Preface:

The Addendum to RS29T is not a new draft of the report. The format used to prepare the Addendum to RS29T is similar to the one used for the Supplemental DPD. For brevity, Sections of the original report that did not change and were not addressed in any comments are not reproduced. Sections where additional information was requested are reproduced (in black) along with the additional text in blue. This format allows the additions to be placed in the proper context while still allowing he reader to easily identify the new material.

RS29T
Draft-02
March 30, 2007

Addendum
Technical Design Evaluation Report
RS29T – Wastewater Treatment Technology
NorthMet Project

October 2007

Table of Contents

Table of Contents (continued)

Table of Contents (continued)

List of Tables

List of Figures

Table of Contents (continued)

List of Appendices

List of Supporting RS Documents

RS13	Process Design – Tailings Basin Water Balance
RS21	Hydrology – Mine Water Model and Balance
RS22	Mine Waste Water Management Systems
RS23T	Reactive Waste Segregation
RS30	Reactive Waste Stockpile Chemical Modification
RS31	Mine Pit Water Quality Model
RS45	Water Treatment Studies – Waste Rock and Lean Ore
RS49	Stockpile Design
RS52	Closure Plan
RS53/42	Wastewater Modeling – Waste Rock and Lean Ore
RS54/46	Wastewater Modeling – Tailing Basin
RS66	Mercury Balance – Water
RS74	Water Quality Changes – Cumulative Impacts Report

List of Acronyms

ARD	Acid Rock Drainage
CFR	Code of Federal Regulations
CPS	Central Pumping Station
DRO	Diesel Range Organics
EDTA	Ethylene-diamine-tetra-acetic acid
EPA	Environmental Protection Agency
EIS	Environmental Impact Statement
EQ	Equalization
gpm	Gallons per minute
GRO	Gasoline Range Organics
HDS	High Density Sludge
ITRC	Interstate Technology and Regulatory Council
MDNR	Minnesota Department of Natural Resources
MPCA	Minnesota Pollution Control Agency
NPV	Net Present Value
O&M	Operation and Maintenance
psi	pounds per square inch
RO	Reverse Osmosis
SOW	Scope of Work (Appendix A)
SPCC	Spill Prevention Control and Countermeasures (Plan)
SSF	Sub-Surface Flow (wetland)
TDS	Total Dissolved Solids
WWTF	Waste Water Treatment Facility

Executive Summary

This Technical Design Evaluation Report – RS29T Wastewater Treatment Technology – has been prepared to summarize the treatment component of the overall water management strategy that will be employed for the NorthMet Project. Process water generated at the Mine Site will contain dissolved chemicals due to oxidation of waste rock and the pit walls. Mine Site process water will be treated and then recycled to the Plant Site, thereby lowering the overall water consumption of the NorthMet operation and eliminating the need for a direct discharge of Mine Site process water to surface water. Thus, the purpose of water treatment within the NorthMet operations is to remove chemicals from the water to maintain the overall quality of the water in the tailings basin at or below process water quality targets.

Water Management Strategy

The water management strategy used at NorthMet will be to recycle and reuse Mine Site process water as the primary source of make-up water for the Plant Site. Because of the mine scheduling and water management strategies used at the Mine Site, the water volume requirements at the Plant Site will exceed the volume of process water generated at the Mine Site. Thus, Mine Site process water will be treated and recycled. Colby Lake water will be used to supplement the water make-up requirements for the Plant Site, after the Mine Site process water has been recycled.

Development of the overall water management strategy for the NorthMet operation incorporated many mitigation efforts as well as extensive hydrologic, hydrogeologic, and geochemical modeling of water quantity and quality. This work was completed in an iterative process, with information from various models linked to provide a comprehensive solution that includes treatment and reuse of the Mine Site process water in the overall water management strategy. All of this information is presented in a sequence of RS documents. The results and conclusions from work presented in several RS documents provide the input data concerning Mine Site process water quantity and quality that will need to be treated, including:

- RS21 – Hydrology – Mine Water Model and Balance,
- RS22 – Mine Waste Water Management Systems,
- RS30 – Reactive Waste Rock Stockpile Chemical Modifications,

- RS31 – Mine Pit Water Quality Model, and
- RS53/RS42 – Waste Rock Characteristics/Waste Water Modeling - Waste Rock and Lean Ore.

The results from these and other RS documents were used to evaluate the need for water treatment at the Mine Site for water sent to the tailings basin for use in the processing the ore. In turn, the predicted results for waste water treatment of the Mine Site process water included in this report have been subsequently used to complete the modeling of the tailings basin water quality and develop water quality predictions for the water that will be contained in the tailings basin during operation. The results of the work completed and presented in RS documents subsequent to the development of these waste water treatment predictions include:

- RS13 – Process Design - Tailings Basin Water Balance, and
- RS54A/RS46 – Flotation Tailings Characteristics/Waste Water Modeling – Tailings.

A similar process was also used to evaluate the need for waste water treatment after closure. Much of the information presented in the previously listed RS reports also applies to closure. However, changes to the overall water management strategy and waste water treatment, as well as potential long term interaction of the Mine Site with groundwater and surface water quality are included in:

- RS52 – Mine Closure Plan, and
- RS74 – Water Quality Changes – Cumulative Impact Report.

Process Water Quality Objectives

The technology required for treatment of Mine Site process waters is dependent upon three factors:

- The quantity and quality of the untreated Mine Site process water,
- The water quality needs of the processing operation, and
- Long term pit water quality and the mine closure plan.

These two factors are both described in this report. Water treatment requirements to maintain the long term pit water quality after mine closure are addressed in the Closure Plan (RS52). As noted previously, the quality and quantity of Mine Site process water is a technical matter that has been addressed through rigorous hydrological and chemical leaching studies to provide the input necessary to evaluate potential water treatment options. The water quality needs of the Beneficiation Plant are generally low, because the primary function of the water is to transport a relatively high concentration of suspended solids through the process and then deliver the tailings to the tailings basin. The water quality and quantity needs of the Hydrometallurgical Plant are independent of the Beneficiation Plant. The Hydrometallurgical Plant is a net consumer of water and will have independent controls to monitor and adjust the quality of processes within the operation.

The minimum water quality requirements of the Beneficiation Plant are similar to those established by the State of Minnesota for surface waters that would be suitable for industrial consumption, or Class 3 waters. Because water will need to be moved between the Mine Site and the tailings basin, and because some of the water that will be stored in the tailings basin may eventually be returned to the West Pit or flow from the tailings basin to the natural groundwater, the process water quality targets established for treatment of the Mine Site process waters also considered the State of Minnesota surface water quality standards for Class 2 waters and the groundwater protection standards. These values establish more conservative water quality standards than those required in the Beneficiation Plant, but maintaining these concentrations throughout the operation significantly reduces the long term impact of the mining and processing operations on water quality after closure.

Comparing the predicted water quality for Mine Site process water with the process water quality targets, establishes the treatment objectives for the wastewater treatment facility at the Mine Site. These objectives include:

- Removing metals and inorganics, including aluminum, antimony, arsenic, cobalt, copper, iron, manganese, mercury, nickel, selenium, thallium, and zinc.
- Reducing the concentration of sulfate and hardness, along with the related parameters of TDS and conductivity to reduce long-term build-up of these parameters in the tailings basin.

Treatment Technology Evaluation

Four technologies were evaluated to meet these objectives – chemical precipitation, membrane separation, ion exchange, and biological transformation. Within each of these categories, multiple process operations were considered using published literature. Numerous references to application of these technologies at a variety of locations, including mining operations are included in the report.

In addition, bench-scale testing of chemical precipitation using water from a stockpile of Duluth Complex rock was conducted to provide a site-specific assessment of the capability of this process to remove metals and inorganics. The results from the bench-scale simulation of a high density sludge treatment process – which uses oxidation and pH adjustment to precipitate and/or co-precipitate iron and heavy metals, such as copper, nickel, and cobalt – showed that, with the exception of mercury, all the metals of concern at the NorthMet operation could be reduced to below the process water quality targets. Sulfate can also be removed by chemical precipitation of gypsum. This process is well documented in the literature and was not evaluated using site-specific testing.

Within all of the four treatment categories evaluated, one or more specific processes were considered technically capable of achieving the treatment objectives. Among those processes that were considered effective, the evaluation further segregated potential treatment techniques based on their implementability and cost. Given the variable nature of the Mine Site process water, and the need to achieve multiple objectives (metals removal and TDS/sulfate reduction) combinations of these technologies were also evaluated based upon their potential implementability and cost.

Treatment Technology Recommendation

A combination of chemical precipitation and nanofiltration is recommended to treat the NorthMet Mine Site process water to achieve the process water quality targets. The combined alternative will include nanofiltration of the process water flows with lower concentrations of dissolved metals and sulfate – primarily the mine pit water – along with chemical precipitation of metals and sulfate (as gypsum) from process water flows with higher concentrations of dissolved metals and sulfate, including the drainage from the Category 3 and Category 4 waste rock stockpiles and the brine from the nanofiltration operation. Treatment efficiency for a combined nanofiltration and chemical precipitation treatment system was estimated using conservative results of the site-specific bench-scale testing, selected removal efficiencies from literature, and chemical stability modeling using PHREEQC. The results of this evaluation (Table 14) showed that, with the exception of mercury and thallium, all of the parameters could be reduced to below the process water quality limits for the first 5 years and that from year 10 through year 20, several parameters would be close to the process water quality targets, including sulfate, aluminum, arsenic, cobalt, and copper. Ongoing optimization of the chemical precipitation and nanofiltration treatment operations can and will be used to reduce the effluent concentrations of these parameters to below the process water quality targets and maintain long-term water quality within the tailings basin.

1.0 Introduction

1.1 Project Overview

1.2 Report Objective and Water Management Overview

The objective of this Wastewater Treatment Technology Evaluation Report is to describe in detail the water treatment requirements and the proposed water treatment technologies for NorthMet process water that will be generated at two locations:

- At the Mine Site, primarily from pit dewatering and stockpile drainage, and
- At the Plant Site, primarily from the beneficiation of the ore and subsequent transport of flotation tailings to the tailings basin.

Schematic drawings of the of the water flows at the Mine Site and the Plant Site are included in Appendix J (Note: additional Appendices included in this Addendum begin after Appendices A through H, which were included in the original Report. Appendix I contains the response to comments on the March 30, 2007 version of RS29T). At the Mine Site, all process water that contacts waste rock, ore, the mine pit, or any of the active mining operations will be carefully managed to eliminate discharge to surface water. Additional details on segregation of Mine Site process water from storm water can be found in RS22. Only non-contact storm water will be discharged from the Mine Site. The Mine Site process water will be treated at a wastewater treatment facility (WWTF) prior to being pumped to the tailings basin, where it will be used as make-up water for the beneficiation process, as described in Section 2 of this report. The WWTF will be designed and operated to maintain water quality within the tailings basin to appropriate process-based targets. This water management plan avoids a direct discharge of wastewater from both the Mine Site and the Plant Site during the proposed 20-year operating life of the project.

Approximately 40 years after closure of the mining operation, when the West Pit has filled with water, it will be necessary to discharge water from the Mine Site. Treatment and discharge of Mine Site process water after closure is addressed in the RS52. In general, the treatment of Mine Site process water after closure of the Mine Site will continue as described in this Report. The volumes of flow will, however, decrease with time as all of the stockpiles are covered. After closure, treated water from the WWTF will no longer be routed to the tailings basin for re-use. Instead, this water will be directed to a wetland that will be constructed in the former East Pit, which will provide additional treatment of the water before it flows to the West Pit and eventually the Partridge River. The schematic drawings in Appendix I show the variations in the direction of water flow during operation of the Mine Site and after closure.

At the Plant Site, PolyMet plans to use the existing tailings basin for disposal of flotation tailings generated by processing the ore (see Figure 2). Water will be used in the grinding and flotation operations and will also be used to transport the tailings to this basin. Water will then be returned from the tailings basin to be re-used in the beneficiation process. During operation of the project, no water will be discharged directly from the Plant Site to surface water. Upon closure, the water in the tailings basin will be pumped back to the Mine Site to accelerate filling of the West Pit. Tailings basin seepage water will also be pumped to the Mine Site after closure.

Additional wastewater streams that will be generated at the Plant Site include the process water from hydrometallurgical residue cells that will be constructed on closed portions of the tailings basin, and wastewater from potable use (toilets, sinks, showers, etc). During operation, the process water from the hydrometallurgical residue cells will be routed back to the hydrometallurgical process, which will consume water during normal operations. Drainage water treatment will be required after closure and is addressed in RS52. Wastewater from potable uses will be treated separately from the process wastewaters described in this report. Therefore, at the Plant Site, the primary focus of this report is the process water in the Beneficiation Plant-tailings basin loop.

1.3 Report Organization

2.0 Reuse/Recycle Water Management Plan

The reuse/recycle plan for water management at NorthMet envisions no discharge of wastewater from any of the processing activities or other operations described in this report. Water will enter the NorthMet operation in the form of precipitation, groundwater inflows to the mine pit, and as make-up water from Colby Lake. This water will be collected, treated when necessary, used in the beneficiation process, and later returned the mine pits to facilitate filling at the conclusion of the mining operations. This water management plan for NorthMet does not include any planned discharge of process water to surface waters of the State of Minnesota until the West Pit overflows to the Partridge River, approximately 40 years after the operation has been closed and the Mine Site has been reclaimed. This is the essence of the reuse/recycle plan for water management. The details of this plan are developed in several other RS documents and integrated into a single plan in the following paragraphs.

Managing process and wastewater generation and consumption to eliminate wastewater discharge to surface water will be a critical aspect of the proposed NorthMet project. Water is required for the grinding of ore and flotation of the ground ore slurry to separate the concentrate from the tailings. Water is consumed in the hydrometallurgical processes used to recover metal from the concentrate. Water is also lost to the tailings basin when tailings are deposited (by filling the space between tailings particles), to evaporation from the surface of the basin, and to deep groundwater (water at the natural groundwater elevation) beneath the tailings basin. All these water-related operations must be balanced, and appropriate factors of safety established, to provide a consistent and reliable – but not excessive – supply of water to the operation. A source of new water, Colby Lake, will then be used to provide any additional water required to maintain the operation.

The implementation of a complete reuse/recycle program for NorthMet is predicated upon the careful management (balancing) of water inflows with consumption, as well as careful modeling of water quality and appropriate treatment, when necessary. The estimates of water quality and quantity at both the Mine Site and the Plant Site have been completed and reported in several individual RS reports including:

- RS13 – Process Design – Tailings Basin Water Balance
- RS21 – Hydrology – Mine Water Model and Balance
- RS22 – Mine Waste Water Management System

- RS31 – Mine Pit Water Quality Model
- RS53/RS42 – Waste Rock Characteristics/Waste Water Modeling -Waste Rock and Lean Ore
- RS54A/RS46 – Flotation Tailings Characteristics/Waste Water Modeling -Tailings
- RS52 – Mine Closure Plan
- RS74 – Water Quality Changes -- Cumulative Impact Report

Small quantities of water (liner leakage) may not be captured by the proposed control systems at the Mine Site. In general, these flows are still captured by pit dewatering operations while the Mine Site is active. After the Mine Site is closed, these uncollected waters (fugitive flows) would flow through the ground, with a portion of this flow eventually reaching into the Partridge River. The potential for these flows to impact surface water quality is evaluated in detail in RS74. For the purpose of this report, all Mine Site process water flows are assumed to be captured in the drainage and collection systems at the Mine Site and routed to the WWTF. This provides a conservative estimate of the flow into the WWTF.

The plan for treatment of water after closure is described in RS52 and summarized in Section 1.2 of this report.

The results of these reports are summarized and combined in the following paragraphs to provide an overall assessment of water management approach and to highlight areas where water treatment is necessary to maintain the water quality needed for plant operations and to maintain appropriate water quality standards near NorthMet.

2.1 Mine Site Process Water

2.1.1 Mine Site Process Water Quantity

Mine Site process water is generated from four sources: groundwater entering the mine pit, direct precipitation on the mine pit, infiltration through or runoff from waste rock stockpiles collected on liner systems (drainage), and runoff from other site operations within the Mine Site—for example the ore Rail Transfer Hopper, and mine service roads. The mine plan includes three separate pits (referred to as the East Pit, the Central Pit and the West Pit), which will be changing over the life of the mining operation. The quantity of process water generated from these pits and associated stockpiles will also vary over the life of the mine. The use of multiple pits helps to reduce the maximum pumping that will be required for mine pit dewatering and also provides a location for storing some of the process water generated at the site after the first eleven years of operation. These options help to provide flexibility and facilitate the development of a reuse/recycle - water management plan.

On an annual average basis, the maximum design rate of process water generation from the sources that will require treatment at the WWTF varies from approximately 500 gpm in the early years to a maximum of approximately 1,600 gpm near Year 10, before initiation of filling activities for the East Pit, and reducing to approximately 1,400 gpm in the final years of operation. The detailed evaluation procedures used to estimate these flows is included in RS22 and summarized in RS21. Table 1 contains a summary of the anticipated annual average Mine Site process water flow rates from all the sources that will require treatment. All of these flows, even during the likely peak in Mine Site process water generation near Year 10 can be consumed by operations at the Plant Site. Within any given year, the process water flow will vary significantly from a minimum flow during the winter months to a maximum flow in the spring. In general the minimum flow is 0.5 to 0.7 times the average annual flow, while the maximum flow ranges from approximately 2.0 to 2.5 times the annual average flow, with a maximum design flow of approximately 2,960 gpm in the Spring of Year 10. This value provides the design basis for the maximum flow rate through the WWTF of 3,000 gpm.

Table 1 Mine Site Process Water Flows to the WWTF

Source	**Estimated high (and low)[1] average annual flow (gpm) in Year:**				
	1	**5**	**10**	**15**	**20**
Category 1/2 Stockpile	58.6(44.4)	195.4(48.4)	120.3(38.4)	205.8(91.8)	205.8(91.8)
Category 3 Stockpile	5.0(3.8)	20(14.7)	35(25.3)	49.5(34.4)	23.2(10)
Category 3 Lean Ore Stockpile	29.9(22.7)	50(36.7)	62.5(33.7)	80.2(26.2)	51.8(22.5)
Category 4 Stockpile	3.8(2.9)	30.4(22.9)	35.3(25.9)	32.2(23.3)	4.6(0.9)
Lean Ore Surge Pile	46.1(35)	46.1(35)	46.1(35)	46.1(35)	46.1(35)
East Pit[2]	200.9	774	820.1	80.7	0
West Pit	79.4	123.8	224.4	486.9	924.3
Haul Roads	46.1	46.7	38.8	36.5	35.3
Rail Transfer Hopper	6	6	6	6	6
Total	476(441)	1,292(1,108)	1,389(1,248)	943(740)	1,297(1,126)

Notes:

1. Lows not shown when same as high estimates
2. Includes Central Pit - Zero flow from East Pit to WWTF starting in Year 12 when East Pit filling is initiated.
3. See RS22 (Table 3.1.1-B and Table 4.1.4.1-B) for flow estimation procedures and results

As contemplated in Phase 3 of the SOW, the work described in RS21 and RS22 was focused on minimizing the Mine Site process water quantity and minimizing impacts to water quality through the use of segregation of waste rock and capping of stockpiles as well as dewatering of multiple pits on independent schedules. These activities contribute to the implementation of a reuse/recycle water management plan as described in the plan for the proposed WWTF at the Mine Site in Section 5.

2.1.2 Mine Site Process Water Quality

The quality of the Mine Site process water will vary based on the source of the water. For example, waste rock is proposed to be segregated into four different ‘categories’ based on the geochemical properties of the rock which drives the potential for water that contacts the rock to impact water quality. Mine pit process water quality will be different than the drainage from the waste rock stockpiles. The anticipated water quality for each of these sources has been predicted (see RS31 and RS53/RS42) using site-specific data obtained from humidity cell testing and site-specific hydrology. Table 2 contains a summary of the expected water quality for the primary sources of Mine Site process water.

Table 2 Mine Site Process Water Quality

Parameter (mg/L)	Category 1/2 Stockpile (Years)					Category 3 Stockpile (Years)				
	1	5	10	15	20	1	5	10	15	20
Fluoride (F)	0.0078	20.0	71.9	36.3	36.3	3.29	9.70	12.2	17.0	85.5
Chloride (Cl)	0.11	82.5	110	0.00	0.00	19.1	12.9	5.74	8.41	53.5
Sulfate (SO_4)	0.68	1737	2340	2340	2340	1539	2340	9600	9600	9600
Aluminum (Al)	0.026	1.68	1.68	1.68	1.68	1.68	1.68	83.0	83.0	83.0
Arsenic (As)	0.0013	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
Barium (Ba)	0.0026	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Beryllium (Be)	0.000029	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0023	0.0023	0.0023
Boron (B)	0.0011	0.76	0.76	0.76	0.76	0.73	0.76	0.76	0.76	0.76
Cadmium (Cd)	0.0000058	0.00018	0.00018	0.00018	0.00018	0.00018	0.00018	0.015	0.015	0.015
Calcium (Ca)	0.29	540	540	540	540	371	540	480	480	480
Chromium (Cr)	0.000032	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Cobalt (Co)	0.000016	0.04	0.052	0.052	0.052	0.052	0.052	15.4	24.0	44.0
Copper (Cu)	0.00025	0.092	0.092	0.092	0.092	0.092	0.092	21.8	33.9	202
Iron (Fe)	0.0045	0.81	0.81	0.81	0.81	0.81	0.81	28.7	44.7	235
Lead (Pb)	0.000018	0.047	0.053	0.053	0.053	0.0092	0.027	0.053	0.053	0.053
Magnesium (Mg)	0.051	93.0	93.0	93.0	93.0	53.1	93.0	1026	1030	1030
Manganese (Mn)	0.00028	0.72	0.75	0.75	0.75	0.75	0.75	47.0	47.0	47.0
Mercury (Hg)	0.0000013	0.00003	0.00003	0.00003	0.00003	0.000006	0.000006	0.000006	0.000006	0.000006
Molybdenum (Mo)	0.000008	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051
Nickel (Ni)	0.000072	0.18	0.66	0.33	0.33	0.86	0.86	182	284	762
Phosphorous (PO_4)	0.0058	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Potassium (K)	0.21	49.0	49.0	49.0	49.0	49.0	49.0	38.0	38.0	38.0
Selenium (Se)	0.000031	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029
Silica (SiO_2)	0.30	8.65	8.65	8.65	8.65	8.65	8.65	3.88	3.88	3.88
Silver (Ag)	0.0000074	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007
Sodium (Na)	0.44	681	681	681	681	267	681	338	338	338
Thallium (Tl)	0.0000029	0.00002	0.00002	0.00002	0.00002	0.00002	0.00002	0.00006	0.00006	0.00006
Zinc (Zn)	0.00039	0.09	0.09	0.09	0.09	0.09	0.09	10.5	16.4	26.0
Nitrate (NO_3)	0.0015	1.07	1.43	0.00	0.00	0.20	0.14	0.060	0.088	0.56
Ammonia (NH_4)	0.0015	1.07	1.43	0.00	0.00	0.20	0.14	0.060	0.088	0.56

Table 2. Mine Site Process Water Quality (continued)

Parameter (mg/L)	Category 3 Lean Ore Stockpile (Years)					Category 4 Stockpile (Years)				
	1	5	10	15	20	1	5	10	15	20
Fluoride (F)	4.11	13.1	28.1	68.2	107	0.20	0.20	0.20	0.20	0.20
Chloride (Cl)	23.8	9.82	17.7	61.4	31.5	6.51	11.2	5.63	0.28	16.1
Sulfate (SO_4)	1925	2340	9600	9600	9600	3107	9600	9600	9600	9600
Aluminum (Al)	1.68	1.68	83.0	83.0	83.0	22.7	83.0	83.0	83.0	83.0
Arsenic (As)	0.71	0.71	0.71	0.71	0.71	0.044	0.19	0.45	0.61	0.71
Barium (Ba)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Beryllium (Be)	0.0002	0.0002	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023
Boron (B)	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Cadmium (Cd)	0.00018	0.00018	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
Calcium (Ca)	465	540	480	480	480	97.3	427	480	480	480
Chromium (Cr)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Cobalt (Co)	0.052	0.052	38.5	44.0	44.0	2.39	10.5	24.6	32.9	44.0
Copper (Cu)	0.092	0.092	54.3	136	202	0.29	1.29	3.03	4.06	107
Iron (Fe)	0.81	0.81	71.7	180	235	235	235	235	235	235
Lead (Pb)	0.012	0.037	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053
Magnesium (Mg)	66.4	93.0	1030	1030	1030	87.4	384	898	1030	1030
Manganese (Mn)	0.75	0.75	47.0	47.0	47.0	7.67	33.7	47.0	47.0	47.0
Mercury (Hg)	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006
Molybdenum (Mo)	0.0051	0.0051	0.0051	0.0051	0.0051	0.0016	0.0051	0.0051	0.0051	0.0051
Nickel (Ni)	0.86	0.86	455	762	762	34.9	153	358	480	762
Phosphorous (PO_4)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Potassium (K)	49.0	49.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0
Selenium (Se)	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029
Silica (SiO_2)	8.65	8.65	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
Silver (Ag)	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007
Sodium (Na)	334	681	338	338	338	45.4	199	338	338	338
Thallium (Tl)	0.00002	0.00002	0.00006	0.00006	0.00006	0.00006	0.00006	0.00006	0.00006	0.00006
Zinc (Zn)	0.09	0.09	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0
Nitrate (NO_3)	0.25	0.10	0.19	0.65	0.33	0.092	0.16	0.08	0.004	0.23
Ammonia (NH_4)	0.25	0.10	0.19	0.65	0.33	0.092	0.16	0.08	0.004	0.23

Table 2. Mine Site Process Water Quality (continued)

Parameter (mg/L)	Lean Ore Surge Pile (Years)					East Pit (Years)		
	1	5	10	15	20	1	5	10
Fluoride (F)	0.18	0.20	0.20	0.20	0.20	0.26	0.26	0.26
Chloride (Cl)	0.62	0.56	1.41	0.27	1.75	1.30	1.31	1.31
Sulfate (SO_4)	268	4499	6475	9600	9600	37.4	25.4	26.3
Aluminum (Al)	1.96	32.9	47.3	83.0	83.0	0.22	0.18	0.18
Arsenic (As)	0.0038	0.064	0.092	0.25	0.20	0.0055	0.0037	0.0041
Barium (Ba)	0.028	0.19	0.19	0.19	0.19	0.019	0.014	0.015
Beryllium (Be)	0.0023	0.0023	0.0023	0.0023	0.0023	0.0003	0.00026	0.00027
Boron (B)	0.11	0.76	0.76	0.76	0.76	0.085	0.086	0.085
Cadmium (Cd)	0.015	0.015	0.015	0.015	0.015	0.00057	0.00052	0.00049
Calcium (Ca)	8.38	141	203	480	436	16.8	14.2	14.8
Chromium (Cr)	0.00066	0.0015	0.0015	0.0015	0.0015	0.0011	0.0011	0.0011
Cobalt (Co)	0.21	3.47	4.99	13.4	10.7	0.017	0.011	0.013
Copper (Cu)	0.025	0.43	0.61	1.65	1.32	0.013	0.0081	0.033
Iron (Fe)	50.6	235	235	235	235	2.68	2.42	2.13
Lead (Pb)	0.0061	0.053	0.053	0.053	0.053	0.0012	0.0012	0.0012
Magnesium (Mg)	7.53	127	182	488	392	7.99	7.83	7.86
Manganese (Mn)	0.66	11.1	16.0	42.8	34.4	0.079	0.056	0.058
Mercury (Hg)	0.000006	0.000006	0.000006	0.000006	0.000006	0.0000051	0.0000028	0.0000031
Molybdenum (Mo)	0.00014	0.0023	0.0033	0.0051	0.0051	0.0043	0.0047	0.0046
Nickel (Ni)	3.00	50.5	72.7	195	156	0.24	0.15	0.17
Phosphorous (PO_4)	0.097	0.20	0.20	0.20	0.20	0.00	0.00	0.00
Potassium (K)	8.22	38.0	38.0	38.0	38.0	1.50	0.75	0.86
Selenium (Se)	0.0029	0.0029	0.0029	0.0029	0.0029	0.0019	0.0020	0.0020
Silica (SiO_2)	3.88	3.88	3.88	3.88	3.88	0.00	0.00	0.00
Silver (Ag)	0.00015	0.0007	0.0007	0.0007	0.0007	0.00089	0.00095	0.00094
Sodium (Na)	3.91	65.8	94.6	254	204	1.65	0.78	0.94
Thallium (Tl)	0.00006	0.00006	0.00006	0.00006	0.00006	0.0017	0.0019	0.0018
Zinc (Zn)	3.19	26.0	26.0	26.0	26.0	0.17	0.16	0.14
Nitrate (NO_3)	0.0079	0.0072	0.018	0.0035	0.022	0.085	0.093	0.092
Ammonia (NH_4)	0.0079	0.0072	0.018	0.0035	0.022	0.085	0.093	0.092

Table 2. Mine Site Process Water Quality (continued)

Parameter (mg/L)	West Pit, Central Pit, Haul Roads (Years)					Rail Transfer Hopper (Years)				
	1	5	10	15	20	1	5	10	15	20
Fluoride (F)	0.26	0.25	0.25	0.26	0.26	0.058	0.058	0.058	0.058	0.058
Chloride (Cl)	1.26	1.25	1.28	1.30	1.32	0.16	0.16	0.16	0.16	0.16
Sulfate (SO_4)	46.6	82.2	89.0	52.8	31.9	32.0	32.0	32.0	32.0	32.0
Aluminum (Al)	0.32	0.33	0.43	0.31	0.20	0.023	0.023	0.023	0.023	0.023
Arsenic (As)	0.019	0.017	0.017	0.012	0.0077	0.0019	0.0019	0.0019	0.0019	0.0019
Barium (Ba)	0.042	0.045	0.044	0.032	0.022	0.0083	0.0083	0.0083	0.0083	0.0083
Beryllium (Be)	0.00030	0.00044	0.00053	0.00038	0.0003	0.00014	0.00014	0.00014	0.00014	0.00014
Boron (B)	0.069	0.076	0.079	0.080	0.082	0.015	0.015	0.015	0.015	0.015
Cadmium (Cd)	0.00020	0.00026	0.00038	0.00031	0.00027	0.000031	0.000031	0.000031	0.000031	0.000031
Calcium (Ca)	20.4	30.7	32.7	23.5	18.5	10.3	10.3	10.3	10.3	10.3
Chromium (Cr)	0.0011	0.0011	0.0011	0.0011	0.0011	0.00014	0.00014	0.00014	0.00014	0.00014
Cobalt (Co)	0.015	0.034	0.070	0.043	0.024	0.0040	0.0040	0.0040	0.0040	0.0040
Copper (Cu)	0.026	0.069	0.58	0.38	0.22	0.0074	0.0074	0.0074	0.0074	0.0074
Iron (Fe)	0.19	0.17	0.17	0.21	0.23	0.010	0.010	0.010	0.010	0.010
Lead (Pb)	0.00079	0.00077	0.00078	0.00087	0.00094	0.00011	0.00011	0.00011	0.00011	0.00011
Magnesium (Mg)	6.61	8.40	8.91	8.09	7.90	2.16	2.16	2.16	2.16	2.16
Manganese (Mn)	0.090	0.17	0.19	0.11	0.072	0.032	0.032	0.032	0.032	0.032
Mercury (Hg)	0.000015	0.000017	0.000017	0.00001	0.0000058	0.000006	0.000006	0.000006	0.000006	0.000006
Molybdenum (Mo)	0.0027	0.0023	0.0025	0.0035	0.0042	0.000048	0.000048	0.000048	0.000048	0.000048
Nickel (Ni)	0.26	0.54	0.96	0.57	0.31	0.080	0.080	0.080	0.080	0.080
Phosphorous (PO_4)	0.00	0.00	0.00	0.00	0.00	0.021	0.021	0.021	0.021	0.021
Potassium (K)	4.19	5.35	5.52	3.35	1.80	1.47	1.47	1.47	1.47	1.47
Selenium (Se)	0.0017	0.0016	0.0017	0.0018	0.0019	0.00016	0.00016	0.00016	0.00016	0.00016
Silica (SiO_2)	0.00	0.00	0.00	0.00	0.00	1.67	1.67	1.67	1.67	1.67
Silver (Ag)	0.00068	0.00061	0.00063	0.00078	0.00089	0.000035	0.000035	0.000035	0.000035	0.000035
Sodium (Na)	6.14	6.61	6.59	4.20	2.26	1.52	1.52	1.52	1.52	1.52
Thallium (Tl)	0.0010	0.00088	0.00093	0.0013	0.0017	0.000014	0.000014	0.000014	0.000014	0.000014
Zinc (Zn)	0.029	0.037	0.059	0.046	0.037	0.0030	0.0030	0.0030	0.0030	0.0030
Nitrate (NO_3)	0.051	0.043	0.045	0.067	0.082	0.0021	0.0021	0.0021	0.0021	0.0021
Ammonia (NH_4)	0.051	0.043	0.045	0.067	0.082	0.0021	0.0021	0.0021	0.0021	0.0021

The water quality predictions developed in RS31 and RS53/RS42, which are summarized in Table 2, are based on the actual groundwater and rock chemistry from the NorthMet site including the results of numerous on-going, site-specific humidity cell tests. The results from on-site groundwater monitoring and site-specific humidity cell testing provide the best available data for consideration of wastewater treatment requirements at the Mine Site. Groundwater samples collected during the Phase II and Phase III hydrogeologic investigations from boreholes completed in the Duluth Complex at the NorthMet site to depths of up to 600 feet did not contain elevated chloride concentrations. Chloride concentrations in these deep boreholes were generally similar to concentrations in samples collected from wells completed in the surficial aquifer at the Mine Site.

While saline groundwater (Cl > 50,000 mg/L) has been encountered in bedrock wells throughout the Lake Superior basin (Morton and Ameel, 1985), salinity is generally greater near the lakeshore and decreases with distance and elevation inland (Swenson, 2007). Generally, wells completed above the elevation of Lake Superior (~600 ft MSL) contain less than 100 mg/L chloride (STS, 1995). The minimum elevations of the East and West pit bottoms are approximately 800 and 900 feet MSL, respectively, 200 to 300 feet above the average elevation of Lake Superior. Based on these factors, it is unlikely that extensive areas of saline groundwater will be encountered during mining. In the event that significantly higher concentrations of chloride and other salts are encountered, in comparison to the values established in the on-site testing program, additional treatment technologies would need to be considered including, but not limited to reverse osmosis and ion exchange treatment. These technologies are generally similar to those already evaluated in Section 4 of this report.

Based on these water quality predictions, process water generated at the Mine Site will need to be treated before it can be piped to the Plant Site. The variation in the expected water quality and quantity for each of the Mine Site process water streams has implications for the sizing and selection of wastewater treatment technologies. The impact of this variability is discussed in Section 5.

2.2 Plant Site Process Water

2.2.1 Plant Site Process Water Quantity

2.2.2 Plant Site Process Water Quality

3.0 Process Water Quality Targets

3.1 Potential Surface Water Quality Standards

Both the Mine Site and the Plant Site are located within the Lake Superior watershed basin, more specifically within the upper reaches of the St. Louis River watershed. The Mine Site is located within the Partridge River watershed, which flows into the St. Louis River. The Process Plant is also located within the Partridge River watershed. A portion of the tailings basin is located within the Partridge River watershed in the headwaters to Knox Creek (Second Creek). The majority of the tailings basin is located within the Embarrass River watershed. The Embarrass River flows into the St. Louis River downstream of the confluence of the Partridge and St. Louis Rivers.

In-stream surface water quality standards for both the Embarrass River and the Partridge River have been established by the State of Minnesota. Both the Partridge River and the Embarrass River are classified by the State of Minnesota as Class 2B waters in accordance with Minnesota Rules[1]. The water quality standards for Class 2B streams have been established to protect aquatic life as well as recreational uses. In addition, because these surface waters are part of the Lake Superior Basin watershed, additional water quality rules for certain parameters such as dissolved metals supersede the general Class 2B rules[2]. Combining the information from these two rules, the in-stream surface water quality values for parameters potentially significant to the NorthMet operation are listed in Table 3. A hardness of 400 mg/L was assumed in order to calculate the hardness-dependent metals standards, as it is likely that the treated water will have hardness from lime treatment. The surface water standards for various other stream classifications may also be applicable to Class 2B waters to protect the use of the water for other uses. Although these additional standards are not needed to protect aquatic life, they are also included in Table 3. For the purpose of this report, these Standards are considered potential, because no discharge to surface waters is envisioned prior to closure of operations at the Mine Site. Thus, these values provide a conservative basis for comparison to the quality of Mine Site process water.

---

[1] MN Rule 7050.0222 Subpart 4.

[2] MN Rule 7052.0222 Subpart 5

Because these surface water standards presented in Table 3 are the ‘in stream’ concentrations, they represent conservative values for process water quality targets because process water will not be discharged to surface waters and any actual surface water discharge limits would be developed with consideration of base flow conditions and the potential for mixing within the stream.

Table 3 Potential Water Quality Standards

Parameter	Surface Water Quality Standard[1] (µg/L, unless noted)	Groundwater Protection Standard[2] (µg/L, unless noted)	Drinking Water Standard[2] (µg/L, unless noted)
Metals/Inorganics			
Aluminum	125		50-200 (S)
Antimony	31	6	6
Arsenic	53		10
Barium		2,000	2,000
Beryllium		0.08	4
Boron	500 (4A)	600	
Cadmium	7.3	4	5
Chromium (+3)	268	20,000	100
Chromium (+6)	11	100	
Cobalt	5	30 (S)	
Copper	30	1,000 (S)	1,300 (1,000 - S)
Iron			300 (S)
Lead	19		15
Manganese		1,000	50 (S)
Mercury	0.0013	2	2
Molybdenum		100 (S)	
Nickel	169	100	100
Selenium	5	30	50
Silver	1	30	100 (S)
Thallium	0.56	0.6	2
Zinc	388	2,000	5,000 (S)
General Parameters			
Ammonia (un-ionized)	40		
Bicarbonate (meq/L)	5 (4A)		
Chloride (mg/L)	230 (100 – 3B)		250 (S)
Cyanide (free)	5.2	100	200
Dissolved Oxygen (mg/L)	>5.0		
Fluoride (mg/L)		4	4 (2-S)
Hardness(mg/L)	250 (3B)		
Nitrate (mg/L)		10	10
Oil	500		
pH (su)	6.0-9.0		
Sodium	60 percent of cations (4A)		
Specific Conductance(uhmos/cm)	1,000 (4A)		
Sulfate	10 (4A[3])		250 (S)
Total Dissolved Solids	700 (4A)		500 (S)
Total Salinity (mg/L)	1,000 (4B)		
Turbidity (NTU)	25		

Notes:

1. Surface Water Standards are for Class 2B waters unless noted as Class 3B, 4A, or 4B in parenthesis.
2. Groundwater Protection and Drinking Water Protection Standards are for protection of human health except where noted as secondary standards (S), which are generally for aesthetics (taste).
3. Only when wild rice is present

3.2 Potential Groundwater Quality Standards

While direct seepage (overland flow) to surface waters or wetlands will be actively controlled, PolyMet recognizes that deep seepage (groundwater recharge out the bottom of the basin) to (underlying, natural) groundwater will occur during operation of the tailings basin and after closure. The State of Minnesota has established Rules for the protection of groundwater resources[3]. In addition, the U.S. EPA has established regulations to protect human health by limiting contaminants in drinking water[4].

PolyMet is the closest groundwater user to the tailings basin. A shallow bedrock well is located approximately one-mile to the southwest of the tailings basin near the offices. The next closest groundwater users are residential wells a minimum of 1.5 miles north of the tailings basin. While these distances provide considerable buffer between the tailings basin and potential groundwater users, the use of groundwater standards as process water quality targets within the basin establishes conservative values that comply with existing rules to be protect the quality of groundwater for human health at the nearest point of use. The State of Minnesota groundwater standards and the U.S. EPA drinking water standards are summarized in Table 3.

