SUCCESSFUL IMPLEMENTATION AND OPERATION OF A PASSIVE TREATMENT SYSTEM IN AN EXTREMELY COLD CLIMATE, NORTHERN QUEBEC, CANADA[1]

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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.

Additional Key Words: Acid rock drainage, acid mine drainage, remote sites, seepage, sulphate reducing bacteria, limestone drain, limestone filter, organic nutrients, wood chips, manure, hay, aerobic cell, anaerobic cell.

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Introduction

The Site

The Cadillac Molybdenite mining site is located on the west shore of Preissac Lake in Northern Quebec, Canada. The site operated between 1965 and 1970 and was decommissioned in 1996. Tailings were deposited at the former mining site, covering an area of about 600 x 400 m and having a thickness ranging from 4 to 15 m. The tailings deposit was revegetated for closure and has a fairly flat surface and steep side slopes (1.5H:1V).

Geochemical characterization of tailings conducted during the site closure work indicated that the tailings had low acid base accounting (ABA) values, where neutralization potential (NP) over acid generation (AG; NP/AG) values were generally less than 3, implying a potential to generate acid mine (or rock) drainage (AMD or ARD). In the winter of 2003, spills occurred at two locations from the tailings deposit along the shore; small seepage streams running towards the lake were noticed in the spring of 2004. Chemical analysis of the seepage indicated typical characteristics of ARD: low pH, high acidity, and elevated metal concentrations. The quality of seepage did not comply with the Provincial Water Quality Objectives (Directive 019) set by the Quebec Ministry of Environment (MENV). Remediation of the site, including rectification of the tailings deposit and the collection and treatment of ARD, was required in order to prevent the discharge of ARD into the lake (MENVIQ,1989: Directive 019. Industries minières). The quality of the acid seepage found at the site and the requirements of Directive 019 are given in Table 1.

Many factors were considered when a passive treatment system approach was chosen as an appropriate treatment technology for this site, including site climate, location, and available infrastructure. The site experiences extremely cold winter conditions (e.g., average below -20°C) for a minimum of six months per year. As well, the site lacks an access road, electrical power, and space for the construction and operation of a treatment facility. These site-specific challenges had to be addressed in order to successfully implement a passive system at the site in a short period of time. Also, a permit had to be obtained from the MENV.

Process Principles and Status of Passive Systems

Although minor removal of base metals by co-precipitation, adsorption and uptake reactions may occur under aerobic conditions in wetlands, base metals such as Cd, Pb, Ni and Zn are not effectively removed from a net-acidic AMD in these environments. Frequently, the most effective passive method for treating base metal ions including Fe^{2+} in net-acidic AMD are anaerobic (i.e., SO_4^{-2} reducing bioreactors) and aerobic systems working in conjunction to create complete, integrated treatment systems. Removal of Al occurs by precipitation, which is dependent on pH and alkalinity levels in the treatment media; Fe^{+3} hydrolysis and $Fe(OH)_3$ precipitation reactions take place when pH levels are >4.5. In passive treatment systems, reduction in Mn levels is usually marginal.

Table 1. Quebec Provincial Water Quality Objectives (Directive 019) and seepage quality observed in May 2004 and 2005

Parameter*	MENV Directive 019	Station 1 May 2004	Station 2 May 2004	Station 2 Average 2005
pH	6.5 – 9.5	**5.6**	**2.7**	**3.4**
TSS	25	22	230.8	840.5
Al	-	5.2	50	33
As	0.5	0.009	0.01	<0.05
Cu	0.3	0.09	0.23	0.19
Fe**	3	**18.5**	**15**	**32.3**
Mn	-	5.65	5.7	4.6
Ni	0.5	0.33	0.46	0.38
Pb	0.2	<0.01	<0.01	0.01
Zn	0.5	0.33	**1.2**	**0.73**
SO_4	-	636	887	661
CN_D	0.1	0.007	<0.004	<0.004
CN_T	1.0	0.008	0.004	<0.003
O&G	15	6.0	<2	4

*All in mg/L, except pH. Temperature (ºC), conductivity (µmhos/s) and flow rate (m^3/min) were respectively 12.7, 1411 and 0.011 at Station 1, and 13.2, 1164 and 0.023 at Station 2 in May 2004.

