometry given in Reaction (2), the results suggest that the primary mechanism for thiocyanate removal was oxidation.

Based on the stoichiometry given in Reaction (2), approximately 0.24 mg/L ammonia would have been formed for every mg/L of thiocyanate oxidised. Complete oxidation therefore would have resulted in the formation of about 27 mg/L additional ammonia-N. This added to the initial concentration of about 32 mg/L suggests that the ammonia-N concentration should have increased to about 59 mg/L over the same timeframe. However, a corresponding increase in the ammonia-N did not materialise. The results suggest that the equivalent of approximately 19 mg/L ammonia-N was removed.

5.3 Ammonia-N

Biological nitrification of ammonia nitrogen is a two step process. In the first step ammonia-N is oxidised to nitrite (mediated by *Nitrosomonas)* and in the second step the nitrite is converted to nitrate (mediated by *Nitrobacter* micro-organisms). The reactions are as follows:

$$NH_4^+ + 3/2\ O_2 \rightarrow 2H^+ + H_2O + NO_2 \quad (3)$$

$$NO_2^- + ½\ O_2 \rightarrow NO_3^- \quad (4)$$

The results suggest that only a small proportion of the ammonia-N was converted to nitrite-N, and little to no free nitrate-N is formed. In addition, the peak nitrate concentration occurred after the peak of the biological activity (as inferred from the dissolved oxygen results) as well as after the highest concentration of ammonia-N from thiocyanate would have occurred.

Ammonia oxidation rates reported elsewhere (Scharer *et al.*, 1999) suggest that all of the ammonia could have been converted to nitrite and nitrate between June and September. This may suggest that the oxidation of ammonia-N to nitrite and nitrate may first have been oxygen limited and then nutrient (phosphorus) limited. It also suggests that ammonia-N removal may have occurred by a mechanism other than oxidation, i.e. ammonia-N may have been taken up directly by algal growth. In a study with marine algae, Rees et al (1998), measured rates of ammonia uptake for passive storage and active assimilation mechanisms. In microalgae such as Chlorela and Chlomydomonas, scientific evidence suggests that the overall rate of incorporation of nitrogen into amino acids is governed by the primary ammonium assimilating enzyme glutamine synthetase. Furthermore, the passive storage pool may increase if the uptake of ammonium exceeds assimilation.

6 Summary and Conclusions

The addition of phosphorus has been shown to facilitate the removal of cyanide compounds from the Tailings Lake water at the Colomac site. Based on the observed increase in sulphate, the likely mechanism for the removal of thiocyanate is oxidation to sulphate and ammonia. Some removal may however also have occurred as a result of direct uptake by algal growth. The maximum rate of thiocyanate oxidation observed in the field ($5.8x10^{-7}$ mmol/L/s) was found to be comparable to the rate determined in the bench scale tests ($6.6x10^{-7}$ mmol/L/s), and significantly higher than that observed for the preceding year (about $4.0x10^{-8}$ mmol/L/s). It is important to note however that the rate of removal is a function of temperature, nutrient concentrations and site conditions.

Total and weak acid dissociable cyanide were reduced to very low concentrations. Degradation of the cyanide complexes also resulted in the removal of some metals from solution, in particular copper, cobalt, iron, nickel and silver.

The ammonia-N concentration in the lake water increased during the period of maximum thiocyanate removal. However, the concentration did not increase to the theoretical value, indicating ammonia removal occurred concurrently with thiocyanate oxidation. The mechanism for ammonia removal is considered to be direct uptake by algal growth rather than biological oxidation to nitrite and nitrate. The reason for this is that a concurrent rapid increase in nitrite and nitrate was not observed during the period of maximum ammonia-N removal. A possible reason is that the oxidation of ammonia-N to nitrite and nitrate was oxygen limited during the period of high biological activity. Only after dissolved oxygen concentrations were observed to increase, was nitrate formation observed.

In general the water quality in Tailings Lake has improved to the point that water licence limits are expected to be met when discharge from Tailings Lake is expected to occur.

Natural removal processes in the Zone 2 pit were hampered by meromixis which prevented migration of contaminants from the deeper anoxic zone to the active surface layer. Aeration of the pit lake effectively mixed the entire water column and promoted the removal of thiocyanate by oxidation. Aeration also promoted the oxidation of ammonia to nitrate. Some phosphorus removal was also observed to occur as a result.

The use of enhanced natural removal of cyanide and its associated compounds through phosphorus addition, combined with improved water management, has proven to be a very cost effective method of managing the contaminated water in the TCA and Zone 2 Pit. If the water was to have been treated by conventional chemical treatment methods, the capital and operating costs would have amounted to several million dollars.

Acknowledgements

The authors acknowledge the guidance and academic contributions of the Colomac Technical Advisory Committee members; Dr. Roger Pieters, Dr. Ken Ashley, Dr. Ken Hall, Dr. Greg Lawrence, Dr. Sue Watson, Hedy Kling, Michael Nahir, Octavio Melo, Daryl Hockley, Anne Wilson, Tony Pearce, Dr. Terry Mudder, Mike Botz, James Edwards, and Dave Bynski.

Special thanks to the technical assistance in the collection of samples to Dr. Roger Pieters, Regan Fielding, Dean Holman, Judy Mah, Stephanie Joyce, Heather Scott. Thanks to TliCho Logistics staff for logistical field support and the installation of the aeration system; Jaymes Dirks, Barry Franklin, Jack Brundage, Barry Henkle and Darryl Freier.

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