Acid mine drainage as a sustainable solution to eliminate risk and reduce costs

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ABSTRACT: Acid mine drainage (AMD) is used to geochemically sequester dissolved sulfides in process water. The sulfides are a product of sulfide reduction in a reclaim process water pond. They create sustainable development risks as they produce hydrogen sulfide, other total reduced sulfur compounds (TRS), and increase the alkalinity of the water.

1 DESCRIPTION AND HISTORY

Brunswick Mine commenced operations in the early 1960's and to date has extracted more than 135 million tonnes of ore from the deposit. Located 20 kilometers southwest of Bathurst, New Brunswick, Canada, the site continues to be one of the largest lead/zinc mines in the world, producing zinc, lead, copper and bulk concentrates. Brunswick Mine employs 950 people, and is expected to cease operations within 2 years, when the orebody is depleted.

Currently, Brunswick operates at a planned mining and milling rate of 9,200 tonnes per day of complex lead, zinc, copper and silver sulphide ore. Four concentrates are produced by selective flotation.

The major mining methods at Brunswick were summarized with the assistance of Barb Rose, P.Eng, Senior Design Engineer; Brunswick's mining methods have progressed from blast hole open stoping during the 1960's, to cut-and-fill mining in 1970, and open stoping method with primary stopes and secondary pillars in 1985. A modified Avoca method has also been employed in areas with weak wall rock. Since 1996 the operation has been in transition to the use of smaller stopes and pillarless mining. This enables better control of the ground around the open stopes, and limits stress concentrations that in the past have led to instability of the remaining pillars. The use of paste backfill has allowed full pillarless mining as well as destress blasting of highly stressed ground with access via tunnels in paste to recover the remaining ore (Rose, personal communication, June 2010).

In 1998, a Semi-Autogenous Grinding (SAG) Mill replaced the crushing, rod mill and primary ball mill circuits in the concentrator. In 2000 implementation of a paste backfill process enabled the conversion of the backfill quarry to a retention pond to increase the amount of reclaim water used for the milling process. In 2005, another project was executed to expand the storage volume of the "reclaim quarry" to allow for a sustainable treatment of thiosalts.

Figure 1 provides a simplified flow sheet for the concentrator. The overall flow sheet involves SAG milling, secondary ball milling, selective flotation, and dewatering by thickening, filtering and drying. The complexity of the flow sheet evolves from the requirements for extremely fine grinding and the production of the four concentrates: Zinc (Zn), Lead (Pb), Copper (Cu) and Bulk (Pb + Zn) through metallurgical beneficiation (Deredin, 2008).

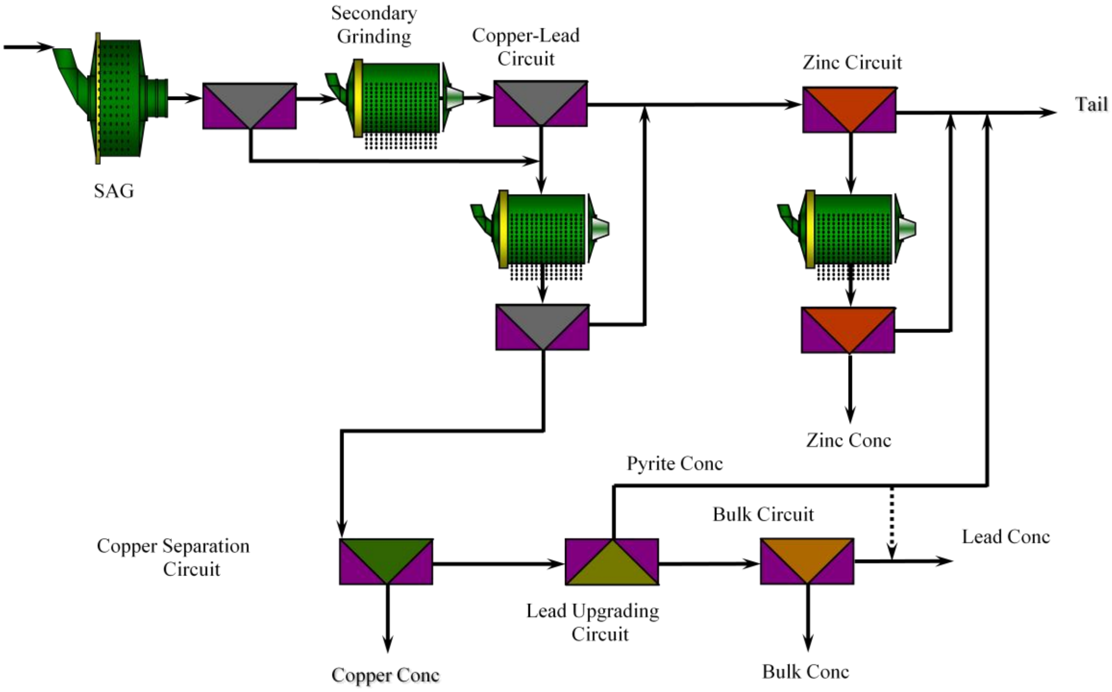

Figure 1. Concentrator Flow Sheet (Roberts, 2008).

Since 2005, consumption of pH modifying reagents used in the ore milling process has consistently increased. During 2007 and 2008, odors of total reduced sulfur compounds from the reclaim quarry became an issue as these odors impacted the air quality in the underground workings, through the ventilation system. During 2009, the concentrations of these odors increased to a level where the entire mine site, as well as the surrounding community (distance of 13 km) were impacted for several weeks, until a solution was developed.