**Greater than 90% of iron was in Fe^{2+} form in 2004.

Under reducing and anaerobic conditions, and in the presence of organic C nutrient sources, SO_4^{-2} reducing bacteria (SRB) can convert AMD sulphate to sulphide. Carbon dioxide, a respiration product of SRB, produces HCO_3^- alkalinity, while sulfide forms insoluble metal complexes, as illustrated by Eq. 1 and 2.

$$2\,CH_2O + SO_4^{-2} \rightarrow HS^- + 2\,HCO_3^- + H^+ \qquad \textbf{(1)}$$

$$Me + H_2S \rightarrow MeS \qquad \textbf{(2)}$$

The removal of acidity and base metals can be achieved in an integrated system where a train of anaerobic and aerobic systems are used. Passive anaerobic treatment systems rely on subsurface flow to maintain reducing conditions that enhance the activities of SRB, subsequently producing biogenic sulfide and alkalinity required for treating net-acidic AMD, as shown above (MEND Manual, 2000).

In contrast to aerobic systems (i.e., wetlands), where surface flow and oxidizing conditions are emphasized, anaerobic systems can perform at lower pH levels and can operate through the winter when they are designed properly. Examples of engineered pilot- and full-scale passive anaerobic treatment systems are documented in Canada, the USA and the UK. Some have been highly successful at removing heavy metals and neutralizing acidity, whereas others have been only marginally successful.

Parameters critical for successful operation of SRB-based passive treatment systems include: nutrients and organic substrate biodegradation; anaerobic/reducing conditions; hydraulic loading and metal loading rate changes; storm water impact; hydraulic design of the system (i.e., to avoid short-circuiting and channelling); gas lock-up; and temperature (Gusek, 2004; Kuyucak, 2002, Kuyucak, 1994a, b, and c). Variations in these parameters create significant design challenges.

Temperature is one of the most critical factors in the successful operation of passive treatment systems. Passive systems are more sensitive to low temperatures at start-up than during operation and should be started at relatively high ambient temperatures (i.e., during warmer months) for optimum performance. Starting up the passive treatment system in warm weather gives the SRB (i.e., *Desulfibrio* populations) and associated microorganisms a chance to build up population density before they encounter cold temperature conditions. The SRB-hosting organic substrate should be protected against freezing conditions by covering it with a thick soil layer (i.e., >0.6m). Burying the organic substrate to conserve heat and prevent freezing is an approach used that has been used by several system designers and operators, such as Gusek (2004) (in Norway).

Despite the challenges that low temperature provides, many passive treatment systems have successfully operated year-round in northern climates. These include:

- The CANMET (Natural Resources Canada) pilot scale system at the Halifax International Airport operated for almost 900 days, maintaining anaerobic conditions and meeting discharge limits even at 0ºC (Bechard et al., 1995).
- Three full-scale successive alkalinity-producing systems were designed and implemented to treat coal mine AMD in Pennsylvania, where winter conditions are comparable to eastern Canada (Kepler and McCleary, 1994). The systems were monitored for two years and were found to consistently remove about 200 to 350 mg/L as $CaCO_3$ acidity.
- A system at the Ferris Haggarty Mine in Wyoming (elevation 2900 m) has been successfully treating neutral to slightly acidic Cu mine AMD having an average temperature <0.2° C for the last three years. (reference)
- Bench- and two-year long pilot scale tests with 4.5 litres per minute (L/min) [1 gallon per minute (gpm)] flow rate at the Fran Mine site in Pennsylvania where cold winter conditions occur demonstrated that a passive system could successfully treat "the nastiest AMD in Pennsylvania" containing >200 mg/L Al (Gusek, 2002) without plugging. The pilot system operated for over four years. Despite being unintentionally over-loaded through the winter of 2002 and 2003, it has not plugged up with Al. During the pilot scale SRBR testing period, the AMD also contained (in mg/L) 1.3 Ni, 2.0 Zn and 0.56 Cu; about 99.2%, 93.5% and 99.8 % of these three constituents were removed, respectively. Based on the successful results, implementation of a full-scale system, buried to protect it from cold weather, was considered to handle about 190 L/min (42 gpm) (Gusek and Schueck, 2004). Close monitoring of the performance of the pilot-scale passive treatment system was useful for the development of detailed system designs.