3.3 Anticipated Process Water Quality Targets

Using the potential surface water quality standards and the potential groundwater quality standards, anticipated process water quality targets have been developed for the parameters of concern listed in the Work Plan for RS29T. Anticipated targets have been developed for both Mine Site process water and for Plant Site process water (the tailings basin). These values are summarized in Table 4. These values will provide the benchmark that will be used to evaluate the treatment of Mine Site and, if necessary, Plant Site process water in the following sections.

In general, the selected process water quality target for each parameter was the surface water quality criteria, for those parameters that have specific surface water standards. For parameters without a surface water standard, the Minnesota groundwater protection standard was selected, and for parameters with neither a Minnesota surface water nor groundwater protection standard, the U.S. EPA drinking water standard was selected.

---

[3] MN Rules 4717.7100 to 4717.7800, and MN Rules 7060

[4] 40 CFR 141 (National Primary Drinking Water Regulations) and 40 CFR 143 (National Secondary Drinking Water Regulations).

Table 4 Process Water Quality Targets

Parameter	Process Water Quality Target (µg/L, unless noted)	Standard	Class/Basis
Metals/Inorganics			
Aluminum	125	Surface Water	2B – Aquatic Life
Antimony	31	Surface Water	2B – Aquatic Life
Arsenic	10	Drinking Water	Primary/Human Health
Barium	2,000	Drinking Water	Primary/Human Health
Beryllium	4	Drinking Water	Primary/Human Health
Boron	500	Surface Water	4A – Irrigation
Cadmium	4	Ground Water[1]	Human Health
Chromium (+3)	100	Ground Water	Human Health
Chromium (+6)	11	Surface Water	2B – Aquatic Life
Cobalt	5	Surface Water	2B – Aquatic Life
Copper	30	Surface Water	2B – Aquatic Life
Iron	300	Drinking Water	Secondary
Lead	19	Surface Water	2B – Aquatic Life
Manganese	50	Drinking Water	Secondary
Mercury	0.0013	Surface Water	2B – Aquatic Life
Molybdenum	100	Drinking Water	Secondary
Nickel	100	Ground Water[1]	Human Health
Selenium	5	Surface Water	2B – Aquatic Life
Silver	1	Surface Water	2B – Aquatic Life
Thallium	0.56	Surface Water	2B – Human Health
Zinc	388	Surface Water	2B – Aquatic Life
General Parameters			
Ammonia (un-ionized)	40	Surface Water	2B – Aquatic Life
Bicarbonate (meq/L)	5	Surface Water	4A – Irrigation
Chloride (mg/L)	230	Surface Water	2B – Aquatic Life
Cyanide (free)	5.2	Surface Water	2B – Aquatic Life
Dissolved Oxygen (mg/L)	>5.0	Surface Water	2B – Aquatic Life
Fluoride (mg/L)	2	Drinking Water	Secondary
Hardness(mg/L)	250	Surface Water	3B – Industrial
Nitrate (mg/L)	10	Drinking Water	Primary
Oil	500	Surface Water	2B
pH (su)	6.0-9.0	Surface Water	2B
Sodium	60% of cations	Surface Water	4A – Irrigation
Specific Conductance (uhmos/cm)	1,000	Surface Water	4A – Irrigation
Sulfate	250	Drinking Water	Secondary
Total Dissolved Solids	700	Surface Water	4A – Irrigation
Total Salinity (mg/L)	1,000	Surface Water	4B – Livestock
Turbidity (NTU)	25	Surface Water	2B

Notes:

1. Ground water standard is more conservative at 400 mg/L hardness

When comparing these process water quality targets to the predicted process water quality at the Mine Site (Table 2), the following objectives for wastewater treatment are identified:

- Mine Site process water will likely need to be treated to remove metals, including aluminum, antimony, arsenic, cobalt, copper, iron, manganese, mercury, nickel, selenium, thallium, and zinc.
- Mine Site concentrations of sulfate and hardness, along with the related parameters of TDS and conductivity will likely also require treatment to reduce long-term build-up of these parameters in the tailings basin. Salinity, in particular sodium and chloride, do not appear to be present at concentrations that would require treatment.
- Plant Site process water will not need to be treated provided the treatment of Mine Site process water, prior to use as make-up water, is adequate to maintain the water quality in the tailings basin below the process water quality targets.

These potential treatment needs will be addressed in the identification and evaluation of potential treatment technologies in the following sections.

4.0 Summary of Potential Wastewater Treatment Technologies

This section contains a summary of information on potential wastewater treatment technologies. As described in the SOW, the primary technologies to be considered in this report are: chemical precipitation, reverse osmosis, ion exchange, constructed wetland, and membrane technology. Because reverse osmosis is a specific type of membrane technology, these processes are described together. Other potential biological treatment options, for example biological sulfate reduction, are considered with wetland processes. This summary is not intended to be a comprehensive review of all literature available on the treatment of mine water, as the available publications on this topic are extensive. For example, a recent review of treatment technologies for metals in groundwater prepared by Kurniawan and others included a review of chemical precipitation, ion exchange, and membrane filtration – three of the primary treatment operations considered in this evaluation – and cited more than 100 references (Kurniawan, Chan, Lo, and Babel, 2006). A limited number of technical references are cited for each technology to provide a basis for the applicability of these technologies. A summary of the references cited in this technology evaluation section are summarized in Appendix K.

The parameters of potential concern listed in the SOW and discussed in the previous section included pH, metals, mercury, sulfate, salinity, and nutrients. These parameters will be discussed in this section in relation to the treatment technologies identified. However, the primary parameters considered in this evaluation are metals and sulfate. For the purposes of this evaluation, the Mine Site water quality presented in Table 2 is considered the potential influent for a wastewater treatment facility (WWTF).

While pH is a potential parameter of concern, it is also – in the case of many wastewater treatment systems – an operational control parameter. The pH of the Mine Site process water will likely need to be modified during treatment operations and will be adjusted to within the target range as a final treatment step. Similarly, the concentrations of nutrients in the Mine Site process water are relatively low and while they are not likely to interfere with potential physical or chemical treatment systems evaluated in this section, they would likely need to be supplemented for the operation of biological treatment system. While nutrients would be a potential concern if discharged to surface water, the elimination of a direct discharge to surface water from the site helps to reduce the potential concern associated with nutrients in process water and the predicted concentrations of nitrogen and phosphorous (Table 2) do not suggest that these parameters will be a concern in the tailings basin.

Mercury is present at very low concentrations in the waste rock and in the precipitation that enters the Mine Site. Both of these sources contribute to the mercury load in the drainage from the waste piles. While the effectiveness of the treatment systems evaluated in this section will consider mercury treatment, the water management plan envisions the reuse/recycling of treated Mine Site process water to the tailings basin rather than discharge to surface water. Reuse/recycling of the treated Mine Site process water at the tailings basin will provide additional mercury removal/treatment because it has been shown that mercury will adsorb to taconite tailings and NorthMet tailings. Additional laboratory testing conducted on behalf of PolyMet is included in Appendix B. This work supports the observation that mercury is adsorbed by tailings. Thus, a majority of the mercury that remains in the treated Mine Site process water will be absorbed and ultimately sequestered in the tailings basin prior to the water recharging to groundwater. The NorthMet Project mercury mass balance is provided in RS66.

Organics (e.g., DRO, GRO and flotation reagents) were also identified as parameters of potential concern, but these are not expected to be present in the Mine Site process water. While fuels containing these materials will be used at the Mine Site, these chemicals would only be associated with wastewater as a result of spills, rather than routine operations. Containment of spills related to fueling operations is addressed in the SPCC plans for the Mine Site and the Plant Site (ER05 and ER06). For this reason, these chemicals are not addressed in this section. Other organics used in the Beneficiation Plant that will report to the tailings basin will be easily degraded or deposited with the tailings to provide a long-term oxygen demand from the tailings basin that will reduce future oxidation and release of inorganics. These parameters are considered in process water from the Beneficiation Plant in Section 6.

4.1 Chemical Precipitation

4.1.1 Technology Description

Chemical precipitation treatment technologies for wastewater treatment rely on the insolubility of various chemical compounds to remove chemicals of concern. In general, one or more chemicals can be removed from the waste stream by the addition of other chemicals that will combine to form insoluble products that can be separated from the liquid stream. A chemical precipitation operation would consist of chemical addition, rapid mixing, coagulation, flocculation, and settling processes, which would facilitate the formation and physical separation of the precipitate from the water. Filtration could be used as a final polishing step for the water, if necessary. A filter press operation would be used to remove as much water as possible from the solids. The treated water would then be piped to the tailings basin for reuse while the dewatered solids would be disposed with the hydrometallurgical residues. In general, the mass of wastewater sludge generated annually at the WWTF would likely be less than one percent of the mass produced annually in the Hydrometallurgical Process. The WWTF sludge would also likely be similar to the hydrometallurgical residues, consisting primarily of gypsum. Thus it would not be expected to change the overall chemical characteristics of the solids in the hydrometallurgical residue cells.

Several potential chemicals can be used to treat the process water from the Mine Site. Some chemicals used in chemical precipitation processes will increase the pH (for example hydrated lime, $Ca(OH)_2$) to facilitate precipitation, while others require the addition of supplementary chemicals to control pH within an optimum range to precipitate the desired chemical compound. The advantages and disadvantages of various chemical precipitation techniques for removal of metals and sulfates (or other salts) are discussed in the following sections.

4.1.2 Metal Precipitation Technologies

Heavy metals may be removed from water by adjusting the pH of waste stream and adding chemicals that will help to form insoluble precipitates. The most common operations form hydroxides, carbonates, or sulfide compounds (Benefield, Judkins, and Weand, 1982). These and other specialized chemical precipitation technologies are described in the following paragraphs.

4.1.2.1 Hydroxide Precipitation

Hydroxide precipitation treatment is primarily used for the removal of heavy metals. Soluble heavy metal ions are converted to insoluble metal-hydroxide precipitates that can be physically removed from the water. Iron, manganese, and potentially magnesium also form precipitates that can be removed, and in the case of iron and manganese, the solid hydroxides facilitate co-precipitation of heavy metals and arsenic as well as nutrients such as phosphorous from the water. The addition of soluble iron to the process can enhance the co-precipitation process, if necessary, to improve the removal of metals. (Ayres, Davis, and Gietka, 1994).

Hydroxide precipitation is accomplished by adjusting the pH of the water to alkaline conditions (generally around pH 10). The most common hydroxide precipitating agents are hydrated lime

($Ca(OH)_2$), caustic soda ($NaOH$), or magnesium hydroxide ($Mg(OH)_2$). However, other alkaline materials, such as Bauxol, cement kiln dust, or flyash could also be used. In mine wastewater treatment, lime is the most common agent because the added calcium will combine with sulfate to form gypsum ($CaSO_4$-$2H_20$) when excess sulfate is present. Excess calcium is also easier to subsequently remove from the water than sodium, potassium, or trace contaminants that could be introduced from other alkaline waste materials.

The solubility products for several metal hydroxides are summarized in Table 5. Because many dissolved metals – including copper, nickel and zinc – exhibit amphoteric behavior (where a soluble metal-hydroxide complex is stable when the pH exceeds that associated with the minimum solubility), the optimum pH for hydroxide precipitation varies with changes in the influent metal characteristics. For example, nickel is removed effectively at pH 10, while copper is removed at pH 8. A single-stage hydroxide precipitation system could be designed to remove both nickel and copper if sufficient iron and manganese are available to act as co-precipitates. Otherwise, a multi-stage process, or additional iron salts may be needed to optimize removal of both these metals. Nickel hydroxide precipitation is also subject to competition with dissolved iron. Thus, sufficient lime and residence time are required to facilitate removal of both iron and nickel.

Table 5: Solubility Products for Various Metal Hydroxides, Carbonates, and Sulfides

Metal	Hydroxide	Hydroxide Solubility Product	Carbonate	Carbonate Solubility Product	Sulfide	Sulfide Solubility Product
Nickel	$Ni(OH)_2$	2.0×10^{-15}	$NiCO_3$	6.6×10^{-9}	NiS	3×10^{-19}
Copper	$Cu(OH)_2$	2.2×10^{-20}	$CuCO_3$	1.4×10^{-10}	CuS	6×10^{-37}
Cobalt	$Co(OH)_2$	1.6×10^{-15}	$CoCO_3$	1.4×10^{-13}	CoS	4.0×10^{-21}
Zinc	$Zn(OH)_2$	1.2×10^{-17}	$ZnCO_3$	1.4×10^{-11}	ZnS	2×10^{-25}
Iron	$Fe(OH)_2$	8.0×10^{-16}	$FeCO_3$	3.2×10^{-11}	FeS	6×10^{-19}
Calcium	$Ca(OH)_2$	5.5×10^{-6}	$CaCO_3$	3.8×10^{-9}	CaS	8.5×10^{-6}

At NorthMet, the hydroxide precipitation process would likely consist of chemical addition and rapid mixing to raise the pH, coagulation and flocculation to allow the precipitates to form, physical (gravity) settling to remove the floc from the water, filtration (as necessary), and a final pH neutralization step. If lime is used to raise the pH, carbon dioxide or sodium bicarbonate would be used for neutralization so that additional calcium can be precipitated as calcium carbonate and removed during the neutralization step, reducing the hardness of the treated water.

The solids generated by this operation would be filter-pressed to remove any water, which would be returned to the water treatment operation. The dewatered solids would contain hydroxides and could either be introduced into the hydrometallurgical process or disposed with the hydrometallurgical residues from the hydrometallurgical process. A portion of the solid precipitate may also be recycled to the beginning of the chemical precipitation process to stimulate the initial crystallization process. This variation of chemical precipitation treatment is commonly referred to as a high-density-sludge (HDS) operation. The HDS process is a variation of the lime precipitation process that increases removal efficiency while reducing the volume of sludge generated in the treatment of metals in mining wastewaters (Sengupta, 1993). The published results from a recent pilot test of the HDS process at the Britannia Mine in British Columbia showed that dissolved copper could be reduced from approximately 40 mg/L to 27 µg/L or less using this process (CEMI, 2002).

The primary advantages of hydroxide precipitation are that it is a well-established and simple technology and that it is relatively inexpensive when compared to other treatment technologies. For these reasons, lime treatment is perhaps the most commonly used treatment for removing heavy metals from mining wastewaters. The primary disadvantage with hydroxide precipitation is that some metals like manganese may not be adequately treated. In addition, some metals require either oxidation or reduction before they can be effectively precipitated as hydroxides. For example, selenium (+6) should be reduced to selenium (+4), while arsenite (+3) should be oxidized to arsenate (+5) to enhance precipitation. Oxidizing cobalt (+2) to cobalt (+3) also greatly enhances removal via hydroxide precipitation (Smith and Martell, 1976).

Bench-scale testing of metal hydroxide precipitation was conducted to evaluate potential application of this technology to the Mine Site process water. A sample of wastewater from the Dunka waste rock stockpiles, located near the PolyMet site, was used as the influent water for the bench-scale testing. The results of this testing are summarized in RS45 and included with this report in Appendix C. The results of this work show that, with the exception of mercury, all of the metals concentrations can be reduced to below the process water quality targets (see Table 9 of Attachment C2 in Appendix C).

Predicted water quality values for drainage from the Category 3 and Category 4 waste rock piles exceeds the concentrations for several of the parameters in the water used for hydroxide precipitation testing for the NorthMet project. The lower concentrations in the influent for the pilot tests result in the calculation of lower removal efficiencies, on a percentage basis. However, the potential effluent concentrations for this and other precipitation processes are controlled by the solubility of the precipitate rather than an absolute value for removal percentage. The low effluent values for metals observed in the pilot test are achievable for waters with greater influent concentrations, provided adequate chemical reaction time and hydroxide producing chemicals are present. Low metal effluent concentrations have been reported using hydroxide precipitation with lime for water with much higher metals concentrations obtained from the Berkeley Pit (U.S. EPA and U.S. DOE, 1997). A single stage neutralization process was able to remove all metals at a pH of 9.6. At higher pH values, aluminum (pH = 10.2), and then cadmium and manganese (pH = 11.2) were not removed as effectively. These results demonstrate that hydroxide precipitation results observed in the pilot testing can be achieved even if influent concentrations are greater than those used in the pilot testing.

4.1.2.2 Sulfide Precipitation

The sulfide precipitation process involves the conversion of soluble metal compounds to relatively insoluble sulfide compounds through the addition of precipitating agents such as: sodium sulfide (Na_2S), sodium hydrosulfide (NaHS), ferrous sulfide (FeS) and calcium sulfide (CaS). As shown in Table 5, metal the solubility product of metal sulfides are generally two or more orders of magnitude less than the solubility product of comparable metal hydroxides. Additionally, metal sulfides do not exhibit amphoteric behavior, and are less sensitive to changes in pH. Efficient metal sulfide precipitation can be achieved over a wide pH range (2 to 12). However, high pH ($pH>7$) is required to prevent formation of hydrogen sulfide (H_2S) gas. The kinetic rate for the formation of a sulfide precipitate is faster than hydroxide precipitation, resulting in a lower required retention times for reaction vessels. In addition, sulfide precipitation results in a solid that could be easily incorporated into the Hydrometallurgical Process for recovery of the metals.

Sulfide precipitation using sodium sulfide was demonstrated using water from the Berkeley Pit with very high metals concentrations. At a low pH (4.3) over 99 percent of the copper and zinc could be recovered as metal sulfides before neutralization of the water and removal of other metals. However, this process resulted in emission of H_2S and produced a sludge that was difficult to filter. Successful removal of metals from wastewater using calcium sulfide was reported by Kim and Amodeo (1983).

The primary disadvantages of metal sulfide precipitation technology are: potential production of H_2S gas (especially at pH values below neutral), potential residual sulfide in treatment effluent, higher capital and operating costs than hydroxide precipitation, increased process complexity compared to hydroxide precipitation, and potential difficulties with floc settlement (Kim and Amodeo 1983).

Operationally, sulfide precipitation would be similar to hydroxide precipitation. The process would likely be initiated with a lime addition step and rapid mix tank to raise the pH. Any precipitation that occurs as a result of this step could be segregated using a conventional coagulation, flocculation and settling operation or could remain suspended during the next phase of treatment. Next, sulfide would be added to the high pH water using another sequence of chemical feed, rapid mix, coagulation, flocculation, and settling. A filtration step may also be needed at the end. Other variations on the sequence of operation could also be considered to match the specific type of sulfide reagent used in the process. The two most commonly used sulfide precipitation processes, soluble sulfide precipitation (SSP) and insoluble sulfide precipitation (ISP), are summarized in Table 6.

Table 6 Comparison of Sulfide Precipitation Technologies

Process	Chemical(s)	Advantages	Disadvantages	Safety Measures
Soluble Sulfide Addition	• Sodium Sulfide (Na_2S) • Sodium Hydrosulfide (NaHS)	• High solubility of these precipitating agents allows the use of high sulfide concentrations in the reaction chamber, causing rapid precipitation of metal sulfides. • Operation can generally achieve very low effluent concentrations.	• Formation of small (pin) floc that may have poor settling characteristics and often requires the addition of a polymer or other chemical to aid in the coagulation of a settleable or filterable precipitate. • Potential to generate hydrogen sulfide gas. • Potential for residual sulfide in the effluent. • Soluble sulfide dose must be sufficient to remove both iron and nickel.	• Gas generation is mitigated by operating at an elevated pH • Sulfide quenching chemicals used to control the residual concentration of dissolved sulfide in effluent.
Insoluble Sulfide Addition	Ferrous Sulfide (FeS) – Sulfex Process (EPA 625/8-80-003).	• Metals with a lower solubility product than iron will exchange with iron and be precipitated as sulfides. • Process works well for metals such as copper and zinc where the solubility product of the metal sulfide is several orders of magnitude less than FeS.	• Solubility products for NiS and FeS are similar (same order of magnitude). • Nickel must be present at concentrations greater than Fe^{2+} for removal to occur. • FeS is unstable and must be generated onsite. • Sulfex process typically requires 2 to 4 times the stoichiometric amount of FeS • Large amount of sludge (up to 3 times more than lime precipitation) is produced.	• Low solubility of FeS limits H_2S production and effluent sulfide concentrations.

Process	Chemical(s)	Advantages	Disadvantages	Safety Measures
	Calcium sulfide (CaS)	• Calcium particles act as nuclei for metal-sulfide precipitates. • CaS precipitation is capable of lower effluent nickel concentrations than Sulfex process. • CaS precipitation provides less sludge than Sulfex process.	• Requires on-site generation of reagent using lime and a sulfide source (H_2S). • Dense sludge may require higher power mixing and handling equipment.	• Limited solubility of CaS minimizes the potential for H_2S generation and sulfide overdose.

Testing of sulfide precipitation was planned for the bench scale chemical precipitation testing, however, this work was not completed because the hydroxide precipitation test, using a HDS simulation (solids recycle) was capable of achieving concentrations below the process water quality targets for all parameters other than mercury.

4.1.2.3 Carbonate Precipitation

4.1.2.4 Xanthate Floatation

4.1.3 Chemical Precipitation Technologies for Sulfate and other Salts

Sulfate, phosphorous, nitrate and several other dissolved solids, in addition to metals as described above, can also be removed using various chemical precipitation technologies. In general, these technologies work better for divalent cations and anions, and for larger compounds. If necessary, some of these chemical technologies can be modified to remove chloride, potassium, and larger monovalent cations. Because the modeling of water quality in the tailings basin did not show that sodium, potassium, chloride, phosphorous, or nitrate were likely to be at concentrations of concern in the beneficiation process or the tailings basin, the following discussion of chemical treatment technologies is focused primarily on the removal of sulfate. If nitrate, chloride, or other anions are present at concentrations significantly different than those predicted for the Mine Site process water, a portion of these chemicals could potentially be removed using the high lime processes described below. Alternatively, treatment processes other than precipitation – for example biological denitrification for nitrate, and reverse osmosis for chloride – would be considered.

4.1.3.1 Lime Treatment Processes

4.1.3.2 Ultra High Lime Processes

In conventional lime treatment, where the influent concentration of sulfate is high enough to promote gypsum precipitation, the concentration of sulfate in the effluent is generally on the order of 1,500 mg/L. The effluent sulfate concentration is limited by the solubility of gypsum, which is also a function of the calcium concentration. The molar ratio of calcium to sulfate at saturation is typically on the order of 0.3 (Abdel-Aal, *et. al*., 2004). Thus, increasing the concentration of calcium in solution can result in a further reduction of sulfate along with silica and other oxyanions. This concept has been demonstrated in the ultra-high lime process (Batchelor, *et. al*., 1991). In this process – after settling, filtering or otherwise removing the solid material that has precipitated at a lower pH to prevent dissolution of metals with amphoteric properties – higher doses of lime are added to the water, raising the pH to between 11 and 12. In the presence of higher pH additional magnesium will precipitate and additional calcium will combine with silicates as well as sulfate to further reduce the concentration of dissolved anions. While this process is commonly used to treat air pollution control scrubber waters, it has not been used extensively in mine wastewater applications. Additional carbon dioxide would be needed in with this process to lower the pH prior to recycle/reuse at the tailings basin.

4.1.3.3 Ultra High Lime with Aluminum

4.2 Reverse Osmosis and other Membrane Technologies

4.2.1 Technology Description

4.2.2 Membrane Types

The most important component of any membrane treatment system is the semi-permeable membrane. Three major types of membranes are commonly used, each having different engineering properties, which are summarized in Table 7 (Aquatechnology.net).

Table 7 Comparison of Membranes Types

Feature	Cellulosic	Aromatic Polyamide	Thin Film Composite*
Rejection of Organic	L	M	H
Rejection of Low Molecular Weight Organics	M	H	H
Water Flux	M	L	H
pH Tolerance	4-8	4-11	2-11
Temperature Stability	Max 35 deg. C.	Max 35 deg. C.	Max 45 deg. C.
Oxidant Tolerance (e.g., free chlorine)	H	L	L
Compaction Tendency	H	H	L
Biodegradability	H	L	L
Cost	L	M	H
L = Low; M = Medium; H = High			
*Thin film composite type having polyamide surface layer			

Of the three basic membrane types, cellulosic membranes have the lowest unit cost and are most resistant to degradation by free chlorine. However, they have several limitations. Due to their asymmetric structure, they are susceptible to compaction (collapsing of membrane pores under high pressure) under high operating pressures especially at elevated temperatures. In addition, they are also susceptible to alkaline hydrolysis, and biodegradation. The operating pH for these membranes is 4 to 8.

Aromatic polyamide membranes are more resistant to biodegradation and alkaline hydrolysis than cellulosic membranes. The operating pH for these membranes is 4 to 11. Even though these membranes are subject to compaction at high temperatures and pressures, they have the capacity to withstand higher temperatures when compared to cellulosic membranes. The salt and organic rejection characteristics of these membranes are also better than that of cellulosic membranes. The principle limitation of these membranes is their susceptibility to degradation by oxidants such as free chlorine. Ammonium ion can also degrade these membranes.

Thin film composite membranes comprise a thin, dense solute-rejecting film underlain by a porous substructure. Thin film composite membranes offer similar advantages and disadvantages to aromatic polyamide membranes. However, materials for the two layers can be selected to optimize water flux and solute rejection, providing greater operational flexibility than other membrane types.

4.2.3 Membrane Configurations

Membrane treatment systems may be configured in a number of different ways, which offer several potential advantages and disadvantages (Lipnizki, 2007):

- Plate-and-frame: Maintenance of these units is simple due to the nature of their assembly but hydraulic flux across the membrane is limited by low specific surface area.
- Spiral-wound: Generally, these units have the lowest cost of installation and can be changed-out easily. The modules can be designed to use turbulence to enhance hydraulic flux and decrease membrane fouling. However, maintenance cleaning and backwashing of these units can be more difficult.
- Hollow-fiber: This configuration offers the greatest packing densities due to high specific surface area of the hollow fibers. The loose arrangements of the hollow fibers allows for more frequent back-washing of the systems. Disadvantages of hollow fiber systems include higher capital cost than spiral wound (similar to tubular systems) and potentially increased operating costs.
- Tubular: This configuration offers enhanced resistance to fouling when operated under turbulent influent conditions. The disadvantages of using a tubular module are high capital costs (similar to the hollow fiber system) and high energy requirements.

4.2.4 Operation and Maintenance

4.2.5 Treatment of Acid Mine Drainage Using Reverse Osmosis

Treatment of acid mine drainage via reverse osmosis has been studied at several different sites (U.S. EPA, 1973). While these studies focused on the removal of iron, aluminum, magnesium, and calcium, the removal characteristics should be similar for nickel, copper, cobalt, and zinc due to their similarity in size and charge to iron and aluminum. Additionally, the operation and maintenance experience gained from these applications can also be applied to NorthMet. Membrane fouling due to calcium sulfate precipitation was identified as the principle limiting factor in operation of these systems. Neutrolosis, or blending of recycled brine into the influent stream, was used to reduce membrane fouling. Pretreatment included filtration (10 μm), ultraviolet disinfection, and pH adjustment. A summary of these early membrane treatment operations using reverse osmosis are summarized in Table 8.

Table 8 Summary of Reverse Osmosis Treatment of Mine Wastewater

Site	Membrane Type	Flux (gal/ft^2/day)	Recovery (%)	Pre-Treatment	pH	Treatment Performance			
						Parameter	**Influent (mg/L)**	**Effluent (mg/L)**	**Removal (%)**
Norton	Spiral-wound, modified cellulose acetate	16.8 to 18.8 @ 600 psi	80	Sand Filter, 10 um cartridge filter	3.1-3.7	Iron	103.3	1.8	98.3
						Calcium	111.7	2.7	97.6
						Magnesium	36	0.8	97.7
						Aluminum	36.3	1.1	96.9
						Sulfate	913.3	13.9	98.5
Morgan-town	Spiral-wound, modified cellulose acetate	13.5 to 19.2 @ 400 to 600 psi	50	Sand Filter, 10 um cartridge filter	2.24-3.14	Iron	1,300	29	97.8
						Calcium	530	9.6	98.2
						Magnesium	420	7.6	98.2
						Aluminum	320	5.0	98.4
						Sulfate	10,900	190	98.3
Ebensburg	Spiral-wound, modified cellulose acetate	7.4 (50°F) to 11.9 (77°F) @ 400 psi	84	Sand Filter, 10 um cartridge filter	3.1-4.8	Iron	98	1	99
						Calcium	186.7	1.4	99.3
						Magnesium	56	0.6	98.9
						Aluminum	33	1.0	96.9
						Sulfate	1,547	12.7	99.2
Mocanaqua	Spiral-wound, modified cellulose acetate	16.8 to 18.8 @ 600 psi	84	10 um filter with UV	4.3	Iron	105.7	1.1	99
						Calcium	150	0.8	99.5
						Magnesium	109.3	1.7	98.4
						Aluminum	13.7	0.5	96.3
						Sulfate	843	7.0	99.2

Note: Results reported for average of multiple runs at Norton (6), Ebensburg (3), and Mocanaqua (3)
Reference: U.S. EPA, 1973.

Based on the results summarized in Table 8, membrane treatment, in particular microfiltration or ultrafiltration as pretreatment for either RO or nanofiltration, is likely capable of producing water that would meet the process water quality targets. While these results do not include information on heavier metals, it is expected that copper, nickel, zinc, and other metals heavier than iron would be preferentially removed by membrane operations because of their larger molecular size. In a recent study, copper was shown to be removed effectively by nanofiltration, especially in the presence of sulfate (Ku, *et. al*., 2005)

The operating pressures used in earlier demonstration tests were relatively high in comparison to typical pressures used today. Pilot testing of membrane treatment technology with current membrane configurations will help to provide additional input on the operating pressures required to achieve similar results and would provide a brine stream that could be evaluated for chemical precipitation treatment. After chemical precipitation, the remaining brine from an RO system would be reincorporated into the treated water flow provided the combined concentrations of chloride and other salts do not exceed the process water quality targets. If higher salt values than anticipated are encountered, the brine could be disposed off-site, evaporated and crystallized on site, or recycled for use as a salt product.

More recent work with the RO treatment process continues to show that this technology is feasible for use in removing sulfate and other dissolved constituents in mine water. In South Africa, RO was used to remove high concentrations of dissolved solids from mine water (Schoeman and Steyn, 2001). In this work, spiral wound RO elements were used to reduce the concentration of total dissolved solids from approximately 4,000 mg/L to less than 120 mg/L, including reducing the sulfate concentration from over 2,000 mg/L to less than 50 mg/L. Similarly, in Australia RO was used in combination with lime treatment and bio-polishing to treat water from a uranium mine with an initial pH in the range of 5 and initial sulfate concentrations over 16,000 mg/L (Topp, et. al., 2005). After the initial precipitation processes, the feed water to the RO units at this facility contained approximately 2,500 mg/L sulfate and 40 ug/L copper, which were reduced to less than 1 mg/L and 3 ug/L respectively.

4.2.6 Treatment of Mine Process Water using Nanofiltration

In addition to being used to remove sulfate from sea water, as noted previously, nanofiltration has also been used to treat sulfate laden mine process water. Water from a South African gold mine with a pH of less than 4 and sulfate concentrations approaching 3,000 mg/L was treated using nanofiltration (Visser, et. al., 2001). After adjusting the pH to near neutral, sulfate removal efficiencies of between 95 and 99 percent were reported. Lower removal efficiencies were measured at lower pH because a portion of the sulfate is present as the mono-valent HSO_4^{1-}. Nanofiltration has also been used in France to remove sulfate from water impacted by a flooded iron mine (Bertrand, *et. al.*, 1997). In this operation, sulfate concentrations approaching 1,800 mg/L were reduced to less than 30 mg/L (~98 percent) using nanofiltration.

4.3 Ion Exchange

4.3.1 Technology Description

The ion exchange process involves the reversible exchange of ions between an insoluble substance and the wastewater. The insoluble substance is usually a synthetic organic ion exchange resin composed of high-molecular-weight polyelectrolytes that can exchange their mobile ions for ions of similar charge from the surrounding medium. Each resin has a distinct number of mobile ion sites that set the maximum quantity of exchanges per unit of resin (www.remco.com).

Ion exchange reactions are stoichiometric and reversible. As an example, a resin with hydrogen ions available for exchange will exchange those ions for nickel ions from solution. The reaction can be written as follows:

$$2(R\text{-}SO_3H) + NiSO_4 => 2(R\text{-}SO_3)Ni + H_2SO_4$$

R indicates the organic portion of the resin and SO3 is the immobile portion of the ion active group. Two resin sites are needed for nickel ions with a plus 2 valence (Ni^{2+}).

When compared to other wastewater treatment alternatives, ion exchange appears to have greater flexibility. While most ion exchange resins are designed for removal of specific chemicals of concern, for example metals, different resin types have the capability to remove various chemicals, and more than one resin can be used in series. Specialty resins are also available that can selectively bond with specific cations for their removal. In addition, ion exchange can be used with fluctuating flow rates. However, this technology may be limited by high concentrations of total dissolved solids (http://www.nesc.wvu.edu).

Ion exchange treatment does not result in the creation of a solid waste, so it does not lead to solids disposal problems, like chemical precipitation, thus lowering the operational costs for the disposal of residual metal solids (Kurniawan et al., 2006). However, the resin does need to be regenerated, either at the site or at an off-site location, which results in a brine waste, which would need to be managed, similar to a membrane treatment approach. To apply ion exchange treatment of mine wastewater, appropriate pretreatment such as removal of suspended solids, removal of organic compounds, and pH adjustment would likely be required.

Chemical removal capabilities of various resin types are described in further detail in the following paragraphs.

4.3.2 Types of Ion Exchange Resins

Ion exchange resins can be divided into three broad categories: cation exchangers, anion exchangers and chelating resins. Cation exchangers have positively charged mobile ions available for exchange, anion exchangers have negatively charged mobile ions for exchange, and chelating resins have a high degree of selectivity for heavy metals (www.remco.com). The cation exchangers can in turn be either strong or weak acid cation exchangers, and similarly the anion exchangers can be either strong or weak base anion exchangers. A brief review of the various resin types is included in the following paragraphs. However, it should be noted that the potential functional groups of the various resin categories are more varied than may be implied in this document. Ion exchange resin technology is a continually evolving field and the available products varies significantly from one manufacturer to another and over time as the quality and function of specific ion exchange resins are modified and improved. The following discussion is not intended to provide details on all potentially available ion exchange resins, but to provide a basic overview of the technology.

4.3.2.1 Strong Acid Cation Resins

4.3.2.2 Weak Acid Cation Resins

4.3.2.3 Strong Base Anion Resins

4.3.2.4 Weak Base Anion Resins

4.3.2.5 Chelating Resins

4.3.2.6 Specialty Resins

4.3.3 Ion Exchange for Acid Mine Drainage Treatment

Ion exchange technology has been applied successfully to remove copper and cobalt at the Soudan underground mine (MDNR, 2001). Using a specialty resin, removal efficiencies of greater than 99 percent were achieved at a resin loading rate of 2 pounds per cubic foot. The water is pumped through cartridge filters to remove aluminum hydroxide and silicate precipitate then through activated carbon filters prior to passing through the ion exchange units. Two ion exchange cartridges are used in a lead-lag configuration. The system treats wastewater at a flow rate of 9 to 15 gpm. When the resin is exhausted, the canister is transported offsite for regeneration. The capital cost for this system was approximately $50,000, with annual operation, maintenance and monitoring costs of approximately $80,000.

Because this system is in operation and treatment efficiencies are known, additional bench-scale testing of this technology is not required at this time.

The GYP-CIX ion exchange process has also been developed to remove high concentrations of sulfate in mine water. This process is reviewed in the Lorax Report (2003) and was evaluated for treatment of mine water with high sulfate concentrations in South Africa (Schoemann and Steyn, 2001). This process uses two resin types in series to first remove sulfate and then remove the counter cation, typically calcium. The two brine streams generated during the regeneration of these two steps is combined to precipitate gypsum. Breaking the process of gypsum precipitation into multiple steps provides some additional control over the process. However, the volume of gypsum produced is increased significantly because of the additional chemicals -- primarily sulfuric acid and lime – needed for the operations. The GYP-CIX operation has been reported to be capable of reducing TDS and sulfate in mine water from 4,500 mg/L and 2,800 mg/L to less than 240 mg/L and 50 mg/L respectively.

4.4 Constructed Wetland

4.4.1 Technology Description

The use of constructed wetlands to treat municipal and industrial wastewater streams has become a widespread, conventional technology. As wastewater flows through a wetland, pollutants are transformed or sequestered through various biological and geochemical reactions involving wetland vegetation, sediments, and bacteria. Wetlands have been used predominantly to degrade organic matter, capture suspended solids in storm water runoff, and adsorb or fix inorganic nutrients such as nitrogen and phosphorus (ITRC, 2003). They have also been used extensively to treat metal- and sulfate-laden mine water discharges, similar to the potential flows that may be generated at NorthMet.

Wetlands are well suited for treating mine drainage because they are capable of transforming many different parameters, most of which will be of potential concern at NorthMet, especially sub-surface flow systems that provide an anaerobic environment and facilitate precipitation of metal sulfides (Wieder, 1988). Wetland sediments can neutralize acid via dissolution of carbonate minerals in the sediments and through the production of alkalinity via microbial decomposition of organic matter. Wetlands are also capable of removing sulfate via microbial reduction to sulfide and subsequent precipitation with metals such as iron. Many of the natural processes that occur in wetlands can also be designed into bioreactors that perform essentially the same functions. Bioreactors generally require less space than constructed wetlands but require much more operation and maintenance to provide the substrate and nutrients for the biological processes and to remove the accumulated solids (U.S. EPA, 2006). This treatment option will also be considered for NorthMet. Separate cost estimates for a sub-surface flow constructed wetland system and a bioreactor system are included in Appendix F and discussed in the cost evaluation portion of Section 5.

A wetland treatment system will be incorporated into the wastewater treatment program for Mine Site process water that is generated after closure of the Mine Site. As described in the Closure Plan (RS52) filling of the East Pit during the mining operations will create approximately 160 acres of land that will be available for construction of new wetlands. These wetlands will be installed with a subsurface drainage system that will allow the area to be used as a constructed wetland treatment system that will provide additional treatment of Mine Site process water effluent from the WWTF beginning in Year 21.

4.4.2 Wetland Removal Mechanisms

4.4.2.1 Uptake of Metals by Plants

4.4.2.2 Ion Exchange/Adsorption of Metals onto Sediment

4.4.2.3 Formation of Insoluble Metal Oxides

Metal oxide surfaces within the wetland substrate can also act as adsorptive sites for metal cations (Tarutus, et al., 1992). In the presence of oxygen, some metals, such as iron and manganese, form insoluble metal oxides. Such oxidation can occur near the sediment-water interface in a surface flow wetland, or in the rhizosphere of emergent wetland vegetation. While zinc, nickel, cobalt, and copper do not form insoluble oxides under typical environmental conditions, these metals can bind to iron and manganese oxide surfaces in a wetland environment in the same way they would bind to iron oxides in a chemical precipitation system (Dzombak and Morel, 1990). However, in a wetland environment, sorption to metal oxide surfaces is more sensitive to changes in substrate redox state, and reducing conditions can result in the release of sorbed metals (Patrick and Turner, 1968).

4.4.2.4 Formation of Insoluble Metal Sulfides in Wetlands

4.4.3 Wetland Treatment of Mine Drainage-Case Studies

5.0 Evaluation of Treatment Options for Mine Site Wastewaters

Brief descriptions and evaluations of cost, implementability, and effectiveness for the four potential technologies for the treatment of Mine Site wastewater are summarized in Table 12. The treatment alternatives are compared in the following sections on an individual basis. However, when appropriate, a discussion of potential combinations of alternatives is included. For complex wastewaters such as those expected at the Mine Site it is not uncommon for wastewater treatment to consist of a combination (or treatment train) of two or more of these technologies in series. Using multiple technologies in series also helps to emphasize the positive aspects of each technology and generally improves the overall treatment operation.

Treatment of Process Water at the Mine Site is the final step in a management system that will include prevention and minimization of Process Water flows through control of mining operations, segregation of waste rock into multiple categories, and staged construction of waste rock stockpile liners and cover systems concurrent with mining operations. These operations are described in detail in other RS documents including, but not limited to RS21, RS22, RS23, RS30, and RS49.