2 WATER QUALITY

2.1 *Recycling Rate*

Over the years, Brunswick Mine has evolved their processes to reduce the fresh water consumption of the milling processes. Jean-Guy Paulin, Six Sigma Black Belt and Energy Management has been appointed to champion the processes related to water management. The evolution of water use at Brunswick has included the implementation of recycling loops, directing the tailings to the tailings basin as a 30 % solids solution, and the water is reclaimed back to the mill, for re-use. Prior to 2001, the reclaim system had very limited storage capacity and the mill's ability to recycle water was constrained by the flow from the tailings decant tower. To remove this constraint and to maximize the recycling rate, a reservoir was required to balance the peak flow requirements, and ensure the milling requirements would not be compromised. In 2001, a paste backfill system for filling underground voids was constructed. This made the rock quarry redundant, and enabled it to be converted to a reservoir for the storage of process water. This quarry measures approximately 500 meters by 500 meters, to depth of 20 meters. Storage of 1.25 million Cubic meters (m^3) was achieved using a depth 5 meters of process water. This enabled the mill to increase the recycling rate from 48 % to 64 %, while reducing the fresh water withdrawal rate from the Nepisiguit River by 20 %. This recycle rate increase also contributed to a step change in concentrations of parameters in the mill process water, since the reduction in fresh water used reduced the dilution of the process water (Roberts 2008).

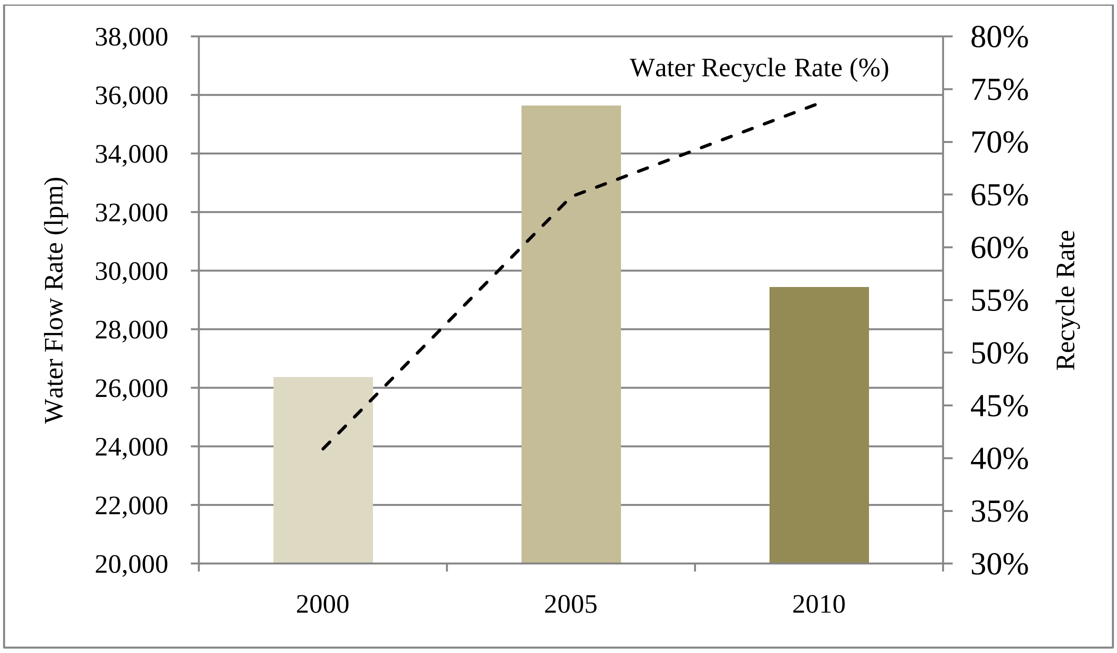

Figure 2. Average volumetric flow rate (lpm) and recycling rate (Paulin, personal communication, June, 2010).