The hydraulic design of the system and its ability to maintain anaerobic conditions and prevent/minimize potential short circuiting and channelling is critical to the success of the treatment system. The results of the Colorado School of Mines Big Five Tunnel project indicate the use of SRB and passive anaerobic treatment systems as a feasible option for treating net-acidic AMD and pointed out the importance of hydraulic design for preventing short-circuiting (Wildeman, 1991). A pilot passive treatment system designed to mimic a natural wetland at the United Keno Silver Mine in the Yukon Territory resulted in greater than 88% Zn removal after it was modified by the installation of baffles to correct hydraulic problems (Sobolewski, 1996).

Designing a system that recognizes progressive biological degradation of the organic substrate and the effect this has on the hydraulics of the SRB cells poses another challenge. Some studies indicate that passive anaerobic systems should be supplemented with fresh organic substrate every six to twelve months, although successfully designed systems are projected to operate for long periods of time – such as 20-30 years – without replacing the substrate (Gusek et al., 1998). The cells installed at ASARCO's West Fork lead mine in Missouri are successfully discharging 5,500 L/min of treated AMD that consistently meets drinking water standards. The organic substrate used at the West Fork Mine consisted of a mixture of sawdust, alfalfa, mulch, manure and limestone. Limestone ($CaCO_3$) in the nutrient media is beneficial because, as pH increases above 6.4 from SRB activities, HCO_3^- is the dominant carbonate species and acidity in the water reacts with limestone to generate alkalinity:

$$CaCO_3 + 2\,H^+ \rightarrow Ca^{+2} + H_2CO_3 \qquad \textbf{(3)}$$

$$CaCO_3 + H_2CO_3 \rightarrow Ca^{+2} + 2\,HCO_3^- \qquad \textbf{(4)}$$

Studies conducted to date demonstrate that passive systems are a successful treatment method for net-acidic AMD, lowering acidity and metals levels to meet water quality objectives. Unfortunately, there is no information available on long-term performance of a full-scale anaerobic system operating for longer than 10 years; most have operated less than 5 years. As a result, long-term costs and requirements for substrate management, future replacement, and system closure are uncertain.

Work Conducted – Method and Material

Site-Specific Challenges Considered for the Design

At the Cadillac Molybdenite mining site, challenges identified include the cold climate, remote site location, limited working space, the identification and selection of locally available nutrient sources and preparation of the nutrient mixture. In addition, all of the required work had to be completed as quickly as possible, before the onset of winter. Site conditions, including topography, subsurface conditions, hydrology/hydrogeology and quantity and quality of acidic seepage, were evaluated and documented for the identification and selection of the most suitable remediation options. Available remediation options, including site clean up, remediation of the tailings stack and ARD treatment methods, were screened and assessed. Construction requirements and associated issues, such as access to the site and construction of access roads, required permits, local availability of materials and contractors, short construction season, etc., as well as cost estimates were addressed.