As noted in Table 2, the predicted quality of wastewater produced at the Mine Site varies significantly between the pit discharge and the stockpile drainage, and will also vary among stockpiles due to the segregation of waste rock according to the potential to produce acid rock drainage (ARD) and leach heavy metals. See RS21 (Figure 1) for additional detail on management of the various Process Water flows at the Mine Site. For the evaluation of potential wastewater treatment alternatives, it is assumed that the Mine Site process water will be pumped into one of two equalization (EQ) ponds (Stage 1 Pond and Stage 2 Pond) to produce two WWTF inflow streams. The first inflow stream (Stage 1) would include process water runoff and drainage from the Category 3 and Category 4 waste rock stockpiles. Stage 1 inflow is generally characterized as low pH (pH<5) with relatively high concentrations of dissolved metals and salts. The second inflow stream (Stage 2) would be comprised of Category 1/2 stockpile process water runoff and liner drainage, mine pit dewatering water, and process water runoff from the haul roads and Rail Transfer Hopper area. Stage 2 is generally characterized as near neutral pH with lower concentrations of dissolved metals and salts. Table 13 provides a summary of the estimated water quality and quantity for inflows to the Stage 1 and Stage 2 EQ Ponds. Separation of the multiple sources of wastewater allows them to be collected in separate equalization ponds and combined into two treatment influent streams, thus allowing the consideration of multiple treatment operations. Due to the water quality variability of the waste streams over time, inflow sources to the Stage 1 and Stage 2 EQ Pond could also be changed over time as necessary to optimize different treatment operations for each stage.

Table 12. Summary of Screening Evaluation of Treatment Technologies for Mine Site Process Water

					Approx. Cost (Detailed estimates in Appendix F)		
Technology	**Implementability**	**Advantages**	**Disadvantages**	**Residuals Generated**	**Capital**	**Annual O&M**	**Net Present Value (20 yrs @ 5%)**
Chemical Precipitation							
Hydroxide Precipitation	-Requires small footprint -Residues are easily managed.	-Simple process control - Well-established technology - Inexpensive chemicals -Co-precipitation with iron oxides	-Less effective for zinc removal, simultaneous removal of certain metals may not be possible	Metal Hydroxide Sludge	$13.2 million	$776,000	$27.4 million
Soluble Sulfide Precipitation	- Requires small footprint - Residues are easily managed	- Effective removal of most metals to low concentrations -Metal sulfides may be easier to recycle into hydrometallurgical process	- Requires control measures for H_2S generation	Metal Sulfide Sludge	$13.6 million	$788,000	$28.1 million
Carbonate Precipitation	-Requires small footprint - Residues are easily managed	- Simple process control	- Ineffective for removal of any metals except zinc, iron, and manganese - Soda ash is expensive, and subject to large price fluctuations - Large sludge volumes produced	Metal Carbonate Sludge	$12.5 million	$1.3 million	$34.8 million

Technology	Implementability	Advantages	Disadvantages	Residuals Generated	Approx. Cost (Detailed estimates in Appendix F)		
					Capital	Annual O&M	Net Present Value (20 yrs @ 5%)
Iron Sulfide Precipitation	-Requires small footprint -Requires on-site production of FeS	-Less potential for residual sulfide than soluble sulfide precipitation	- Nickel removal is ineffective - Requires larger reagent dose than soluble sulfide precipitation - Generates more sludge than soluble sulfide precipitation - Metal sulfide precipitates managed as hazardous waste	Metal (Iron) Sulfide Sludge	$13.9 million	$1.4 million	$38.0 million
Calcium Sulfide Precipitation	- Requires small footprint - Requires onsite generation of CaS	- Less potential for residual sulfide than soluble sulfide precipitation - Required CaS dose is less than for FeS precipitation	- Metal sulfide precipitates managed as hazardous waste	Metal Sulfide Sludge	$13.9 million	$920,000	$30.4 million
Membrane Treatment							
Nanofiltration-Stage 1	-Requires small footprint - Requires management of brine	-Selectively removes multivalent ions, resulting in lower TDS brine	-Membrane subject to fouling - Pre-treatment required	Metal hydroxide and gypsum sludge	$15.2 million	$1.2 million	$40.1 million
Nanofiltration-Stage 2	-Requires small footprint - Requires management of brine	-Selectively removes multivalent ions, resulting in lower TDS brine	-Membrane subject to fouling - Pre-treatment required	Metal hydroxide and gypsum sludge	$13.2 million	$1.4 million	$37.0 million

					Approx. Cost (Detailed estimates in Appendix F)		
Technology	Implementability	Advantages	Disadvantages	Residuals Generated	Capital	Annual O&M	Net Present Value (20 yrs @ 5%)
Reverse Osmosis:	-Requires small footprint - Requires management of brine	-Can remove metals and dissolved solids to very low concentrations for excellent water quality.	-Membrane subject to fouling by organics, calcium sulfate precipitation. -Performance subject to presence of divalent anions (e.g., sulfate, nitrate). -Membrane cleaned on-site, generates waste stream. -Extensive pretreatment likely required	Rejected Brine with Sulfate, Metals	$24.5 million	$2.3 million	$64.2 million
Ion Exchange							
Ion Exchange	-Requires small footprint - Spent resin and activated carbon require management	-No potentially hazardous materials are added to the water.	-Resin subject to fouling by organic compounds, Al, Fe, Mn. -Sensitive to interference from chelating agents and fluctuations in influent concentration -Pretreatment pH adjustment and carbon filtration likely required	Metal hydroxide sludge	$21.2 million	$1.6 million	$48.6 million
Biological Treatment							

Technology	Implementability	Advantages	Disadvantages	Residuals Generated	Approx. Cost (Detailed estimates in Appendix F)		
					Capital	Annual O&M	Net Present Value (20 yrs @ 5%)
Constructed Wetland	-Requires large footprint - No residual	-Metals are sequestered as stable sulfide compounds in the sediment -More metals storage capacity is produced as the wetland ages -No secondary waste stream generated	-Land-intensive technology -Hydraulic/hydrologic limitations -Requires maturation period for best metals removal results	No residuals	$54.6 million	$488,000	$72.8 million
Bioreactor Treatment – Stage 1	-Requires handling of ethanol substrate	-Sulfate is reduced to sulfide by bacteria, then precipitated with iron -Metals are removed as metal sulfide precipitates	-Produces a biological sludge in addition to chemical sludge - Requires large inputs of ethanol and iron - Control of a biological system can be difficult	Biological sludge, metal sulfides	$13.6 million	$1.8 million	$42.9 million
Bioreactor Treatment – Stage 2	-Requires handling of ethanol substrate	-Sulfate is reduced to sulfide by bacteria, then precipitated with iron -Metals are removed as metal sulfide precipitates	-Produces a biological sludge in addition to chemical sludge - Requires large inputs of ethanol and iron - Control of a biological system can be difficult	Biological sludge, metal sulfides	$18.9 million	$1.0 million	$38.3 million

Table 13 Stage 1 and Stage 2 Equalization Pond Inflow Predicted Water Quality

		Year 1		Year 5		Year 10		Year 15		Year 20	
Parameter	**units**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**
Flow	gpm	102	377	209	999	233	1,128	189	702	177	1,091
Hardness	mg/L	629	66	1,565	155	2,740	137	4,083	305	2,825	217
Fluoride (F)	mg/L	1.90	0.23	8.56	1.22	17.9	2.70	30.1	4.97	37.7	3.29
Chloride (Cl)	mg/L	10.4	1.13	27.7	5.23	27.1	5.00	14.1	1.12	14.4	1.20
Sulfate (SO_4)	mg/L	791	36	2,914	118	5,026	120	7,276	352	5,020	226
Aluminum (Al)	mg/L	2.55	0.23	16.3	0.28	38.7	0.29	53.9	0.48	33.9	0.32
Arsenic (As)	mg/L	0.22	0.009	0.39	0.04	0.39	0.031	0.71	0.10	0.56	0.07
Barium (Ba)	mg/L	0.15	0.025	0.23	0.028	0.23	0.028	0.30	0.052	0.28	0.036
Beryllium (Be)	mg/L	0.0018	0.00027	0.0020	0.00029	0.0027	0.00032	0.0027	0.00036	0.0026	0.00029
Boron (B)	mg/L	0.50	0.07	0.92	0.12	0.88	0.11	1.07	0.17	1.10	0.14
Cadmium (Cd)	mg/L	0.0069	0.00037	0.0063	0.00046	0.010	0.00045	0.010	0.00029	0.0073	0.00026
Calcium (Ca)	mg/L	179	15.9	396	42.5	375	36.8	622	91	541	62.4
Chromium (Cr)	mg/L	0.0039	0.00093	0.0057	0.0011	0.0057	0.0011	0.0049	0.0011	0.0070	0.0011
Cobalt (Co)	mg/L	0.20	0.0140	1.82	0.017	10.9	0.027	17.1	0.044	10.6	0.0265
Copper (Cu)	mg/L	0.097	0.016	0.34	0.023	11.4	0.164	27.0	0.343	39.0	0.206
Iron (Fe)	mg/L	29.4	1.49	74.0	1.94	82.4	1.61	106	0.29	92.2	0.28
Lead (Pb)	mg/L	0.010	0.0009	0.038	0.0033	0.040	0.0028	0.060	0.008	0.051	0.0053
Magnesium (Mg)	mg/L	44.6	6.50	141	12.0	438	11.0	615	19.1	359	15.0
Manganese (Mn)	mg/L	0.89	0.073	6.22	0.11	20.1	0.11	29.5	0.20	16.4	0.13
Mercury (Hg)	mg/L	3.17E-05	7.95E-06	3.30E-05	6.59E-06	3.62E-05	7.18E-06	4.94E-05	1.29E-05	4.79E-05	7.80E-06
Molybdenum	mg/L	0.013	0.0032	0.021	0.0043	0.021	0.0041	0.016	0.0036	0.027	0.0042
Nickel (Ni)	mg/L	2.99	0.22	26.4	0.22	138	0.37	254	0.54	176	0.314
Phosphorous	mg/L	0.094	0.00101	0.15	0.010	0.13	0.0069	0.22	0.026	0.18	0.017
Potassium (K)	mg/L	24.5	2.24	40.1	3.87	36.1	3.59	56.7	9.3	48.3	5.77
Selenium (Se)	mg/L	0.0074	0.0016	0.010	0.0020	0.010	0.0019	0.009	0.0020	0.013	0.0020
Silica (SiO_2)	mg/L	3.90	0.063	5.15	0.43	3.39	0.30	6.48	1.15	5.80	0.74
Silver (Ag)	mg/L	0.0027	0.00070	0.0043	0.00087	0.0043	0.00086	0.0031	0.00077	0.0053	0.00087
Sodium (Na)	mg/L	97	3.0	358	34.8	255	25.4	524	93	451	59
Thallium (Tl)	mg/L	0.0044	0.0013	0.0072	0.0016	0.0072	0.0016	0.0041	0.0012	0.0088	0.0015
Zinc (Zn)	mg/L	2.21	0.102	7.82	0.13	12.3	0.12	14.8	0.052	10.3	0.041
Nitrate (NO_3)	mg/L	0.32	0.073	0.76	0.16	0.73	0.15	0.11	0.000018	0.079	0.000012
Ammonia (NH_4)	mg/L	0.32	0.073	0.76	0.16	0.73	0.15	0.11	0.000018	0.079	0.000012

5.1 Effectiveness

Effectiveness is based on the ability of a treatment technology to address all of the parameters of concern at NorthMet. With the exception of carbonate precipitation, all of the technologies reviewed in Section 4 have the potential to be effective in treating the parameters of potential concern in the process water from the Mine Site. A membrane or a wetland treatment system could be designed to treat all of the parameters of concern simultaneously. While this would be effective, and relatively simple to operate, it may not necessarily be efficient. Chemical precipitation and ion exchange can be used to remove one or more specific parameters of concern, for example metals or sulfate, but would likely require a multi-step process to be effective in treating all of the parameters of concern. For example, in the case of chemical precipitation one stage may be needed to remove metals with a second stage to remove sulfate. This would increase the complexity of the treatment operation, but could also potentially reduce the operating costs. Complexity is addressed in the following discussion of implementability and costs for various alternatives.

This evaluation confirms that the pre-screening of alternatives that was conducted in the development of the SOW for this evaluation selected technologies that can all be designed to be effective. Thus, the selection of a preferred alternative is reduced to consideration of the implementability and the cost for each particular option. These factors are discussed in the following paragraphs.

5.2 Implementability

5.2.1 Chemical Precipitation

Implementation of chemical precipitation for the Mine Site process water would likely require a multi-stage system to be able to achieve the desired process water quality targets. Using chemical precipitation, metals would likely be removed as a hydroxide precipitate or as a co-precipitate with iron hydroxides. Sulfate would be removed as a gypsum precipitate. If additional sulfate removal is required, a chemical treatment system could be upgraded with the addition of aluminum salts using an ultra high lime with aluminum process as described in Section 4.1.3.3 of this report. The concentrations of other dissolved solids, for example silica, phosphorous, or nitrate would likely be reduced in the precipitation process. Calcium, which would be added to the process, could be removed in a final neutralization step with carbon dioxide or soda ash.

Chemical precipitation may require filtration as a final polishing step and would require solids handling and management, most likely incorporating the solids into the hydrometallurgical process.

The implementation of a chemical precipitation treatment system is a viable option at the Mine Site. The chemical precipitation treatability testing conducted for this evaluation (Appendix C) demonstrated that with the exception of mercury, all the parameters of concern at NorthMet can be removed using lime with an HDS operating configuration. As noted in Section 4, chemical precipitation at higher influent concentrations produce similar effluent concentrations (with greater removal efficiencies) provided adequate reaction time is provided, because the final concentrations are driven by solubility limits for the precipitates formed (U.S. EPA and U.S. DOE, 1997). The footprint for a chemical precipitation process at the Mine Site would be relatively small, most likely less than 10 acres. Power, chemicals, and other inputs for a chemical precipitation plant at the Mine Site can be delivered, and road access between the Mine Site and the Plant Site could accommodate the transportation of wastewater solids for reuse or disposal. A chemical treatment system can also be designed with two or more units in parallel to deal with variable incoming flow rates both seasonally and over the lifetime of the project.

5.2.2 Membrane Treatment

5.2.3 Ion Exchange

5.2.4 Constructed Wetland

5.2.4.1 Hydraulic Design

5.2.4.2 Required Sulfate Reduction Rate

5.2.4.3 Carbon Utilization Rates

5.2.4.4 NorthMet Wetland Size Requirements

A constructed wetland could be used as a secondary treatment step to remove additional sulfate after the use of a chemical precipitation step to remove a majority of the sulfate. Assuming a sulfate input of 25,000 pounds per day for the Mine Site wastewater based on an average annual flow of 1,300 gpm and a sulfate concentration of 540 mg/L after lime treatment of the Stage 1 flow and blending of the Stage 1 and Stage 2 flows, the corresponding carbon demands required to meet a 250 mg/L sulfate discharge criterion would be approximately 110,000 moles C/day. Assuming a conservative photosynthetic carbon input of 50 moles C/m^2/yr, the required size of a wetland treatment system at the Mine Site would be approximately 200 acres. This would represent a significant additional land requirement for the project, and would not likely fit within the currently available land.

In lieu of a constructed wetland, a bioreactor could be constructed to remove sulfate. The combination of biological sulfate reduction with chemical precipitation also provides an opportunity for excess sulfide generated by sulfate reducing bacteria to be used to promote metal precipitation. In this configuration, a sulfate reducing bioreactor or a portion of the treated wastewater from a constructed wetland could be recycled into the chemical precipitation process to provide soluble sulfide that should enhance the metal precipitation process.

While a constructed wetland has the potential to be a very effective treatment technology for the Mine Site process water, it is not likely to be implementable during the operation of the mine, due to the size requirements. Although a constructed wetland can effectively treat the parameters of potential concern in the Mine Site process water, the land requirements for this type of system are likely prohibitive.

A constructed wetland is, however, considered a potentially viable technology for removing additional metals and sulfate from the smaller volume of process water flows that are predicted for after the closure of the Mine Site. This is described in greater detail in RS52.

5.3 Cost

5.3.1 Chemical Precipitation

Tables F-1 through F-5 are cost estimates for treatment of the Mine Site process water using five different chemical precipitation methods: hydroxide, sulfide, carbonate, ferrous sulfide and calcium sulfide. Hydroxide precipitation is least expensive chemical precipitation technology, with a net present value (NPV) of $27.4 million (20 years at 5%). Sulfide precipitation and carbonate precipitation had NPV costs of $28.1 million and $34.8 million, respectively. While the capital cost for the three technologies is similar ($12.5 to $13.6 million), annual operating costs vary widely ($776,000, $788,000, and $1.3 million for hydroxide, sulfide, and carbonate precipitation, respectively.

The estimated NPV cost for insoluble sulfide precipitation via ferrous sulfide is approximately $38 million, assuming four times the required stoichiometric FeS dose as indicated in the literature. The subsequent increase in sludge generation also increases annual costs. NPV cost for calcium sulfide precipitation is about $30.4 million, due to the roughly stoichiometric calcium sulfide dose.

Metal recovery costs are not considered in this evaluation as all of the solid residues will be disposed in the hydrometallurgical residue cells. Metal recovery could be included in any or of these processes, which could be recycled into the hydrometallurgical process. For any of these technologies, a metal-recovery step would likely focus on collecting the metals before moving on to precipitate most of the sulfate as gypsum. This would mean minimizing the addition of calcium in the first step to inhibit gypsum precipitation, which would favor sulfide precipitation over other technologies.

5.3.2 Membrane Treatment

5.3.3 Ion Exchange

5.3.4 Constructed Wetland

5.4 Recommended Alternative

Based on the comparative evaluation of potential treatment technologies described above, a multi-technology approach is recommended for the treatment of the Mine Site process water. Chemical precipitation treatment will be used to remove metals and sulfate. However, given the limitation of chemical precipitation as gypsum to reduce sulfate to the process water quality target, nanofiltration will be used to concentrate sulfate in a brine stream prior to precipitation. Blending the permeate stream with the treated water from the chemical precipitation operations would produce a combined flow that with limited exceptions will meet the conservative process water quality targets throughout the operating life of the Mine Site.

As noted in Section 4, chemical precipitation has been used to reduce concentrations of metals and sulfate in mine waters, including highly contaminated waters from the Berkeley Pit (U.S. EPA and U.S. DOE, 1997). Similarly, nanofiltration has been used to successfully reduce the concentrations of dissolved salts in mine water at several sites. The concept of combining these technologies to treat mine water has also been applied to treat water from a former mine pit in New Mexico (Kuipers, 2002). The combination of these technologies offers flexibility of operation and the capacity to treat the range characteristics expected in all of the Mine Site process water flows.

Nanofiltration will be used to treat the Stage 2 process water flows with high volume and relatively low concentrations of metals and sulfate including mine pit process water, runoff from the working areas of the Mine Site, and drainage from the Category 1/2 stockpile. These flows generally have a neutral pH and as noted in Table 2, the concentrations metals in these flows are near the process water quality targets while the concentration of sulfate is generally too low to remove sulfate as gypsum. Concentrating this stream will provide a clean permeate and a brine stream with qualities similar to the anticipated Stage 1 flow (drainage from the Category 3 Waste Rock stockpile, Category 3 Lean Ore stockpile, Category 4 Waste Rock stockpile and the Lean Ore surge pile).

Pretreatment prior to nanofiltration will include filtration using sand filters or a combination of micro or ultrafiltration membranes. Anti-scalants would also be added, as necessary, to condition the feed to the nanofiltration membranes and optimize operations (minimize operating pressures and membrane cleaning events). The brine from the nanofiltration operation as well as the Stage 1 drainage would then be treated using a two-stage chemical precipitation operation.

The Wastewater Treatment Facility (WWTF) will consist of two parallel units, which will allow the system to be built in stages and will allow the system operating capacity to increase and decrease with time as the volume of flow changes throughout the process of mining and filling the pits. At the maximum extent, the WWTF will occupy approximately 5 acres. The plant will be located in the southwest portion of the Mine Site, near the Central Pumping Station (CPS) that will be used to convey treated Mine Site process water to the tailings basin. A conceptual layout of the WWTF is shown in Figure 4. A conceptual flow-diagram of the wastewater treatment system is shown on Figure 5. The following paragraphs describe the preliminary conceptual design details for the individual process units. Final sizing of process units and pumps and selection of materials of construction for all of the process units will be completed during the detailed design phase of the project.

5.4.1 Flow Equalization

5.4.2 Nanofiltration Pre-Treatment

5.4.3 Nanofiltration Membrane Unit

5.4.4 Chemical Addition and Rapid Mixing

5.4.5 Coagulation and Flocculation

5.4.6 Clarification (Settling)

5.4.7 Recarbonation

5.4.8 Process Monitoring and Control

5.5 Potential Treatment System Performance

As noted in Section 3, the goal of the WWTF at the Mine Site will be to produce a treated effluent that will not adversely impact the operation of the Beneficiation Plant or the subsequent hydrometallurgical processes at the Plant Site. In addition, the objective of wastewater treatment will be to achieve the process water quality targets listed in Table 4. These process water quality targets have been conservatively established based on in-stream water quality standards for the Partridge and Embarrass Rivers and the protection of groundwater. These values have been used because the Treated Water Pipeline will cross several streams within the Partridge River watershed between the Mine Site and the Plant Site and also because these values provide very conservative treatment goals that will help to maintain the long-term water quality of the water in the Tailings Basin, which will eventually be returned to the mine pit.

Estimates of the potential WWTF effluent quality are listed in Table 14 along with the water quality process targets. The basis for these estimates is provided in Appendix G. These values show that, on an annual average basis, WWTF should be capable of achieving the process water quality targets for most of the parameters of concern with limited exceptions that may require enhanced chemical treatment.

The effluent predictions are based on the annual average flows and use the low flow estimates, because the low flow scenario results in the highest potential influent concentrations to the WWTF. Because the WWTF will be sized to accommodate the high flow conditions, the plant will have additional retention time in all the process units that could facilitate improved performance.

Table 14 Stage 1 and Stage 2 Treatment Systems Effluent and CPS Pond Predicted Water Quality

Parameter	units	Year 1			Year 5			Year 10			Year 15			Year 20			Process Water Quality Targets
		Stage 1 Effluent	Stage 2 Effluent	CPS Effluent	Stage 1 Effluent	Stage 2 Effluent	CPS Effluent	Stage 1 Effluent	Stage 2 Effluent	CPS Effluent	Stage 1 Effluent	Stage 2 Effluent	CPS Effluent	Stage 1 Effluent	Stage 2 Effluent	CPS Effluent	
Flow	gpm	102	441	674	209	1108	1313	233	1247	1378	189	821	875	177	1159	1159	
Hardness	mg/L	629	148	97	1565	302	255	2740	517	468	4083	953	895	2825	443	443	
F	mg/L	1.90	0.45	0.29	2.14	0.46	0.39	4.47	0.96	0.86	7.53	1.95	1.83	9.41	1.60	1.60	2.0
Cl	mg/L	10.4	2.44	1.60	27.7	5.46	4.61	27.1	5.27	4.77	14.1	3.29	3.09	14.4	2.27	2.27	230
SO4 *	mg/L	791	184	121	1500	288	243	1500	285	**258**	1500	360	**338**	1500	240	240	250
Al	mg/L	0.025	0.016	0.010	0.16	0.043	0.036	0.39	0.09	0.08	0.54	0.14	**0.14**	0.34	0.067	0.067	0.125
As	mg/L	0.02	0.005	0.004	0.04	0.009	0.008	0.04	0.009	0.008	0.07	0.02	**0.020**	0.06	0.012	**0.012**	0.010
Ba	mg/L	0.15	0.036	0.023	0.23	0.044	0.037	0.23	0.043	0.039	0.30	0.072	0.068	0.28	0.045	0.045	2.0
Be	mg/L	0.0018	0.00044	0.00029	0.0020	0.00039	0.00033	0.0027	0.00051	0.00047	0.0027	0.00064	0.00060	0.0026	0.00041	0.00041	0.004
B	mg/L	0.47	0.11	0.07	0.88	0.17	0.14	0.84	0.16	0.15	1.02	0.24	0.23	1.05	0.17	0.17	0.5
Cd	mg/L	0.0069	0.0016	0.0011	0.0063	0.0012	0.0010	0.010	0.0018	0.0017	0.010	0.0024	0.0023	0.0073	0.0011	0.0011	0.004
Ca	mg/L	179	42.0	150	396	76.6	150	375	71.6	150	622	147	150	541	86	150	
Cr	mg/L	0.0039	0.00094	0.00062	0.0057	0.0011	0.0009	0.0057	0.0011	0.0010	0.0049	0.0012	0.0011	0.0070	0.0011	0.0011	0.100
Co	mg/L	0.00040	0.00069	0.00045	0.0036	0.0014	0.00121	0.022	0.0053	0.0048	0.034	0.0098	**0.0092**	0.021	0.0045	0.0045	0.005
Cu **	mg/L	0.00048	0.00079	0.00052	0.0017	0.0013	0.00113	0.057	0.018	0.0163	0.14	0.046	**0.043**	0.20	0.040	**0.040**	0.030
Fe	mg/L	0.029	0.070	0.046	0.074	0.10	0.086	0.082	0.09	0.080	0.11	0.037	0.034	0.092	0.027	0.027	0.3
Pb	mg/L	0.010	0.0023	0.0015	0.038	0.0074	0.0062	0.040	0.0076	0.0069	0.060	0.014	0.013	0.051	0.008	0.008	0.019
Mg	mg/L	2.23	0.79	0.52	7.03	1.87	1.58	21.9	4.58	4.15	30.7	7.90	7.41	18.0	3.46	3.46	
Mn	mg/L	0.0009	0.0033	0.0022	0.0062	0.0061	0.0051	0.020	0.0088	0.0079	0.029	0.015	0.014	0.016	0.0086	0.0086	0.05
Hg	mg/L	3.2E-05	7.7E-06	**5.0E-06**	3.3E-05	6.5E-06	**5.5E-06**	3.6E-05	7.1E-06	**6.4E-06**	4.9E-05	1.2E-05	**1.1E-05**	4.8E-05	7.7E-06	**7.7E-06**	1.3E-06
Mo	mg/L	0.013	0.0031	0.0020	0.021	0.0042	0.0036	0.021	0.0041	0.0038	0.016	0.0038	0.0036	0.027	0.0043	0.0043	0.100
Ni **	mg/L	0.0030	0.0099	0.0065	0.026	0.015	0.0126	0.14	0.043	0.039	0.25	0.081	0.076	0.18	0.042	0.042	0.100
P	mg/L	0.047	0.011	0.0072	0.07	0.015	0.012	0.067	0.013	0.012	0.11	0.026	0.025	0.09	0.014	0.014	
K	mg/L	24.5	5.75	3.77	40.1	7.7	6.54	36.1	6.90	6.24	56.7	13.5	12.6	48.3	7.7	7.7	
Se	mg/L	0.0074	0.0018	0.0012	0.010	0.0020	0.0017	0.010	0.0020	0.0018	0.009	0.0021	0.0020	0.013	0.0020	0.0020	0.005
Si	mg/L	3.90	0.90	0.59	5.15	0.99	0.84	3.39	0.65	0.59	6.48	1.54	1.45	5.80	0.92	0.92	
Ag	mg/L	0.0027	0.00066	0.00043	0.0043	0.00086	0.00072	0.0043	0.00084	0.00076	0.0031	0.00076	0.00071	0.0053	0.00086	0.00086	0.001
Na	mg/L	97	22.6	14.8	358	69	58.3	255	48.6	44.0	524	125	117	451	72	72	

		Year 1			**Year 5**			**Year 10**			**Year 15**			**Year 20**			**Process Water Quality Targets**
Parameter	**units**	**Stage 1 Effluent**	**Stage 2 Effluent**	**CPS Effluent**	**Stage 1 Effluent**	**Stage 2 Effluent**	**CPS Effluent**	**Stage 1 Effluent**	**Stage 2 Effluent**	**CPS Effluent**	**Stage 1 Effluent**	**Stage 2 Effluent**	**CPS Effluent**	**Stage 1 Effluent**	**Stage 2 Effluent**	**CPS Effluent**	
Tl	mg/L	0.0044	0.0011	**0.00070**	0.0072	0.0014	**0.0012**	0.0072	0.0014	**0.0013**	0.0041	0.0010	**0.00094**	0.0088	0.0014	**0.0014**	0.00056
Zn **	mg/L	0.22	0.055	0.036	0.78	0.15	0.13	1.23	0.23	0.21	1.48	0.34	0.32	1.03	0.16	0.16	0.388
NO3	mg/L	0.32	0.078	0.051	0.76	0.15	0.13	0.73	0.14	0.13	0.11	0.025	0.023	0.08	0.012	0.012	10.0
NH4	mg/L	0.32	0.078	0.051	0.76	0.15	0.13	0.73	0.14	0.13	0.11	0.025	0.023	0.08	0.012	0.012	

Notes: * Secondary Drinking Water Standard

** Varies with Hardness Concentration (Assumed 400 mg/L Hardness)

Parameters that could potentially exceed these targets and potential plans to mitigate these values, if necessary, include:

- Sulfate – The primary contribution of sulfate to the Mine Site process water is from Category 3 and Category 4 stockpiles. The drainage from the Category 3 and 4 stockpiles is proposed to be routed to the Stage 1 EQ Pond and will undergo chemical precipitation treatment. Concentrating the sulfate in the Stage 2 flows prior to chemical precipitation will improve the overall effectiveness of the WWTF and provide a permeate that when blended with the treated stream from the chemical precipitation unit will achieve the process water quality targets in all years modeled except Year 15. Given the variability of the concentration of sulfate in Stage 1 and Stage 2 flows, the effluent estimate for sulfate is potentially sensitive to significant changes in the ratio between these flows as well as the concentration of sulfate in any flow. The values used in this evaluation, however, are conservative, and the proposed treatment operation is capable of treating a wide range of potential volumes and concentrations. For example, in Year 15 when the estimated flows to Stage 2 decrease, a portion of the Stage 1 flows could be routed into Stage 2 to concentrate more of the mass flow in Stage 1 and provide additional permeate in Stage 2.
- Metals (Aluminum, Arsenic, Cobalt, and Copper) – The primary contributor of these parameters to the Mine Site process water is also from Category 3 and Category 4 stockpiles. The predicted effluent values for these parameters are close to the process water quality targets using conservative removal percentages from the treatability study. Additional removal of these parameters is anticipated using the HDS process, as demonstrated in the absolute values obtained in the treatability study (Table 9 in Attachment C2), which showed all these parameters below the process water quality targets. If necessary, additional coagulation and flocculation time, or the addition of iron salts to the process would improve removal efficiencies. No other process modification would be required.

- Mercury –Mercury will likely exceed the process water quality target. However, this water will be pumped to the tailings basin where additional mercury removal is anticipated due to exposure to the NorthMet tailings. No other process modifications are anticipated to remove additional mercury.

- Thallium – The analytical results from several sources used in the prediction of the influent water quality to the WWTF reported thallium as non-detect at values above the process water quality target. Thus the reported value is likely a maximum value. At this time, thallium is not expected to be a concern, however, additional analysis of input flows will be needed to confirm the actual inputs and, if necessary, evaluate removal efficiencies using the proposed unit operations.

The ability of the WWTF to achieve the level of performance established by the process water quality targets will be monitored during the operation of the facility. If necessary, improvements to the process can be developed and/or additional technologies can be added to achieve treatment objectives.

5.6 Solid Waste Management Plan

A portion of the solids removed from the Stage 1clarifier will be returned to the rapid mix tank at the beginning of the chemical precipitation treatment process to promote crystal formation. The remaining solids will be conveyed to a sludge thickening unit and then pumped to a filter press operation where excess liquids will be removed prior to being returned to the influent stream of the Stage 1 treatment system. One press will be installed for the Stage 1 clarifier and an additional press will be installed for the solids from the final (recarbonation) clarifier to allow the solid waste streams generated from each of these operations to be managed individually. Dewatered solids will be disposed with the hydrometallurgical residues.

As noted in Section 4.1.1 of this report, the mass of wastewater sludge generated annually at the WWTF would likely be less than one percent of the mass produced annually in the Hydrometallurgical Process. The WWTF sludge would also likely be similar to the hydrometallurgical residues, consisting primarily of gypsum. Thus it would not be expected to change the overall chemical characteristics of the solids in the hydrometallurgical residue cells.

6.0 Evaluation of Treatment Options for Tailings Basins Water

7.0 Summary

8.0 References

8.1 Printed Materials

Abdel-Aal, E.A., Rashad, M. M., and El-Shall, H. 2004. Crystallization of Calcium Sulfate Dihydrate at Different Super-saturation Ratios and Different Free Sulfate Concentrations. *Crystal Research and Technology*, **39**:4, 313-321

Ayres, David M., Davis, Allen P., and Gietka, Paul M., 1994. *Removing Heavy Metals from Wastewater*. University of Maryland, Engineering Research Center Report.

Batchelor, B., Lasala, M.B., McDevitt, M., and Peacock, E., 1991. Technical and Economic Feasibility of Ultra-High Lime Treatment for Recycled Cooling Water. *Research Journal of the Water Pollution Control Federation*, **63**:7, 982-990.

Bertrand, S., Lemaitre, I., and Wittmann, E., 1997. Performance of a Nanofiltration Plant on Hard and Highly Sulfated Water during Two Years of Operation. *Desalination*. **113**:277-281.

Brinson, M.M., Lugo, A.E., and Brown, S. 1981. Primary productivity, decomposition, and consumer activity in freshwater wetlands. Annu. *Rev. Ecol. Syst.*, **12**: 123-161.

CEMI, 2002. Pilot Scale Testing of the High Density Sludge Process. Prepared for BC Ministry of Water Land, and Air Protection. Contract No. CLM02-57, Acid Mine Drainage Treatment, Britannia Beach, BC. Prepared by Canadian Environmental and Metallurgical Inc. (CEMI), May 2002.

Davis, R.A., McElhiney, J.E., 2002. The Advancement of Sulfate Removal from Seawater in Offshore Waterflood Operations. Proceedings: Corrosion 2002.

Dzombak, D.A. and Morel, F.M.M. 1990. *Surface Complexation Modeling – Hydrous Ferric Oxide*. John Wiley and Sons, New York, NY.

Eger, P., Wagner, J., Melchert, G., Antonson, D., and Jackson, A. 2000. Long Term Wetland Treatment of Mine Drainage at LTV Steel Mining Company's Dunka Mine. Minnesota DNR.

Gula, M. and Harvey, J., 1996. *Novel Silica-Based Ion Exchange Resin* .Eichrom Industries, Inc. Darien, IL, Conference on Industry, Morgantown, WV, October 22-24, 1996.

ITRC, 2003. Technical and regulatory guidance document for constructed treatment wetlands.

Kim, B.M. and Amodeo, P.A., 1983. Calcium sulfide process for treatment of metal-containing wastes. *Environmental Progress* **2**: 175-180.

Ku, Y., Chen, S.W., and Wang, W.Y., 2005. Effect of Solution Composition on the Removal of Copper Ions by Nanofiltration. *Separation and Purification Technology*. **43**:135-142

Kuipers, J.P., 2002. Water Treatment as a Mitigation for Pit Lakes. *Southwest Hydrology*, September/October 2002.

Kurniawan, T. A., Chan, G. Y. S., Lo, W., and Babel, S. Physico-chemical treatment techniques for wastewater laden with heavy metals. *Chemical Engineering Journal*, January, 2006.

Le Gouellec, Y.A., Elimelech, M., 2002. Control of Calcium sulfate (Gypsum) Scale in Nanofiltration of Saline Agricultural Drainage Water. *Environmental Engineering Science*, 19:6. 387-397.

Lipnizki, J. 2007. Strategies for Controlling Membrane Fouling. *Chemical Engineering*, Sept. 2007, 62-64.

Lorax Environmental, 2003. Treatment of Sulphate in Mine Effluents. Prepared for the International Network for Acid Prevention, October 2003.

Madigan, M.T., Martinko, J.M., and Parker, J. 1997. Brock Biology of Microorganisms, 8th Edition. Prentice Hall, Inc., Upper Saddle River, NJ.

Minnesota Department of Natural Resources, Paul Eger, Andrea Johnson, Jon Wagner, 2001, “Investigation of Elevated Copper and Cobalt Concentrations in Soudan Mine Drainage” (MNDNR, 2001)

Morton, P., and Ameel, J. 1985. *Saline Waters as Indicators of Economic Mineralization*, Minnesota Department of Natural Resources Report 241-1.

Patrick, W.H. and Turner, F.T. 1968. Effect of redox potential on manganese transformation in waterlogged soil. *Nature* **220**, 476-478.

Schoeman, J.J., and Steyn, A., 2001. Investigation into Alternative Water Treatment Technologies for the Treatment of Underground Mine Water Discharged by Grootvlei Proprietary Mines Ltd into the Blesbokspruit in South Africa. *Desalination* **133**:13-30

Sencindiver, J.C. and Bhumbla, D.K. 1988. Effects of cattail (Typha) on metal removal from mine drainage. Mine Drainage and Surface Mine Reclamation **1**: 359-366.

Smit, J. and Sibilski, U.E., October 2003. Pilot Plant Study to Treat Typical Gold Mine Minewater Using the SAVMIN Process. Proceedings, Water in Mining Conference.

Smith, R., and Martell, A.E. 1976. *Critical Stability Constants* Vol. 4. Plenum Press, New York, NY

STS Consultants, 1995. *Evaluation of boron impacted wells*. Report to LTV Steel.

Swenson, J.B. 2007. Continental Glaciation as a Groundwater-Impelling Mechanism: Pleistocene Flushing of Deep Brines in the Lake Superior basin. Unpublished data.

Tarutus, W.J., Unz, R.F., and Brooks, R.P. 1992. Behavior of sedimentary Fe and Mn in a natural wetland receiving acidic mine drainage, Pennsylvania, USA. *Applied Geochemistry*, **7**:77-85.

Taylor, G.J. and Crowder, A.A. 1982. Uptake and accumulation of copper, nickel, and iron by Typha latifolia grown in solution culture. *Canadian Journal of Botany*, **61**:1825-1830.

Topp, H., Russell, H., Davidson, J., Jones, D., Levy, V., Gilderdale, M., Davis, G., Ring, R., Conway, G., Macintosh, P., and Sertorio, L. 2003. Process Water Treatment at the Ranger Uranium Mine in Northern Australia. *Water Science and Technology*. **47**:10, 155-162.

US Army Corps of Engineers, 2001. “Precipitation/coagulation/flocculation Engineering and Design Manual, EM 1110-1-4012”

U.S. Environmental Protection Agency, 2006. “Management and Treatment of Water from Hard Rock Waste Sites”, Office of Research and Development, National Risk Management Research Laboratory, Cincinnati, Ohio. EPA-625/R-06/014.

U.S. Environmental Protection Agency, 1999. "Final Report – Berkeley Pit Innovative Technologies Project, Phase III: Hydrometrics, Inc. Demonstration of Sulfate Removal using the Walhalla Process, Mine Waste Technology Program Activity IV, Project 7". Prepared by Montana Tech of the University of Montana and MSE Technology Applications, Inc., February 1999.

U.S. Environmental Protection Agency, 1996. "Capsule Report: Reverse Osmosis Process", EPA-625/R-96/009.

U.S. Environmental Protection Agency, 1980. "Summary Report: Control and Treatment Technology for the Metal Finishing Industry". EPA 625/8-80-003.

U.S. Environmental Protection Agency, 1973. "Applications of Reverse Osmosis to Acid Mine Drainage Treatment", EPA-670/2-73-100.

U.S. Environmental Protection Agency and U.S. Dept. of Energy, 1997. Final Report – Berkeley Pit Water Treatment Research Project. Mine Waste Technology Program, Activity IV, Project 1. Prepared by Montana Tech of the University of Montana and MSE Technology Applications, Inc. April 1997.

Visser, T.J.K., Modise, S.J., Kreig, H.M., and Keizer, K., 2001. The Removal of Acid Sulfate Pollution by Nanofiltration. *Desalination*. **140**:79-86

Vymazal, 1995. "Algae and Nutrient Cycling in Wetlands". CRC Press/Lewis Publishers, Boca Raton, Florida.