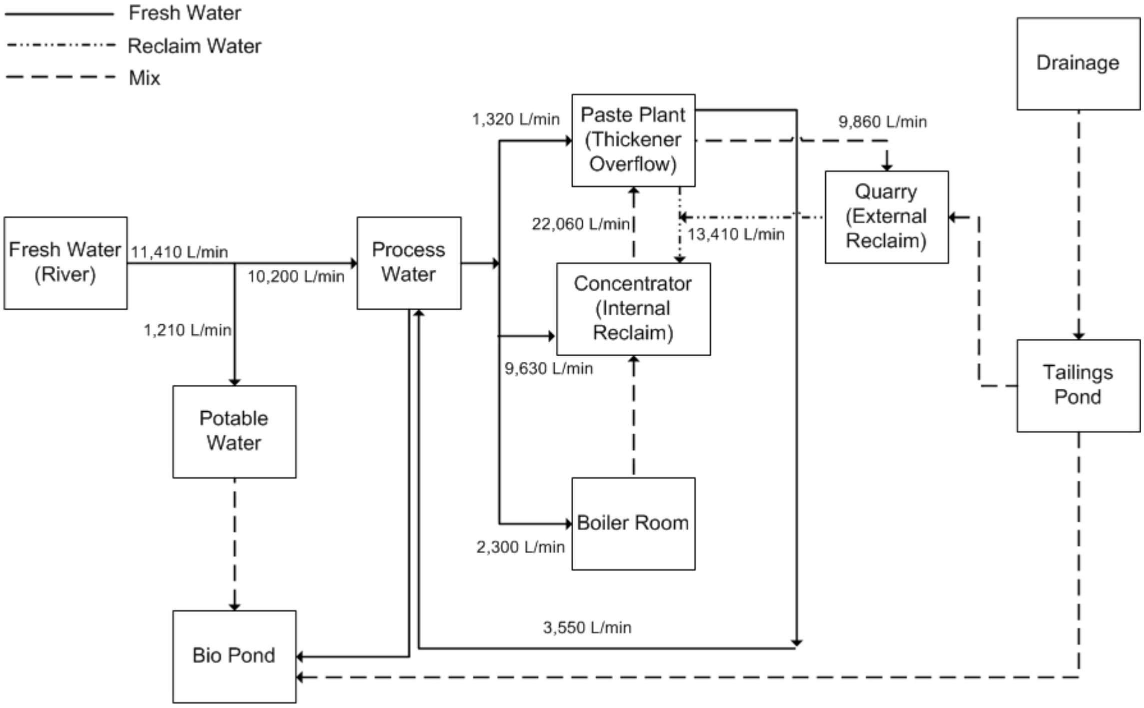

Figure 3. Site water balance (Roberts, 2008).

2.2 *Thiosalts*

The milling process creates partially oxidized intermediate sulfur compounds, these compounds, (thiosalts) are in the form $S_nO_m^{-2}$. The majority of thiosalts are Thiosulphate ($S_2O_3^{-2}$), Trithionate ($S_3O_6^{-2}$), and Tetrathionate ($S_4O_6^{-2}$). Thiosalt neutralization is not achieved in the conventional lime neutralization process used in the Brunswick Mine Effluent Treatment Plant (ETP). Technology to treat thiosalts in water involves completion of the reaction by oxidation to stable sulfates, and neutralizing the resulting acidic solution. During the spring and summer months, the thiosalts are oxidized in the receiving water of the Brunswick Mine effluent. This oxidation resulted in pH depression in the natural environment, and consequently impacted Little River.

In 2005, a thiosalt concentrations management project commenced to reduce the risk of pH depressions downstream of the effluent discharge. This project consisted of increasing the level in the reclaim quarry to 10 m, and storing up to 2.5 million m^3 of process water until the concentrations of thiosalts could be effectively treated with hydrogen peroxide (H_2O_2) which completes the oxidation of the thiosalts prior to treatment at the ETP. A proportional trend showed Thiosalt concentrations have increased as the recycling rate has increased over the years.

2.3 *Sulfates*

The process water used in the milling process has a high concentration of sulfates. In 2001, sulfate concentrations in process water were measured at 2 g/L (2,000 mg/L). Over time, these concentrations gradually increased to the 2010 levels measured at 4 g/L (4,000 mg/L).

2.4 *Alkalinity*

Measurements of alkalinity in the reclaim water began in the fall of 2001. The reduction in fresh water, and increase in recycling rate had a slight effect on the alkalinity of the reclaim water, but concentrations were relatively stable at 200 mg/L. In 2004, the alkalinity decreased as the quarry level was raised and more water was put into storage. The alkalinity remained at a low level until early in 2007, when the alkalinity increased steadily from less than 50 mg/L to the peak values measured in the fall of 2009 at over 1000 mg/L. Figure 4 portrays the historical alkalinity values.

The peak alkalinity values measured in the fall of 2009 resulted in risks to production. The quantity of soda ash required for the milling process was threatening to exceed the rate at which soda ash could be delivered. Although production shutdowns due to lack of reagent availability did not occur, a difficult situation was created for procurement to manage. It is possible that if the rate of increasing consumption had continued the delivery and availability of pH modifiers would create a constraint to production rates.

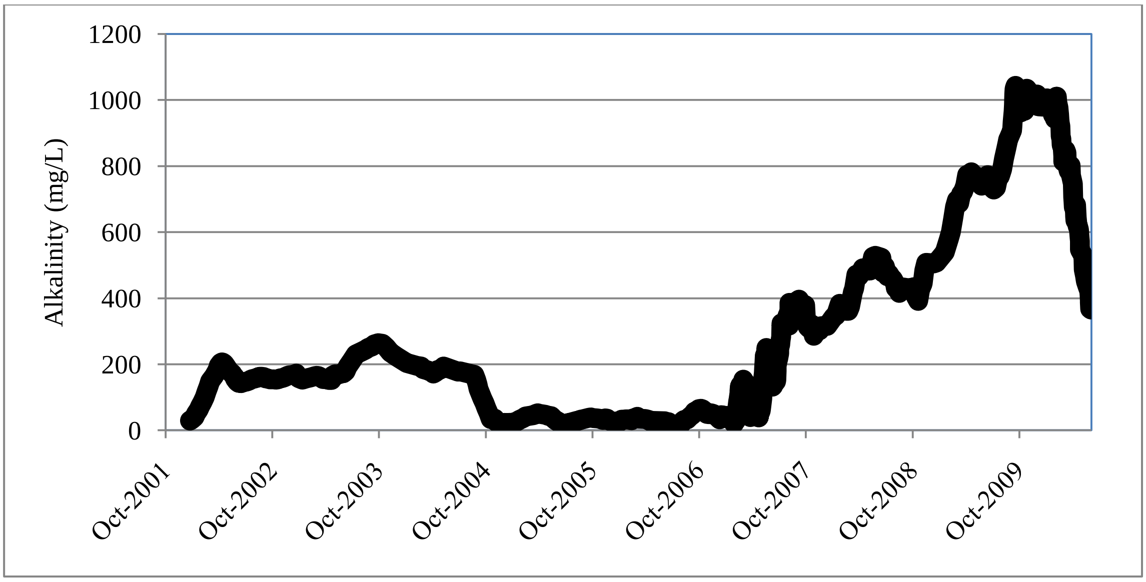

Figure 4. Alkalinity in the reclaim water (Cormier, 2010)

2.5 *Comparison of Plant Tailings and Quarry Reclaim Concentrations*

Historically, the quarry reclaim water is lower in thiosulfate concentrations than the concentrations of thiosulfate in the plant tailings. The relative difference remains constant over time, sulfate levels are relatively consistent. The concentration has increased consistently in both thiosulfate and sulfate, resulting in double the concentrations in 2009 compared to the concentrations in 2001.