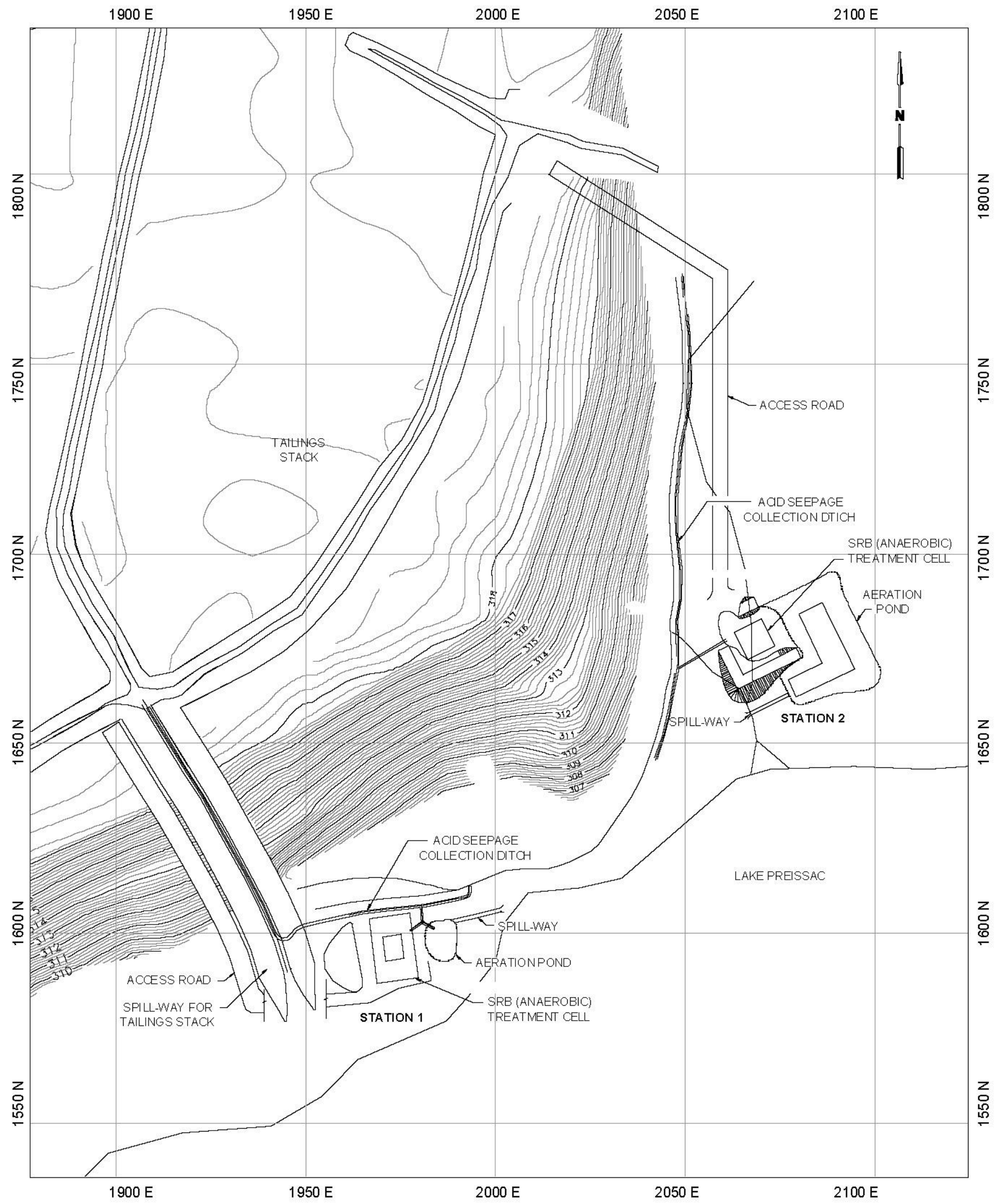
Implementation of site-specific remediation measures requires the identification of appropriate remediation options, preparation of permitting documents, and procurement of permits from federal and provincial agencies. A document summarizing the site conditions; remediation requirements; recommended action plans and suitable remediation options; construction requirements; and monitoring programs was prepared and submitted to MENV to obtain a permit for the implementation of the proposed passive treatment system at the site. The document contained a performance-based summary of passive ARD treatment systems as well as a conceptual presentation of the proposed passive treatment system for the Cadillac Molybdenite site.

Due to limited space and site topography, it was decided that collection and treatment of ARD at two different locations (i.e., Station 1 and 2) would be more feasible than one location. Figure 1 illustrates the general site view including the locations arranged for collection and treatment of ARD. Due to relatively high pH levels that existed in seepage occurring at Station 1, Fe^{+2} could be oxidized to Fe^{+3} in an aerated (oxidation) pond, which could then be precipitated as Fe_2O_3 complexes due to hydrolysis reactions resulting in removal/ reduction of Fe in the system. Heavy metal ions could also be removed as a result of adsorption by the Fe^{+3} compounds. In addition, inclusion of a limestone drain downstream of the system could provide further polishing and buffering to the treated water by adding alkalinity and filtering the treated seepage. Therefore, it was decided that, at least for the first year, acid seepage (ARD) occurring at Station 1 could be collected and treated using an aerobic system and limestone drain.

ARD at Station 2 had lower pH values than Station 1, making an integrated passive treatment system necessary. A stepped approach in a relatively small system could be considered for the first year to accommodate the existing site conditions. The treatment system could be supplemented by adding new modules in the following years, as required. In this communication, the emphasis will be given to the discussions related to the design and implementation of an integrated passive system for treating seepage at Station 2.

Continuous occurrence of ARD seepage from the toe of the tailings deposit required a year-round treatment system. Although passive systems have been used effectively at many sites worldwide, the proposed system would be the first of its kind due to the requirements for year round treatment under prevailing severe climatic conditions at the site. The successful operation and monitoring of a unit, which would be constructed for the known conditions, during the cold period for the first year were essential. If the system operated smoothly year round and demonstrated capability for treating ARD, it could be expanded, if required, in the following year. The experience gained from the operation of the first unit could be incorporated in the design and implementation of an improved system at this site and elsewhere.