Wieder, R.K. 1988. Determining the capacity for metal retention in man-made wetlands constructed for treatment of coal mine drainage. Mine Drainage and Surface Mine Reclamation **1**: 375-380.

Wieder, R.K. 1990. Metal cation binding to *Sphagnum* peat and sawdust: relation to wetland treatment of metal-polluted waters. *Water, Air, and Soil Pollution*, **53**: 391-400.

Wieder, R.K. and Lange, G.E. 1988. Cycling of inorganic and organic sulfur in peat from Big Run Bog, West Virginia. *Biogeochemistry*, **5**, 221-242.

Worrall, F., Reed, M., Warburton, J., and Burt, T. 2003. Carbon budget for a British upland peat catchment. *The Science of the Total Environment*. **312**: 133-146.

8.2 Electronic Materials

http://www.aquatechnology.net, Accessed April 13, 2006.

http://www.frtr.gov/matrix2/section4/4_52.html#cost, Accessed April 17, 2006.

http://gewater.com/library/tp/833_WHat_Is.jsp, Accessed April 13, 2006.

http://www.nesc.wvu.edu/ndwc/pdf/OT/TB/TB4_IonExchange.pdf, Accessed April 17, 2006.

http://www.nmfrc.org/pdf/ro.htm, Accessed June 23, 2006.

http://www.remco.com/ix.htm, Accessed April 17, 2006.

Technical Design Evaluation Report
RS29T – Wastewater Treatment Technology

NorthMet Project
Hoyt Lakes, Minnesota

Prepared for
PolyMet Mining, Inc

March 2007

Technical Design Evaluation Report
RS29T – Wastewater Treatment Technology

NorthMet Project
Hoyt Lakes, Minnesota

Prepared for
PolyMet Mining, Inc.

March 2007

4700 West 77th Street
Minneapolis, MN 55435-4803
Phone: (952) 832-2600
Fax: (952) 832-2601

RS 29T
Draft-02
March 30, 2007

Technical Design Evaluation Report
RS29T – Wastewater Treatment Technology
NorthMet Project

March 2007

Table of Contents

Table of Contents (continued)

List of Tables

List of Figures

List of Appendices

1.0 Introduction

1.1 Project Overview

PolyMet Mining, Inc. (PolyMet) plans to excavate and process low-grade, polymetallic, disseminated, magmatic-sulfide NorthMet-deposit ore in northeastern Minnesota, approximately 6 miles south of the town of Babbitt, Minnesota. Figure 1 shows the location of the proposed Mine Site, Process Plant, and tailings basin.

PolyMet is proposing to manage process waters from mining and metal recovery operations in a manner that eliminates the need for any direct discharge to the surface waters of the State of Minnesota. This report describes the process waters generated by the proposed NorthMet project, the treatment technologies that have been evaluated, and the preferred treatment methods that are proposed to reuse/recycle this water.

1.2 Report Objective and Water Management Overview

The objective of this Wastewater Treatment Technology Evaluation Report is to describe in detail the water treatment requirements and the proposed water treatment technologies for NorthMet process water that will be generated at two locations:

- At the Mine Site, primarily from pit dewatering and stockpile drainage, and
- At the Plant Site, primarily from the beneficiation of the ore and subsequent transport of flotation tailings to the tailings basin.

At the Mine Site, all process water that contacts waste rock, ore, the mine pit, or any of the active mining operations will be carefully managed to eliminate discharge to surface water. Only non-contact storm water will be discharged from the Mine Site. The Mine Site process water will be treated at a wastewater treatment facility (WWTF) prior to being pumped to the tailings basin, where it will be used as make-up water for the beneficiation process, as described in Section 2 of this report. The WWTF will be designed and operated to maintain water quality within the tailings basin to appropriate process-based targets. This water management plan avoids a direct discharge of wastewater from both the Mine Site and the Plant Site during the proposed 20-year operating life of the project.

Approximately 40 years after closure of the mining operation, when the West Pit has filled with water, it will be necessary to discharge water from the Mine Site. Treatment and discharge of Mine Site process water after closure is addressed in the RS52.

At the Plant Site, PolyMet plans to use the existing tailings basin for disposal of flotation tailings generated by processing the ore (see Figure 2). Water will be used in the grinding and flotation operations and will also be used to transport the tailings to this basin. Water will then be returned from the tailings basin to be re-used in the beneficiation process. During operation of the project, no water will be discharged directly from the Plant Site to surface water. Upon closure, the water in the tailings basin will be pumped back to the Mine Site to accelerate filling of the West Pit. Tailings basin seepage water will also be pumped to the Mine Site after closure.

Additional wastewater streams that will be generated at the Plant Site include the leachate from hydrometallurgical residue cells that will be constructed on closed portions of the tailings basin, and wastewater from potable use (toilets, sinks, showers, etc). During operation, the leachate from the hydrometallurgical residue cells will be routed back to the hydrometallurgical process, which will consume water during normal operations. Drainage water treatment will be required after closure and is addressed in RS52. Wastewater from potable uses will be treated separately from the process wastewaters described in this report. Therefore, at the Plant Site, the primary focus of this report is the process water in the Beneficiation Plant-tailings basin loop.

1.3 Report Organization

The Scope of Work (SOW) for RS29T was specified in Attachment A of the Final Scoping Decision Document for the PolyMet EIS. The evaluation of wastewater treatment technology is divided into five phases.

- Phase 1 of the study, presented in Section 3, establishes potential process water quality targets for implementation of a complete reuse/recycle water management plan.

- The potential wastewater treatment technologies are described in Section 4 and constitute Phase 2 of the study.

- Phase 3 of the study, described in Section 2, describes wastewater quantity and quality information for the project. This section focuses on the Mine Site as this is the location where wastewater will be treated. The wastewater quantity and quality at the Plant Site is discussed in relation to how treatment of the Mine Site process water affects water quality at the Plant Site.

- Phases 4 and 5 of the study outline, discussed in Sections 5 and 6 of the report, contain an evaluation of the effectiveness, implementability, and cost of the potential wastewater treatment technologies discussed in Section 4, for Mine Site process water and Plant Site process water wastewater, respectively.

A copy of the original SOW for this report is included in Appendix A. The original SOW was developed with the assumption that treated wastewater would need to be discharged to surface water. However, the Final Scoping Decision Document also noted that PolyMet may consider other options for managing wastewater, including the reuse/recycle of Mine Site process water as make-up water for the plant operations. Reuse/recycle of Mine Site process water provides the basis for the current water management plan to eliminate surface water discharges. Because the focus of wastewater treatment is different than was contemplated when the SOW for this report was prepared, the order in which items are discussed in this report has been revised. For example, the quantity and quality of water generated and consumed at NorthMet are significant to the overall development of the reuse/recycle water management plan. Thus, the plan for water management, which is summarized in the following Section, is of primary importance when compared to the discussion of potential discharge goals and is, therefore, addressed first.

2.0 Reuse/Recycle Water Management Plan

The reuse/recycle plan for water management at NorthMet envisions no discharge of wastewater from any of the processing activities or other operations described in this report. Water will enter the NorthMet operation in the form of precipitation, groundwater inflows to the mine pit, and as make-up water from Colby Lake. This water will be collected, treated when necessary, used in the beneficiation process, and later returned the mine pits to facilitate filling at the conclusion of the mining operations. This water management plan for NorthMet does not include any planned discharge of process water to surface waters of the State of Minnesota until the West Pit overflows to the Partridge River, approximately 40 years after the operation has been closed and the Mine Site has been reclaimed. This is the essence of the reuse/recycle plan for water management. The details of this plan are developed in several other RS documents and integrated into a single plan in the following paragraphs.

Managing process and wastewater generation and consumption to eliminate wastewater discharge to surface water will be a critical aspect of the proposed NorthMet project. Water is required for the grinding of ore and flotation of the ground ore slurry to separate the concentrate from the tailings. Water is consumed in the hydrometallurgical processes used to recover metal from the concentrate. Water is also lost to the tailings basin when tailings are deposited (by filling the space between tailings particles), to evaporation from the surface of the basin, and to deep groundwater beneath the tailings basin. All these water-related operations must be balanced, and appropriate factors of safety established, to provide a consistent and reliable – but not excessive – supply of water to the operation. A source of new water, Colby Lake, will then be used to provide any additional water required to maintain the operation.

The implementation of a complete reuse/recycle program for NorthMet is predicated upon the careful management of water inflows and consumption, as well as careful modeling of water quality and appropriate treatment, when necessary. The estimates of water quality and quantity at both the Mine Site and the Plant Site have been completed and reported in several individual RS reports including:

- RS13A – Process Design – Tailings Basin Water Balance - Operations
- RS21 – Hydrology – Mine Water Model and Balance
- RS22 – Mine Wastewater Management System
- RS31 – Mine Pit Water Quality Model

- RS53/RS42 – Waste Rock Characteristics/Waste Water Modeling -Waste Rock and Lean Ore
- RS54A/RS46 – Flotation Tailings Characteristics/Waste Water Modeling -Tailings
- RS52 – Mine Closure Plan

The results of these reports are summarized and combined in the following paragraphs to provide an overall assessment of water management approach and to highlight areas where water treatment is necessary to maintain the water quality needed for plant operations and to maintain appropriate water quality standards near NorthMet.

2.1 Mine Site Process Water

2.1.1 Mine Site Process Water Quantity

Mine Site process water is generated from four sources: groundwater entering the mine pit, direct precipitation on the mine pit, infiltration through or runoff from waste rock stockpiles collected on liner systems (drainage), and runoff from other site operations within the Mine Site—for example the ore Rail Transfer Hopper, and mine service roads. The mine plan includes three separate pits (referred to as the East Pit, the Central Pit and the West Pit), which will be changing over the life of the mining operation. The quantity of process water generated from these pits and associated stockpiles will also vary over the life of the mine. The use of multiple pits helps to reduce the maximum pumping that will be required for mine pit dewatering and also provides a location for storing some of the process water generated at the site after the first eleven years of operation. These options help to provide flexibility and facilitate the development of a reuse/recycle - water management plan.

On an annual average basis, the maximum design rate of process water generation from the sources that will require treatment at the WWTF varies from approximately 500 gpm in the early years to a maximum of approximately 1,600 gpm near Year 10, before initiation of filling activities for the East Pit, and reducing to approximately 1,400 gpm in the final years of operation. Table 1 contains a summary of the anticipated annual average Mine Site process water flow rates from all the sources that will require treatment. All of these flows, even during the likely peak in Mine Site process water generation near Year 10 can be consumed by operations at the Plant Site. Within any given year, the process water flow will vary significantly from a minimum flow during the winter months to a maximum flow in the spring. In general the minimum flow is 0.5 to 0.7 times the average annual flow, while the maximum flow ranges from approximately 2.0 to 2.5 times the annual average flow, with a maximum design flow of approximately 2,960 gpm in the Spring of Year 10. This value provides the design basis for the maximum flow rate through the WWTF of 3,000 gpm.

Table 1 Mine Site Process Water Flows to the WWTF

Source	Estimated high (and low)[1] average annual flow (gpm) in Year:				
	1	5	10	15	20
Category 1/2 Stockpile	113.1(85.8)	217.5(99.6)	281.5(50.1)	270.4(120.6)	270.4(120.6)
Category 3 Stockpile	5.0(3.8)	20(14.7)	35(25.3)	49.5(34.4)	23.2(10)
Category 3 Lean Ore Stockpile	29.9(22.7)	50(36.7)	62.5(33.7)	80.2(26.2)	51.8(22.5)
Category 4 Stockpile	3.8(2.9)	30.4(22.9)	35.3(25.9)	32.2(23.3)	4.6(0.9)
Lean Ore Surge Pile	46.1(35)	46.1(35)	46.1(35)	46.1(35)	46.1(35)
East Pit[2]	200.9	774	820.1	80.7	0
West Pit	79.4	123.8	224.4	486.9	924.3
Haul Roads	46.1	46.7	38.8	36.5	35.3
Rail Transfer Hopper	6	6	6	6	6
Total	530(480)	1,320(1,160)	1,550(1,260)	1,090(850)	1,360(1,155)

Notes:
1. Lows not shown when same as high estimates
2. Includes Central Pit - Zero flow from East Pit to WWTF starting in Year 12 when East Pit filling is initiated.

As contemplated in Phase 3 of the SOW, the work described in RS21 and RS22 was focused on minimizing the Mine Site process water quantity and minimizing impacts to water quality through the use of segregation of waste rock and capping of stockpiles as well as dewatering of multiple pits on independent schedules. These activities contribute to the implementation of a reuse/recycle water management plan as described in the plan for the proposed WWTF at the Mine Site in Section 5.

2.1.2 Mine Site Process Water Quality

The quality of the Mine Site process water will vary based on the source of the water. For example, waste rock is proposed to be segregated into four different ‘categories’ based on the geochemical properties of the rock which drives the potential for water that contacts the rock to impact water quality. Mine pit process water quality will be different than the drainage from the waste rock stockpiles. The anticipated water quality for each of these sources has been predicted (see RS31 and RS53/RS42) using site-specific data obtained from humidity cell testing and site-specific hydrology. Table 2 contains a summary of the expected water quality for the primary sources of Mine Site process water.

Table 2 Mine Site Process Water Quality

Parameter (mg/L)	Category 1/2 Stockpile (Years)					Category 3 Stockpile (Years)				
	1	**5**	**10**	**15**	**20**	**1**	**5**	**10**	**15**	**20**
Fluoride (F)	1.3E+00	1.4E+01	6.1E+01	3.5E+01	3.5E+01	3.2E+00	9.5E+00	1.2E+01	1.7E+01	8.4E+01
Chloride (Cl)	1.9E+01	6.2E+01	1.0E+02	0.0E+00	0.0E+00	1.9E+01	1.3E+01	5.6E+00	8.3E+00	5.3E+01
Sulfate (SO_4)	1.2E+02	1.2E+03	2.3E+03	2.3E+03	2.3E+03	1.5E+03	2.3E+03	9.6E+03	9.6E+03	9.6E+03
Aluminum (Al)	1.7E+00	1.7E+00	1.7E+00	1.7E+00	1.7E+00	1.7E+00	1.7E+00	8.3E+01	8.3E+01	8.3E+01
Arsenic (As)	2.3E-01	7.1E-01	7.1E-01	7.1E-01	7.1E-01	7.1E-01	7.1E-01	7.1E-01	7.1E-01	7.1E-01
Barium (Ba)	1.9E-01	1.9E-01	1.9E-01	1.9E-01	1.9E-01	1.9E-01	1.9E-01	1.9E-01	1.9E-01	1.9E-01
Beryllium (Be)	2.0E-04	2.0E-04	2.0E-04	2.0E-04	2.0E-04	2.0E-04	2.0E-04	2.3E-03	2.3E-03	2.3E-03
Boron (B)	2.0E-01	7.6E-01	7.6E-01	7.6E-01	7.6E-01	7.1E-01	7.6E-01	7.6E-01	7.6E-01	7.6E-01
Cadmium (Cd)	1.8E-04	1.8E-04	1.8E-04	1.8E-04	1.8E-04	1.8E-04	1.8E-04	1.5E-02	1.5E-02	1.5E-02
Calcium (Ca)	5.0E+01	5.1E+02	5.4E+02	5.4E+02	5.4E+02	3.7E+02	5.4E+02	4.8E+02	4.8E+02	4.8E+02
Chromium (Cr)	1.5E-03	1.5E-03	1.5E-03	1.5E-03	1.5E-03	1.5E-03	1.5E-03	1.5E-03	1.5E-03	1.5E-03
Cobalt (Co)	2.7E-03	2.8E-02	5.2E-02	5.2E-02	5.2E-02	5.2E-02	5.2E-02	1.5E+01	2.4E+01	4.4E+01
Copper (Cu)	4.3E-02	9.2E-02	9.2E-02	9.2E-02	9.2E-02	9.2E-02	9.2E-02	2.1E+01	3.3E+01	2.0E+02
Iron (Fe)	7.7E-01	8.1E-01	8.1E-01	8.1E-01	8.1E-01	8.1E-01	8.1E-01	2.8E+01	4.4E+01	2.4E+02
Lead (Pb)	3.2E-03	3.3E-02	5.3E-02	5.3E-02	5.3E-02	9.1E-03	2.7E-02	5.3E-02	5.3E-02	5.3E-02
Magnesium (Mg)	8.8E+00	9.0E+01	9.3E+01	9.3E+01	9.3E+01	5.2E+01	9.3E+01	1.0E+03	1.0E+03	1.0E+03
Manganese (Mn)	4.9E-02	5.0E-01	7.5E-01	7.5E-01	7.5E-01	7.5E-01	7.5E-01	4.7E+01	4.7E+01	4.7E+01
Mercury (Hg)	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06
Molybdenum (Mo)	1.4E-03	5.1E-03	5.1E-03	5.1E-03	5.1E-03	5.1E-03	5.1E-03	5.1E-03	5.1E-03	5.1E-03
Nickel (Ni)	1.2E-02	1.3E-01	5.6E-01	3.2E-01	3.2E-01	8.6E-01	8.6E-01	1.8E+02	2.8E+02	7.6E+02
Phosphorous (PO_4)	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01
Potassium (K)	3.6E+01	4.9E+01	4.9E+01	4.9E+01	4.9E+01	4.9E+01	4.9E+01	3.8E+01	3.8E+01	3.8E+01
Selenium (Se)	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03
Silica (SiO_2)	8.7E+00	8.7E+00	8.7E+00	8.7E+00	8.7E+00	8.7E+00	8.7E+00	3.9E+00	3.9E+00	3.9E+00
Silver (Ag)	7.0E-04	7.0E-04	7.0E-04	7.0E-04	7.0E-04	7.0E-04	7.0E-04	7.0E-04	7.0E-04	7.0E-04
Sodium (Na)	7.5E+01	6.8E+02	6.8E+02	6.8E+02	6.8E+02	2.6E+02	6.8E+02	3.4E+02	3.4E+02	3.4E+02
Thallium (Tl)	2.0E-05	2.0E-05	2.0E-05	2.0E-05	2.0E-05	2.0E-05	2.0E-05	6.0E-05	6.0E-05	6.0E-05
Zinc (Zn)	6.7E-02	9.0E-02	9.0E-02	9.0E-02	9.0E-02	9.0E-02	9.0E-02	1.0E+01	1.6E+01	2.6E+01
Nitrate (NO_3)	2.5E-01	8.0E-01	1.3E+00	0.0E+00	0.0E+00	2.0E-01	1.3E-01	5.9E-02	8.7E-02	5.5E-01
Ammonia (NH_4)	2.5E-01	8.0E-01	1.3E+00	0.0E+00	0.0E+00	2.0E-01	1.3E-01	5.9E-02	8.7E-02	5.5E-01

Table 2. Mine Site Process Water Quality (continued)

Parameter (mg/L)	Category 3Lean Ore Stockpile (Years)					Category 4 Stockpile (Years)				
	1	5	10	15	20	1	5	10	15	20
Fluoride (F)	4.0E+00	1.3E+01	2.8E+01	6.7E+01	1.1E+02	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01
Chloride (Cl)	2.3E+01	9.6E+00	1.7E+01	6.0E+01	3.1E+01	7.2E-01	1.3E+01	4.5E+00	8.3E-01	5.2E+01
Sulfate (SO_4)	1.9E+03	2.3E+03	9.6E+03	9.6E+03	9.6E+03	3.4E+02	9.6E+03	9.6E+03	9.6E+03	9.6E+03
Aluminum (Al)	1.7E+00	1.7E+00	8.3E+01	8.3E+01	8.3E+01	2.5E+00	8.3E+01	8.3E+01	8.3E+01	8.3E+01
Arsenic (As)	7.1E-01	7.1E-01	7.1E-01	7.1E-01	7.1E-01	4.9E-03	2.8E-01	4.8E-01	6.1E-01	7.1E-01
Barium (Ba)	1.9E-01	1.9E-01	1.9E-01	1.9E-01	1.9E-01	3.6E-02	1.9E-01	1.9E-01	1.9E-01	1.9E-01
Beryllium (Be)	2.0E-04	2.0E-04	2.3E-03	2.3E-03	2.3E-03	2.3E-03	2.3E-03	2.3E-03	2.3E-03	2.3E-03
Boron (B)	7.6E-01	7.6E-01	7.6E-01	7.6E-01	7.6E-01	1.4E-01	7.6E-01	7.6E-01	7.6E-01	7.6E-01
Cadmium (Cd)	1.8E-04	1.8E-04	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02
Calcium (Ca)	4.6E+02	5.4E+02	4.8E+02	4.8E+02	4.8E+02	1.1E+01	4.8E+02	4.8E+02	4.8E+02	4.8E+02
Chromium (Cr)	1.5E-03	1.5E-03	1.5E-03	1.5E-03	1.5E-03	8.5E-04	1.5E-03	1.5E-03	1.5E-03	1.5E-03
Cobalt (Co)	5.2E-02	5.2E-02	3.8E+01	4.4E+01	4.4E+01	2.6E-01	1.5E+01	2.6E+01	3.3E+01	4.4E+01
Copper (Cu)	9.2E-02	9.2E-02	5.3E+01	1.3E+02	2.0E+02	3.3E-02	1.8E+00	3.2E+00	4.1E+00	1.1E+02
Iron (Fe)	8.1E-01	8.1E-01	7.0E+01	1.8E+02	2.4E+02	6.5E+01	2.4E+02	2.4E+02	2.4E+02	2.4E+02
Lead (Pb)	1.1E-02	3.6E-02	5.3E-02	5.3E-02	5.3E-02	7.8E-03	5.3E-02	5.3E-02	5.3E-02	5.3E-02
Magnesium (Mg)	6.5E+01	9.3E+01	1.0E+03	1.0E+03	1.0E+03	9.7E+00	5.5E+02	9.5E+02	1.0E+03	1.0E+03
Manganese (Mn)	7.5E-01	7.5E-01	4.7E+01	4.7E+01	4.7E+01	8.5E-01	4.7E+01	4.7E+01	4.7E+01	4.7E+01
Mercury (Hg)	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06
Molybdenum (Mo)	5.1E-03	5.1E-03	5.1E-03	5.1E-03	5.1E-03	1.8E-04	5.1E-03	5.1E-03	5.1E-03	5.1E-03
Nickel (Ni)	8.6E-01	8.6E-01	4.5E+02	7.6E+02	7.6E+02	3.9E+00	2.2E+02	3.8E+02	4.8E+02	7.6E+02
Phosphorous (PO_4)	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	1.2E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01
Potassium (K)	4.9E+01	4.9E+01	3.8E+01	3.8E+01	3.8E+01	1.1E+01	3.8E+01	3.8E+01	3.8E+01	3.8E+01
Selenium (Se)	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03
Silica (SiO_2)	8.7E+00	8.7E+00	3.9E+00	3.9E+00	3.9E+00	3.9E+00	3.9E+00	3.9E+00	3.9E+00	3.9E+00
Silver (Ag)	7.0E-04	7.0E-04	7.0E-04	7.0E-04	7.0E-04	2.0E-04	7.0E-04	7.0E-04	7.0E-04	7.0E-04
Sodium (Na)	3.3E+02	6.8E+02	3.4E+02	3.4E+02	3.4E+02	5.0E+00	2.8E+02	3.4E+02	3.4E+02	3.4E+02
Thallium (Tl)	2.0E-05	2.0E-05	6.0E-05	6.0E-05	6.0E-05	6.0E-05	6.0E-05	6.0E-05	6.0E-05	6.0E-05
Zinc (Zn)	9.0E-02	9.0E-02	2.6E+01	2.6E+01	2.6E+01	4.1E+00	2.6E+01	2.6E+01	2.6E+01	2.6E+01
Nitrate (NO_3)	2.5E-01	1.0E-01	1.8E-01	6.3E-01	3.3E-01	1.0E-02	1.8E-01	6.4E-02	1.2E-02	7.4E-01
Ammonia (NH_4)	2.5E-01	1.0E-01	1.8E-01	6.3E-01	3.3E-01	1.0E-02	1.8E-01	6.4E-02	1.2E-02	7.4E-01

Table 2. Mine Site Process Water Quality (continued)

Parameter (mg/L)	Lean Ore Surge Pile (Years)					East Pit (Years)		
	1	**5**	**10**	**15**	**20**	**1**	**5**	**10**
Fluoride (F)	1.8E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.6E-01	2.6E-01	2.6E-01
Chloride (Cl)	6.2E-01	5.6E-01	1.4E+00	2.7E-01	1.7E+00	1.3E+00	1.3E+00	1.3E+00
Sulfate (SO_4)	2.7E+02	4.8E+03	9.3E+03	9.6E+03	9.6E+03	9.5E+01	4.1E+01	5.1E+01
Aluminum (Al)	2.0E+00	3.5E+01	6.8E+01	8.3E+01	8.3E+01	6.0E-01	2.8E-01	3.3E-01
Arsenic (As)	3.8E-03	6.8E-02	1.3E-01	3.2E-01	2.9E-01	3.3E-02	1.2E-02	1.6E-02
Barium (Ba)	2.8E-02	1.9E-01	1.9E-01	1.9E-01	1.9E-01	2.7E-02	1.7E-02	1.9E-02
Beryllium (Be)	2.3E-03	2.3E-03	2.3E-03	2.3E-03	2.3E-03	3.8E-04	2.8E-04	3.0E-04
Boron (B)	1.1E-01	7.6E-01	7.6E-01	7.6E-01	7.6E-01	1.3E-01	9.8E-02	1.0E-01
Cadmium (Cd)	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	6.8E-04	5.6E-04	5.3E-04
Calcium (Ca)	8.4E+00	1.5E+02	2.9E+02	4.8E+02	4.8E+02	2.4E+01	1.6E+01	1.8E+01
Chromium (Cr)	6.6E-04	1.5E-03	1.5E-03	1.5E-03	1.5E-03	1.1E-03	1.1E-03	1.1E-03
Cobalt (Co)	2.1E-01	3.7E+00	7.1E+00	1.7E+01	1.6E+01	1.2E-02	1.0E-02	9.2E-03
Copper (Cu)	2.5E-02	4.5E-01	8.8E-01	2.1E+00	1.9E+00	9.4E-03	5.0E-03	5.9E-03
Iron (Fe)	5.1E+01	2.4E+02	2.4E+02	2.4E+02	2.4E+02	2.8E+00	2.5E+00	2.2E+00
Lead (Pb)	6.1E-03	5.3E-02	5.3E-02	5.3E-02	5.3E-02	1.6E-03	1.3E-03	1.3E-03
Magnesium (Mg)	7.5E+00	1.3E+02	2.6E+02	6.3E+02	5.7E+02	8.4E+00	8.0E+00	8.0E+00
Manganese (Mn)	6.6E-01	1.2E+01	2.3E+01	4.7E+01	4.7E+01	7.5E-02	5.6E-02	5.7E-02
Mercury (Hg)	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	5.1E-06	2.8E-06	3.1E-06
Molybdenum (Mo)	1.4E-04	2.4E-03	4.7E-03	5.1E-03	5.1E-03	4.6E-03	4.7E-03	4.7E-03
Nickel (Ni)	3.0E+00	5.4E+01	1.0E+02	2.5E+02	2.3E+02	1.6E-01	1.3E-01	1.2E-01
Phosphorous (PO_4)	9.7E-02	2.0E-01	2.0E-01	2.0E-01	2.0E-01	0.0E+00	0.0E+00	0.0E+00
Potassium (K)	8.2E+00	3.8E+01	3.8E+01	3.8E+01	3.8E+01	3.3E+00	1.3E+00	1.7E+00
Selenium (Se)	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.9E-03	2.0E-03	2.0E-03	2.0E-03
Silica (SiO_2)	3.9E+00	3.9E+00	3.9E+00	3.9E+00	3.9E+00	0.0E+00	0.0E+00	0.0E+00
Silver (Ag)	1.5E-04	7.0E-04	7.0E-04	7.0E-04	7.0E-04	9.2E-04	9.5E-04	9.5E-04
Sodium (Na)	3.9E+00	7.0E+01	1.4E+02	3.3E+02	3.0E+02	2.2E+01	6.7E+00	9.8E+00
Thallium (Tl)	6.0E-05	6.0E-05	6.0E-05	6.0E-05	6.0E-05	1.7E-03	1.9E-03	1.8E-03
Zinc (Zn)	3.2E+00	2.6E+01	2.6E+01	2.6E+01	2.6E+01	1.8E-01	1.6E-01	1.4E-01
Nitrate (NO_3)	7.9E-03	7.2E-03	1.8E-02	3.5E-03	2.2E-02	8.5E-02	9.3E-02	9.2E-02
Ammonia (NH_4)	7.9E-03	7.2E-03	1.8E-02	3.5E-03	2.2E-02	8.5E-02	9.3E-02	9.2E-02

Table 2. Mine Site Process Water Quality (continued)

Parameter (mg/L)	West Pit, Central Pit, Haul Roads (Years)					Rail Transfer Hopper (Years)				
	1	5	10	15	20	1	5	10	15	20
Fluoride (F)	2.6E-01	2.5E-01	2.5E-01	2.6E-01	2.6E-01	5.8E-02	5.8E-02	5.8E-02	5.8E-02	5.8E-02
Chloride (Cl)	1.3E+00	1.2E+00	1.2E+00	1.3E+00	1.3E+00	1.6E-01	1.6E-01	1.6E-01	1.6E-01	1.6E-01
Sulfate (SO_4)	1.6E+02	3.6E+02	3.8E+02	2.0E+02	1.1E+02	3.2E+01	3.2E+01	3.2E+01	3.2E+01	3.2E+01
Aluminum (Al)	1.1E+00	2.2E+00	2.3E+00	1.2E+00	6.5E-01	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02
Arsenic (As)	7.5E-02	1.5E-01	1.5E-01	8.3E-02	4.3E-02	1.9E-03	1.9E-03	1.9E-03	1.9E-03	1.9E-03
Barium (Ba)	6.1E-02	8.4E-02	8.4E-02	5.2E-02	3.2E-02	8.3E-03	8.3E-03	8.3E-03	8.3E-03	8.3E-03
Beryllium (Be)	4.5E-04	8.1E-04	8.5E-04	5.3E-04	3.7E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04
Boron (B)	1.5E-01	2.7E-01	2.8E-01	1.8E-01	1.3E-01	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02
Cadmium (Cd)	4.4E-04	8.3E-04	8.6E-04	5.4E-04	3.8E-04	3.1E-05	3.1E-05	3.1E-05	3.1E-05	3.1E-05
Calcium (Ca)	3.4E+01	6.2E+01	6.7E+01	4.1E+01	2.7E+01	1.0E+01	1.0E+01	1.0E+01	1.0E+01	1.0E+01
Chromium (Cr)	1.1E-03	1.2E-03	1.2E-03	1.1E-03	1.1E-03	1.4E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04
Cobalt (Co)	5.7E-03	8.6E-03	8.7E-03	6.1E-03	4.1E-03	4.0E-03	4.0E-03	4.0E-03	4.0E-03	4.0E-03
Copper (Cu)	2.0E-02	3.3E-02	3.5E-02	2.1E-02	1.2E-02	7.4E-03	7.4E-03	7.4E-03	7.4E-03	7.4E-03
Iron (Fe)	5.6E-01	1.4E+00	1.4E+00	8.3E-01	6.1E-01	1.0E-02	1.0E-02	1.0E-02	1.0E-02	1.0E-02
Lead (Pb)	1.5E-03	2.4E-03	2.5E-03	1.8E-03	1.4E-03	1.1E-04	1.1E-04	1.1E-04	1.1E-04	1.1E-04
Magnesium (Mg)	7.3E+00	1.0E+01	1.1E+01	9.0E+00	8.4E+00	2.2E+00	2.2E+00	2.2E+00	2.2E+00	2.2E+00
Manganese (Mn)	7.4E-02	1.3E-01	1.4E-01	8.7E-02	5.7E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02
Mercury (Hg)	6.0E-06	6.0E-06	6.0E-06	6.0E-06	5.7E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06	6.0E-06
Molybdenum (Mo)	3.3E-03	3.7E-03	3.9E-03	4.2E-03	4.6E-03	4.8E-05	4.8E-05	4.8E-05	4.8E-05	4.8E-05
Nickel (Ni)	6.8E-02	1.1E-01	1.1E-01	7.2E-02	4.5E-02	8.0E-02	8.0E-02	8.0E-02	8.0E-02	8.0E-02
Phosphorous (PO_4)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.1E-02	2.1E-02	2.1E-02	2.1E-02	2.1E-02
Potassium (K)	7.8E+00	1.3E+01	1.4E+01	7.7E+00	4.0E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00
Selenium (Se)	1.9E-03	2.1E-03	2.1E-03	2.1E-03	2.0E-03	1.6E-04	1.6E-04	1.6E-04	1.6E-04	1.6E-04
Silica (SiO_2)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.7E+00	1.7E+00	1.7E+00	1.7E+00	1.7E+00
Silver (Ag)	7.0E-04	7.1E-04	7.4E-04	8.3E-04	9.1E-04	3.5E-05	3.5E-05	3.5E-05	3.5E-05	3.5E-05
Sodium (Na)	4.6E+01	1.0E+02	1.1E+02	5.6E+01	2.8E+01	1.5E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00
Thallium (Tl)	1.0E-03	8.8E-04	9.3E-04	1.3E-03	1.7E-03	1.4E-05	1.4E-05	1.4E-05	1.4E-05	1.4E-05
Zinc (Zn)	2.9E-02	6.2E-02	5.6E-02	4.1E-02	3.7E-02	3.0E-03	3.0E-03	3.0E-03	3.0E-03	3.0E-03
Nitrate (NO_3)	5.1E-02	4.3E-02	4.5E-02	6.7E-02	8.2E-02	2.1E-03	2.1E-03	2.1E-03	2.1E-03	2.1E-03
Ammonia (NH_4)	5.1E-02	4.3E-02	4.5E-02	6.7E-02	8.2E-02	2.1E-03	2.1E-03	2.1E-03	2.1E-03	2.1E-03

Based on these water quality predictions, process water generated at the Mine Site will need to be treated before it can be piped to the Plant Site. The variation in the expected water quality and quantity for each of the Mine Site process water streams has implications for the sizing and selection of wastewater treatment technologies. The impact of this variability is discussed in Section 5.

2.2 Plant Site Process Water

2.2.1 Plant Site Process Water Quantity

Process water at the Plant Site is consumed in two distinct plants: the Beneficiation Plant and the Hydrometallurgical Plant. Other than the exchange of the concentrate from the Beneficiation Plant to the Hydrometallurgical Plant, the water operations within these two plants operate independently. Water that enters the Hydrometallurgical Plant is not returned to the Beneficiation Plant or the tailings basin for future treatment or reuse. Instead all water that enters the Hydrometallurgical Plant is consumed within the hydrometallurgical processes – either exiting as steam or being entrained within the solid waste residues or products generated by the hydrometallurgical process. The average annual water demand rate for the Hydrometallurgical Plant is expected to be 370 gpm. However, the monthly rate of water consumption in the Hydrometallurgical Plant will vary from 0 to 600 gpm based on operating and climate conditions.

Hydrometallurgical process residues (primarily gypsum salts) will be disposed in hydrometallurgical residue cells. During operations, the ponded water in the hydrometallurgical residue cells will be returned to the Hydrometallurgical Plant. At closure of the plant, the hydrometallurgical residue water will be transported to the Mine Site for treatment and then discharged into the wetlands on the reclaimed surface of the East Pit. Additional details on treatment of the hydrometallurgical cell water during closure are described in RS52.

Process water in the Beneficiation Plant will be used to carry the ore through a series of grinding and separation steps and then to transport the tailings to the tailings basin. The process water that is used to transport tailings to the basin is then returned to the Beneficiation Plant to the extent practical. However, some losses occur.

The tailings basin is the central focus for the overall water balance at the Plant Site. The tailings basin is the final collection and equalization basin for process water that flows through the Beneficiation Plant. Direct precipitation and run-off from process areas at the Plant Site are also directed to the tailings basin. Process water that may otherwise be lost to surface water from seeps around the perimeter of the tailings basin is captured and returned to the basin. The collection of seep water will help to protect surface water quality (by eliminating a discharge) and to minimize the volume of make-up water required. The primary losses of water from the tailings basin system include evaporation, loss to storage within the pores of the deposited tailings, and water that moves to the deep groundwater beneath the tailings basin. These water losses will be made-up by a combination of treated Mine Site process water and, if necessary, new water from Colby Lake.

A detailed evaluation of the process water balance for the tailings basin has been prepared and is included in RS13A. Figure 3 summarizes the primary flow components of the tailings basin process water balance. The water balance model for the tailings basin shows that wastewater discharge from the tailings basin to surface water is not required to maintain an adequate working volume within the tailings basin.

2.2.2 Plant Site Process Water Quality

A detailed evaluation of the water quality within the tailings basin is included in RS54A/RS46. This model incorporates the predicted effluent quality from the WWTF at the Mine Site estimated in Section 5 of this report.

The tailings basin equalizes water quality at the Plant Site in the same manner that it equalizes flows. The quality of water in the tailings basin is dependent on the variability and nature of all of the sources, as well as chemical reactions that may occur within the tailings basin or Beneficiation Plant. The quality of the process water in the tailings basin has been estimated by combining the volumetric inputs to the basin with chemical inputs from the beneficiation process, the make-up water (in the form of treated water from the Mine Site or from Colby Lake), return seepage, run-on to the basin, and chemical reactions occurring within the basin. Of these flows, the dominant source of dissolved chemicals is expected to be the treated wastewater from the Mine Site. Thus, the water quality within the basin will be dependent on the type of wastewater treatment implemented at the Mine Site.

One of the objectives for wastewater treatment at the Mine Site will be to maintain the quality of the water in the tailings basin so that it can be recycled through the Beneficiation Plant. In addition, any water that leaves the basin, eventually entering the groundwater regime, would need to have adequate quality to protect the groundwater resource. These two criteria have been used to establish treatment goals for tailings basin process water in this report.

Within the basin the predominant chemical activities are continued oxidation of tailings exposed to intermittent weathering (for example on beaches), settling and filtration of fine particles during seepage through the tailings, and adsorption or precipitation of chemicals onto the solid surfaces of the tailings.

3.0 Process Water Quality Targets

In this section, water-quality-based process targets for wastewater treatment are developed for both the Mine Site and Plant Site process waters. The parameters of concern addressed in this section, as described in Phase 1 of the SOW for RS29T are pH, metals, mercury, sulfate, salinity, nutrients, and organics. Although no water is expected to be discharged to surface waters at either the Mine Site or the Plant Site, these process targets have been developed as benchmarks for the evaluation of potential wastewater treatment technologies, which are described in Section 4. Treatment of wastewater to these process targets would significantly reduce the need for contingency planning or other regulatory requirements that may otherwise be needed to pipe process water from the Mine Site to the tailings basin or to store process water within the tailings basin.

The process water quality targets are based on potential discharge limits for surface water and groundwater. Water that is stored in the tailings basin with concentrations below the surface water quality discharge limits has no potential to adversely impact surface water quality in the event that water would need to be released, or would potentially seep from the basin to surface water. Similarly, water that is lost from the tailings basin to groundwater will not impact the quality of the groundwater if it already meets limits that have been established to prevent degradation of the groundwater resource. Thus, by considering both surface water and groundwater standards in the development of process water quality targets, those targets are conservative.

While discharge of treated process waters to surface waters will be eliminated during operations, potential discharge to surface water may occur after closure. The surface water discharge criteria for water that may be treated and discharged to surface water after closure will be addressed in RS52.

3.1 Potential Surface Water Quality Standards

Both the Mine Site and the Plant Site are located within the Lake Superior watershed basin, more specifically within the upper reaches of the St. Louis River watershed. The Mine Site is located within the Partridge River watershed, which flows into the St. Louis River. The Process Plant is also located within the Partridge River watershed. A portion of the tailings basin is located within the Partridge River watershed in the headwaters to Knox Creek (Second Creek). The majority of the tailings basin is located within the Embarrass River watershed. The Embarrass River flows into the St. Louis River downstream of the confluence of the Partridge and St. Louis Rivers.