Table 1. Concentrations of thiosulfate and sulfate in the reclaim quarry and tailings streams (Cormier, 2009).

	Thiosulfate in Quarry (mg/L)	Sulfate in Quarry (mg/L)	Thiosulfate in Tailings (mg/L)	Sulfate in Tailings (mg/L)
April 2002	500	2263	983	2212
Sept 2005	1314	3470	1501	3500
Sept 2009	1870	4722	2233	5121

2.6 *Other Parameters*

Research and data compilation indicates that the pH of the reclaim system does not show any significant trends. Occasional measurements made for dissolved oxygen have indicated anoxic conditions in the lower layer of the reclaim quarry.

3 REDUCED SULFUR

For many years, odors of total reduced sulfur (TRS) compounds were detected in the immediate vicinity of the reclaim quarry. In the fall of 2007, the concentrations of these odors increased which resulted in TRS odors, including H_2S which were detected throughout the mine site. These odors resulted in production impacts, since the ventilation system for the underground operations was withdrawing air from the surface that contained concentrations of TRS compounds that were above human threshold detection levels of 20 parts-per-billion (ppb) (Gerits 2009). Within a few days, the concentration of TRS odors returned to lower levels, before the determination of cause was completed. A similar episode occurred in the fall of 2008.

The growth cycle of sulfate reducing bacteria (SRB) begins in the lag phase (a period of slow growth when the cells are adapting to the high-nutrient environment and preparing for fast growth). The lag phase has high biosynthesis rates, as proteins necessary for rapid growth are produced. The second phase of growth is the exponential phase. The exponential (log) phase is marked by rapid exponential growth. During log phase, nutrients are metabolized at maximum speed until one of the nutrients is depleted and starts limiting growth. The final phase of growth is the stationary phase and is caused by depleted nutrients.

The concentrations of nutrients Sulfates and Thiosalts in this biosystem (reclaim quarry) were increasing over time. This was due to the fact that the minimum operating low level in the quarry contained 40 % of the volume. Another factor was the lack of dilution of fresh water addition. The effect of increased recycling rates has reduced the fresh water consumption. As a result, the concentrations of sulfates and thiosalts increased more than double their concentrations than in 2001.

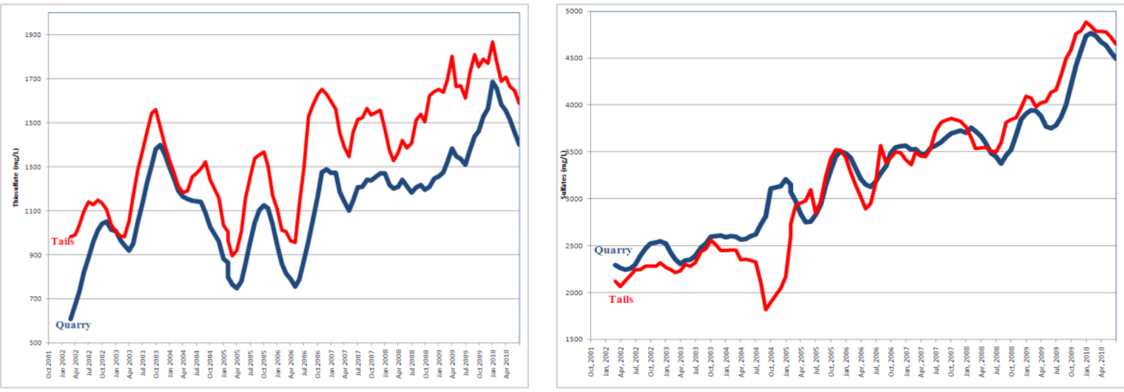

Figure 5. Concentrations over time of thiosulfate (left) and sulfate (right) in plant tails and reclaim quarry (Cormier, 2010).

The conditions in the quarry (concentrations of sulfates and thiosulfates, lack of dissolved oxygen, pH, and temperature) enabled the Sulfate Reducing Bacteria (SRB) populations to reduce sulfate in large amounts to obtain energy and expel the resulting sulfides as waste; this is known as dissimilatory sulfate reduction.

Sulfides are formed by disproportionation of Thiosulfates (Gerits 2009):

$$S_2O_3^{2-} + H_2O \rightarrow SO_4^{2-} + HS^- + H^+$$

Or sulfate reduction:

$$SO_4^{2-} + 2CH_2O \rightarrow H_2S + HCO_3^-$$

In the fall of 2009, following an unseasonably dry August, the concentration of TRS gases from the reclaim quarry were much higher concentrations that had been observed in previous autumns. The concentrations were at such levels that inquiries were received at the mine site for the local community (> 10 km South of the mine site), depending on wind direction. All employees on the mine site were easily able to detect these TRS odors, as the odor threshold of 20 ppb was exceeded on a regular basis.