Identification and selection of locally available nutrient sources and preparation of the nutrient mixture in a short period of time had to be achieved, as well as conditioning of the organic nutrient mixture during the warmer days. Therefore, the nutrient mixture was prepared coincidentally with permit documents to allow enough time for a suitable bacteria population to develop. However, since an approval regarding the use of a passive system was not available, preparing the nutrient media ahead would pose environmental risks and the work had to be performed in a manner that would not interfere with the permitting process. The nutrient mixture consisted of wood chips, limestone, hay and manure. A mixture of the organic nutrient materials were mixed with ARD in a well-sealed pool, which was excavated at the site. The organic mixture blended with ARD was completely wrapped with low permeability materials (e.g., geomembrane sheets) and covered with a layer of soil to prevent exposure to the atmosphere.



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GENERAL SITE VIEW AND ARRANGED ARD TREATMENT LOCATIONS

Golder Associates
Ottawa, Ontario

FIGURE 1

Laboratory Tests, Design and Preparations for Site Implementation

Laboratory tests were conducted at the Golder Ottawa office using locally available materials and ARD samples from the site (e.g., Station 1 and 2). The materials included wood chips, topsoil, manure (e.g., cattle, poultry), straw/hay, limestone (e.g., agricultural lime). Suitable materials and their required proportions were determined in lab-scale tests. A large batch of the nutrient mixture was prepared at the site in August 2004 and left for conditioning at the site, as described above. In addition, various design options were evaluated and permeability tests were conducted on the conditioned organic nutrient mixture to determine the level of compaction that would be required to obtain a suitable permeability in the organic mixture, resulting in a sufficient retention time for the ARD. Subsequently, the treatment capacity of the system could be defined.

The retained design included an ARD collection ditch running at the toe of the tailings deposit, an anaerobic SRB treatment cell, an aerobic (oxidation) pond and a limestone drain filter. Figure 2 shows the layout and cross-sections of the selected ARD treatment option. Insulating material placed atop the ARD collection ditch and the SRB treatment cell would prevent the system from freezing and allow year round operation.

Approval for the proposed mitigation options and the treatment system was obtained in October 2004, so the construction of the ARD collection ditches, the treatment system and the mitigation work all had to be carried out in a few weeks before the onset of freezing conditions and snow. Priority was given to the mitigation work at Station 2 as it included an anaerobic SRB treatment cell that required transportation of the preconditioned organic mixture. Work at Station 1 included the construction of a spillway for the tailings deposit, ARD collection ditches, and a passive treatment system consisting of an ARD holding pond to enhance oxidation and precipitation of Fe and a limestone drain (filter) system to further polish the treated seepage.

Field Work: Installation of the Treatment Process Units

ARD Collection Ditch Design and Construction

The ARD collection drains were excavated at the toe of the tailings deposit and two collection/treatment stations (Station 1 and 2) were prepared, as shown in Fig. 1. Figure 2 shows the layout of the Station 2 acid seepage (ARD) collection ditch and treatment facility as well as a cross section. A ditch approximately 1.3 m deep and 0.8 m wide was excavated along the toe of the tailing deposit. Figure 3 presents a cross-section of the ARD collection ditch system. The bottom of the ditch was covered with a geomembrane material and a layer of clean coarse granular rock (e.g., 1.3-2.0 cm diameter). Drain pipes (e.g., common perforated pipes) were laid on top of the clean rock layer and covered with more clean coarse granular rock until the ditch was filled. Then, the top of the rock layer was covered with a non-woven geotextile material. Soil excavated for construction was placed over the geotextile material to form a slope from the toe of the tailings stack and covered with an insulating material (50 mm polystyrene sheets) and about a 0.25m thick clay layer. The surface was sloped to avoid accumulation of water and was vegetated the following year.