In-stream surface water quality standards for both the Embarrass River and the Partridge River have been established by the State of Minnesota. Both the Partridge River and the Embarrass River are classified by the State of Minnesota as Class 2B waters in accordance with Minnesota Rules[1]. The water quality standards for Class 2B streams have been established to protect aquatic life as well as recreational uses. In addition, because these surface waters are part of the Lake Superior Basin watershed, additional water quality rules for certain parameters such as dissolved metals supersede the general Class 2B rules[2]. Combining the information from these two rules, the in-stream surface water quality values for parameters potentially significant to the NorthMet operation are listed in Table 3. A hardness of 400 mg/L was assumed in order to calculate the hardness-dependent metals standards, as it is likely that the treated water will have hardness from lime treatment. Potential surface water standards for lower stream classifications may also be applicable to Class 2B waters to protect the use of the water for other uses. Although these additional standards are not needed to protect aquatic life, they are also included in Table 3.

Because these surface water standards presented in Table 3 are the ‘in stream’ concentrations, they represent conservative values for process water quality targets because process water will not be discharged to surface waters and any actual surface water discharge limits would be developed with consideration of base flow conditions and the potential for mixing within the stream.

---

[1] MN Rule 7050.0222 Subpart 4.

[2] MN Rule 7052.0222 Subpart 5

Table 3 Potential Water Quality Standards

Parameter	Surface Water Quality Standard[1] (µg/L, unless noted)	Groundwater Protection Standard (µg/L, unless noted)	Drinking Water Standard (µg/L, unless noted)
Metals/Inorganics			
Aluminum	125		50-200 (S)
Antimony	31	6	6
Arsenic	53		10
Barium		2,000	2,000
Beryllium		0.08	4
Boron	500 (4A)	600	
Cadmium	7.3	4	5
Chromium (+3)	268	20,000	100
Chromium (+6)	11	100	
Cobalt	5	30 (S)	
Copper	30	1,000 (S)	1,300 (1,000 - S)
Iron			300 (S)
Lead	19		15
Manganese		1,000	50 (S)
Mercury	0.0013	2	2
Molybdenum		100 (S)	
Nickel	168	100	100
Selenium	5	30	50
Silver	1	30	100 (S)
Thallium	0.56	0.6	2
Zinc	388	2,000	5,000 (S)
General Parameters			
Ammonia (un-ionized)	40		
Bicarbonate (meq/L)	5 (4A)		
Chloride (mg/L)	230 (100 – 3B)		250 (S)
Cyanide (free)	5.2	100	200
Dissolved Oxygen (mg/L)	>5.0		
Fluoride (mg/L)		4	4 (2-S)
Hardness(mg/L)	250 (3B)		
Nitrate (mg/L)		10	10
Oil	500		
pH (su)	6.0-9.0		
Sodium	60 percent of cations (4A)		
Specific Conductance(uhmos/cm)	1,000 (4A)		
Sulfate	10 (4A[2])		250 (S)
Total Dissolved Solids	700 (4A)		500 (S)
Total Salinity (mg/L)	1,000 (4B)		
Turbidity (NTU)	25		

Notes:

1. Surface Water Standards are for Class 2B waters unless noted
2. Only when wild rice is present

3.2 Potential Groundwater Quality Standards

While direct seepage to surface waters or wetlands will be actively controlled, PolyMet recognizes that deep seepage to groundwater will occur during operation of the tailings basin and after closure. The State of Minnesota has established Rules for the protection of groundwater resources[3]. In addition, the U.S. EPA has established regulations to protect human health by limiting contaminants in drinking water[4].

PolyMet is the closest groundwater user to the tailings basin. A shallow bedrock well is located approximately one-mile to the southwest of the tailings basin near the offices. The next closest groundwater users are residential wells a minimum of 1.5 miles north of the tailings basin. While these distances provide considerable buffer between the tailings basin and potential groundwater users, the use of groundwater standards as process water quality targets within the basin provides additional conservatism as they are intended to be protective of human health at the actual point of use. The State of Minnesota groundwater standards and the U.S. EPA drinking water standards are summarized in Table 3.

3.3 Anticipated Process Water Quality Targets

Using the potential surface water quality standards and the potential groundwater quality standards, anticipated process water quality targets have been developed for the parameters of concern listed in the Work Plan for RS29T. Anticipated targets have been developed for both Mine Site process water and for Plant Site process water (the tailings basin). These values are summarized in Table 4. These values will provide the benchmark that will be used to evaluate the treatment of Mine Site and, if necessary, Plant Site process water in the following sections.

---

[3] MN Rules 4717.7100 to 4717.7800

[4] 40 CFR 141 (National Primary Drinking Water Regulations) and 40 CFR 143 (National Secondary Drinking Water Regulations).

Table 4 Process Water Quality Targets

Parameter	Process Water Quality Target (µg/L, unless noted)	Standard	Class/Basis
Metals/Inorganics			
Aluminum	125	Surface Water	2B – Aquatic Life
Antimony	31	Surface Water	2B – Aquatic Life
Arsenic	10	Drinking Water	Primary/Human Health
Barium	2,000	Drinking Water	Primary/Human Health
Beryllium	4	Drinking Water	Primary/Human Health
Boron	500	Surface Water	4A – Irrigation
Cadmium	4	Ground Water[1]	Human Health
Chromium (+3)	100	Ground Water	Human Health
Chromium (+6)	11	Surface Water	2B – Aquatic Life
Cobalt	5	Surface Water	2B – Aquatic Life
Copper	30	Surface Water	2B – Aquatic Life
Iron	300	Drinking Water	Secondary
Lead	19	Surface Water	2B – Aquatic Life
Manganese	50	Drinking Water	Secondary
Mercury	0.0013	Surface Water	2B – Aquatic Life
Molybdenum	100	Drinking Water	Secondary
Nickel	100	Ground Water[1]	Human Health
Selenium	5	Surface Water	2B – Aquatic Life
Silver	1	Surface Water	2B – Aquatic Life
Thallium	0.56	Surface Water	2B – Human Health
Zinc	388	Surface Water	2B – Aquatic Life
General Parameters			
Ammonia (un-ionized)	40	Surface Water	2B – Aquatic Life
Bicarbonate (meq/L)	5	Surface Water	4A – Irrigation
Chloride (mg/L)	230	Surface Water	2B – Aquatic Life
Cyanide (free)	5.2	Surface Water	2B – Aquatic Life
Dissolved Oxygen (mg/L)	>5.0	Surface Water	2B – Aquatic Life
Fluoride (mg/L)	2	Drinking Water	Secondary
Hardness(mg/L)	250	Surface Water	3B – Industrial
Nitrate (mg/L)	10	Drinking Water	Primary
Oil	500	Surface Water	2B
pH (su)	6.0-9.0	Surface Water	2B
Sodium	60% of cations	Surface Water	4A – Irrigation
Specific Conductance (uhmos/cm)	1,000	Surface Water	4A – Irrigation
Sulfate	250	Drinking Water	Secondary
Total Dissolved Solids	700	Surface Water	4A – Irrigation
Total Salinity (mg/L)	1,000	Surface Water	4B – Livestock
Turbidity (NTU)	25	Surface Water	2B

Notes:

1. Ground water standard is more conservative at 400 mg/L hardness

When comparing these process water quality targets to the predicted process water quality at the Mine Site (Table 2), the following objectives for wastewater treatment are identified:

- Mine Site process water will likely need to be treated to remove metals, including aluminum, antimony, arsenic, cobalt, copper, iron, manganese, mercury, nickel, selenium, thallium, and zinc.

- Mine Site concentrations of sulfate and hardness, along with the related parameters of TDS and conductivity will likely also require treatment to reduce long-term build-up of these parameters in the tailings basin. Salinity, in particular sodium and chloride, do not appear to be present at concentrations that would require treatment.

- Plant Site process water will not need to be treated provided the treatment of Mine Site process water, prior to use as make-up water, is adequate to maintain the water quality in the tailings basin below the process water quality targets.

These potential treatment needs will be addressed in the identification and evaluation of potential treatment technologies in the following sections.

4.0 Summary of Potential Wastewater Treatment Technologies

This section contains a summary of information on potential wastewater treatment technologies. As described in the SOW, the primary technologies to be considered in this report are: chemical precipitation, reverse osmosis, ion exchange, constructed wetland, and membrane technology. Because reverse osmosis is a specific type of membrane technology, these processes are described together. Other potential biological treatment options, for example biological sulfate reduction, are considered with wetland processes. This summary is not intended to be a comprehensive review of all literature available on the treatment of mine water, as the available publications on this topic are extensive. Rather, this review relies on examples where the proposed treatment technologies have been employed on water with quality as close to the predicted quality of the Mine Site process water as possible.

The parameters of potential concern listed in the SOW and discussed in the previous section included pH, metals, mercury, sulfate, salinity, and nutrients. These parameters will be discussed in this section in relation to the treatment technologies identified. However, the primary parameters considered in this evaluation are metals and sulfate. For the purposes of this evaluation, the Mine Site water quality presented in Table 2 is considered the potential influent for a wastewater treatment facility (WWTF).

While pH is a potential parameter of concern, it is also – in the case of many wastewater treatment systems – an operational control parameter. The pH of the Mine Site process water will likely need to be modified during treatment operations and will be adjusted to within the target range as a final treatment step. Similarly, the concentrations of nutrients in the Mine Site process water are relatively low and while they are not likely to interfere with potential physical or chemical treatment systems evaluated in this section, they would likely need to be supplemented for the operation of biological treatment system. While nutrients would be a potential concern if discharged to surface water, the elimination of a direct discharge to surface water from the site helps to reduce the potential concern associated with nutrients in process water and the predicted concentrations of nitrogen and phosphorous (Table 2) do not suggest that these parameters will be a concern in the tailings basin.

Mercury is present at very low concentrations in the waste rock and in the precipitation that enters the Mine Site. Both of these sources contribute to the mercury load in the drainage from the waste piles. While the effectiveness of the treatment systems evaluated in this section will consider mercury treatment, the water management plan envisions the discharge of treated Mine Site process water to the tailings basin rather than to surface water. Discharging the treated Mine Site process water into the tailings basin will provide additional mercury removal/treatment because it has been shown that mercury will adsorb to taconite tailings and NorthMet tailings. Additional laboratory testing conducted on behalf of PolyMet is included in Appendix B. This work supports the observation that mercury is adsorbed by tailings. Thus, a majority of the mercury that remains in the treated Mine Site process water will be absorbed and ultimately buried in the tailings basin prior to discharge to groundwater. The NorthMet Project mercury mass balance is provided in RS66.

Organics (e.g., DRO, GRO and flotation reagents) were also identified as parameters of potential concern, but these are not expected to be present in the Mine Site process water. While fuels containing these materials will be used at the Mine Site, these chemicals would only be associated with wastewater as a result of spills, rather than routine operations. Containment of spills related to fueling operations is addressed in the SPCC plans for the Mine Site and the Plant Site (ER05 and ER06). For this reason, these chemicals are not addressed in this section. Other organics used in the Beneficiation Plant that will report to the tailings basin will be easily degraded or deposited with the tailings to provide a long-term oxygen demand from the tailings basin that will reduce future oxidation and release of inorganics. These parameters are considered in process water from the Beneficiation Plant in Section 6.

4.1 Chemical Precipitation

4.1.1 Technology Description

Chemical precipitation treatment technologies for wastewater treatment rely on the insolubility of various chemical compounds to remove chemicals of concern. In general, one or more chemicals can be removed from the waste stream by the addition of other chemicals that will combine to form insoluble products that can be separated from the liquid stream. A chemical precipitation operation would consist of chemical addition, rapid mixing, coagulation, flocculation, and settling processes, which would facilitate the formation and physical separation of the precipitate from the water. Filtration could be used as a final polishing step for the water, if necessary. A filter press operation would be used to remove as much water as possible from the solids. The treated water would then be piped to the tailings basin for reuse while the dewatered solids could either be introduced into the hydrometallurgical process or disposed with the hydrometallurgical residues.

Several potential chemicals can be used to treat the process water from the Mine Site. Some chemicals used in chemical precipitation processes will increase the pH (for example hydrated lime, $Ca(OH)_2$) to facilitate precipitation, while others require the addition of supplementary chemicals to control pH within an optimum range to precipitate the desired chemical compound. The advantages and disadvantages of various chemical precipitation techniques for removal of metals and sulfates (or other salts) are discussed in the following sections.

4.1.2 Metal Precipitation Technologies

4.1.2.1 Hydroxide Precipitation

Hydroxide precipitation treatment is primarily used for the removal of heavy metals. Soluble heavy metal ions are converted to insoluble metal-hydroxide precipitates that can be physically removed from the water. Iron, manganese, and potentially magnesium also form precipitates that can be removed, and in the case of iron and manganese, the solid hydroxides facilitate co-precipitation of heavy metals and arsenic as well as nutrients such as phosphorous from the water. The addition of soluble iron to the process can enhance the co-precipitation process, if necessary, to improve the removal of metals.

Hydroxide precipitation is accomplished by adjusting the pH of the water to alkaline conditions (generally around pH 10). The most common hydroxide precipitating agents are hydrated lime ($Ca(OH)_2$), caustic soda (NaOH), or magnesium hydroxide ($Mg(OH)_2$). However, other alkaline materials, such as Bauxol, cement kiln dust, or flyash could also be used. In mine wastewater treatment, lime is the most common agent because the added calcium will combine with sulfate to form gypsum ($CaSO_4$-$2H_20$) when excess sulfate is present. Excess calcium is also easier to subsequently remove from the water than sodium, potassium, or trace contaminants that could be introduced from other alkaline waste materials.

The solubility products for several metal hydroxides are summarized in Table 5. Because many dissolved metals – including copper, nickel and zinc – exhibit amphoteric behavior (where a soluble metal-hydroxide complex is stable when the pH exceeds that associated with the minimum solubility), the optimum pH for hydroxide precipitation varies with changes in the influent metal characteristics. For example, nickel is removed effectively at pH 10, while copper is removed at pH 8. A single-stage hydroxide precipitation system could be designed to remove both nickel and copper if sufficient iron and manganese are available to act as co-precipitates. Otherwise, a multi-stage process, or additional iron salts may be needed to optimize removal of both these metals.

Nickel hydroxide precipitation is also subject to competition with dissolved iron. Thus, sufficient lime and residence time are required to facilitate removal of both iron and nickel.

Table 5: Solubility Products for Various Metal Hydroxides, Carbonates, and Sulfides

Metal	Hydroxide	Hydroxide Solubility Product	Carbonate	Carbonate Solubility Product	Sulfide	Sulfide Solubility Product
Nickel	$Ni(OH)_2$	2.0×10^{-15}	$NiCO_3$	6.6×10^{-9}	NiS	3×10^{-19}
Copper	$Cu(OH)_2$	2.2×10^{-20}	$CuCO_3$	1.4×10^{-10}	CuS	6×10^{-37}
Cobalt	$Co(OH)_2$	1.6×10^{-15}	$CoCO_3$	1.4×10^{-13}	CoS	4.0×10^{-21}
Zinc	$Zn(OH)_2$	1.2×10^{-17}	$ZnCO_3$	1.4×10^{-11}	ZnS	2×10^{-25}
Iron	$Fe(OH)_2$	8.0×10^{-16}	$FeCO_3$	3.2×10^{-11}	FeS	6×10^{-19}
Calcium	$Ca(OH)_2$	5.5×10^{-6}	$CaCO_3$	3.8×10^{-9}	CaS	

At NorthMet, the hydroxide precipitation process would likely consist of chemical addition and rapid mixing to raise the pH, coagulation and flocculation to allow the precipitates to form, physical (gravity) settling to remove the floc from the water, filtration (as necessary), and a final pH neutralization step. If lime is used to raise the pH, carbon dioxide or sodium bicarbonate would be used for neutralization so that additional calcium can be precipitated as calcium carbonate and removed during the neutralization step, reducing the hardness of the treated water.

The solids generated by this operation would be filter-pressed to remove any water, which would be returned to the water treatment operation. The dewatered solids would contain hydroxides and could either be introduced into the hydrometallurgical process or disposed with the hydrometallurgical residues from the hydrometallurgical process. A portion of the solid precipitate can also be recycled to the beginning of the chemical precipitation process to stimulate the initial crystallization process. This variation of chemical precipitation treatment is commonly referred to as a high-density-sludge (HDS) operation.

The primary advantages of hydroxide precipitation are that it is a well-established and simple technology and that it is relatively inexpensive when compared to other treatment technologies. For these reasons, lime treatment is perhaps the most commonly used treatment for removing heavy metals from mining wastewaters. The primary disadvantage with hydroxide precipitation is that some metals like manganese may not be adequately treated. In addition, some metals require either oxidation or reduction before they can be effectively precipitated as hydroxides. For example, selenium (+6) should be reduced to selenium (+4), while arsenite (+3) should be oxidized to arsenate

(+5) to enhance precipitation. Oxidizing cobalt (+2) to cobalt (+3) also greatly enhances removal via hydroxide precipitation.

Bench-scale testing of metal hydroxide precipitation was conducted to evaluate potential application of this technology to the Mine Site process water. A sample of wastewater from the Dunka waste rock stockpiles, located near the PolyMet site, was used as the influent water for the bench-scale testing. The results of this testing are summarized in RS45 and included with this report in Appendix C. The results of this work show that, with the exception of mercury, all of the metals concentrations can be reduced to below the process water quality targets (see Table 9 of Attachment C2 in Appendix C).

4.1.2.2 Sulfide Precipitation

The sulfide precipitation process involves the conversion of soluble metal compounds to relatively insoluble sulfide compounds through the addition of precipitating agents such as: sodium sulfide (Na_2S), sodium hydrosulfide (NaHS), ferrous sulfide (FeS) and calcium sulfide (CaS). As shown in Table 5, metal the solubility product of metal sulfides are generally two or more orders of magnitude less than the solubility product of comparable metal hydroxides. Additionally, metal sulfides do not exhibit amphoteric behavior, and are less sensitive to changes in pH. Efficient metal sulfide precipitation can be achieved over a wide pH range (2 to 12). However, high pH (pH>7) is required to prevent formation of hydrogen sulfide (H_2S) gas. The kinetic rate for the formation of a sulfide precipitate is faster than hydroxide precipitation, resulting in a lower required retention times for reaction vessels.

The primary disadvantages of metal sulfide precipitation technology are: potential production of H_2S gas, potential residual sulfide in treatment effluent, higher capital and operating costs than hydroxide precipitation, increased process complexity compared to hydroxide precipitation, and potential difficulties with floc settlement.

Operationally, sulfide precipitation would be similar to hydroxide precipitation. The process would likely be initiated with a lime addition step and rapid mix tank to raise the pH. Any precipitation that occurs as a result of this step could be segregated using a conventional coagulation, flocculation and settling operation or could remain suspended during the next phase of treatment. Next, sulfide would be added to the high pH water using another sequence of chemical feed, rapid mix, coagulation, flocculation, and settling. A filtration step may also be needed at the end. Other variations on the sequence of operation could also be considered to match the specific type of sulfide reagent used in the process. The two most commonly used sulfide precipitation processes, soluble sulfide precipitation (SSP) and insoluble sulfide precipitation (ISP), are summarized in Table 6.

Table 6 Comparison of Sulfide Precipitation Technologies

Process	Chemical(s)	Advantages	Disadvantages	Safety Measures
Soluble Sulfide Addition	• Sodium Sulfide (Na_2S) • Sodium Hydrosulfide (NaHS)	• High solubility of these precipitating agents allows the use of high sulfide concentrations in the reaction chamber, causing rapid precipitation of metal sulfides. • Operation can generally achieve very low effluent concentrations.	• Formation of small (pin) floc that may have poor settling characteristics and often requires the addition of a polymer or other chemical to aid in the coagulation of a settleable or filterable precipitate. • Potential to generate hydrogen sulfide gas. • Potential for residual sulfide in the effluent. • Soluble sulfide dose must be sufficient to remove both iron and nickel.	• Gas generation is mitigated by operating at an elevated pH • Sulfide quenching chemicals used to control the residual concentration of dissolved sulfide in effluent.
Insoluble Sulfide Addition	Ferrous Sulfide (FeS) – Sulfex Process (EPA 625/8-80-003).	• Metals with a lower solubility product than iron will exchange with iron and be precipitated as sulfides. • Process works well for metals such as copper and zinc where the solubility product of the metal sulfide is several orders of magnitude less than FeS.	• Solubility products for NiS and FeS are similar (same order of magnitude). • Nickel must be present at concentrations greater than Fe^{2+} for removal to occur. • FeS is unstable and must be generated onsite. • Sulfex process typically requires 2 to 4 times the stoichiometric amount of FeS • Large amount of sludge (up to 3 times more than lime precipitation) is produced.	• Low solubility of FeS limits H_2S production and effluent sulfide concentrations.
	Calcium sulfide (CaS)	• Calcium particles act as nuclei for metal-sulfide precipitates. • CaS precipitation is capable of lower effluent nickel concentrations than Sulfex process. • CaS precipitation provides less sludge than Sulfex process.		• Limited solubility of CaS minimizes the potential for H_2S generation and sulfide overdose.

Testing of sulfide precipitation was planned for the bench scale chemical precipitation testing, however, this work was not completed because the hydroxide precipitation test, using a HDS simulation (solids recycle) was capable of achieving concentrations below the process water quality targets for all parameters other than mercury.

4.1.2.3 Carbonate Precipitation

The carbonate precipitation process uses a carbonate precipitating agent such as soda ash (Na_2CO_3), sodium bicarbonate ($Na(HCO_3)_2$), or calcium carbonate ($CaCO_3$). Calcium carbonate results in faster precipitation kinetics, but greater sludge volume than sodium carbonate. The optimum pH range for carbonate precipitation is 7 to 9. In this pH range, metal carbonate precipitates are generally less soluble than metal hydroxides, but more soluble than metal sulfides. Additionally, at this range, pH adjustment after precipitation would not be required. The advantages of carbonate precipitation include: carbonate sludge may be more amenable to subsequent metals recovery than hydroxide sludge, carbonate reagents are relatively easy to handle, and lower pH conditions are required for optimum treatment.

The disadvantages of this process are: carbonate sludge is gelatinous and difficult to settle, and the similarity in solubility products for calcium carbonate and nickel carbonate makes the removal of nickel via carbonate precipitation difficult. If the dissolved Ca^{2+} is assumed to be in equilibrium with $CaCO_3$, the minimum effluent nickel concentration that can be achieved via carbonate precipitation is 3.6 mg/L. Likewise, carbonate precipitation of copper and cobalt (2+) results in minimum effluent concentrations of 85 μg/L, and 59 μg/L, respectively. Zinc, iron, and manganese carbonate precipitation result in minimum effluent concentrations of 8.7 μg/L, 0.5 μg/L, and 12.4 μg/L, respectively. Thus, while carbonate precipitation may be able to meet zinc, manganese, and iron process standards, it is likely insufficient to achieve the process water quality targets for nickel, cobalt, or copper. Because carbonate precipitation would only be applicable to a limited number of metal parameters, no bench scale testing of this process was considered.

4.1.2.4 Xanthate Floatation

Xanthates are sulfonated organic compounds that are able to exchange sodium or potassium for heavy metals. High pH (>9) is typically required. The exchange of heavy metals with sodium results in precipitation of the xanthate-metal complex. The main disadvantage of this process is the large amount of sludge generated. Advantages of this process are: the process is less sensitive to pH fluctuations and is capable of removing selective metals. In addition, this process is operationally similar to the chemical separation process that will be used in the flotation plant to separate the concentrate from the ore. Thus, any solids generated in this process may be more amenable to further processing and metal recovery in the hydrometallurgical process with less impact to the operation than other potential wastewater solids. This operation was considered less favorable than hydroxide precipitation and no bench-scale testing of this operation was considered.

4.1.3 Chemical Precipitation Technologies for Sulfate and other Salts

Sulfate, phosphorous, nitrate and several other dissolved solids, in addition to metals as described above, can also be removed using various chemical precipitation technologies. In general, these technologies work better for divalent cations and anions, and for larger compounds. If necessary, some of these chemical technologies can be modified to remove chloride, potassium, and larger monovalent cations. Because the modeling of water quality in the tailings basin did not show that sodium, potassium, chloride, phosphorous, or nitrate were likely to be at concentrations of concern in the beneficiation process or the tailings basin, the following discussion of chemical treatment technologies is focused primarily on the removal of sulfate.

4.1.3.1 Lime Treatment Processes

Treatment of sulfate laden mine waters with calcium, either in the form of calcium carbonate or hydrated lime, as discussed for heavy metals removal, will result in the precipitation of gypsum ($CaSO_4$-$2H_2O$) when sulfate is present at concentrations that exceed the solubility of gypsum. This generally occurs when the concentration of sulfate exceeds 1,500 mg/L. However, gypsum crystals form slowly and the onset of precipitation can be delayed resulting in concentrations in solution that exceed those expected by solubility (Abdel-Aal, et. al., 2004). To increase the rate at which the gypsum precipitate will form, the HDS process is commonly used.

4.1.3.2 Ultra High Lime Processes

In conventional lime treatment, where the influent concentration of sulfate is high enough to promote gypsum precipitation, the concentration of sulfate in the effluent is generally on the order of 1,500 mg/L. The effluent sulfate concentration is limited by the solubility of gypsum, which is also a function of the calcium concentration. The molar ratio of calcium to sulfate at saturation is typically on the order of 0.3 (Abdel-Aal, et. al., 2004). Thus, increasing the concentration of calcium in solution can result in a further reduction of sulfate along with silica and other oxyanions. This concept has been demonstrated in the ultra-high lime process (Batchelor, et. al., 1991). In this process, higher doses of lime are added to the water, raising the pH to between 11 and 12. In the presence of higher pH additional magnesium will precipitate and additional calcium will combine with silicates as well as sulfate to further reduce the concentration of dissolved anions. While this process is commonly used to treat air pollution control scrubber waters, it has not been used extensively in mine wastewater applications.

4.1.3.3 Ultra High Lime with Aluminum

New methods for the precipitation of additional sulfate – beyond values achievable by gypsum precipitation alone – have been developed by adding aluminum salts to the ultra-high lime process. This form of chemical precipitation for sulfate removal has been investigated in several configurations for the treatment of mine wastewater (Lorax, 2003). Two of these potential processes have been evaluated at the pilot-scale or larger – the SAVMIN process and the Walhalla^{TM} process. Both of these technologies use a multi-step treatment train that begins with conventional lime treatment to remove sulfate as gypsum. After this initial treatment, aluminum is added in a follow-up step to form calciumaluminosulfate ($Ca_6(Al(OH)_6)_2)(SO_4)_3*26H_2O$), which is also referred to by the mineral name ettringite and is virtually insoluble when the pH is maintained between approximately 11.4 and 12.4. The high pH requirement for the formation of this precipitate makes this process well-suited as an add-on technology for conventional or high-lime treatment processes.

The SAVMIN process, which has been demonstrated at the pilot-scale, uses aluminum hydroxide as the aluminum source (Smit and Sibilski, 2003). Using a wastewater with an influent sulfate concentration of approximately 700 mg/L, the potential effluent sulfate concentrations reported from this operation were less than 100 mg/L. The unique component of the SAVMIN is the use of a pH reduction step following ettringite precipitation. This step dissolves the ettringite, promotes the re-precipitation of sulfate as gypsum, and allows the aluminum hydroxide to be recovered for re-use in the ettringite precipitation operation. This operation saves money by reducing the cost for aluminum, and converts the precipitate to a more stable form, because gypsum is stable across a wide range of pH values.

The Walhalla™ process uses a proprietary chemical – SX-44 – to precipitate ettringite, and has been pilot-tested using sulfate laden mine water from the Berkeley Pit in Montana (EPA, 1999). In a series of tests using water with an initial sulfate concentration of up to 8,000 mg/L, the Walhalla process was capable of reducing the effluent sulfate concentration to less than 500 mg/L, the target effluent concentration for the study. This result was obtained by varying the concentration of SX-44 reagent added to the process and the retention time used to allow the ettringite precipitation reaction to occur. The preferred operating values were a reagent addition rate of approximately an equal mass of SX-44 to sulfate and a reaction time of approximately 90 minutes. The primary differences between the Walhalla process and the SAVMIN process include the replacement of generic aluminum hydroxide with SX-44, which is obtained from the cement industry, and elimination of the ettringite dissolution step. While both processes have been shown to remove significant sulfate from mine wastewaters, recycling of the aluminum in the SAVMIN process significantly lowers the cost of this technology in comparison to the Walhalla process.

4.2 Reverse Osmosis and other Membrane Technologies

4.2.1 Technology Description

Reverse osmosis (RO) and other membrane technologies separate water from a mixed solution containing suspended and dissolved solids by forcing the water molecules through a semi permeable membrane (nmfrc.org). In general, membranes technologies work by passing water while retaining the suspended or dissolved items that are removed from the water.

Membranes are divided into four basic categories by decreasing pore size – microfiltration, ultrafiltration, nanofiltration, and RO. Microfiltration and ultrafiltration are generally not capable of removing ‘dissolved’ constituents, but are very good at removing small particulates or suspended solids. For this reason, microfiltration or ultrafiltration are often used as pre-treatment for nanofiltration or RO operations, and would be suitable final polishing steps for solids removal from chemical precipitation treatment operations. Nanofiltration is similar to reverse osmosis in removing dissolved constituents from water. However, it is not generally capable of removing small, mono-valent ions such as sodium or chloride. Nanofiltration can be used to remove sulfate and larger salts as well as divalent cations such as calcium, magnesium (Davis and McElhiney, 2002). Nanofiltration could also be used to remove dissolved heavy metals of potential concern at NorthMet. RO membranes have the smallest pore sizes and can restrict the flow of virtually all molecules other than water. For this reason, RO is capable of removing a high percentage of almost all inorganic ions, turbidity, bacteria, and viruses (gewater.com). RO membranes are among the few viable technologies for removing highly soluble mono-valent cations and anions such as sodium and chloride from water.

In membrane treatment, as pressure is applied to the mixed solution, water – and other constituents, based on the membrane type – passes through pores in the membrane. The purified stream that passes through the membrane is called permeate, and the remaining stream containing a higher concentration of suspended and/or dissolved solids is called the concentrate or the brine. The cost to apply this pressure is one of the major operating expenses with membrane systems. Recent improvements in the use of membrane treatment have focused on reducing the pressure required to achieve separation across the membrane.

Membrane technologies work on particulate and dissolved species simultaneously, so the application of this technology to all the potential dissolved chemicals of concern at NorthMet is considered at the same time in the following paragraphs. Moreover, because the ionic species permeate the membrane as ion-pairs, the rejection of an ion is also dependent on the rejection of its counter-ion. For example, sodium rejection is greater when the counter-ion is sulfate (Na_2SO_4) than when the counter-ion is chloride (NaCl) (gewater.com), primarily due to the differences in solubility. This limitation to a membrane treatment system for NorthMet is discussed below.

For mine wastewaters, calcium sulfate scaling is typically the factor limiting water recovery for a RO or nanofiltration system. This could be a concern for process water from the Mine Site. The maximum achievable recovery can be estimated as follows (EPA, 1973):

$$R = 100 - 0.055 \times \sqrt{Ca^{2+} \times SO_4^{\ 2-}}$$

Where: R = Maximum recovery, percent
Ca = Calcium concentration, mg/L
SO_4 = Sulfate concentration, mg/L

Softening of the influent stream via chemical precipitation, ion exchange, or some other treatment could increase the maximum recovery of a membrane system. Antiscalants have also been shown to reduce the potential precipitation of gypsum and allow increased recovery of permeate in membrane systems (Le Gouellec, and Elimelech, 2002). Because Mine Site process water is likely to have high calcium and sulfate concentrations, pretreatment could likely include chemical precipitation, filtration, pH adjustment, and potentially antiscalant or antimicrobial addition. Depending on the ammonia content of the water, breakpoint chlorination may also be required to prevent degradation of the membrane by free ammonia.

The brine produced by membrane treatment of Mine Site process water could potentially contain high concentrations of metals and salts. The brine could be treated using chemical precipitation, or may be suitable for direct metal recovery in the hydrometallurgical plant. If chemical precipitation is used, the precipitated solids would be either sent to the hydrometallurgical process or the hydrometallurgical residue cells. If the brine is treated using chemical precipitation, the remaining liquids could potentially be blended with the permeate prior to being sent to the tailings basin. Alternatively, this waste stream could be thickened using evaporators, crystallizers, and a filter press. The resultant solids could be disposed in the hydrometallurgical residues cells or at a permitted landfill.

4.2.2 Membrane Types

The most important component of any membrane treatment system is the semi-permeable membrane. Three major types of membranes are commonly used, each having different engineering properties, which are summarized in Table 7 (Aquatechnology.net).

Table 7 Comparison of Membranes Types

Feature	Cellulosic	Aromatic Polyamide	Thin Film Composite*
Rejection of Organic	L	M	H
Rejection of Low Molecular Weight Organics	M	H	H
Water Flux	M	L	H
pH Tolerance	4-8	4-11	2-11
Temperature Stability	Max 35 deg. C.	Max 35 deg. C.	Max 45 deg. C.
Oxidant Tolerance (e.g., free chlorine)	H	L	L
Compaction Tendency	H	H	L
Biodegradability	H	L	L
Cost	L	M	H
L = Low; M = Medium; H = High			
*Thin film composite type having polyamide surface layer			

Of the three basic membrane types, cellulosic membranes have the lowest unit cost and are most resistant to degradation by free chlorine. However, they have several limitations. Due to their asymmetric structure, they are susceptible to compaction (collapsing of membrane pores under high temperature) under high operating pressures especially at elevated temperatures. In addition, they are also susceptible to alkaline hydrolysis, and biodegradation. The operating pH for these membranes is 4 to 8.

Aromatic polyamide membranes are more resistant to biodegradation and alkaline hydrolysis than cellulosic membranes. The operating pH for these membranes is 4 to 11. Even though these membranes are subject to compaction at high temperatures and pressures, they have the capacity to withstand higher temperatures when compared to cellulosic membranes. The salt and organic rejection characteristics of these membranes are also better than that of cellulosic membranes. The principle limitation of these membranes is their susceptibility to degradation by oxidants such as free chlorine. Ammonium ion can also degrade these membranes.

Thin film composite membranes comprise a thin, dense solute-rejecting film underlain by a porous substructure. Thin film composite membranes offer similar advantages and disadvantages to aromatic polyamide membranes. However, materials for the two layers can be selected to optimize water flux and solute rejection, providing greater operational flexibility than other membrane types.

4.2.3 Membrane Configurations

Membrane treatment systems may be configured in a number of different ways:

- Plate-and-frame: Maintenance of these units is simple due to the nature of their assembly but hydraulic flux across the membrane is limited by low specific surface area.
- Spiral-wound: The modules can be designed to use turbulence to enhance hydraulic flux and decrease membrane fouling. However, maintenance of these units is difficult.
- Hollow-fiber: This configuration offers the greatest packing densities due to high specific surface area of the hollow fibers.
- Tubular: This configuration offers enhanced resistance to fouling when operated under turbulent influent conditions. The disadvantages of using a tubular module are high capital costs and high energy requirements.

4.2.4 Operation and Maintenance

Membrane cleaning or replacement due to fouling is the most important maintenance requirement in a membrane treatment operation. Membrane fouling typically occurs over a period of time due to poor feed solution characteristics. Fouling due to suspended solids, chemical precipitates (scaling), and biofilms can reduce membrane performance significantly. Membrane integrity is also affected by extreme pH or oxidative attack. Thus, adequate pretreatment processes addressing these issues are necessary to extend membrane life. Pretreatment may include chemical precipitation (softening), filtration of suspended solids, pH adjustment, addition of antiscalants, or addition of antimicrobial agents to prevent biofilm growth.

4.2.5 Treatment of Acid Mine Drainage Using Reverse Osmosis

Treatment of acid mine drainage via reverse osmosis has been studied at several different sites (U.S. EPA, 1973). While these studies focused on the removal of iron, aluminum, magnesium, and calcium, the removal characteristics should be similar for nickel, copper, cobalt, and zinc due to their similarity in size and charge to iron and aluminum. Additionally, the operation and maintenance experience gained from these applications can also be applied to NorthMet. Membrane fouling due to calcium sulfate precipitation was identified as the principle limiting factor in operation of these systems. Neutrolosis, or blending of recycled brine into the influent stream, was used to reduce membrane fouling. Pretreatment included filtration (10 μm), ultraviolet disinfection, and pH adjustment. A summary of these early membrane treatment operations using reverse osmosis are summarized in Table 8.

Table 8 Summary of Reverse Osmosis Treatment of Mine Wastewater

Site	Membrane Type	Flux (gal/ft^2/day)	Recovery (%)	Pre-Treatment	pH	Treatment Performance			
						Parameter	Influent (mg/L)	Effluent (mg/L)	Removal (%)
Norton	Spiral-wound, modified cellulose acetate	16.8 to 18.8 @ 600 psi	80	Sand Filter, 10 um cartridge filter	3.1-3.7	Iron	103.3	1.8	98.3
						Calcium	111.7	2.7	97.6
						Magnesium	36	0.8	97.7
						Aluminum	36.3	1.1	96.9
						Sulfate	913.3	13.9	98.5
Morgan-town	Spiral-wound, modified cellulose acetate	13.5 to 19.2 @ 400 to 600 psi	50	Sand Filter, 10 um cartridge filter	2.24-3.14	Iron	1,300	29	97.8
						Calcium	530	9.6	98.2
						Magnesium	420	7.6	98.2
						Aluminum	320	5.0	98.4
						Sulfate	10,900	190	98.3
Ebensburg	Spiral-wound, modified cellulose acetate	7.4 (50°F) to 11.9 (77°F) @ 400 psi	84	Sand Filter, 10 um cartridge filter	3.1-4.8	Iron	98	1	99
						Calcium	186.7	1.4	99.3
						Magnesium	56	0.6	98.9
						Aluminum	33	1.0	96.9
						Sulfate	1,547	12.7	99.2
Mocanaqua	Spiral-wound, modified cellulose acetate	16.8 to 18.8 @ 600 psi	84	10 um filter with UV	4.3	Iron	105.7	1.1	99
						Calcium	150	0.8	99.5
						Magnesium	109.3	1.7	98.4
						Aluminum	13.7	0.5	96.3
						Sulfate	843	7.0	99.2

Note: Results reported for average of multiple runs at Norton (6), Ebensburg (3), and Mocanaqua (3)
Reference: U.S. EPA, 1973.

Based on the results summarized in Table 8, membrane treatment, in particular microfiltration or ultrafiltration as pretreatment for either RO or nanofiltration, is likely capable of producing water that would meet the process water quality targets. The operating pressures used in earlier demonstration tests were relatively high in comparison to typical pressures used today. Pilot testing of membrane treatment technology with current membrane configurations will help to provide additional input on the operating pressures required to achieve similar results and would provide a brine stream that could be evaluated for chemical precipitation treatment.

4.3 Ion Exchange

4.3.1 Technology Description

The ion exchange process involves the reversible exchange of ions between an insoluble substance and the wastewater. The insoluble substance is usually a synthetic organic ion exchange resin composed of high-molecular-weight polyelectrolytes that can exchange their mobile ions for ions of similar charge from the surrounding medium. Each resin has a distinct number of mobile ion sites that set the maximum quantity of exchanges per unit of resin (www.remco.com).

Ion exchange reactions are stoichiometric and reversible. As an example, a resin with hydrogen ions available for exchange will exchange those ions for nickel ions from solution. The reaction can be written as follows:

$$2(R\text{-}SO_3H) + NiSO_4 = (R\text{-}SO_3)2Ni^+\ H_2SO_4\ (2)$$

R indicates the organic portion of the resin and SO3 is the immobile portion of the ion active group. Two resin sites are needed for nickel ions with a plus 2 valence (Ni+2).

When compared to other wastewater treatment alternatives, ion exchange appears to have greater flexibility. While most ion exchange resins are designed for removal of specific chemicals of concern, for example metals, different resin types have the capability to remove various chemicals, and more than one resin can be used in series. Specialty resins are also available that can selectively bond with specific cations for their removal. In addition, ion exchange can be used with fluctuating flow rates. However, this technology may be limited by high concentrations of total dissolved solids (http://www.nesc.wvu.edu).

Ion exchange treatment does not result in the creation of a solid waste, so it does not lead to solids disposal problems, like chemical precipitation, thus lowering the operational costs for the disposal of residual metal solids (Kurniawan et al., 2006). However, the resin does need to be regenerated, either at the site or at an off-site location, which results in a brine waste, which would need to be managed, similar to a membrane treatment approach. To apply ion exchange treatment of mine wastewater, appropriate pretreatment such as removal of suspended solids, removal of organic compounds, and pH adjustment would likely be required.