The decrease in thiosalt concentrations between the plant tailings and reclaim quarry indicate a disproportionation of thiosulfate ($S_2O_3^{-2}$) is occurring. The rate of reduction of concentration of thiosulfate is relatively constant over the years, but the concentration has doubled since 2001, resulting the twice the quantity of thiosulfates available for reduction by SRB to dissolved sulfides. The average monthly reduction in thiosalts of 500 mg/L (95% CI 461, 561) represents a tremendous quantity of thiosulfates available for reduction by SRB to dissolved sulfides.

This resulted from concentrations of dissolved total sulfides (passing 0.45 micron) in the reclaim water at 280 mg/L. Thiosulfate and sulfate concentrations also reached the peak measured values. The sulfide concentrations grossly exceeded the solubility in water, and TRS odors were detected downwind of the Mine for several kilometers.

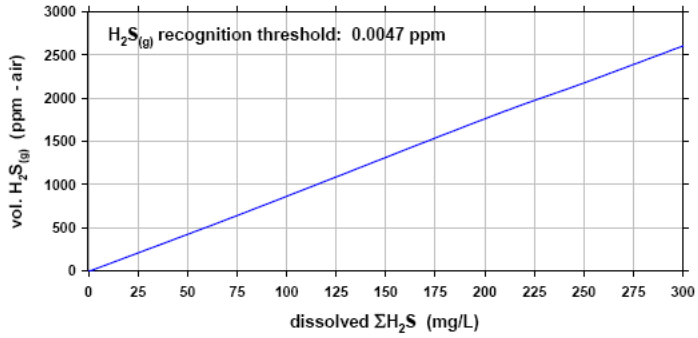

Figure 6. H_2S(g) in quarry water and air at (H_2S) of 0-300 mg/L (Gerits, 2009).

The reported partial pressure (atm) and volumetric concentration (ppm) of H_2S(g) in the air refer to a closed system. At the time TRS odors from the quarry was detected in the surrounding community, the dissolved sulphide concentration in the quarry water had reached 280 mg/L corresponding to a concentration of 2440 ppm in the air (closed system). This implies that even after approximately 1:2 million times (*i.e.* 1,926,230) dilution in the air, the H_2S(g) from the quarry could still be detected in the surrounding community (Gerits 2009).

4 INCIDENT MANAGEMENT

4.1 *Health and Safety*

Completion of a risk assessment determined that the risk of these TRS odors entering the underground work environment was high. Employees in the underground environment rely on their olfactory system to detect the stench gas (ethyl mercaptan) released to alert them of an emergency. The TRS odors also could be confounded to be odors from a fire in the underground environment. The concentrations measured on site were as high as 200 ppb instantaneous, with an hourly average peaking at 20 ppb. These concentrations are below published exposure limits, but short term exposures at these concentrations have been reported to cause headaches and nausea. The Joint Health and Safety implemented a code of practice to reduce these risks of confusion over the odors, and actions to take when odors were detected. An employee communication program was developed. All employees were informed of the situation, and the code of practice. During September and October there were more than 30 hours of lost production impacted by the odors, which resulted in a calculated loss of $ 300,000.

4.2 *Environment & Community*

A full disclosure presentation was made to the New Brunswick Department of the Environment. Several inquiries were received from residents at Nepisiguit Falls, 8 km south of mine site and Rose Hill 10 km. On September 17th 2009, reports of TRS odors in Allardville (25 km East) were received. Prevailing winds from the mine site are from the West and Northwest, causing TRS odors to be carried downwind to the communities East and Southeast of the Mine.

Sulfide concentrations in water can be acutely lethal to fish, (Smith, 1974), and are recognized to be contributors to toxicity observed in effluent failing to meet the 96-Hour acute lethality test, required by the Metal Mining Effluent Regulations (MMER). The concentrations of sulfides were also a risk to compliance with the MMER. The reclaim quarry level is lowered in the fall and winter seasons, which enables adequate storage water in the reclaim quarry for the spring freshet. The water is typically pumped and/or siphoned into the water management system. The water management system consists of a series of collection ponds, which discharge into an 820,000 m^3 buffer pond. The water is pumped from the buffer pond to the high density sludge (HDS) effluent treatment plant. The ETP is capable of treatment rates as high as 60,000 lpm. Treatment consists of lime neutralization and clarification prior to discharge to the Little River.

5. DEVELOPMENT OF A SOLUTION

The response from the employee communication sessions was overwhelming, many employees offered suggestions for potential solutions. A list of the opportunities was developed which included aeration, oxidation, chemical treatment, sulfide specific chemicals, odor masking agents, de-odorizers. All solutions presented risks, including cost and effectiveness uncertainties. Personnel from Brunswick, Xstrata Zinc, and a 3rd Party environmental consulting firm CH2MHill collaborated to analyze the options. During the analysis of these options it was it was discovered that acid mine drainage (AMD) could treat the aqueous sulfide which was produced by the sulfate reducing bacteria. It has been recognized for many years that sulfide bioreactors could successfully be used to treat AMD. At Brunswick Mine, AMD has been treated by the HDS process. A full scale SRB bioreactor has never been developed. The natural sulphide production by SRB in the quarry created an opportunity to reduce sulfide concentrations with AMD. This was confirmed in consultation with CH2MHill's Associate Consultant Robert (B.T.) Thomas, Ph.D.