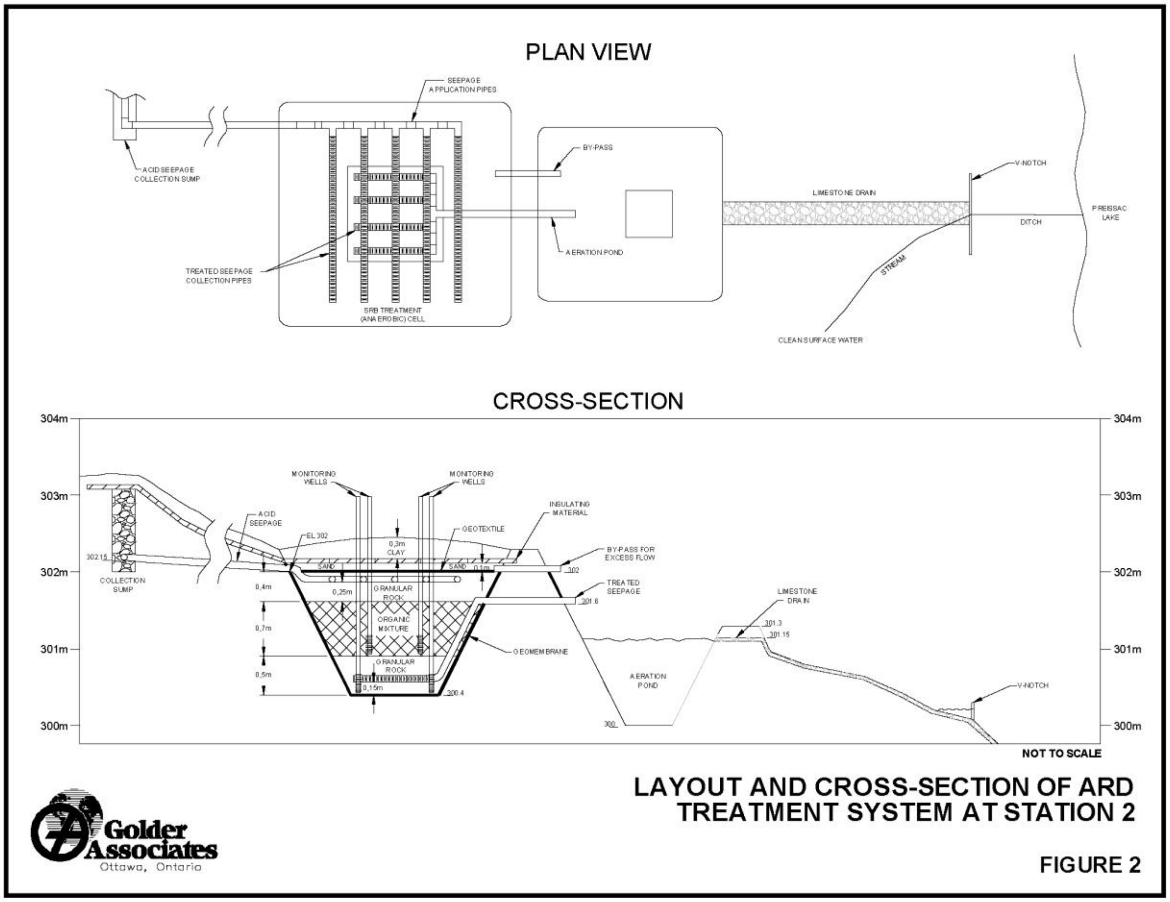

Figure 2. Layout and Cross-Section of ARD Treatment System at Station 2

<u>SRB (Anaerobic) Treatment Cell</u>

A cell, with a surface area of about 100 m^2 and a total depth of about 1.7 m, was constructed by partially excavating the ground and constructing a berm, with the excavated clay soil used for the berm construction. Despite the low permeability clayey nature of the natural soil at the site, a low permeability (geomembrane) material was also installed in the cell to prevent potential leakage. A layer of gravel and drainage collection pipes were placed at the bottom of the cell; this was covered by the organic mixture, which was slightly compacted, giving about a 0.7 m thickness and about 0.1 $m^3/m^2/d$ ARD application rate. A layer of gravel was installed along with the ARD application pipes over the organic mixture and covered with an impermeable material. The cell surface was insulated with polystyrene sheets and clay. An overflow drain and a valve were installed in the SRB cell and in the ARD collection sump (which functioned as an ARD transfer box) to allow, respectively, the excess ARD to bypass the SRB cell and flow directly to the oxidation pond in case of increased flow rates. The final surface was sloped to avoid pooling over the SRB treatment cell. Four monitoring wells were installed in the SRB cell to obtain samples for chemical analysis and conduct field measurements such as pH, oxidation/reduction potential (Eh), temperature and dissolved oxygen (DO).