Chemical removal capabilities of various resin types are described in further detail in the following paragraphs.

4.3.2 Types of Ion Exchange Resins

Ion exchange resins can be divided into three broad categories: cation exchangers, anion exchangers and chelating resins. Cation exchangers have positively charged mobile ions available for exchange, anion exchangers have negatively charged mobile ions for exchange, and chelating resins have a high degree of selectivity for heavy metals (www.remco.com). The cation exchangers can in turn be either strong or weak acid cation exchangers, and similarly the anion exchangers can be either strong or weak base anion exchangers.

4.3.2.1 Strong Acid Cation Resins

These resins are highly ionized in both the acid ($R-SO_3H$) and salt ($R-SO_3Na$) form (www.remco.com). The ionizable group in these resins is the sulfonic acid group (SO_3H).The hydrogen and sodium forms of strong acid resins are highly dissociated and the exchangeable Na^+ and H^+ are readily available for exchange over the entire pH range. Consequently, the exchange capacity of strong acid resins is independent of solution pH.

4.3.2.2 Weak Acid Cation Resins

Weak acid cation resins have carboxylic acid (COOH) group as the exchange site. Weak acid resins have a much higher affinity for hydrogen ions when compared to strong acid resins. The solution pH has a strong influence on the dissociation of a weak acid resin. These resins are unsuitable for deionizing acid mine drainage water, because they have a limited capacity below pH 6. However, they require less acid for regeneration when compared strong acid and strong base resins.

4.3.2.3 Strong Base Anion Resins

The ionizable site in this type of resin is a trimethylammonium group. Strong base resins are highly ionized and can be used over the entire pH range similar to the strong acid cation resins. These resins can remove sulfate and similar anions from water; however, they are typically charged and then subsequently regenerated with chloride ions. Thus, for Mine Site water with very high sulfate concentrations, replacing sulfate with chloride would not provide complete treatment. This operation, however, could potentially be advantageous as a pre-treatment step for a reverse osmosis operation where eliminating sulfate would reduce the potential for gypsum to precipitate and foul the membranes.

4.3.2.4 Weak Base Anion Resins

Weak base anion resins have amino group as the ionizable site. These resins are like weak acid resins in that the degree of ionization is strongly influenced by pH. Consequently, weak base resins exhibit minimum exchange capacity above a pH of 7.

4.3.2.5 Chelating Resins

The functional group in chelating resins is an EDTA compound. These behave similarly to weak acid cation resins but exhibit a high degree of selectivity for heavy metal cations over other cations in solution. Chelating resins have the tendency to form stable complexes with the heavy metals. The main drawbacks of chelating resins are slow metal uptake kinetics, limited operating pH range (Gula and Harvey, 1996) and higher cost than other types of resins. Table 9 lists the selectivity coefficients (KM) for various metal ions relative to calcium for chelating resins.

Table 9 Chelating Cation Resin Selectivity Coefficients (KM) for Metal Ions

Metal	KM/Ca
Hg^{+2}	2,800
Cu^{+2}	2,300
Pb^{+2}	1,200
Ni^{+2}	57
Zn^{+2}	17
Cd^{+2}	15
Co^{+2}	6.7
Fe^{+2}	4.7
Mn^{+2}	1.2
Ca^{+2}	1

Source: http://www.remco.com/ix.htm.

4.3.2.6 Specialty Resins

Specialty resins are available to selectively remove certain metal ions. One example is Diphonix, a hybrid chelating/strong sulfuric acid resin that combines the selectivity of a chelating resin with the kinetics of a strong acid cation resin.

4.3.3 Ion Exchange for Acid Mine Drainage Treatment

Ion exchange technology has been applied successfully to remove copper and cobalt at the Soudan underground mine (MDNR, 2001). Using a specialty resin, removal efficiencies of greater than

99 percent were achieved at a resin loading rate of 2 pounds per cubic foot. The pH of the wastewater stream is adjusted to 4.3 and the water flows through activated carbon filters prior to passing through the ion exchange units. Two ion exchange cartridges are used in a lead-lag configuration. The system treats wastewater at a flow rate of 9 to 15 gpm. When the resin is exhausted, the canister is transported offsite for regeneration. The capital cost for this system was approximately $50,000, with annual maintenance costs of approximately $80,000.

Because this system is in operation and treatment efficiencies are known, additional bench-scale testing of this technology is not required at this time.

4.4 Constructed Wetland

4.4.1 Technology Description

The use of constructed wetlands to treat municipal and industrial wastewater streams has become a widespread, conventional technology. As wastewater flows through a wetland, pollutants are transformed or sequestered through various biological and geochemical reactions involving wetland vegetation, sediments, and bacteria. Wetlands have been used predominantly to degrade organic matter, capture suspended solids in storm water runoff, and adsorb or fix inorganic nutrients such as nitrogen and phosphorus (ITRC, 2003). They have also been used extensively to treat metal- and sulfate-laden mine water discharges, similar to the potential flows that may be generated at NorthMet.

Wetlands are well suited for treating mine drainage because they are capable of transforming many different parameters, most of which will be of potential concern at NorthMet (Wieder, 1988). Wetland sediments can neutralize acid via dissolution of carbonate minerals in the sediments and through the production of alkalinity via microbial decomposition of organic matter. Wetlands are also capable of removing sulfate via microbial reduction to sulfide and subsequent precipitation with metals such as iron. Many of the natural processes that occur in wetlands can also be designed into bioreactors that perform essentially the same functions. Bioreactors generally require less space than constructed wetlands but require much more operation and maintenance to provide the substrate and nutrients for the biological processes and to remove the accumulated solids (U.S. EPA, 2006). This treatment option will also be considered for NorthMet.

4.4.2 Wetland Removal Mechanisms

The wetland mechanisms that would be potentially important to the removal of metals and other parameters of concern at NorthMet are described in the following sections.

4.4.2.1 Uptake of Metals by Plants

Plants typically take up small amounts of metals as micronutrients. The magnitude of the metals uptake mechanism is small relative to the magnitude of metals input in a typical acid mine drainage stream (Sencindiver and Bhumbla, 1988; Wieder et al., 1990; Baek et al., 1991; Taylor and Crowder, 1982). Thus, plant uptake of metals is not an important long-term removal mechanism in this application.

4.4.2.2 Ion Exchange/Adsorption of Metals onto Sediment

Cations within the substrate of the wetland sediments – such as sodium, magnesium, and potassium – may be exchanged for heavy metal cations such as nickel, copper, cobalt, zinc, and iron (Wieder, 1990). The ion exchange capacity of wetland substrates varies depending on substrate type as shown in Table 10.

Table 10 Stability Series for Metal-organic Interactions in Various Substrates

Material	Stability Series	Reference
Soil Organic Matter	$Cu^{2+}>Ni^{2+}>Co^{2+}>Zn^{2+}>Fe^{2+}>Mn^{2+}$	Irving-Williams, 1948
Soil Organic Matter	$Cu^{2+}> Fe^{2+}>Ni^{2+}>Co^{2+}> Mn^{2+}>Zn^{2+}$	Jones and Jarvis, 1981
Sphagnum Peat	$Al^{3+}> Fe^{2+}>Cd^{2+}= Ni^{2+}= Mn^{2+}>Ca^{2+}=Mg^{2+}>K^{+}>Na^{+}$	Wieder, 1990
Sawdust	$Al^{3+}> Fe^{2+}>Cd^{2+}= Ni^{2+}= Zn^{2+}=Mn^{2+}>Ca^{2+}=Mg^{2+}>K^{+}>Na^{+}$	Wieder, 1990

Adsorption of cations to *Sphagnum* peat and sawdust has been described using the Langmuir equation (Wieder, 1990):

$$ADS = \frac{YMAX \times CONC}{K + CONC}$$

Where:

ADS = Adsorption of a cation to an organic substrate, μeq/g

YMAX = Maximum capacity of a particular organic substrate to adsorb a cation, μeq/g

CONC = Equilibrium concentration of cation, μeq/L

K = Affinity constant associated with half-maximal adsorption, μeq/L

Table 11 summarizes the Langmuir parameters for various cations in *Sphagnum* peat and sawdust.

Table 11 Langmuir Parameters for Metal-organic Interactions in Peat and Sawdust (Wieder, 1990)

Cation	**Sphagnum Peat**		**Sawdust**	
	YMAX, μeq/g	**K, μeq/L**	**YMAX, μeq/g**	**K, μeq/L**
Al^{3+}	226.4	238	98.0	1,112
Fe^{2+}	198.3	842	75.6	1,286
Cd^{2+}	180.0	1,184	105.9	2,250
Ni^{2+}	183.0	1,391	84.0	2,497
Zn^{2+}	209.4	1,769	102.1	1,064
Mn^{2+}	155.5	1,782	65.3	2,153
Ca^{2+}	125.6	2,863	44.9	13,717
Mg^{2+}	79.0	3,641	46.4	3,593
K^{+}	142.0	9,420	35.5	3,097
Na^{+}	161.5	16,881	--	--

The ion exchange capacity of a wetland substrate is limited by the total number of available adsorptive sites. New adsorptive sites are likely created by the accumulation of plant detritus, thus the rate at which these sites become available for metal adsorption is dependent on the rate of plant growth. Additionally, ion exchange can be affected by changes in cation ratios. Thus, the wetland could act as a source of loosely bound cations (for example sodium) under certain circumstances where more tightly bound cations are entering the system, similar to a conventional ion-exchange system.

4.4.2.3 Formation of Insoluble Metal Oxides

Metal oxide surfaces within the wetland substrate can also act as adsorptive sites for metal cations (Tarutus, et al., 1992). In the presence of oxygen, some metals, such as iron and manganese, form insoluble metal oxides. Such oxidation can occur near the sediment-water interface in a surface flow wetland, or in the rhizosphere of emergent wetland vegetation. While zinc, nickel, cobalt, and copper do not form insoluble oxides under typical environmental conditions, these metals can bind to iron and manganese oxide surfaces in a wetland environment in the same way they would bind to iron oxides in a chemical precipitation system. However, in a wetland environment, sorption to metal oxide surfaces is more sensitive to changes in substrate redox state, and reducing conditions can result in the release of sorbed metals (Patrick and Turner, 1968).

4.4.2.4 Formation of Insoluble Metal Sulfides in Wetlands

Metals and sulfate are liberated from mine waste rock via bacterial oxidation of metal sulfide minerals. However, in the anoxic regions of wetland substrates, this process can be reversed. Sulfate reducing bacteria can convert sulfate to sulfide, and metal cations, including nickel, copper, cobalt, and zinc, readily form insoluble precipitates with sulfide. It can be seen from the relative magnitudes of the solubility products (Table 5) that nickel precipitation requires at least 100-fold more sulfide than precipitation of an equal amount of any of the other metals. Copper sulfide precipitation requires far less sulfide than any of the other metals. The implications of these observations on metals removal via sulfide precipitation in a wetland treatment system are:

- Copper removal should be achieved almost immediately upon exposure of the runoff to sulfate reducing conditions.
- Zinc precipitation should require more sulfide and, therefore, more residence time than copper.
- Cobalt precipitation should require more residence time than zinc.
- Nickel precipitation should require more residence time than any of the other metals and, therefore, should be the limiting process for design purposes.
- Nickel precipitation may be inhibited by competition from iron. As aqueous iron concentrations can be several orders of magnitude greater than nickel, this could be a significant concern.

- In the event of a system upset (i.e., interruption of bacterial sulfate reduction), nickel sulfide could re-solubilize before any of the other metal sulfides. Thus, nickel-releasing behavior could be an important indicator of system upset.

Metal sulfide precipitation is limited by the rate of bacterial sulfate reduction. Sulfate reducing bacteria require an electron donor (energy source) and carbon source for growth. Sulfate reducing bacteria must compete with other, faster-growing bacteria for energy and carbon sources. In order to stimulate bacterial sulfate reduction:

- The more energetically favorable electron acceptors (i.e., oxygen, nitrate, ferric iron, manganese [IV]) must be exhausted; or
- Carbon and energy sources must be supplied in excess of the demands of the microbial consortium.

Constructed bioreactors can be used to generate conditions that favor sulfate reducing bacteria over other microorganisms by providing substrate that is preferred by these organisms or through the use of other processes to remove other electron accepting chemicals that could inhibit sulfate reduction (U.S. EPA, 2006).

4.4.3 Wetland Treatment of Mine Drainage-Case Studies

Wetland treatment technology has been applied to mine drainage at a number of existing sites. Most of these applications, however, focus on removal of iron and manganese, which are not contaminants of concern at NorthMet. Fortunately, several wetlands currently in use at the nearby Dunka Mine can have been designed and installed to treat water that is potentially similar to the waste rock drainage at NorthMet.

A review of the operation and performance of these wetlands is included in Appendix D. This review of Dunka wetland performance suggests that a subsurface flow wetland where an anaerobic, sulfate reducing environment can be established and maintained provides the best overall removal of the parameters of concern at NorthMet. Additional testing of this technology is not required as the existing information can be used to design a self-sustaining system by balancing the natural carbon input to the system with the carbon demand from the applied sulfate load.

5.0 Evaluation of Treatment Options for Mine Site Wastewaters

Brief descriptions and evaluations of cost, implementability, and effectiveness for the four potential technologies for the treatment of Mine Site wastewater are summarized in Table 12. The treatment alternatives are compared in the following sections on an individual basis. However, when appropriate, a discussion of potential combinations of alternatives is included. For complex wastewaters such as those expected at the Mine Site it is not uncommon for wastewater treatment to consist of a combination (or treatment train) of two or more of these technologies in series. Using multiple technologies in series also helps to emphasize the positive aspects of each technology and generally improves the overall treatment operation.

As noted in Table 2, the predicted quality of wastewater produced at the Mine Site varies significantly between the pit discharge and the stockpile drainage, and will also vary among stockpiles due to the segregation of waste rock according to the potential to produce acid rock drainage (ARD) and leach heavy metals. For the evaluation of potential wastewater treatment alternatives, it is assumed that the Mine Site process water will be discharged into one of two equalization (EQ) ponds (Stage 1 Pond and Stage 2 Pond) to produce two WWTF inflow streams. The first inflow stream (Stage 1) would include process water runoff and drainage from the Category 3 and Category 4 waste rock stockpiles. Stage 1 inflow is generally characterized as low pH (pH<5) with relatively high concentrations of dissolved metals and salts. The second inflow stream (Stage 2) would be comprised of Category 1/2 stockpile process water runoff and liner drainage, mine pit dewatering water, and process water runoff from the haul roads and Rail Transfer Hopper area. Stage 2 is generally characterized as near neutral pH with lower concentrations of dissolved metals and salts. Table 13 provides a summary of the estimated water quality and quantity for inflows to the Stage 1 and Stage 2 EQ Ponds. Separation of the multiple sources of wastewater allows them to be collected in separate equalization ponds and combined into two treatment influent streams, thus allowing the consideration of multiple treatment operations. Due to the water quality variability of the waste streams over time, inflow sources to the Stage 1 and Stage 2 EQ Pond could also be changed over time as necessary to optimize different treatment operations for each stage.

Table 12. Summary of Screening Evaluation of Treatment Technologies for Mine Site Process Water

Technology	Implementability	Advantages	Disadvantages	Residuals Generated	Approximate Cost (Appendix F)		
					Capital	Annual O&M	Net Present Value (20 yrs @ 5%)
Chemical Precipitation							
Hydroxide Precipitation	-Requires small footprint -Residues are easily managed.	-Simple process control - Well-established technology - Inexpensive chemicals	-Ineffective for zinc removal, simultaneous removal of certain metals may not be possible	Metal Hydroxide Sludge	$13.2 million	$776,000	$27.4 million
Soluble Sulfide Precipitation	- Requires small footprint - Residues are easily managed	- Effective removal of most metals to low concentrations	- Requires control measures for H_2S generation - Metal sulfide precipitates managed as hazardous waste	Metal Sulfide Sludge	$13.6 million	$788,000	$28.1 million
Carbonate Precipitation	-Requires small footprint - Residues are easily managed	- Simple process control	- Ineffective for removal of any metals except zinc, iron, and manganese - Soda ash is expensive, and subject to large price fluctuations - Large sludge volumes produced	Metal Carbonate Sludge	$12.5 million	$1.3 million	$34.8 million
Iron Sulfide Precipitation	-Requires small footprint -Requires on-site production of FeS	-Less potential for residual sulfide than soluble sulfide precipitation	- Nickel removal is ineffective - Requires larger reagent dose than soluble sulfide precipitation - Generates more sludge than soluble sulfide precipitation - Metal sulfide precipitates managed as hazardous waste	Metal (Iron) Sulfide Sludge	$13.9 million	$1.4 million	$38.0 million

Technology	Implementability	Advantages	Disadvantages	Residuals Generated	Approximate Cost (Appendix F) Capital	Approximate Cost (Appendix F) Annual O&M	Approximate Cost (Appendix F) Net Present Value (20 yrs @ 5%)
Calcium Sulfide Precipitation	- Requires small footprint - Requires onsite generation of CaS	- Less potential for residual sulfide than soluble sulfide precipitation - Required CaS dose is less than for FeS precipitation	- Metal sulfide precipitates managed as hazardous waste	Metal Sulfide Sludge	$13.9 million	$920,000	$30.4 million
Membrane Treatment							
Nanofiltration-Stage 1	-Requires small footprint - Requires management of brine	-Selectively removes multivalent ions, resulting in lower TDS brine	-Membrane subject to fouling - Pre-treatment required	Metal hydroxide and gypsum sludge	$15.2 million	$1.2 million	$40.1 million
Nanofiltration-Stage 2	-Requires small footprint - Requires management of brine	-Selectively removes multivalent ions, resulting in lower TDS brine	-Membrane subject to fouling - Pre-treatment required	Metal hydroxide and gypsum sludge	$13.2 million	$1.4 million	$37.0 million
Reverse Osmosis:	-Requires small footprint - Requires management of brine	-Can remove metals and dissolved solids to very low concentrations for excellent water quality.	-Membrane subject to fouling by organics, calcium sulfate precipitation. -Performance subject to presence of divalent anions (e.g., sulfate, nitrate). -Membrane cleaned on-site, generates waste stream. -Extensive pretreatment likely required	Rejected Brine with Sulfate, Metals	$24.5 million	$2.3 million	$64.2 million

					Approximate Cost (Appendix F)		
Technology	**Implementability**	**Advantages**	**Disadvantages**	**Residuals Generated**	**Capital**	**Annual O&M**	**Net Present Value (20 yrs @ 5%)**
Ion Exchange							
Ion Exchange	-Requires small footprint - Spent resin and activated carbon require management	-No potentially hazardous materials are added to the water.	-Resin subject to fouling by organic compounds, Al, Fe, Mn. -Sensitive to interference from chelating agents and fluctuations in influent concentration -Pretreatment pH adjustment and carbon filtration likely required	Metal hydroxide sludge	$21.2 million	$1.6 million	$48.6 million
Biological Treatment							
Constructed Wetland	-Requires large footprint - No residual	-Metals are sequestered as stable sulfide compounds in the sediment -More metals storage capacity is produced as the wetland ages -No secondary waste stream generated	-Land-intensive technology -Hydraulic/hydrologic limitations -Requires maturation period for best metals removal results	No residuals	$54.6 million	$488,000	$72.8 million
Bioreactor Treatment – Stage 1	-Requires handling of ethanol substrate	-Sulfate is reduced to sulfide by bacteria, then precipitated with iron -Metals are removed as metal sulfide precipitates	-Produces a biological sludge in addition to chemical sludge - Requires large inputs of ethanol and iron - Control of a biological system can be difficult	Biological sludge, metal sulfides	$13.6 million	$1.8 million	$42.9 million

Technology	Implementability	Advantages	Disadvantages	Residuals Generated	Approximate Cost (Appendix F)		
					Capital	Annual O&M	Net Present Value (20 yrs @ 5%)
Bioreactor Treatment – Stage 2	-Requires handling of ethanol substrate	-Sulfate is reduced to sulfide by bacteria, then precipitated with iron -Metals are removed as metal sulfide precipitates	-Produces a biological sludge in addition to chemical sludge - Requires large inputs of ethanol and iron - Control of a biological system can be difficult	Biological sludge, metal sulfides	$18.9 million	$1.0 million	$38.3 million

Table 13 Stage 1 and Stage 2 Equalization Pond Inflow Predicted Water Quality

		Year 1		Year 5		Year 10		Year 15		Year 20	
Parameter	**units**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**
Flow	gpm	106	418	214	1,050	234	1,139	192	731	177	1,086
Hardness	mg/L	679	80	1,751	196	2,934	180	4,407	400	3,205	282
Fluoride (F)	mg/L	1.83	0.20	8.35	1.16	17.8	2.67	29.7	4.77	37.7	3.30
Chloride (Cl)	mg/L	10.0	1.02	27.0	4.98	26.9	4.94	13.8	1.06	14.2	1.15
Sulfate (SO_4)	mg/L	992	94	3,106	169	5,507	228	7,947	554	5,776	355
Aluminum (Al)	mg/L	4.03	0.63	18.0	0.72	41.1	0.83	56.0	1.28	36.5	0.76
Arsenic (As)	mg/L	0.32	0.038	0.67	0.10	0.61	0.078	1.01	0.19	0.85	0.12
Barium (Ba)	mg/L	0.18	0.032	0.30	0.044	0.29	0.041	0.39	0.074	0.36	0.049
Beryllium (Be)	mg/L	0.0021	0.00032	0.0023	0.00036	0.0031	0.00042	0.0031	0.00048	0.0029	0.00035
Boron (B)	mg/L	0.64	0.11	1.26	0.19	1.19	0.17	1.48	0.28	1.48	0.20
Cadmium (Cd)	mg/L	0.0071	0.00046	0.0067	0.00056	0.010	0.00059	0.011	0.00047	0.0078	0.00035
Calcium (Ca)	mg/L	199	21.7	460	56.2	445	52.0	742	123	666	83.9
Chromium (Cr)	mg/L	0.0039	0.00087	0.0060	0.0011	0.0059	0.0011	0.0052	0.0012	0.0072	0.0011
Cobalt (Co)	mg/L	0.17	0.0075	1.75	0.011	10.7	0.011	16.8	0.014	10.5	0.0094
Copper (Cu)	mg/L	0.079	0.011	0.31	0.018	10.7	0.016	25.6	0.032	38.0	0.021
Iron (Fe)	mg/L	28.9	1.53	73.5	2.12	83.5	1.93	107	0.82	94.4	0.63
Lead (Pb)	mg/L	0.011	0.0012	0.039	0.0035	0.045	0.0039	0.070	0.010	0.062	0.0071
Magnesium (Mg)	mg/L	44.4	6.26	147	13.5	443	12.4	622	22.8	375	17.7
Manganese (Mn)	mg/L	0.83	0.059	6.04	0.10	19.9	0.11	29.1	0.20	16.5	0.13
Mercury (Hg)	mg/L	2.04E-05	4.47E-06	1.99E-05	3.61E-06	2.11E-05	3.89E-06	2.54E-05	6.00E-06	3.60E-05	5.77E-06
Molybdenum	mg/L	0.013	0.0032	0.023	0.0046	0.023	0.0045	0.019	0.0043	0.029	0.0046
Nickel (Ni)	mg/L	2.51	0.10	25.4	0.13	136	0.13	249	0.10	175	0.068
Phosphorous	mg/L	0.091	0.00091	0.19	0.019	0.14	0.0089	0.24	0.033	0.21	0.022
Potassium (K)	mg/L	30.7	3.94	58.3	7.79	50.0	6.58	75.8	14.5	66.9	8.96
Selenium (Se)	mg/L	0.0075	0.0015	0.011	0.0021	0.011	0.0021	0.010	0.0022	0.013	0.0021
Silica (SiO_2)	mg/L	3.75	0.056	6.99	0.83	3.79	0.39	7.61	1.44	7.15	0.97
Silver (Ag)	mg/L	0.0027	0.00065	0.0045	0.00089	0.0045	0.00089	0.0033	0.00080	0.0054	0.00088
Sodium (Na)	mg/L	175	24.5	534	72.8	424	61.9	769	159	691	101
Thallium (Tl)	mg/L	0.0043	0.0011	0.0071	0.0015	0.0071	0.0015	0.0041	0.0011	0.0086	0.0015
Zinc (Zn)	mg/L	2.13	0.095	7.68	0.14	12.2	0.12	14.6	0.049	10.3	0.043
Nitrate (NO_3)	mg/L	0.31	0.065	0.74	0.15	0.72	0.15	0.11	0.000017	0.080	0.000012
Ammonia (NH_4)	mg/L	0.31	0.065	0.74	0.15	0.72	0.15	0.11	0.000017	0.080	0.000012

5.1 Effectiveness

Effectiveness is based on the ability of a treatment technology to address all of the parameters of concern at NorthMet. With the exception of carbonate precipitation, all of the technologies reviewed in Section 4 have the potential to be effective in treating the parameters of potential concern in the process water from the Mine Site. A membrane or a wetland treatment system could be designed to treat all of the parameters of concern simultaneously. While this would be effective, and relatively simple to operate, it may not necessarily be efficient. Chemical precipitation and ion exchange can be used to remove one or more specific parameters of concern, for example metals or sulfate, but would likely require a multi-step process to be effective in treating all of the parameters of concern. This would increase the complexity of the treatment operation, but could also potentially reduce the operating costs. Complexity is addressed in the following discussion of implementability and costs for various alternatives.

This evaluation confirms that the pre-screening of alternatives that was conducted in the development of the SOW for this evaluation selected technologies that can all be designed to be effective. Thus, the selection of a preferred alternative is reduced to consideration of the implementability and the cost for each particular option. These factors are discussed in the following paragraphs.

5.2 Implementability

Implementability will be is considered within the context of the complexity of the operation needed to use any of the desired treatment approaches – for example what, if any pre-treatment operations may be required and what type of solids or secondary waste streams are generated.

5.2.1 Chemical Precipitation

Implementation of chemical precipitation for the Mine Site process water would likely require a multi-stage system to be able to achieve the desired process water quality targets. Using chemical precipitation, metals would likely be removed as a hydroxide precipitate or as a co-precipitate with iron hydroxides. Sulfate would be removed as a gypsum precipitate. If additional sulfate removal is required, a chemical treatment system could be upgraded with the addition of aluminum salts using an ultra high lime with aluminum process. The concentrations of other dissolved solids, for example silica, phosphorous, or nitrate would likely be reduced in the precipitation process. Calcium, which would be added to the process, could be removed in a final neutralization step with carbon dioxide or soda ash.

Chemical precipitation may require filtration as a final polishing step and would require solids handling and management, most likely incorporating the solids into the hydrometallurgical process.

The implementation of a chemical precipitation treatment system is a viable option at the Mine Site. The chemical precipitation treatability testing conducted for this evaluation (Appendix C) demonstrated that with the exception of mercury, all the parameters of concern at NorthMet can be removed using lime with an HDS operating configuration. The footprint for a chemical precipitation process at the Mine Site would be relatively small, most likely less than 10 acres. Power, chemicals, and other inputs for a chemical precipitation plant at the Mine Site can be delivered, and road access between the Mine Site and the Plant Site could accommodate the transportation of wastewater solids for reuse or disposal. A chemical treatment system can also be designed with two or more units in parallel to deal with variable incoming flow rates both seasonally and over the lifetime of the project.

5.2.2 Membrane Treatment

Membrane treatment is a viable option for the Mine Site process water. Either a reverse osmosis (RO) or a nanofiltration system would likely be capable of treating Mine Site process water for the parameters of potential concern. A single system would be capable of removing all of the chemicals. Pre-treatment stages, such as filtration would likely be required to improve the overall operation of the membrane unit.

The brine from a membrane treatment operation would require additional treatment. This waste stream could be trucked off-site for disposal, or could be treated at the site. On-site treatment would likely consist of a small chemical precipitation operation. Solids from this operation could then be recycled at the hydrometallurgical plant or disposed with the hydrometallurgical residues. The remaining treated water from the chemical precipitation operation could then be blended with permeate from the membrane unit prior to being discharged to the tailings basin or, if necessary, could be evaporated.

The potential footprint for a membrane treatment system would likely be similar to a chemical precipitation plant, again likely less than 10 acres. A membrane treatment system can also be installed will multiple units in parallel to help manage variable flows. Power, chemicals, and other items needed for a membrane treatment operation, including truck access for brine or water treatment solids removal is readily available.

5.2.3 Ion Exchange

Ion exchange would have limited viability as stand-alone treatment alternative for the mine-site process water. While ion exchange can effectively remove metals from solution, it would be less likely to be able to effectively remove sulfate than any of the other three technologies considered in this evaluation, because it would most likely need to ‘exchange’ the sulfate for chloride. Excess chloride would need to be treated, which would likely require RO. Thus, ion exchange would be most effective as a pre-treatment operation for sulfate removal using membranes.

An ion exchange system would likely require a relatively small footprint at the Mine Site (similar to membrane treatment or chemical precipitation). As the concentration of total dissolved solids in the Mine Site process water increases with time, ion exchange treatment will require additional treatment capacity and will likely also require more frequent resin change-out or regeneration. Because it would be relatively easy to place additional ion exchange treatment capacity on-line over the operating time of NorthMet, ion exchange could provide some operational advantages. Unfortunately, for the units that are on-site and in operation, daily or even seasonal variations in the flow rate to the ion exchange system can stress the operation and efficiency of individual ion exchange units that would need to be mitigated by equalizing the inflow rates.

Pre-treatment would likely be required for an ion exchange treatment system. This would include filtration of very small particulates, and potentially an activated carbon unit to remove any trace organics that could foul the ion exchange media. While the concentration of organic matter in the process water at the Mine Site is expected to be very low, even a low concentration of organic matter could react with the ion exchange resin and reduce the treatment efficiency of the system

5.2.4 Constructed Wetland

Implementation of a constructed wetland would require a site-specific design to match the expected load with the wetland capacity. The potential design process is outlined below.

5.2.4.1 Hydraulic Design

A decision tree for mine water treatment (ITRC, 2003) is included in Appendix E. Application of the decision tree to the Mine Site process water suggests that a subsurface-flow (SSF) wetland would be the best configuration for a constructed wetland at NorthMet to provide long-term removal of trace metals by sulfide precipitation. A SSF wetland can be designed to operate in one of two configurations:

- Vertical flow: Water is ponded on top of the wetland substrate or added to the subsurface through an infiltration gallery. Water to be treated then flows vertically (downward or upward) through the media. This configuration can treat high volumetric flow rates because flow is distributed across the entire wetland area.
- Horizontal flow: Water flows horizontally through the root zone, from one end of the wetland to the other. This configuration is generally used to treat low volumetric flow rates because flow is distributed across a smaller area.

In either configuration, key design parameters are:

- hydraulic conductivity,
- hydraulic head required to maintain the design flow rate, and
- flow distribution in the wetland

Hydraulic conductivity will decrease with time as metal precipitates fill void spaces in the substrate. Thus, more hydraulic head will be required to maintain the design flow. A means for balancing inflow and outflow from the wetland is also important to prevent the substrate from drying out during periods of low flow. In the case of horizontal-flow wetlands, the aspect ratio (length to width) should generally be between 3:1 and 5:1 to prevent short-circuiting.

5.2.4.2 Required Sulfate Reduction Rate

Bacterial sulfate reduction is the key process in removal of trace metals by this method. The design equation for the required rate of sulfate reduction is (ITRC, 2003):

$$\text{Required Rate of Sulfate Reduction} = \sum mmol\ divalent\ metals + 1.5\sum mmol\ Fe^{3+} + 0.5(mmol\ acid)$$

ITRC (2003) recommends a sulfate reduction rate of 300 mmoles/d/m^3 wetland substrate. Assuming a 0.5-meter substrate depth, sulfate reduction rates of 1,500 moles/ha/day are attainable under adequate growth conditions for sulfate reducing bacteria. Adequate growth conditions for sulfate reducing bacteria are dependent on anoxic conditions as well as the availability of carbon substrate, as discussed in the following paragraphs.

5.2.4.3 Carbon Utilization Rates

Wieder et al. (1988) observed sulfate reduction in Big Run Bog, a peat bog in West Virginia. They estimated the sulfate reduction rate in the bog to be approximately 17.0 mol $SO_4^{2-}/m^2/yr$. The corresponding carbon utilization required to fuel sulfate reduction was 34.2 mol C/m^2/yr. This corresponds to a carbon requirement of 2.0 mol C/mol SO_4^{2-}.

While carbon can be supplied by incorporating organic matter into the substrate during construction, long-term performance requires a continuous input of carbon to the wetland. Typical primary production rates for wetlands have been reported on the order of 1,000 g/m^2/yr (Vymazal, 1995). However, as much as 40 percent of this carbon production may be unavailable to support bacterial growth. Thus, the bioavailable carbon supply would be on the order of 600 g/m^2/yr or approximately 50 mol/m^2/yr.

5.2.4.4 NorthMet Wetland Size Requirements

A constructed wetland could be used as a secondary treatment step to remove additional sulfate after the use of a chemical precipitation step to remove a majority of the sulfate. Assuming a sulfate input of 25,000 pounds per day for the Mine Site wastewater based on an average annual flow of 1,300 gpm and a sulfate concentration of 540 mg/L after lime treatment of the Stage 1 flow, the corresponding carbon demands required to meet a 250 mg/L sulfate discharge criterion would be approximately 110,000 moles C/day. Assuming a conservative photosynthetic carbon input of 50 moles C/m^2/yr, the required size of a wetland treatment system at the Mine Site would be approximately 200 acres. This would represent a significant additional land requirement for the project, and would not likely fit within the currently available land.

In lieu of a constructed wetland, a bioreactor could be constructed to remove sulfate. The combination of biological sulfate reduction with chemical precipitation also provides an opportunity for excess sulfide generated by sulfate reducing bacteria to be used to promote metal precipitation. In this configuration, a sulfate reducing bioreactor or a portion of the treated wastewater from a constructed wetland could be recycled into the chemical precipitation process to provide soluble sulfide that should enhance the metal precipitation process.

While a constructed wetland has the potential to be a very effective treatment technology for the Mine Site process water, it is not likely to be implementable during the operation of the mine, due to the size requirements. Although a constructed wetland can effectively treat the parameters of potential concern in the Mine Site process water, the land requirements for this type of system are likely prohibitive.

A constructed wetland is, however, considered a potentially viable technology for removing additional metals and sulfate from the smaller volume of process water flows that are predicted for after the closure of the Mine Site. This is described in greater detail in RS52.

5.3 Cost

Costs for the potential treatment technologies considered in this evaluation are outlined in Appendix F. These estimates represent preliminary (feasibility study level) costs, not detailed costs that would be associated with the design and construction of a wastewater treatment facility. These costs are developed as a basis for comparing alternatives in this evaluation.

5.3.1 Chemical Precipitation

Tables F-1 through F-5 are cost estimates for treatment of the Mine Site process water using five different chemical precipitation methods: hydroxide, sulfide, carbonate, ferrous sulfide and calcium sulfide. Hydroxide precipitation is least expensive chemical precipitation technology, with a net present value (NPV) of $27.4 million (20 years at 5%). Sulfide precipitation and carbonate precipitation had NPV costs of $28.1 million and $34.8 million, respectively. While the capital cost for the three technologies is similar ($12.5 to $13.6 million), annual operating costs vary widely ($776,000, $788,000, and $1.3 million for hydroxide, sulfide, and carbonate precipitation, respectively.

The estimated NPV cost for insoluble sulfide precipitation via ferrous sulfide is approximately $38 million, assuming four times the required stoichiometric FeS dose as indicated in the literature. The subsequent increase in sludge generation also increases annual costs. NPV cost for calcium sulfide precipitation is about $30.4 million, due to the roughly stoichiometric calcium sulfide dose.

5.3.2 Membrane Treatment

Cost estimates for membrane treatment of Mine Site process water using either RO or nanofiltration are presented in Tables F-6 through F-8. The capital cost for an RO operation is $24.5 million, with annual costs of $2.3 million. NPV cost of an RO operation is $64.2 million. By comparison, the estimated capital cost, annual operating cost, and NPV cost of nanofiltration are $13.2 million, $1.4 million, and $37.0 million, respectively for nanofiltration of the Stage 2 flow. Significant cost components for either an RO or nanofiltration treatment system would include pre-treatment (ultrafiltration) and disposal of the rejected brine. The capital costs for nanofiltration are similar to the capital costs for chemical precipitation. However, the operating costs, primarily additional operating costs for membrane cleaning and maintenance increase the overall NPV of this option.

5.3.3 Ion Exchange

A cost estimate for ion exchange treatment of Mine Site process water is in Table F-9. The capital cost for this alternative is $21.2 million, with annual costs of $1.6 million. NPV cost of this alternative is $48.6 million. Significant cost components include the cost of large volumes of resin and activated carbon.

5.3.4 Constructed Wetland

Cost estimates for treatment of Mine Site process water using a constructed wetland or a bioreactor are included in Tables F-10 through F-12. Capital costs ($54.6 million) associated with construction of a 200-acre wetland account for the majority of the cost for this option. Wetland treatment is a land-intensive technology. A large amount of surface area is required to provide enough photosynthetic carbon input to fuel enough sulfate reduction to meet secondary water quality criteria (250 mg/L sulfate). Annual costs are relatively low ($488,000), and are primarily associated with chemical precipitation treatment of the Stage 1 water and monitoring the water levels within the wetland system. The NPV cost of this option is $72.8 million.

Using a bioreactor instead of a constructed wetland to remove sulfate together with chemical precipitation for metals removal does reduce the cost of this alternative. Treating the Stage 2 flow biologically together with chemical precipitation of the Stage 1 flow would have a capital cost of $ 18.9 million, an annual operating cost of $1 million, and a NPV of $38.3 million.

5.4 Recommended Alternative

Based on the comparative evaluation of potential treatment technologies described above, a multi-technology approach is recommended for the treatment of the Mine Site process water. Chemical precipitation treatment will be used to remove metals and sulfate. However, given the limitation of chemical precipitation as gypsum to reduce sulfate to the process water quality target, nanofiltration will be used to concentrate sulfate in a brine stream prior to precipitation. Blending the permeate stream with the treated water from the chemical precipitation operations would produce a combined flow that with limited exceptions will meet the conservative process water quality targets throughout the operating life of the Mine Site.

Nanofiltration will be used to treat the Stage 2 process water flows with high volume and relatively low concentrations of metals and sulfate including mine pit process water, runoff from the working areas of the Mine Site, and drainage from the Category 1/2 stockpile. These flows generally have a neutral pH and as noted in Table 2, the concentrations metals in these flows are near the process water quality targets while the concentration of sulfate is generally too low to remove sulfate as gypsum. Concentrating this stream will provide a clean permeate and a brine stream with qualities similar to the anticipated Stage 1 flow (drainage from the Category 3 Waste Rock stockpile, Category 3 Lean Ore stockpile, Category 4 Waste Rock stockpile and the Lean Ore surge pile).

Pretreatment prior to nanofiltration will include filtration using sand filters or a combination of micro or ultrafiltration membranes. Anti-scalants would also be added, as necessary, to condition the feed to the nanofiltration membranes and optimize operations (minimize operating pressures and membrane cleaning events). The brine from the nanofiltration operation as well as the Stage 1 drainage would then be treated using a two-stage chemical precipitation operation.

The Wastewater Treatment Facility (WWTF) will consist of two parallel units, which will allow the system to be built in stages and will allow the system operating capacity to increase and decrease with time as the volume of flow changes throughout the process of mining and filling the pits. At the maximum extent, the WWTF will occupy approximately 5 acres. The plant will be located in the southwest portion of the Mine Site, near the Central Pumping Station (CPS) that will be used to convey treated Mine Site process water to the tailings basin. A conceptual layout of the WWTF is shown in Figure 4. A conceptual flow-diagram of the wastewater treatment system is shown on Figure 5. The following paragraphs describe the preliminary conceptual design details for the individual process units. Final sizing of process units and pumps and selection of materials of construction for all of the process units will be completed during the detailed design phase of the project.