Brunswick Mine has two sources of AMD, the underground operations at the Brunswick # 12 mine, and the Brunswick # 6 open pit, which has been closed since 1984. Bench tests were conducted with reclaim water and AMD, and odors were eliminated at concentrations as low as 0.1 % (v/v) AMD. AMD from # 6 open pit typically contains 1,100 mg/L dissolved iron (400 mg/L Ferrous), and 200 mg/L dissolved zinc with a pH level of 3.0. AMD can be effective in removal of sulfides in water, due to the fact that sulfide has a naturally high affinity for complexing with certain metals, thereby causing an immediate reaction producing stable metal sulfides. The reaction of dissolved metals (Ferrous Iron and Zinc) and aqueous sulfides produces insoluble metal sulfides ZnS and FeS. Removal of dissolved sulfides in water would eliminate the odors, by lowering the sulfide concentration below the solubility levels in water. Bench testing showed that concentrations at 5 % (v/v) AMD lowered sulfide concentrations to 100 mg/L, and maintained the pH near neutral (pKa of H_2S is 7).

The concept of adding AMD from the # 6 open pit to the quarry was evaluated through a risk assessment approach, and it was determined that the overall risk ranking was very low. An interim system was quickly implemented to re-direct the AMD from the pipe discharge to the reclaim quarry, a distance of 5 km. During the installation of this system, trucks were contracted to transport the AMD. Jan Gerits, Ph.D, Senior Environmental Geochemist with LORAX Environmental visited the site on September 24th, shortly after AMD additions had started, and developed a technical memorandum on the remediation of the reclaim water. In November, the pumping system at the # 6 pit was de-commissioned for the winter. A project was developed to permanently pump the AMD from # 12 underground mine. This system was commissioned on February 25th, 2010. It was capable of delivering 1000 lpm of AMD, containing typical concentrations of Iron at 1,000 mg/L (600 mg/L Ferrous) and 1,500 mg/L Zinc.

5 RESULTS

5.1 *Chemistry*

The addition of AMD to the quarry had an immediate positive effect. The TRS odors were immediately reduced and eventually eliminated. The only constraints were mixing and volumetric flow rate. The color of the water changed from an opaque black to a light orange. Concentrations of sulfides were reduced by 40 % as of June 30th, 2010, reaching concentrations of 150 mg/L. Alkalinity was also reduced (- 66%) with levels reaching 350 mg/L while suspended solids levels remained constant.

Dissolved concentrations of Fe and Zn were reduced to less than 1 mg/L. pH levels have remained near 7 despite the addition of 1,000 lpm of AMD at pH 3. Figure 7 shows the pH fluctuating between 6.8 and 9 the alkalinity and sulfides have been reduced significantly.

Concentrations of both thiosulfates and sulfates have also reversed their increasing trends, and have been declining steadily since the AMD additions were implemented. This tread is illustrated in Figure 5, where the concentrations of both thiosulfates and sulfates had been increasing, prior to October 2009, and decreasing since.

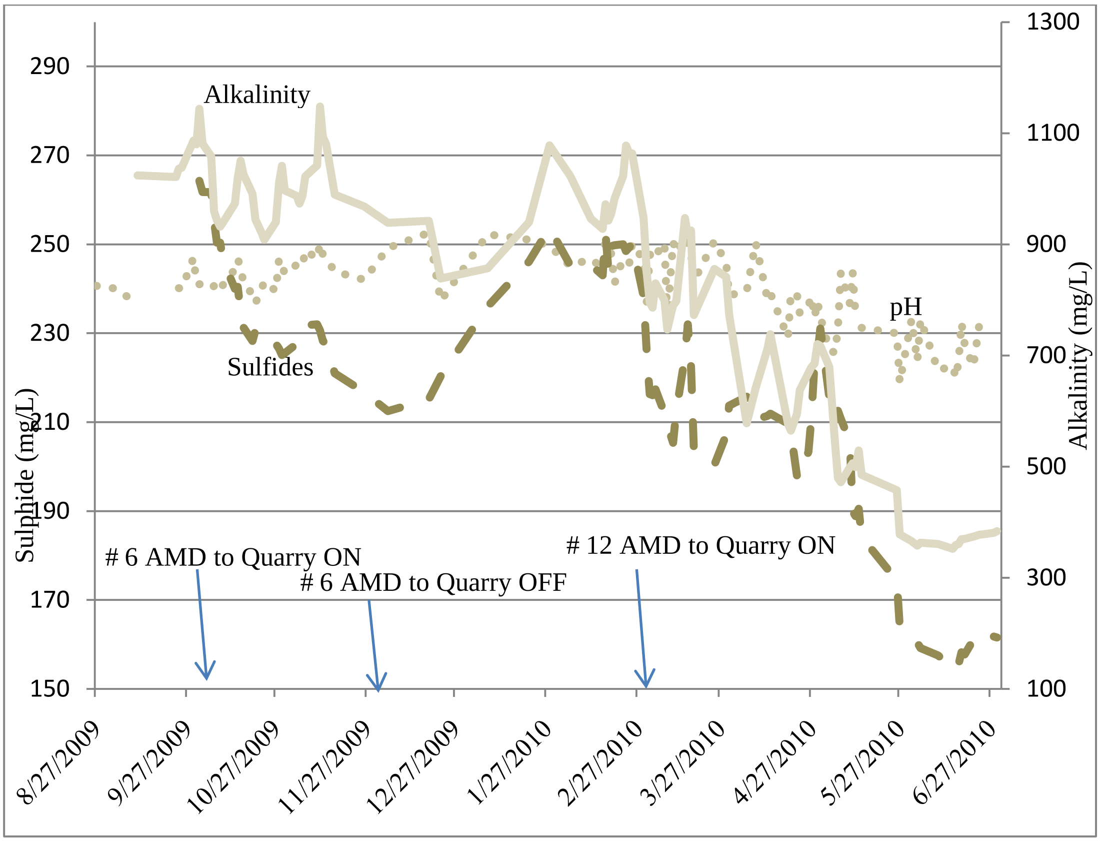

Figure 7. Alkalinity and sulphide Concentrations (Cormier, 2010).