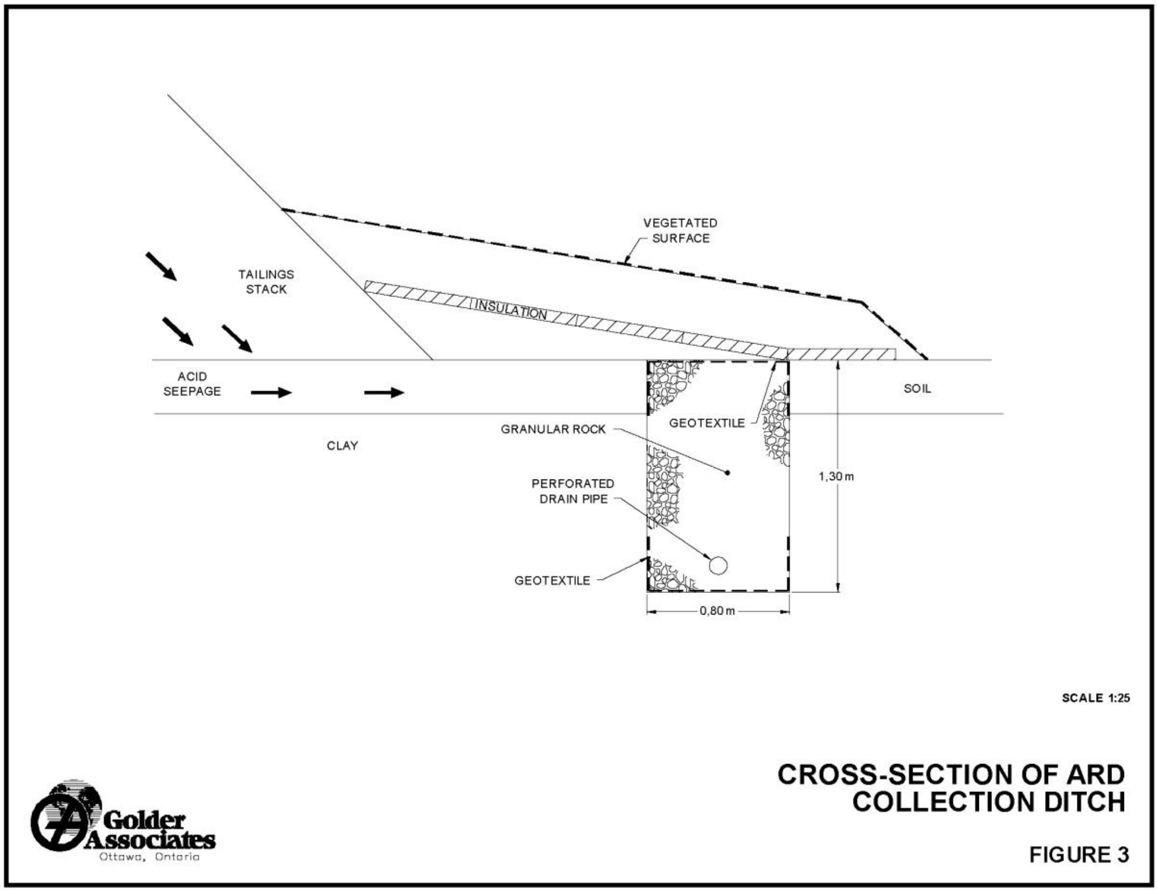

Figure 3: Cross-Section of the ARD Collection Ditch System

<u>Oxidation Pond and Limestone Drain</u>

The pond, with a surface area of about 150 m^2, and about 1.5 m deep, was excavated in clayey soil and a geomembrane liner was installed at the bottom of the pond; the liner was covered with about 0.25m of clay material. Limestone and rocks were placed at the outflow of the pond to minimize potential erosion. A ditch was excavated at the outlet of the pond and filled with limestone to act as a filter media for the treated seepage. A line of trees was left on the side of the lake.