5.4.1 Flow Equalization

A flow-equalization pond system will be used to provide a constant feed to the two-stage water treatment system. The Stage 1 EQ Pond will receive the Stage 1 inflow stream. This average annual flow will increase throughout the mining operation. For Stage 1, the average annual flow will range from 64 to 485 gpm (Table 1). It is estimated that the instantaneous flow within any given year will range from 0 to 2.9 times the anticipated annual average, with the highest flows expected in the spring and lower flows expected throughout the winter months (See RS21 and RS22). Estimated annual drainage flows from the Category 3 and Category 4 stockpiles will peak in approximately

Year 15, before decreasing to an estimated 130 gpm at Year 20 (Table 1). On a preliminary basis, the Stage 1 EQ Pond will be designed for a working capacity of approximately 4 acre-feet. The Stage 1 EQ Pond will be lined and designed to meet the MPCA performance standards for surface impoundments.

The Stage 2 EQ Pond will receive the Category 1 / 2 stockpile process water drainage, pit dewatering water process water, runoff from all other active areas of the Mine Site, and process water runoff from the Rail Transfer Hopper area. As with the equalization pond for the Stage 1 treatment, the inflows to the Stage 2 EQ Pond will vary over the life of the operation as well as seasonally. As can be seen in Table 1 the average annual flow for these streams will increase throughout the mining operation with estimated flows ranging from 340 to 1,000 gpm. The estimated instantaneous flow within any given year will range from 0.4 to 2.3 times the anticipated annual average, with the highest flows expected in the spring and lower flows expected throughout the winter months.

The Stage 2 EQ Pond will be designed for a working capacity of approximately 6 acre-feet. The Stage 2 EQ Pond will be lined and designed to meet MPCA performance standards for surface impoundments. The side walls will be protected with rip-rap or vegetated to prevent erosion.

5.4.2 Nanofiltration Pre-Treatment

Prior to nanofiltration, the Stage 2 water will be filtered to remove any particulate matter. The Stage 2 EQ Pond should provide some time for settling and removal of larger size particles, so it is anticipated that the pre-treatment would consist of ultrafiltration alone or in combination with microfiltration ahead of the ultrafiltration unit. The objective of these operations is to remove any very fine particulate matter that could potentially foul the nanofiltration membrane and increase operating pressures or the required frequency of cleaning.

The ultrafiltration unit would consist of two parallel banks of filters each filter bank would contain an equal number of filter units and would be designed to operate with a minimum of units for small flow volumes up to all units operating simultaneously. Configuration of the membrane treatment units will vary depending on which vendor is selected to provide this equipment.

Solids removed in the pre-treatment filtration step will be removed by periodically washing the filters. Filter washing operations will also be vendor specific. Solids removed with the wash water will be directed to the Stage 1 chemical precipitation treatment operations.

5.4.3 Nanofiltration Membrane Unit

After passing through the ultrafiltration unit, the Stage 2 water would be treated with nanofiltration membranes. As with ultrafiltration, two parallel banks of spiral-wound membrane units would be used. For each bank, the likely operation would consist of a ‘Christmas Tree’ arrangement of filters at a ratio of 3:2:1. All water would pass through the first line of filters (the 3 row). The permeate from the first row would be discharged to the CPS while the brine from the first row of filters would then pass through the second row. A similar separation strategy would then be used for the third row. At the conclusion, the brine from the final row would be sent to the chemical precipitation operations for the Stage 1 flows described below.

Similar to the pre-treatment operation, membrane washing and maintenance would generate a waste stream that would be directed to the Stage 1 chemical precipitation treatment process.

5.4.4 Chemical Addition and Rapid Mixing

Chemical addition and rapid mixing will be the first step in of the chemical precipitation operation. Calcium hydroxide [$Ca(OH)_2$ or hydrated lime] will be the primary chemical added to raise the pH and generate hydroxides. However, as previously discussed, additional chemicals – aluminum hydroxide [$Al(0H)_3$], sodium hydrosulfide [NaHS], or additional iron salts – may be used at different times throughout the operation of the mine to enhance removal of sulfate or metals. Two parallel chemical addition/rapid mix units will be used to accommodate the projected inflow rate variability. Each rapid mix unit will be sized to provide between one and three minutes of contact time.

Chemicals will be added using chemical metering pumps. Hydrated lime will be injected as concentrated slurry. Rapid mixing will be achieved using high-speed agitators in relatively small volume tanks to achieve complete mixing of the lime with the influent flow. The lime addition rate will be controlled to maintain a pH of approximately 10 in both stages of treatment. However, a higher pH may be used in the first stage to increase the sulfate removal rate. Sludge generated in later operations will also be injected into the rapid mixing operations to provide solid surfaces that will promote chemical precipitation in the following stages.

Hydrated lime will be prepared at the Process Plant site and transported to the WWTF and stored in a lime silo. A screw conveyor system will be used to formulate the lime slurry for addition to the rapid mix units.

5.4.5 Coagulation and Flocculation

The chemical precipitation system will contain tanks for coagulation and flocculation. The primary purpose of this operation will be to keep the water adequately mixed to promote aeration of the wastewater and to prevent settling of suspended solids while providing adequate retention time for the precipitate to form large enough crystals to facilitate removal by gravity settling in the subsequent clarification units. Mixing will be accomplished using low-shear mixing paddles spaced throughout the tanks. Valves and baffles will be included to allow the units to accommodate the variable flows anticipated during mining operations while maintaining the necessary retention time identified in the preliminary bench-scale testing. The anticipated retention time for the coagulation/flocculation units will be approximately 1 hour. Additional retention time will be provided in the event that supplementary chemicals such as aluminum hydroxide, sodium hydrosulfide, or iron salts need to be added to improve removal efficiencies. Chemical metering pumps for the addition of a flocculating agent will be installed near the discharge from the coagulation units to the clarifiers to promote settleable floc formation.

5.4.6 Clarification (Settling)

Two clarifiers will be installed in parallel for the chemical precipitation process. Each clarifier will be sized to provide up to 60 minutes of solids settling time. Mechanical sludge removal equipment will be installed in each unit. The shape (round or square), and the need for settling tubes or other settlement aids, and final dimensions will be determined during the final design stages. Solids management is described in Section 5.6.

5.4.7 Recarbonation

The treated water from the chemical precipitation operation is expected to have a pH of approximately 10 and will have a relatively high concentration of calcium. This water will be treated with carbon dioxide [CO_2] to reduce the pH to approximately 8 in two steps. In the first step, calcium will be removed by precipitation as calcium carbonate [$CaCO_3$] at approximately pH 9. In the second step the pH will be reduced to between 7.5 and 8 to limit any further precipitation of carbonate minerals and reduce scaling in the Treated Water Pipeline. Additional clean-up steps could also be added, if necessary, for example if the effluent pH from chemical precipitation is well above 10, to provide removal of trace metals over a wider range of pH conditions to that would optimize removal efficiencies.

Carbon dioxide will be added to the liquid stream as a gas under pressure to promote dissolution and reaction with dissolved calcium. A final flocculation tank and clarifier (two each in parallel) will be used to recarbonate the water and remove the carbonate precipitate. Carbon dioxide gas will be delivered to the site in bulk and stored in an on-site carbon dioxide tank.

5.4.8 Process Monitoring and Control

The WWTF operations will be monitored continuously using the pH, temperature, and conductivity of the influent water and treated water at various stages within the process to control the addition of lime (and other chemicals as needed) in both treatment stages. Additional wastewater quality monitoring will be conducted on a daily basis for parameters such as total dissolved solids or turbidity and on a less frequent basis for a variety of parameters (e.g., copper, nickel, calcium, sulfate, and others). Continuous monitoring will be used to adjust the lime dosage rates for both stages of chemical treatment using an automated feedback loop, which will be monitored and adjusted, as necessary.

5.5 Potential Treatment System Performance

As noted in Section 3, the goal of the WWTF at the Mine Site will be to produce a treated effluent that will not adversely impact the operation of the Beneficiation Plant or the subsequent hydrometallurgical processes at the Plant Site. In addition, the objective of wastewater treatment will be to achieve the process water quality targets listed in Table 4. These process water quality targets have been conservatively established based on in-stream water quality standards for the Partridge and Embarrass Rivers and the protection of groundwater. These values have been used because the Treated Water Pipeline will cross several streams within the Partridge River watershed between the Mine Site and the Plant Site and also because these values provide very conservative treatment goals that will help to maintain the long-term water quality of the water in the Tailings Basin, which will eventually be returned to the mine pit.

Estimates of the potential WWTF effluent quality are listed in Table 14 along with the water quality process targets. The basis for these estimates is provided in Appendix G. These values show that, on an annual average basis, WWTF should be capable of achieving the process water quality targets for most of the parameters of concern with limited exceptions that may require enhanced chemical treatment.

The effluent predictions are based on the annual average flows and use the low flow estimates, because the low flow scenario results in the highest potential influent concentrations to the WWTF. Because the WWTF will be sized to accommodate the high flow conditions, the plant will have additional retention time in all the process units that could facilitate improved performance.

Table 14 Stage 1 and Stage 2 Treatment Systems Effluent and CPS Pond Predicted Water Quality

		Year 1			Year 5			Year 10			Year 15			Year 20			Process Water Quality Targets
Parameter	**units**	**Stage 1 Effluent**	**Stage 2 Effluent**	**CPS Effluent**	**Stage 1 Effluent**	**Stage 2 Effluent**	**CPS Effluent**	**Stage 1 Effluent**	**Stage 2 Effluent**	**CPS Effluent**	**Stage 1 Effluent**	**Stage 2 Effluent**	**CPS Effluent**	**Stage 1 Effluent**	**Stage 2 Effluent**	**CPS Effluent**	
Flow	gpm	106	482	696	214	1159	1396	234	1259	1397	192	850	903	177	1155	1155	
Hardness	mg/L	679	153	106	1751	333	276	2934	553	498	4407	1013	952	3205	505	505	
F	mg/L	1.83	0.41	0.28	2.09	0.44	0.36	4.45	0.95	0.85	7.42	1.88	1.77	9.43	1.60	1.60	2.0
Cl	mg/L	10.0	2.24	1.55	27.0	5.22	4.34	26.9	5.22	4.70	13.8	3.16	2.98	14.2	2.23	2.23	230
SO4 *	mg/L	992	222	154	1500	285	237	1500	289	**260**	1500	363	**341**	1500	247	247	250
Al	mg/L	0.040	0.036	0.025	0.18	0.066	0.055	0.41	0.11	0.10	0.56	0.18	**0.17**	0.36	0.092	0.092	0.125
As	mg/L	0.16	0.037	**0.026**	0.33	0.066	**0.055**	0.30	0.060	**0.054**	0.51	0.12	**0.12**	0.43	0.071	**0.071**	0.010
Ba	mg/L	0.18	0.041	0.029	0.30	0.058	0.048	0.29	0.055	0.050	0.39	0.091	0.085	0.36	0.057	0.057	2.0
Be	mg/L	0.0021	0.00047	0.00033	0.0023	0.00045	0.00037	0.0031	0.00060	0.00054	0.0031	0.00073	0.00069	0.0029	0.00046	0.00046	0.004
B	mg/L	0.61	0.14	0.10	1.20	0.23	0.19	1.13	0.22	0.20	1.40	0.33	0.31	1.41	0.23	0.23	0.5
Cd	mg/L	0.0071	0.0016	0.0011	0.0067	0.0013	0.0010	0.010	0.0020	0.0018	0.011	0.0025	0.0023	0.0078	0.0012	0.0012	0.004
Ca	mg/L	199	44.8	150	460	87.5	150	445	85.0	150	742	173	150	666	106	150	
Cr	mg/L	0.0039	0.00089	0.00062	0.0060	0.0012	0.0010	0.0059	0.0012	0.0010	0.0052	0.0012	0.0012	0.0072	0.0012	0.0012	0.100
Co	mg/L	0.00035	0.00040	0.00028	0.0035	0.0011	0.00094	0.021	0.0045	0.0040	0.034	0.0082	**0.0077**	0.021	0.0037	0.0037	0.005
Cu **	mg/L	0.00040	0.00055	0.00038	0.0016	0.0011	0.00091	0.053	0.011	0.0096	0.13	0.030	0.028	0.19	0.030	0.030	0.030
Fe	mg/L	0.029	0.073	0.050	0.074	0.11	0.091	0.084	0.10	0.093	0.11	0.060	0.056	0.094	0.044	0.044	0.3
Pb	mg/L	0.011	0.0024	0.0017	0.039	0.0074	0.0061	0.045	0.0085	0.0077	0.070	0.016	0.015	0.062	0.010	0.010	0.019
Mg	mg/L	2.22	0.76	0.53	7.35	1.97	1.64	22.2	4.67	4.21	31.1	8.00	7.52	18.8	3.71	3.71	
Mn	mg/L	0.0008	0.0027	0.0019	0.0060	0.0055	0.0046	0.020	0.0085	0.0077	0.029	0.015	0.014	0.016	0.0088	0.0088	0.05
Hg	mg/L	2.0E-05	4.7E-06	**3.2E-06**	2.0E-05	3.8E-06	**3.2E-06**	2.1E-05	4.1E-06	**3.7E-06**	2.5E-05	6.0E-06	**5.6E-06**	3.6E-05	5.8E-06	**5.8E-06**	1.3E-06
Mo	mg/L	0.013	0.0031	0.0021	0.023	0.0045	0.0038	0.023	0.0045	0.0041	0.019	0.0044	0.0042	0.029	0.0046	0.0046	0.100
Ni **	mg/L	0.0025	0.0048	0.0033	0.025	0.010	0.0086	0.14	0.031	0.028	0.25	0.061	0.057	0.18	0.030	0.030	0.100
P	mg/L	0.045	0.010	0.0069	0.10	0.018	0.015	0.072	0.014	0.012	0.12	0.029	0.027	0.10	0.017	0.017	
K	mg/L	30.7	6.93	4.80	58.3	11.1	9.24	50.0	9.57	8.63	75.8	17.8	16.7	66.9	10.7	10.7	
Se	mg/L	0.0075	0.0017	0.0012	0.011	0.0022	0.0018	0.011	0.0022	0.0019	0.010	0.0023	0.0021	0.013	0.0022	0.0022	0.005
Si	mg/L	3.75	0.83	0.57	6.99	1.33	1.10	3.79	0.72	0.65	7.61	1.78	1.68	7.15	1.14	1.14	
Ag	mg/L	0.0027	0.00062	0.00043	0.0045	0.00087	0.00072	0.0045	0.00087	0.00078	0.0033	0.00079	0.00074	0.0054	0.00087	0.00087	0.001
Na	mg/L																
		175	39.6	27.4	534	102	84.7	424	81.4	73.4	769	180	170	691	111	111	

Parameter	units	Year 1			Year 5			Year 10			Year 15			Year 20			Process Water Quality Targets
		Stage 1 Effluent	Stage 2 Effluent	CPS Effluent	Stage 1 Effluent	Stage 2 Effluent	CPS Effluent	Stage 1 Effluent	Stage 2 Effluent	CPS Effluent	Stage 1 Effluent	Stage 2 Effluent	CPS Effluent	Stage 1 Effluent	Stage 2 Effluent	CPS Effluent	
Tl	mg/L	0.0043	0.0010	**0.00068**	0.0071	0.0014	**0.0011**	0.0071	0.0014	**0.0013**	0.0041	0.0010	**0.00091**	0.0086	0.0014	**0.0014**	0.00056
Zn **	mg/L	0.21	0.051	0.035	0.77	0.15	0.12	1.22	0.23	0.21	1.46	0.33	0.31	1.03	0.16	0.16	0.388
NO3	mg/L	0.31	0.071	0.049	0.74	0.14	0.12	0.72	0.14	0.13	0.11	0.024	0.022	0.08	0.012	0.012	10.0
NH4	mg/L	0.31	0.071	0.049	0.74	0.14	0.12	0.72	0.14	0.13	0.11	0.024	0.022	0.08	0.012	0.012	

Notes: * Secondary Drinking Water Standard
** Varies with Hardness Concentration (Assumed 400 mg/L Hardness)

Parameters that could potentially exceed these targets and potential plans to mitigate these values, if necessary, include:

- Sulfate – The primary contribution of sulfate to the Mine Site process water is from Category 3 and Category 4 stockpiles. The drainage from the Category 3 and 4 stockpiles is proposed to be routed to the Stage 1 EQ Pond and will undergo chemical precipitation treatment. Concentrating the sulfate in the Stage 2 flows prior to chemical precipitation will improve the overall effectiveness of the WWTF and provide a permeate that when blended with the treated stream from the chemical precipitation unit will achieve the process water quality targets in all years modeled except Year 15. Given the variability of the concentration of sulfate in Stage 1 and Stage 2 flows, the effluent estimate for sulfate is potentially sensitive to significant changes in the ratio between these flows as well as the concentration of sulfate in any flow. The values used in this evaluation, however, are conservative, and the proposed treatment operation is capable of treating a wide range of potential volumes and concentrations. For example, in Year 15 when the estimated flows to Stage 2 decrease, a portion of the Stage 1 flows could be routed into Stage 2 to concentrate more of the mass flow in Stage 1 and provide additional permeate in Stage 2.
- Metals (Aluminum, Arsenic and Cobalt) – The primary contributor of these parameters to the Mine Site process water is also from Category 3 and Category 4 stockpiles. The predicted effluent values for these parameters are close to the process water quality targets using conservative removal percentages from the treatability study. Additional removal of these parameters is anticipated using the HDS process, as demonstrated in the absolute values obtained in the treatability study (Table 9 in Attachment C2), which showed all these parameters below the process water quality targets. If necessary, additional coagulation and flocculation time, or the addition of iron salts to the process would improve removal efficiencies. No other process modification would be required.

- Mercury –Mercury will likely exceed the process water quality target. However, this water will be pumped to the tailings basin where additional mercury removal is anticipated due to exposure to the NorthMet tailings. No other process modifications are anticipated to remove additional mercury.

- Thallium – The analytical results from several sources used in the prediction of the influent water quality to the WWTF reported thallium as non-detect at values above the process water quality target. Thus the reported value is likely a maximum value. At this time, thallium is not expected to be a concern, however, additional analysis of input flows will be needed to confirm the actual inputs and, if necessary, evaluate removal efficiencies using the proposed unit operations.

The ability of the WWTF to achieve the level of performance established by the process water quality targets will be monitored during the operation of the facility. If necessary, improvements to the process can be developed and/or additional technologies can be added to achieve treatment objectives.

5.6 Solid Waste Management Plan

A portion of the solids removed from the Stage 1clarifier will be returned to the rapid mix tank at the beginning of the chemical precipitation treatment process to promote crystal formation. The remaining solids will be conveyed to a sludge thickening unit and then pumped to a filter press operation where excess liquids will be removed prior to being returned to the influent stream of the Stage 1 treatment system. One press will be installed for the Stage 1 clarifier and an additional press will be installed for the solids from the final (recarbonation) clarifier to allow the solid waste streams generated from each of these operations to be managed individually. Dewatered solids will be disposed with the hydrometallurgical residues or may be re-pulped and fed into the hydrometallurgical process for metals recovery.

6.0 Evaluation of Treatment Options for Tailings Basins Water

No additional wastewater treatment operations are anticipated at the Plant Site. The reuse/recycle water management program for NorthMet, the separation of the process water loops between the Beneficiation Plant and the Hydrometallurgical Plant, and the wastewater treatment operation for process water at the Mine Site as described in Section 5 result in water quality within the tailings basin that is generally below the process water quality targets.

As noted in RS54A/RS46, the primary contributors of dissolved chemicals of potential concern to the tailings basin water are the make-up water from the mine site and chemical transformations within the tailings basin, such as oxidation on the beaches. By treating the Mine Site process water to achieve the process water quality targets before adding this water to the tailings basin, the overall water quality is maintained.

The potential load from recycling water from the tailings basin through the Beneficiation Plant was evaluated during two pilot tests. A technical memo summarizing the water quality from the pilot plant and estimating the potential load to the tailings basin was developed and is included with this report as Appendix H. The results of this modeling show that the concentrations in the water returning to the tailings basin from the Beneficiation Plant are lower than the concentrations in the WWTF effluent. The water through the Beneficiation Plant is not a major source for metals, as these are primarily captured with the concentrate. Sulfate added to the flotation process does report to the tailings basin. However, the load is lower than the load from the WWTF effluent. RS54A/RS46 developed a more conservative calculation of values for the potential load from the Beneficiation Plant to the tailings basin than those calculated in Appendix H. Those values were used in RS54A/RS46 to develop water quality predictions for the basin which adds additional conservatism to the water quality predictions for the tailings basin.

In the event that the predictions in Appendix H and RS54A/RS46 underestimate the loads to the tailings basin from the Beneficiation Plant, the seepage return drains, or other sources, the parameters closest to the process water quality targets, and therefore the first parameters of potential concern would likely be sulfate and nickel. Because the concentration of sulfate would likely be too low to be removed by chemical precipitation as gypsum, a likely wastewater treatment scenario at the Plant Site, if any additional treatment were necessary, would be to use nanofiltration to ‘concentrate’ the sulfate in the tailings basin water, similar to the plan for concentrating sulfate in the Stage 2 (low sulfate concentration) water at the Mine Site. Permeate could then be returned to the tailings basin while the brine could be treated to remove the sulfate as gypsum, most likely by sending the brine to the Hydrometallurgical Plant.

7.0 Summary

This report has addressed potential wastewater quality concerns at NorthMet and evaluated different treatment technologies for process water. This report follows the SOW established during the scoping of the EIS for the NorthMet project. Although wastewater discharges were being considered during the development of the SOW, PolyMet will be using a reuse/recycle water management plan at NorthMet to eliminate the need for discharge of water to surface water. The reuse/recycle water management plan is outlined in Section 2 along with a summary of the water quantity and quality at the Mine Site and the Plant Site as outlined in Phase 3 of the SOW.

Phase 1 of the SOW is presented as Section 3. The work described in Section 3 developed conservative process water quality targets based on surface water and groundwater quality standards. Phase 2, developed in Section 4 of the report, detailed potential wastewater treatment technologies for the removal of dissolved metals, sulfate, and other chemicals of concern. The use of chemical precipitation, membrane treatment, ion exchange, and constructed wetlands for treatment of the Mine Site process water, including removal of dissolved metals, sulfate and other parameters of potential concern was detailed in Section 5 in compliance with Phase 4 of the SOW. No treatment of water is required at the Plant Site. Section 6 of this report outlined the basis for this conclusion and provided contingent treatment scenarios for removal of chemicals of concern in the event that actual concentrations exceed process water quality targets.

At the completion of the treatment technology evaluation in Section 5, a proposed treatment program for Mine Site process water was presented. The proposed treatment system would include chemical precipitation treatment for the low-volume high-strength flows from the Mine Site including the drainage from waste rock stockpiles along with nanofiltration to concentrate the high-volume, low-strength flows prior to chemical precipitation treatment. This basic combination of technologies achieves the process water quality targets for most parameters of concern throughout the operating period of the Mine Site and has the flexibility for enhanced chemical treatment (e.g., addition of iron salts) if necessary to achieve process water quality targets for all parameters. Estimates for potential wastewater effluent quality were presented in Table 14. The predicted effluent concentrations were calculated using the combination of low flow and high concentration water quantity and quality values from the hydrologic and geochemical modeling completed at the Mine Site.

8.0 References

8.1 Printed Materials

Batchelor, B., Lasala, M.B., McDevitt, M., and Peacock, E., 1991. Technical and Economic Feasibility of Ultra-High Lime Treatment for Recycled Cooling Water. *Research Journal of the Water Pollution Control Federation*, **63**:7, 982-990.

Brinson, M.M., Lugo, A.E., and Brown, S. 1981. Primary productivity, decomposition, and consumer activity in freshwater wetlands. Annu. *Rev. Ecol. Syst.*, **12**: 123-161.

Davis, R.A., McElhiney, J.E., 2002. The Advancement of Sulfate Removal from Seawater in Offshore Waterflood Operations. Proceedings: Corrosion 2002.

Eger, P., Wagner, J., Melchert, G., Antonson, D., and Jackson, A. 2000. Long Term Wetland Treatment of Mine Drainage at LTV Steel Mining Company's Dunka Mine. Minnesota DNR.

Gula, M. and Harvey, J., 1996. *Novel Silica-Based Ion Exchange Resin* .Eichrom Industries, Inc. Darien, IL, Conference on Industry, Morgantown, WV, October 22-24, 1996.

ITRC, 2003. Technical and regulatory guidance document for constructed treatment wetlands.

Kim, B.M. and Amodeo, P.A., 1983. Calcium sulfide process for treatment of metal-containing wastes. *Environmental Progress* **2**: 175-180.

Kurniawan, T. A., Chan, G. Y. S., Lo, W., and Babel, S. Physico-chemical treatment techniques for wastewater laden with heavy metals. *Chemical Engineering Journal*, January, 2006.

Le Gouellec, Y.A., Elimelech, M., 2002. Control of Calcium sulfate (Gypsum) Scale in Nanofiltration of Saline Agricultural Drainage Water. *Environmental Engineering Science*, 19:6. 387-397.

Lorax Environmental, 2003. Treatment of Sulphate in Mine Effluents. Prepared for the International Network for Acid Prevention, October 2003.

Madigan, M.T., Martinko, J.M., and Parker, J. 1997. Brock Biology of Microorganisms, 8th Edition. Prentice Hall, Inc., Upper Saddle River, NJ.

Minnesota Department of Natural Resources, Paul Eger, Andrea Johnson, Jon Wagner, 2001, "Investigation of Elevated Copper and Cobalt Concentrations in Soudan Mine Drainage" (MNDNR, 2001)

Patrick, W.H. and Turner, F.T. 1968. Effect of redox potential on manganese transformation in waterlogged soil. *Nature* **220**, 476-478.

Sencindiver, J.C. and Bhumbla, D.K. 1988. Effects of cattail (Typha) on metal removal from mine drainage. Mine Drainage and Surface Mine Reclamation **1**: 359-366.

Smit, J. and Sibilski, U.E., October 2003. Pilot Plant Study to Treat Typical Gold Mine Minewater Using the SAVMIN Process. Proceedings, Water in Mining Conference.

Tarutus, W.J., Unz, R.F., and Brooks, R.P. 1992. Behavior of sedimentary Fe and Mn in a natural wetland receiving acidic mine drainage, Pennsylvania, USA. *Applied Geochemistry*, **7**:77-85.

Taylor, G.J. and Crowder, A.A. 1982. Uptake and accumulation of copper, nickel, and iron by Typha latifolia grown in solution culture. *Canadian Journal of Botany*, **61**:1825-1830.

US Army Corps of Engineers, 2001. “Precipitation/coagulation/flocculation Engineering and Design Manual, EM 1110-1-4012”

U.S. Environmental Protection Agency, 2006. “Management and Treatment of Water from Hard Rock Waste Sites”, Office of Research and Development, National Risk Management Research Laboratory, Cincinnati, Ohio. EPA-625/R-06/014.

U.S. Environmental Protection Agency, 1999. “Final Report – Berkeley Pit Innovative Technologies Project, Phase III: Hydrometrics, Inc. Demonstration of Sulfate Removal using the Walhalla Process, Mine Waste Technology Program Activity IV, Project 7”. Prepared by Montana Tech of the University of Montana and MSE Technology Applications, Inc., February 1999.

U.S. Environmental Protection Agency, 1996. “Capsule Report: Reverse Osmosis Process”, EPA-625/R-96/009.

U.S. Environmental Protection Agency, 1980. “Summary Report: Control and Treatment Technology for the Metal Finishing Industry”. EPA 625/8-80-003.

U.S. Environmental Protection Agency, 1973. “Applications of Reverse Osmosis to Acid Mine Drainage Treatment”, EPA-670/2-73-100.

Vymazal, 1995. “Algae and Nutrient Cycling in Wetlands”. CRC Press/Lewis Publishers, Boca Raton, Florida.

Wieder, R.K. 1988. Determining the capacity for metal retention in man-made wetlands constructed for treatment of coal mine drainage. Mine Drainage and Surface Mine Reclamation **1**: 375-380.

Wieder, R.K. 1990. Metal cation binding to *Sphagnum* peat and sawdust: relation to wetland treatment of metal-polluted waters. *Water, Air, and Soil Pollution*, **53**: 391-400.

Wieder, R.K. and Lange, G.E. 1988. Cycling of inorganic and organic sulfur in peat from Big Run Bog, West Virginia. *Biogeochemistry,* **5**, 221-242.

Worrall, F., Reed, M., Warburton, J., and Burt, T. 2003. Carbon budget for a British upland peat catchment. *The Science of the Total Environment*. **312**: 133-146.

8.2 Electronic Materials

http://www.aquatechnology.net, Accessed April 13, 2006.

http://www.frtr.gov/matrix2/section4/4_52.html#cost, Accessed April 17, 2006.

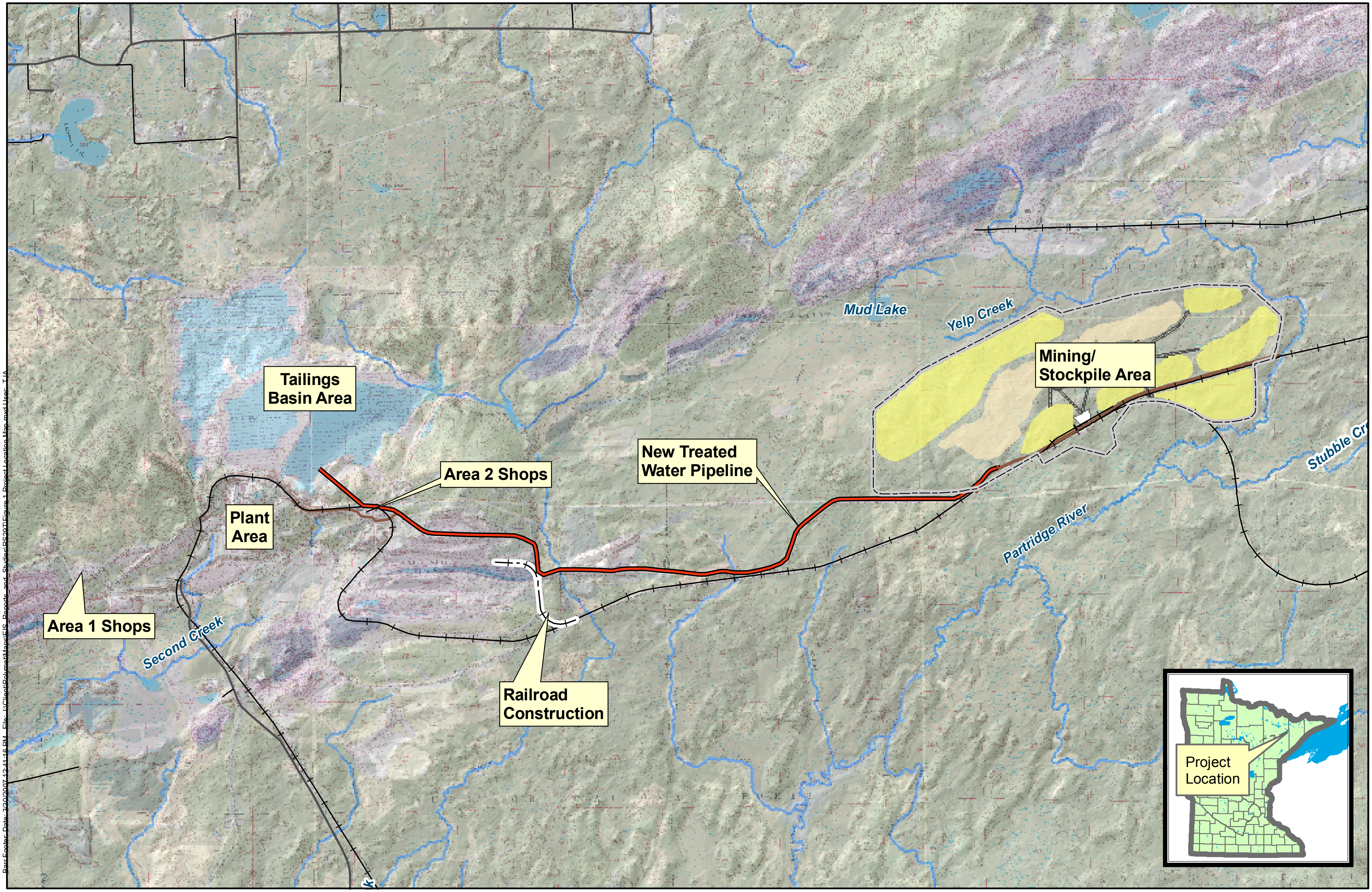
http://gewater.com/library/tp/833_WHat_Is.jsp, Accessed April 13, 2006.

http://www.nesc.wvu.edu/ndwc/pdf/OT/TB/TB4_IonExchange.pdf, Accessed April 17, 2006.

http://www.nmfrc.org/pdf/ro.htm, Accessed June 23, 2006.

http://www.remco.com/ix.htm, Accessed April 17, 2006.

Figures



▭ Mine Site
▬ Treated Water Pipeline
🟨 Proposed Stockpiles
▨ Proposed Pits

N

0 0.625 1.25 2.5
Miles

Figure 1
PROJECT LOCATION MAP
NorthMet Project
PolyMet Mining Inc.
Hoyt Lakes, MN

Figure 2
TAILINGS BASIN
NorthMet Project
PolyMet Mining Inc.
Hoyt Lakes, MN

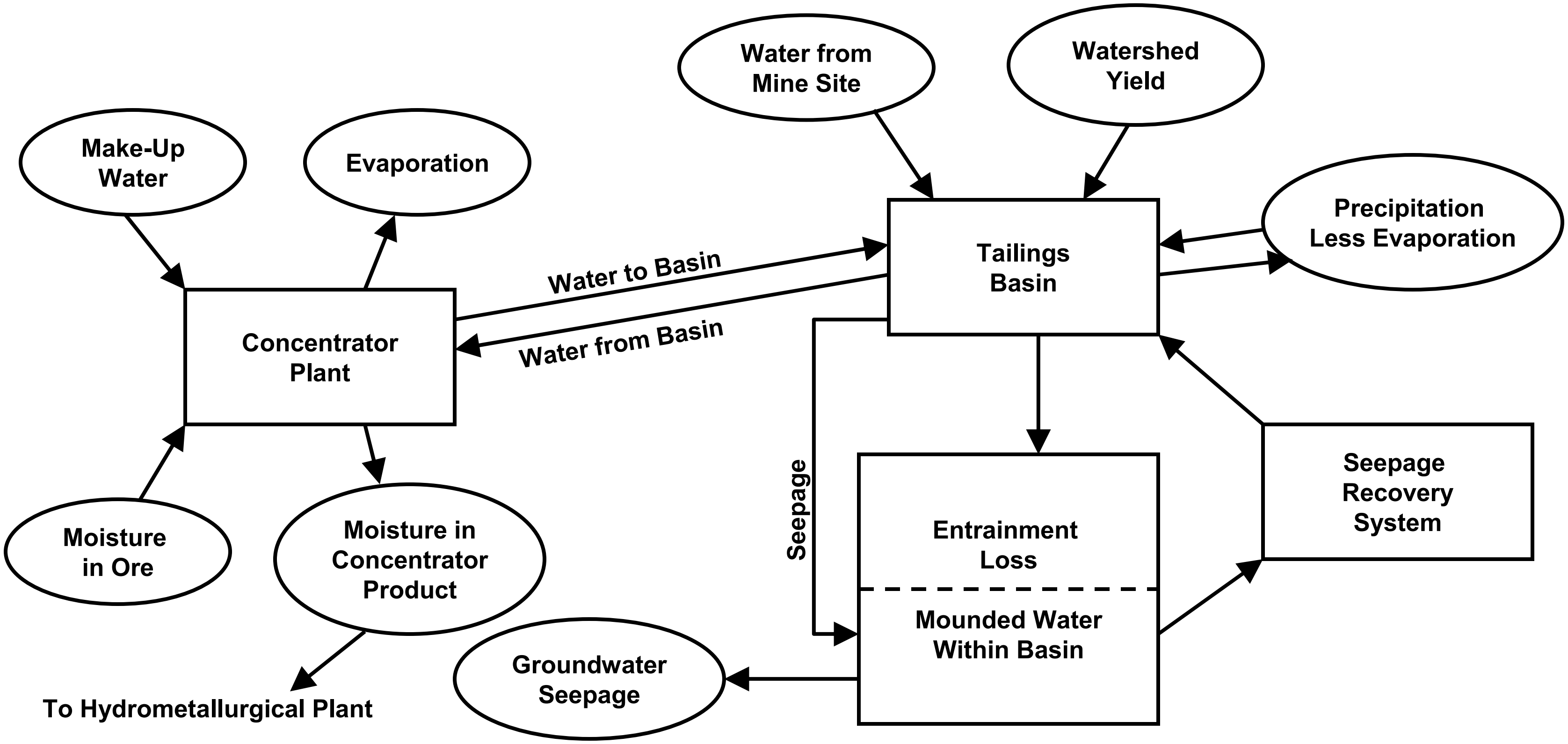


Figure 3
TAILINGS BASIN PROCESS
WATER FLOW DIAGRAM

NorthMet Project
PolyMet Mining Inc.
Hoyt Lakes, MN

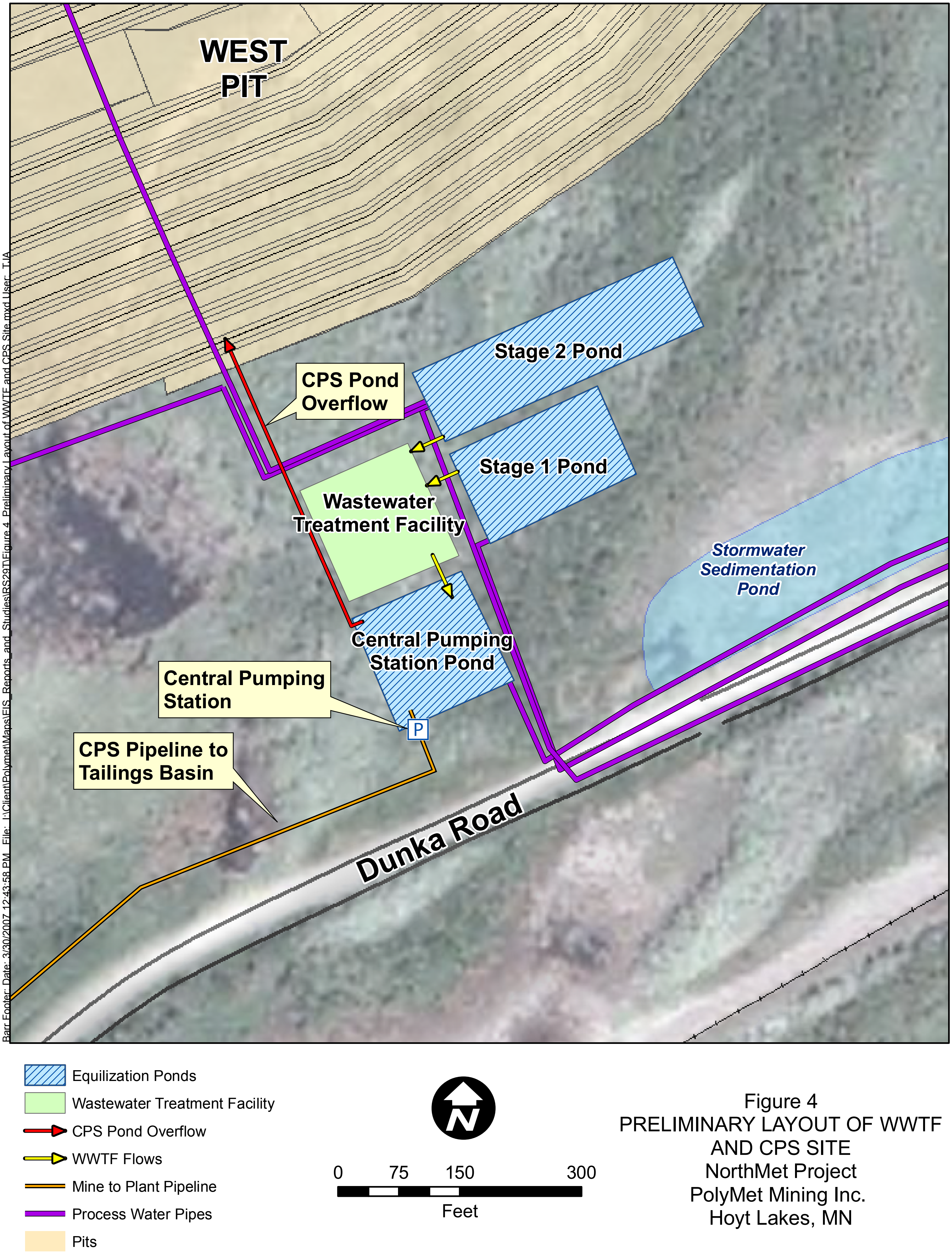


Figure 4
PRELIMINARY LAYOUT OF WWTF
AND CPS SITE
NorthMet Project
PolyMet Mining Inc.
Hoyt Lakes, MN

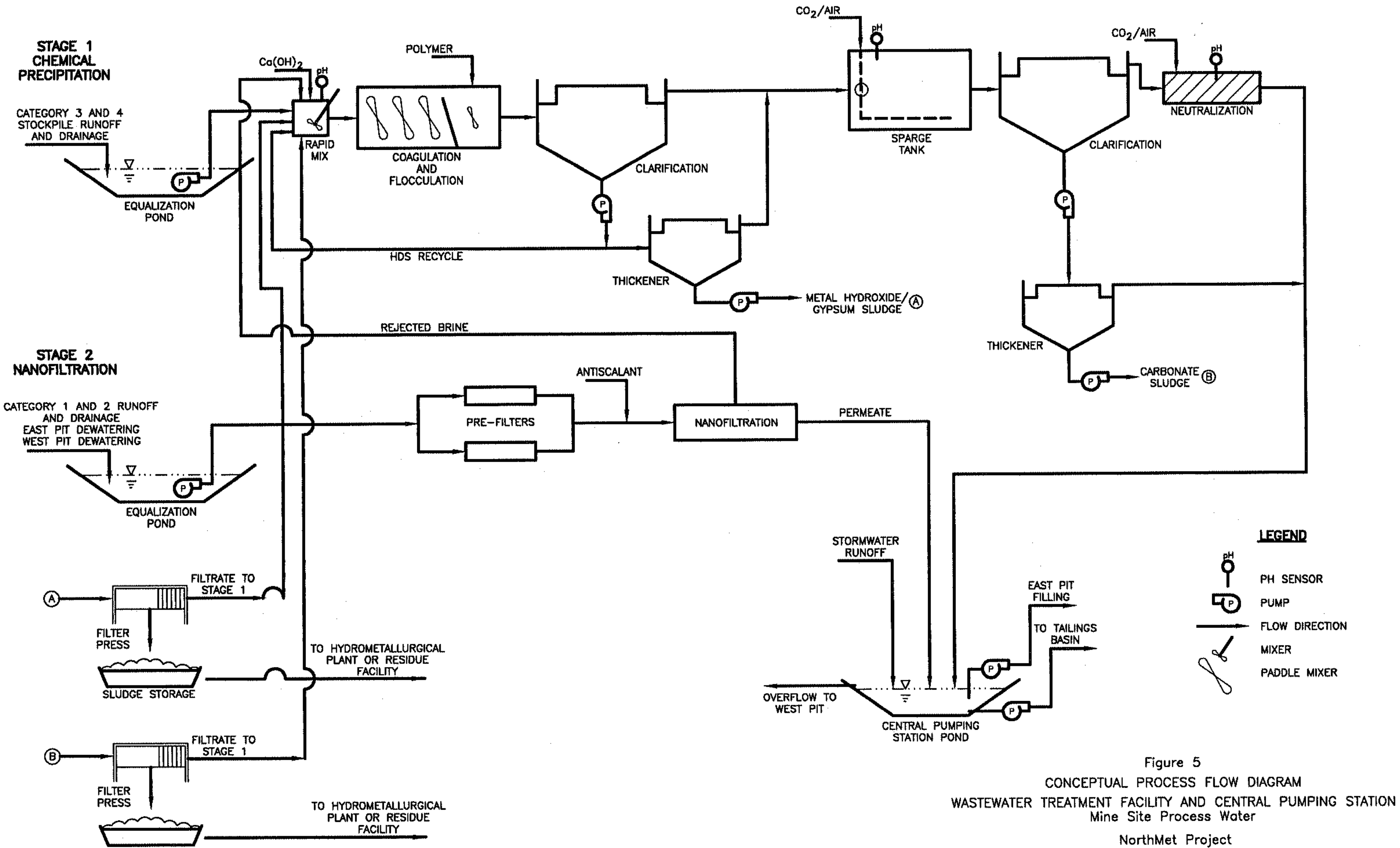


Figure 5
CONCEPTUAL PROCESS FLOW DIAGRAM
WASTEWATER TREATMENT FACILITY AND CENTRAL PUMPING STATION
Mine Site Process Water

NorthMet Project
PolyMet Mining, Inc.
Hoyt Lakes, Mn.

nrd M:\CAD\2369862\26012_1.DWG Plot at 0 03/23/2007 07:45:42

Appendix A

Technical Design Evaluation Report – Scope of Work

NorthMet Project – Technical Design Evaluation Report – Scope of Work
October 24, 2005

Name: Wastewater Treatment Technology **Due Date:** 4/4/06

Timeline Reference: RS29 **Scoping Decision Reference:** 2.5

Objective:

Study and report on wastewater treatment technologies for mine site reactive runoff water and plant site process water and provide conceptual sketches of the proposed design.