Biweekly samples at 4 locations, and at 3 meter depth intervals revealed stratification below 6 meters from the surface. At these depths anoxic conditions exist and Sulfide levels are 200 mg/L. This remains a risk for a short-term episode if an annual mixing event were to occur as the reclaim quarry behaves like a meromitic lake. Water quality parameter levels in the water column at 6 meters depth are consistent throughout the reclaim quarry. Alkalinity and sulfide concentrations show a strong linear correlation and the reduction in sulfides results in alkalinity levels returning to concentrations similar to 2007 levels. The addition of 1000 lpm of AMD has not significantly impacted the pH of the reclaim quarry water, as shown in Figure 7, but the AMD additions have reduced the sulfide concentrations, which has resulted in decreased alkalinity.

6 EFFLUENT QUALITY

The sulfide concentration in the reclaim quarry will have an effect on the sulfide concentrations in the ETP effluent, when the level in the reclaim quarry is lowered. In November, when the # 6 Open Pit pumping system was de-commissioned for the winter, sulfide levels had reached a low of 211 mg/L. In the elapsed time between the de-commissioning of the # 6 Open Pit pumping system, and the commissioning of the # 12 Mine pumping system on February 25th, the dissolved sulfide concentrations were measured at 250 mg/L. The variation of sulfide concentrations in the reclaim quarry is shown in Figure 7.

In March 2010, an effluent sample collected from the discharge of the ETP did not meet the requirements for the 96-Hour acute lethality test. An Acute Lethality Response Protocol (ALRP) investigation conducted with Lesley Novak, M. Sc., Vice President, Senior Aquatic Toxicologist, Aquatox Testing and Consulting of Guelph, Ontario determined that dissolved sulfide concentrations in the effluent were the root cause of the toxicity (Novak, Personal Communication, March 2010).

Shortly after the # 12 Mine pumping system was fully operational, the concentrations of sulfides returned to the previous minimum concentrations of 210 mg/L and by the end of March concentrations were 200 mg/L. Also at the end of March concentrations of sulfides in the ETP Effluent were less than the detection limit of 0.02 mg/L. Samples collected from the effluent showed mortality in the 96 Hour test to have dissolved H_2S concentrations of 3 – 5 mg/L (Novak, Personal Communication, March 2010).

6.1 *Reagent Consumption*

The reduction in alkalinity (60 % as of June 30th) has resulted in a huge impact on the consumption of pH modifying reagents used in the milling process. Sodium Carbonate (Na_2CO_3) and Sulfur Dioxide (SO_2) were reduced by 20 and 25 % respectively. This reduction has resulted in a cost savings of $ 970,000 at the end of the 2010 second quarter, and is projected to save approximately $ 1 million in the 3rd and 4th Quarters, for an annual savings of $ 2.0 million. Further reductions in alkalinity should continue to positively impact savings in the future.

Addition reagent consumption reductions were observed at the effluent treatment plant (ETP). The removal of dissolved Fe and Zn, as well as the reduction in alkalinity of the reclaim quarry water has reduced the lime demand at the ETP. This has resulted in an additional savings of $ 30,000 through June 2010 from reduction of lime consumption.

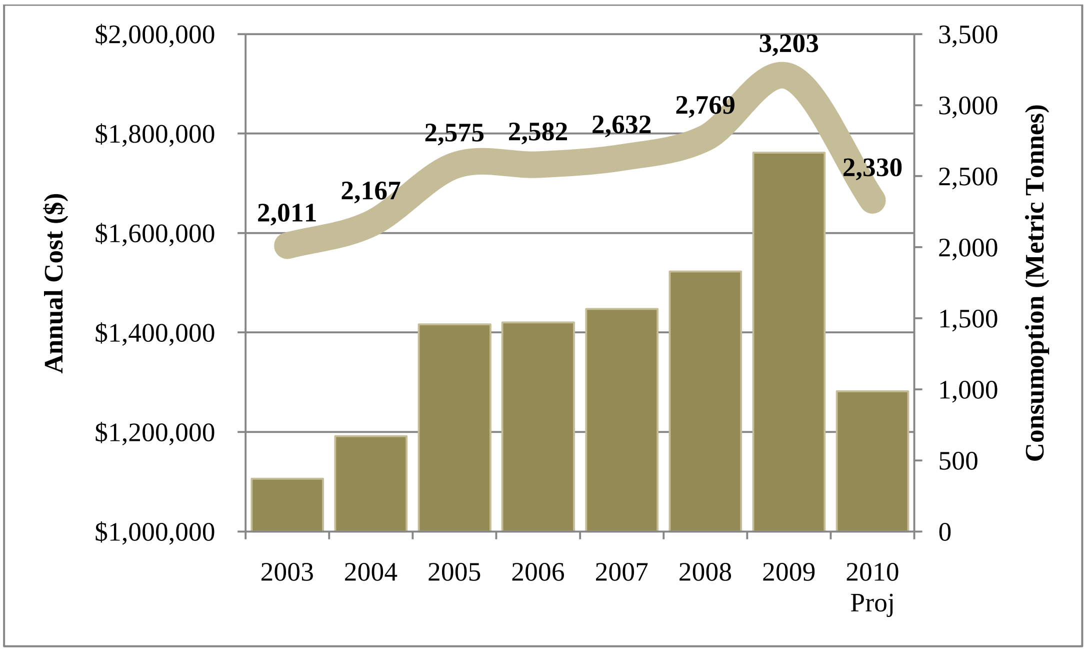

Figure 8. Annual consumption of sulfur dioxide (Cormier, 2010).