<u>Results and Discussion</u>

ARD flow rates were increased to more than double the initial value of 0.011 m^3/min to 0.023 m^3/min, after the installation of the seepage collection and treatment facility at Stations 1 and 2. This is attributed to efficient collection of seepage from the tailings stack and the absence of leakage from the system. During the winter, the temperature of the seepage dropped to about3 °C and the temperature in the anaerobic SRB cell was consistently greater than 4 °C. Black colored precipitates and H_2S odor were distinct in the water samples collected from the monitoring wells and the outlet of the SRB cell. While the redox potential had positive values in

Table 2. Water Quality before and after Passive Treatment System at Station 2

Parameter *	**Directive 019**	**Before** Treatment	**After Treatment**						
		Average *	**Nov'04**	**Dec'04**	**Jan'05**	**Feb'05**	**Mar'05**	**Apr'05**	**Average 2005**
pH	6.5	3.45	6.4	6.3	6.3	6.3	6.4	6.6	6.7
TSS	25	230	32	3.5	17	22	14	17	11.7
Al	-	43	-	-	-	18	19	11	9.4
Cu	0.3	0.3	0.1	0.06	<0.01	<0.01	<0.01	<0.01	0.008
Fe**	3	13.5 (32)***	10.5	11	2.8	1	0.6	0.3	0.12
Mn	-	5.8	-	-	-	5.7	5.5	3	3.5
Ni	0.5	0.6	0.33	0.18	0.04	0.02	0.02	<0.01	0.01
Zn	0.5	1.35	0.48	0.3	0.02	0.02	0.02	0.02	0.012
SO_4	-	887	798	690	700	620	500	360	-

*All in mg/L, except pH, and average of values observed between February and April. Temperature ranged between 0 and 4^0C in ARD and was about 4^0C during this period. The flow rate showed a significant increase from a range of 0.011 to 0.023 m^3/min to a range of 2 to 3.2 m^3/min in January 2005. As between mid May to early August, oxidation/reduction potential (ORP) showed significantly negative values (e.g., -300 mV), the rest of year they were positive.

** Greater than 90% of iron was in ferrous iron (Fe^{2+}) form.

***Average in 2005

the seepage coming from the tailings stack, the redox potential in the samples taken from the SRB cell were always negative, indicating the presence of reducing conditions and subsequent establishment of SRB in the anaerobic cell as expected. Right after installation of the treatment facility at the site, the quality of the seepage improved significantly. During the cold winter period, the pH increased from about 3 to greater than 6, reaching the borderline of MENV (Directive 019) objectives. Following the arrival of spring (April 2005), the pH values increased to >6.5, complying with Directive 019. The highest levels of SO_4^{-2} reduction coincided with the arrival of the warmer period, lowering the initial SO_4^{-2} concentrations from about 820 mg/L to less than 210 mg/L in the treated seepage. Removal of metal ions including Ni, Cu and Zn were excellent resulting in a minimum of an order of magnitude reduction, with final concentrations well below the regulated limits. In general, Fe was removed to levels less than the required objectives. However, the SRB treated seepage contains relatively high TSS levels due to Fe-precipitates. In the winter period, due to freezing conditions, poor settling was obtained in the aeration (oxidation) pond, resulting in high TSS and Fe concentrations in the treated seepage. Alkalinity levels were increased to values greater than 400 mg/L $CaCO_3$ from net-acid concentrations of about 350 mg/L as $CaCO_3$. As the ambient temperature increased, the concentration of alkalinity also increased, as the activity of SRB in the media improved. The reduction in Al concentrations was also enhanced by the warming temperature. As expected, the removal of Mn was poor and the system reached steady-state conditions during April 2005, and continued to perform well during the summer period. Table 2 presents a compilation of the water quality before and after the implementation of the passive treatment system during the winter months and spring months. As the treatment system reached steady-state conditions, the leachate application rate stabilized around 0.07 $m^3/m^2/d$, which was lower than the design criterion of 0.1 $m^3/m^2/d$ application rate. The hydraulic retention time at the lowered seepage application rate is about five days.

A flow of water was observed on the top of the cell, indicating that the capacity of the cell was not large enough to allow the treatment of all the water. That water has been directed to the oxidation pond via a surface pipe.

Conclusions

The overall performance of the treatment system at Station 2 is showing good results, even in cold temperatures. Monitoring will be continued to gather more information on system performance but an expansion of the system is required to treat the total seepage flow occurring at the site. This work is planned for 2006 once more data on the performance of the system have been obtained and assessed. Revegetation of the surface of the collection ditches and berms of the oxidation pond is being considered, as well as placing riprap at the outlet of each process unit and expanding the limestone drain at the outlet of the treatment facility to improve the performance of the treatment facility.

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