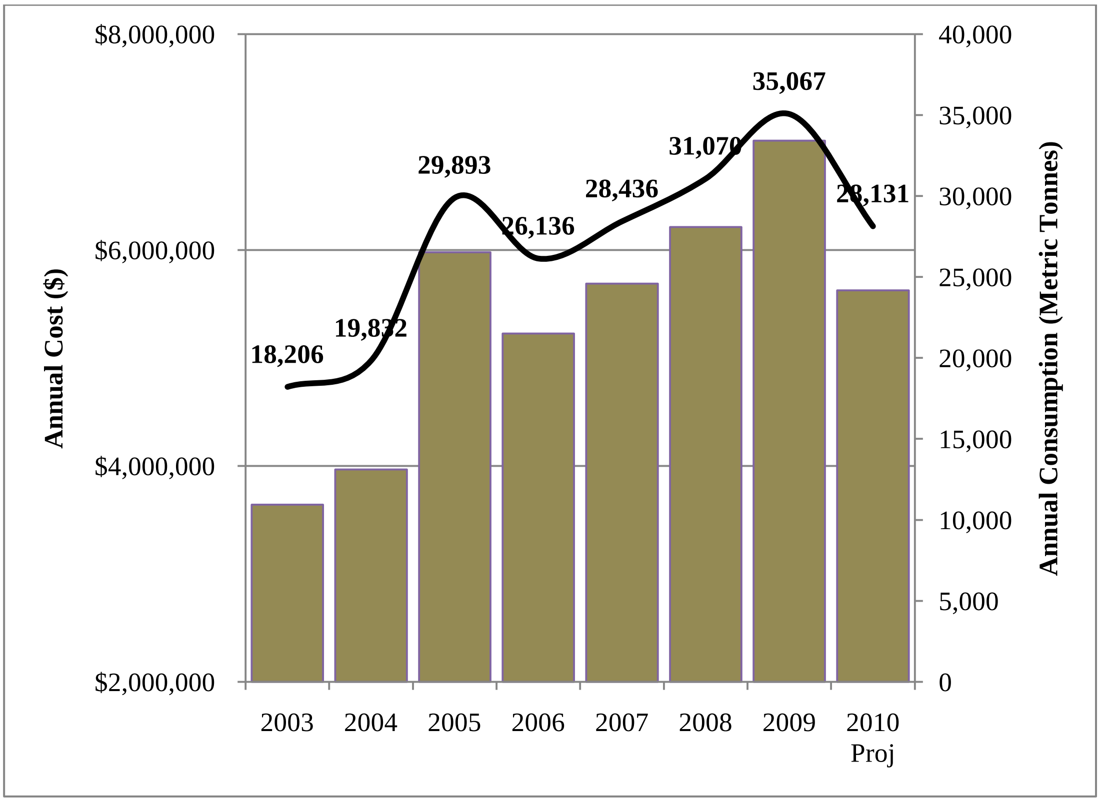

Figure 9. Annual consumption of soda ash (Cormier, 2010).

7 SUSTAINABLE DEVELOPMENT SOLUTION

A health, environmental, community and production risk was not treated effectively and an extended incident occurred. The sustainable solution to eliminate this risk was treatment with a waste. The treatment with a waste was very effective in eliminating the risk and also resulted in an improvement in water quality for water recycled in the milling process. The improved water quality significantly reduced consumption of chemicals. The reduction in consumption of these chemicals has reduced operating costs by $ 970,000 in the first 6 months of 2010. This is a prime example of what William McDonough principles of design for sustainability, with one of his foundations of a cradle-to-cradle design, **waste equals food** (McDonough 2002).

8 CONCLUSION

This case study exhibits a successful application of the principles of sustainable development in mining. Although the details of the application are specific to Brunswick Mine, the strategy used to develop a solution is applicable to any sustainable development risk.

Many components of Xstrata's sustainable development management system were applied. Effective communication and engagement throughout the incident management process led to the development of a list of potential solutions. Evaluation of the potential solutions using a rigorous risk and change management system led to the selection of a sustainable solution. Effective assessment of the solutions resulted in the determination of the best option of using a technology that was well established in mining, (sulfide bioreactors are used to treat AMD). In this case some counter-intuitive thinking was required to apply the process in reverse and use AMD as the treatment for the un-intended product of the reclaim quarry sulfide bioreactor.

As a matter of sustainable development, the use of a waste to treat the waste from another process is classic use of the "**waste equals food**" concept.

ACKNOWLEDGEMENTS

Many people contributed to the success of this project, including but not limited to the following: employees at Brunswick Mine, Robert (BT) Thomas (CH2MHill), Florian Reher (Venture Engineering and Construction), Lesley Novak (Aquatox Testing and Consulting), Paul Deveau (Xstrata Zinc Canada), Rick Schwenger (Xstrata Zinc Canada) and Christina Vink (Memorial University).

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