Scope:

Phase 1 of the study will develop anticipated water quality effluent discharge limits for permitted discharges at the mine site and plant site. The specific parameters to be studied are:

a. pH
b. Metals
c. Mercury
d. Sulfate
e. 'Salinity' (chloride, alkalinity, specific conductance, hardness, TDS)
f. Nutrients
g. Organics, GRO, DRO

Phase 2 of the study will collect information on the potential treatment (removal) efficiency for the parameters listed in Phase 1, using the following wastewater treatment technologies:

a. Precipitation (neutralization, Bauxaul, sulfide, etc.)
b. Reverse osmosis
c. Ion exchange
d. Constructed Wetland
e. Membrane technology

Phase 3 of the study will address wastewater minimization by developing a matrix of potential wastewater quantity and quality values associated with various capping and segregation scenarios for the sources of wastewater including:

a. Mine pit dewatering
b. Stockpile run-off
    i. Reactive Waste Rock
    ii. Lean Ore
    iii. Ore
c. Process water discharged from the tailings basin

Phase 4 of the study will evaluate the effectiveness, implementability and cost of the studied technologies (including practical combinations - pretreatment, staged and series) for wastewater minimization and treatment of mine site reactive runoff (Mine Pit Dewatering and Reactive Waste Rock/Ore/Lean Ore Stockpile Seepage).

Phase 5 of the study will evaluate the effectiveness, implementability and cost of the studied technologies (including practical combinations – pretreatment, staged and series) for plant site process water (Tailings Basin).

For Phases 4 and 5 of the evaluation protocol will include

- I. Technological feasibility
    - a. Ability to meet effluent limits
    - b. Design limitations
        - i. Hydraulic and chemical capacity
        - ii. Effects of temperature
    - c. Short term effectiveness
    - d. Long term effectiveness (closure)
    - e. Metal recovery (recycling for further processing) from wastewater or sludge
- II. Economic implications
    - a. Capital costs
    - b. Operating and maintenance costs
    - c. Closure costs
- III. Implementability considerations

Existing/Provided Information:

Details on predicted pre discharge water quality and discharge water quantity will be provided in the following reports or studies:

1. Hydrology – Mine Water Model and Balance
2. Process Design – Tailings Basin Water Balance
3. Mine Pit Water Quality Model
4. Wastewater Modeling - Waste Rock and Lean Ore
5. Wastewater Modeling – Tailings
6. Mine Wastewater Management Systems
7. Reactive Waste Segregation

Deliverable:

A report summarizing the wastewater management (including combinations of wastewater minimization and treatment) scenarios for mine site and plant site (study details to be included as an appendix) and ranking them on effectiveness, implementability and cost is required. Highest effectiveness, easiest implementability and lowest cost would be an optimum solution. However, it is likely that trade-offs between effectiveness, implementability, and cost will need to be considered. Wherever possible, quantitative estimates of effectiveness will be provided (e.g., concentration and mass of pollutants in effluent and pollutant removal efficiency). Cost will include construction, operation and post closure costs. Sketches of the proposed design will be included, consisting of plan location, alignment and cross sections.

Appendix B

Laboratory Study of Mercury Adsorption to LTV Taconite and NorthMet Tailings

Appendix B

Laboratory Study of Mercury Adsorption to LTV Taconite and NorthMet Tailings

Table of Contents

List of Attachments

1.0 Laboratory Testing

1.1 Background

Dissolved mercury is ubiquitous in surface water in Northeastern Minnesota as a result of atmospheric deposition from distant sources. This has caused issues with wastewater management due to the extremely low discharge limits for mercury, especially for surface waters within the Lake Superior watershed, where the discharge limit is set at 1.3 ng/L in accordance with the international "Great Lakes Initiative."

The NorthMet project will use a reuse/recycle water management strategy to eliminate the need to discharge water from either the Plant Site or the Mine Site to the Surface Waters of the State of Minnesota. Water generated at the Mine Site will be treated to meet process water quality targets and then pumped to the tailings basin for use as make-up water in the Beneficiation Plant. With this plan, low concentrations of mercury in the Mine Site process water will be partially reduced by treatment at the wastewater treatment facility (WWTF) located at the Mine Site. The remaining mercury will be discharged to the tailings basin.

Water quality monitoring of taconite tailings basins has suggested that mercury in tailings basin surface waters will be adsorbed by the fine tailings material and buried within the tailings basins. This removal mechanism was also considered likely for the NorthMet tailings and was assessed in laboratory tests conducted on behalf of PolyMet by Northeast Technical Services, Inc. of Virginia, Minnesota (NTS).

2.0 Materials and Methods

2.1 Collection of Water and Tailings Samples

Water and NorthMet tailings used in the experiments were obtained from pilot testing of the ore crushing and concentrating pilot tests conducted by SGS Lakefield Research Limited in accordance with the *Environmental Sampling and Analysis Plan, Pilot Test – NorthMet Deposit*, prepared by Barr Engineering (June 2005).

Flotation tests were conducted with three different ore grades with and without copper sulfate addition. NorthMet tailings samples were collected from each run and stored in sealed 5-gallon polyethylene containers. Tailings samples were collected in a saturated condition and maintained with approximately 5 cm of water above the surface of the tailings. All containers were labeled and stored in the on-site Lakefield walk-in cooler at 5ºC. Bulk process water samples associated with each type of ore grade (with and without copper sulfate) were also collected from each run and stored in sealed 55-gallon drums. Three drums per test cycle were collected and stored in the Lakefield 5ºC cooler.

A 20 L sub-sample of the archived process water inventory at Lakefield was obtained by Lakefield staff from a designated archive sample (P1L-BCS) using a peristaltic pump with new tubing (rinsed with deionized water) and shipped directly to NTS. The sample container was filled completely (minimal headspace), surrounded with protective bubble-wrap, placed on-ice in coolers and shipped via overnight carrier.

A sub-sample of the NorthMet tailings was also prepared by Lakefield staff and shipped directly to NTS. The tailings sub-sample was obtained using a clean scooping utensil (plastic preferred) to remove tailings from the specified sample container (P1S-CCS), filling a new 1-gallon polyethylene pail with minimal headspace. The tailings sub-sample was also bubble-wrapped, placed on-ice in a cooler and shipped overnight.

2.2 Experimental Set-up

To evaluate mercury adsorption to tailings over time, large-volume (2.5 L) shake-flask tests were conducted. One pre-cleaned shake flask was used for each time-series experiment. Process water obtained from Lakefield was spiked with additional dissolved mercury and then placed into the Experimental flask (Jug C) and the Process Control flask (Jug D). At the beginning of the experiment, PolyMet tailings were added to Jug C at a concentration of 50 g/L, while Jug D contained only water.

At time zero (0) and seven additional time steps (5, 15, 30, 60, 120, 240, and 480 minutes), an aliquot was removed from each jug, filtered (0.45 µm) and submitted for analysis of dissolved mercury. Other metals were also analyzed at 0, 30, and 480 minutes. All samples were analyzed by NTS, along with appropriate samples for quality control.

3.0 Results

3.1 Adsorption of Mercury by PolyMet Tailings

The concentration of mercury remaining in solution in shake-flask experiments with (Jug C) and without (Jug D) the addition of PolyMet tailings is reported in the table in Attachment B1 and shown graphically on the figure in Attachment 1 (Laboratory reports for analytical data are available from NTS upon request). The results show that mercury removal by adsorption to PolyMet tailings occurs rapidly and remains stable throughout the conditions of this experiment. The concentration of mercury in contact with PolyMet tailings is below the process water quality target for mercury. In contrast, the results in the control show that mercury is not lost and remains above the process water quality target. Together these results show that PolyMet tailings adsorb mercury.

3.2 Adsorption of Metals by PolyMet Tailings

The concentrations of the heavy metals cadmium, cobalt, copper, nickel, and zinc were analyzed in the large-shake flask experiments at 0, 30, and 480 minutes and are reported in the table in Attachment B1. Over the 480 minutes of the experiment, the following trends were observed:

- cadmium and zinc were not detected in any of the samples in either of the shake flasks
- cobalt concentrations decreased with time in both flasks, although the change was likely not significant
- copper concentrations increased slightly in the experiment that included PolyMet tailings, but did not change in the control flask
- nickel concentrations decreased in the experiment with PolyMet tailings and increased slightly in the control flask

Other dissolved parameters were also measured including calcium, magnesium, iron, manganese, chloride, and sulfate. None of these parameters showed any significant trends in the process control test. In the test with PolyMet tailings, a slight increase in the concentrations of calcium, chloride, and sulfate were observed. The concentrations of iron magnesium and manganese did not change.

Attachment B1

NTS Experiment Summary

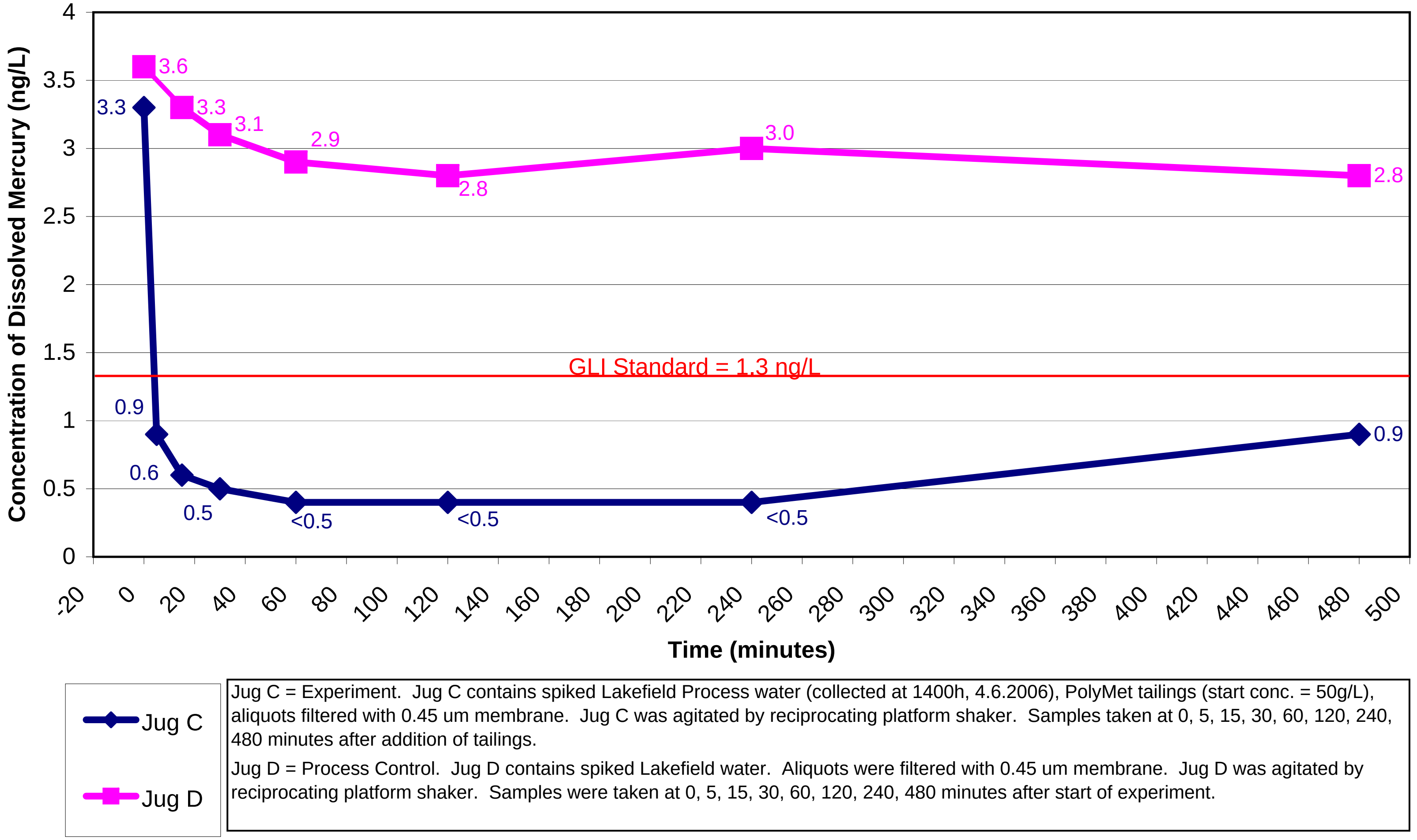
PolyMet Mercury Study
Experiment #8: Kinetics (Lakefield #2 and PolyMet Tailings)
6.22.2006

		Jug C									Jug D							
		0	**5**	**15**	**30**	**60**	**60.2**	**120**	**240**	**480**	**0**	**15**	**30**	**60**	**120**	**240**	**480**	**EB**
Alkalinity	(as CaCO3)	140			151					185	153		146				167	
Cadmium, diss.	ug/L	<0.2			<0.2					<0.2	<0.2		<0.2				<0.2	
Calcium, diss.	mg/L	19.7			24.8					25.1	19.8		19.9				19.7	
Chloride, diss.	mg/L	67.7			69.1					70.8	64.7		64.5				66.8	
Cobalt, diss.	ug/L	1.2			<1					<1	1.1		1.1				<1	
Copper, diss.	ug/L	<2			2.4					4.5	<2		<2				<2	
DOC	mg/L	106.7			107.9					108.5	107.8		107.2				109	
Iron, diss.	mg/L	<0.05			<0.05					<0.05	<0.05		<0.05				<0.05	
Magnesium, diss.	mg/L	11.1			11.0					11.6	11.2		11.2				11.1	
Manganese, diss.	mg/L	0.04			0.02					0.02	0.04		0.04				0.04	
Mercury (LL), diss.	ng/L	3.3	0.9	0.6	0.5	<0.5	<0.5	<0.5	<0.5	0.9	3.6	3.3	3.1	2.9	2.8	3.0	2.8	<0.2
Nickel, diss.	ug/L	16.9			7.4					5.2	17.4		17.8				20.5	
pH		8.2			8.3					8.3	8.1		8.2				8.2	
Sulfate	mg/L	126			153					146	135		124				140	
Zinc, diss.	ug/L	<5			<5					<5	<5		<5				<5	

Experiment #8 - Kinetics

PolyMet (6472K.08)

6.23.2006



Jug C = Experiment. Jug C contains spiked Lakefield Process water (collected at 1400h, 4.6.2006), PolyMet tailings (start conc. = 50g/L), aliquots filtered with 0.45 um membrane. Jug C was agitated by reciprocating platform shaker. Samples taken at 0, 5, 15, 30, 60, 120, 240, 480 minutes after addition of tailings.

Jug D = Process Control. Jug D contains spiked Lakefield water. Aliquots were filtered with 0.45 um membrane. Jug D was agitated by reciprocating platform shaker. Samples were taken at 0, 5, 15, 30, 60, 120, 240, 480 minutes after start of experiment.

Appendix C

RS45 – Water Treatment Studies – Waste Rock and Lean Ore

Appendix C

RS45 – Waste Rock and Lean Ore Wastewater Treatability Study Report

Table of Contents

List of Tables

List of Attachments

1.0 Introduction

1.1 Background

PolyMet Mining, Inc. (PolyMet) plans to excavate and process low-grade, polymetallic, disseminated, magmatic-sulfide NorthMet-deposit ore in northeastern Minnesota, approximately 6 miles south of the town of Babbitt, Minnesota, as described in RS29T and other reports.

PolyMet is proposing to reuse/recycle process water from the Mine Site in the operations at the Plant Site and to eliminate any direct discharge from NorthMet to the surface waters of the State of Minnesota. A key component of this water management plan will include treatment of Mine Site process water.

1.2 Purpose and Objectives

The objective of this Waste Rock and Lean Ore Wastewater Treatability Study Report (RS45) is to summarize the results of treatability studies completed for the wastewater generated at the Mine Site – collectively referred to as Mine Site process water. With the reuse/recycle water management plan, this water is not being treated for discharge, but for reuse within the Beneficiation Plant at NorthMet. Thus, treatment requirements are considered within the context of the overall operation, which is somewhat different than the objectives envisioned during the development of the preliminary outline for this report with the DNR.

1.3 Report Organization

The outline developed for this report in consultation with DNR staff has been used to prepare this report. However, since most of the information contemplated in the development of this report has been included in other reports, the content of several of these sections is limited. In accordance with the original outline:

- Section 2 contains a summary of information from predecessor reports,
- Section 3 contains a literature evaluation of potential treatment technologies,
- Section 4 summarizes the bench-scale treatability studies, and
- Section 5 outlines the conclusions and recommendations from this work and identifies future data needs.

2.0 Synthesis of Predecessor Reports

The recycle/reuse water management plan for NorthMet envisions no discharge of wastewater from either the Mine Site or the Plant Site to the surface waters of the State of Minnesota. This plan is summarized in Section 2 of RS29T. Detailed portions of this plan were developed in several other documents, which are referred to in Section 2 of RS29T.

3.0 Literature Evaluation of Potential Treatment Technologies

Potential treatment technologies for Mine Site process water are described in detail in Section 4 of RS29T. The technologies described include chemical precipitation, membrane technologies (including reverse osmosis and nanofiltration), ion exchange, and constructed wetlands (including bioreactor treatment systems). As described in RS29T, all of these technologies are potentially viable for the anticipated Mine Site process water.

All these technologies have advantages and disadvantages. These are identified in Section 5 of RS29T along with a discussion of the benefits of using two of these technologies in combination to improve overall treatment effectiveness in meeting the process water quality targets.

Several technologies that do not relate directly to wastewater treatment, but instead could be implemented to reduce either the volume or the strength of Mine Site process water, have been considered throughout the development of reports for the NorthMet Project. For example, techniques that have been used to reduce the volumes of runoff or drainage water from waste rock stockpiles are described in RS49, Stockpile Conceptual Design, while several technologies that could be implemented during the construction of the waste rock piles to reduce the strength of waste rock drainage were described in RS30, Reactive Waste Rock Stockpile Chemical Modification.

4.0 Bench-Scale Treatability Testing

4.1 Treatability Testing Protocol

Bench-scale treatability testing was conducted in accordance with the *Wastewater Treatability Study Protocol* (Attachment C1). The protocol outlined the source of water that would be used (Dunka seep water), the technologies that would be tested, and the methods that would be used to evaluate the treatment technologies. A split sample of the seep water was also collected and submitted to CAS for analysis.

4.2 Treatability Testing Results

The treatability testing outlined in the protocol was completed by Canadian Environmental and Metallurgical, Inc. (CEMI) in Burnaby, BC. The results of the testing are summarized in the *Wastewater Treatability Study Report* (Attachment C2). The analytical results from the split sample submitted to CAS are included in Table C1

The results show that metals can be removed to very low concentrations using the high density sludge (HDS) process. The removal efficiency of the HDS process, based on percent removal for individual parameters, is summarized in Table C2. These percentages represent conservative removal estimates for water with higher initial concentrations, because the removal mechanism and the potential effluent concentration are based on solubility. Greater removal percentages may be possible with higher initial values, but effluent concentrations would not likely be lower than those reported in Attachment C2 with lower influent concentrations.

Table C2 Treatability Study Removal Efficiencies

Parameter	Influent (mg/L)	Effluent (mg/L)	Percent Removed
Aluminum	0.017	0.003	82
Arsenic	0.001	0.0007	30
Boron	0.402	0.366	9
Cadmium	0.002	0.00004	98
Cobalt	0.0673	<0.00002	99
Copper	0.281	0.0064	94
Manganese	1.68	0.00096	99
Nickel	1.48	0.0076	99
Zinc	0.52	0.0017	99

5.0 Conclusions and Recommendations

The following conclusions and recommendations have been developed from the wastewater treatability testing completed by CEMI.

5.1 Conclusions

Based on the results presented in Attachment C2, chemical precipitation using the HDS recycle method is capable of reducing the concentrations of metals to below the process water quality targets.

The removal efficiencies calculated from the HDS removal simulation, on a percentage basis, will be used to evaluate potential removal for a chemical precipitation wastewater treatment operation at the Mine Site in RS29T (Section 5).

The parameters used in the testing program – specifically the hydraulic retention times in both the coagulation/flocculation step (60 minutes) and in the settling/clarification step (60 minutes) will be incorporated into the full-scale design.

The HDS process will facilitate the precipitation of sulfate as gypsum; however, the effluent concentration will be limited by the solubility of gypsum.

5.2 Recommendations and Identification of Additional Data Needs

The results from the treatability testing completed by CEMI show very good results for metals removal, but do not fully address other parameters of concern, including mercury and sulfate. Combinations of technologies should be considered in RS29T to incorporate treatment of these parameters.

Table C1
Dunka Seep Water Quality Data
(concentrations in ug/L, unless noted otherwise)

Location	**Minnesota Surface Water Quality Criteria Class 2B Chronic**	**WS004**	**WS004**	**WS004**	**WS004**	**WS004**
Date	**1/31/2000**	**5/3/2006**	**5/3/2006**	**5/3/2006**	**5/3/2006**	**5/3/2006**
Lab		**CAS**	**CAS**	**CAS**	**CAS**	**CAS**
Exceedance Key	**Bold**					
General Chemical Parameters, mg/L						
Alkalinity, (hydrox.) as @CaCO3	--	<2	--	--	--	--
Alkalinity, bicarbonate as CaCO3	--	103	--	--	--	--
Alkalinity, total	--	103	--	--	--	--
Bromide	--	<2.0 *	--	--	--	--
Carbonate	--	<2	--	--	--	--
Chemical Oxygen Demand	--	14	--	--	--	--
Chloride	230	5.5	--	--	--	--
Fluoride	--	<4.0 *	--	--	--	--
Nitrate + Nitrite	--	440	--	--	--	--
Nitrogen total kjeldahl	--	100	--	--	--	--
Nitrogen, ammonia as N	40	<50	--	--	--	--
Phosphorus total	--	0.01	--	--	--	--
Solids, total suspended	--	<5	--	--	--	--
Sulfate	--	1930	--	--	--	--
Sulfide total	--	<2	--	--	--	--
Sulfite	--	<2	--	--	--	--
Chlorine	11	<0.1	--	--	--	--
pH, standard units	6.5-9.0 PH	**7.36**	--	--	--	--
Metals, ug/L						
Aluminum	125	--	**229**	**196**	**198**	**224**
Antimony	31	--	<0.05	<0.05	<0.05	<0.05
Arsenic	53	--	0.6	0.6	0.6	0.7
Barium	--	--	12.8	12.4	12.8	13.0
Beryllium	--	--	0.04	0.03	0.03	0.03
Boron	--	--	441	418	437	423
Cadmium	1.1 HD	--	**1.90**	**1.76**	**1.85**	**1.82**
Calcium	--	--	288000	277000	285000	281000
Chromium	11 CR6	--	0.3	0.3	0.3	0.6
Cobalt	5.0	--	**62.6**	**58.3**	**59.9**	**62.7**
Copper	9.8 HD	--	**349**	**330**	**343**	**336**
Iron	--	--	40.5	54.1	38.6	40.5
Lead	3.2 HD	--	<0.02	<0.02	<0.02	<0.02
Magnesium	--	--	371000	355000	367000	357000
Manganese	--	--	1620	1550	1610	1580
Mercury	0.0069	0.0013	--	--	--	--
Molybdenum	--	--	0.81	0.86	0.87	0.92
Nickel	158 HD	--	**1460**	**1400**	**1430**	**1420**
Potassium	--	--	6400	6330	5940	6340
Selenium	5.0	--	<2.0	<2.0	<2.0	<2.0
Silver	1.0 HD	--	<0.02	<0.02	<0.02	<0.02
Sodium	--	--	57200	54800	56600	54900
Thallium	0.56	--	<0.02	<0.02	<0.02	0.02
Tin	--	--	<0.1	<0.1	<0.1	<0.1
Titanium	--	--	<10	<10	<10	<10
Zinc	106 HD	--	**526**	**503**	**519**	**512**

Attachment C1

Wastewater Treatability Study Protocol

Wastewater Treatability Study Protocol
Phase I: Chemical Precipitation
Waste Rock and Lean Ore
PolyMet Mining, Inc.
NorthMet Project

March 2006

Table of Contents

List of Tables

List of Appendices

1.0 Introduction

This Wastewater Treatability Study Protocol (Protocol) presents a proposed approach for treatability testing for chemical precipitation. Chemical precipitation is a wastewater treatment technology that can be used to treat the wastewater that is anticipated to be generated from waste rock and lean ore materials during mining operations at the NorthMet Mine Site.

1.1 Objectives

The objective of these treatability tests is to demonstrate the feasibility of chemical precipitation – a conventional wastewater treatment technology that has been used in numerous full-scale applications – to treat wastewater from the NorthMet Mine Site. The results of this treatability testing program will be used to estimate removal efficiency, effluent quality, chemical addition requirements, sludge generation rates, and design parameters for a pilot-scale and a full-scale chemical precipitation treatment system. This is the first phase of testing that will be completed to determine the levels of treatment necessary to treat the NorthMet wastewaters to meet discharge water quality standards consistent with a new or existing NPDES discharge permit. In a full-scale treatment system, more than one treatment process may be needed in series to achieve acceptable results. Chemical precipitation, the focus of this test, would likely be the first treatment operation in a full-scale wastewater treatment system.

The results of these tests will be incorporated into the process of developing an environmental impact statement (EIS) that will evaluate the potential impacts associated with the proposed mining activities and to provide a baseline for pilot-scale testing and full-scale operation of a wastewater treatment system (or systems) for the NorthMet mine.

1.2 Basis for Selection of Treatment Methods for Testing

Treatment processes presented in this Protocol include:

- chemical precipitation with lime addition, and
- chemical precipitation with calcium sulfide or another similar sulfide solution as a secondary or polishing step.

Both of these methods are conventional wastewater treatment unit operations and have been used in full-scale systems to treat metals such as copper, nickel, mercury, and zinc – the primary chemicals of concern in the wastewater that will be generated at the North Met Mine Site. Lime addition adds hydroxide ions to the water, which raises the pH. Within a specific range of pH (which varies for each metal), the hydroxide ions will also react with metals to produce insoluble precipitates that can be removed from the water by settling (coagulation and flocculation) and filtering, if necessary.

Sulfides such as Na_2S or CaS can be used to precipitate most metals. One advantage of sulfide metal precipitation is that the solubility of the metal sulfide precipitate is often lower than respective hydroxide or carbonate precipitates formed during lime precipitation. Sulfide precipitation is typically used after lime treatment as a polishing process to reduce trace metals levels (e.g., cadmium). This combined lime and sulfide treatment process reduces the demand for sulfide reagent and is typically more cost-effective as sulfide reagent costs are high.

2.0 Laboratory Materials and Methods

2.1 Wastewater

Wastewater for use in the treatability studies will be obtained from one or more sources including:

- synthetic wastewater formulated based on (i) chemical characteristics observed in wastewater from laboratory leaching tests using waste rock or lean ore, or, (ii) predicted for seepage from waste rock or lean ore or under field conditions; and
- waste rock leachate from stockpiles associated with the former mining operations at the Dunka Mine Pit.

The source waters selected for the proposed testing should closely approximate the water quality expected from the waste rock and lean ore. A comparison of the wastewater modeling results and the available Dunka Pit water quality data has been conducted to determine the most representative wastewater source for conducting these tests. Blending of two source waters – for example leachate from Dunka Mine waste piles and synthetic water – will likely be used to obtain the range of potential wastewater characteristics that will be representative of wastewater from the two sources considered in this testing. In general, wastewater from the waste rock piles should typically have a higher quality (lower concentrations of metals and inorganic chemicals of potential concern) when compared to the wastewater from lean ore. The treatability study approach described below will be repeated using two wastewaters that will represent the ranges offered from these two sources.

Table 1 presents the preliminary results from the waste rock wastewater modeling results. Also shown in Table 1 are the anticipated discharge water quality criteria (Class 2B, chronic standards) and water quality data from the Dunka waste rock stockpiles. Based on these data, preliminary proposed target concentrations for the source water to be used for the waste rock and lean ore treatability tests are presented in Table 2. The target concentrations for the two waste streams will be formulated using a combination of water from the Dunka stockpile leach water and a dilution water containing pre-determined concentrations of constituents to achieve the desired concentrations of the parameters of concern. Prior to developing the blended waters the unblended water will be analyzed for all the parameters (List 1 and List 2) as described below.

2.2 Sampling and Analytical Procedures

Water and sludge samples will be collected from the bench-scale treatability testing. All water and sludge samples will be collected by the test facility personnel in accordance with the Barr Engineering Company Standard Operating Procedures (SOP) for sample collection, which is included in Appendix A. All sample collection activities will be documented using a Chain of Custody that will also be completed in accordance with the Barr Engineering Company SOP. Water samples will be submitted directly to Columbia Analytical Services (CAS) for analysis of one or more of the groups of parameters listed in Table 3. Table 3 also provides a summary of the laboratory test methods, reporting limits, and method detection limits for each parameter. Table 4 provides additional details for the collection of the environmental samples including container requirements, sample preservation, storage, and shipping requirements for various analytical parameters. Solid samples will be dried and weighed at the testing laboratory.

Since mercury is a parameter of high interest, ultra-clean glassware and laboratory procedures that will ensure the integrity of the results will be required for all the steps described in this Protocol.

2.3 Experimental Set-up

2.3.1 Step Testing of Lime and Sulfide Precipitation

This Protocol for chemical precipitation treatability testing will consist of three steps. The first step will consist of a preliminary screening procedure to evaluate lime dosage rates. The first step of the experiment will be conducted using conventional Phipps-Bird type jar testing equipment. Aliquots of 500 mL of the selected source water will be added to up to three (3) 1-L beakers suitable for use with the jar testing equipment. Lime will be added in different dosages to yield a final pH range from 8.0 to 10.0 (in 1.0 pH increments). Rapid mixing will be used and pH will be maintained at the desired pH level with addition of lime. After 60 minutes of high agitation, allowing time for oxidation, the rate of the stirring mechanism will be reduced to simulate the flocculation step. After a reasonable flocculation period, the stirring mechanism will be turned off and the propellers removed from the jars. A quiescent period of approximately 60 minutes will then take place to simulate solids settling.

During the settling period, a visual observation of any changes in floc settleability and supernatant clarity with time will be recorded at approximately 5-minute intervals. Digital photographs will be taken of individual tests. At the conclusion of the settling period, the solution will be filtered. The solids will be dried and weighed to determine the mass of sludge generated and the filtrate will be submitted to CAS for analysis of the List 1 parameters in Table 3.

In the second step of the test procedure, the lime dosages used in the first step will remain the same but the rapid mix and flocculation stages of the test will be altered to determine the affect of longer or shorter reaction and settling times on effluent water quality (clarity) and sludge production. A total of four(4) jar tests will be used for each water type with reaction and flocculation times increased and decreased by up to 50 percent of the values used in step one (e.g., 30- and 90-minute rapid mix and 60-minute floc, 60-minute rapid mix, and 30- and 90-minute floc time). Floc settling in these tests will be documented and photographs taken as described in step one. At the completion of the tests, the solution will be filtered as described in step one. The solids will be dried and weighed to determine the mass of sludge generated and the filtrate will be submitted to CAS for analysis of the List 1 parameters in Table 3.

At the conclusion of the first two steps of the treatability testing, three factors will be evaluated to determine the preferred treatment scenario for further testing. These factors, in order, will be:

- lowest concentration of metals in the filtrate,
- lowest mass of sludge, and
- shortest operating time.

The objective of step three in the treatability testing process will be to determine the affect of the addition of either calcium sulfide or calcium polysulfide on water quality and sludge production. In step three, five (5) jar tests will be conducted for each wastewater. The lime dosage and operating time will be determined based on the results from steps one and two. This step will be repeated three times for each wastewater to generate a sufficient quantity of treated water to perform the sulfide evaluation portion of this testing procedure. After lime treatment and separation of the filtrate from the lime sludge, calcium sulfide or polysulfide will be added at a single dose rate to five jars each with 0.5 liters of treated wastewater. This number of jars is required to generate approximately 2.5 liters of sulfide-treated wastewater per sulfide dose required for laboratory analysis. This step is repeated for five different doses ranging from 0.5 to 2.5 times the approximate stoichiometric sulfide concentration needed to precipitate the residual metal cations in solution. Sulfide precipitant will be allowed to react, flocculate, and settle using the same operating times as the lime sludge. The samples will then be filtered. As with step one and two, the filtrate will be submitted to CAS. However, the parameter list for step three will include List 1 and List 2 parameters shown in Table 3.

3.0 Data Review, Validation, and Reporting

3.1 Quality Assurance Objectives

Quality assurance objectives (QAOs) have been established to ensure accuracy, precision, sensitivity, completeness, and comparability of laboratory analytical data and to meet the Quality Control (QC) acceptance criteria of analytical protocols in support of project needs. Overall, QAO procedures for field sampling, chain-of-custody, laboratory analysis, and reporting will provide the level of data required for determining the concentration of potential contaminants in air, solid, and water samples.

Four individual QAOs, including precision, accuracy, sensitivity, and completeness will be used to meet the QAOs for this project. Precision will measure the reproducibility of measurements at the laboratory by comparing analytical results between matrix spike/matrix spike duplicates (MS/MSD), laboratory duplicates, and/or masked duplicates collected in the field. The relative percent difference will be calculated for each pair of duplicate analyses. Accuracy will be measured by the agreement of results with a known value. Accuracy of results will be assessed using the analytical results of method blanks, field blanks, reagent/preparation blank, matrix spike/matrix spike duplicate samples, and laboratory control samples. Completeness is defined as the number of valid measurements obtained compared to the planned number of measurements and is expressed as a percentage. Barr expects that the contracted laboratory will provide useable and acceptable data for at least 95 percent of all samples tested using the specified analytical method. Sensitivity (reporting limits) is dependent upon instrument sensitivity, sample matrix, and composition effects and will be monitored by the laboratory. Final laboratory reporting limits are listed in Table 3. Actual reporting limits achieved may depend on sample size available, sample matrix interferences, and parameter concentrations. 100 percent of the data will be reviewed.

3.2 Data Reporting

At the conclusion of the sampling and analytical events, a report will be generated summarizing the results. This report will include a summary of sampling activities including locations and numbers of samples collected, a summary of the analytical results including a data table with any qualifiers issued based on the quality assurance review, a summary of the quality assurance review, copies of all laboratory reports, and any conclusions that can be made based on the data.

The report will be made available in electronic format (pdf file) on the PolyMet project management web-site hosted by Barr Engineering. All data generated will be also available as a simple Excel spreadsheet with columns for sample location, sample date, sample time, parameter name, units, reporting limit, analytical method, results, and qualifiers.

3.3 Data Evaluation

After the data have been reviewed, the analytical results for metals in the step one and step two tests will be used to generate solubility curves that show pH versus metal concentrations. Similarly, a plot of metal concentration as a function of sulfide ion addition will be prepared to assess the sulfide demand to achieve optimal metal removals for key parameters.

At the conclusion of this treatability test, the effectiveness of chemical precipitation will be evaluated based on the removal efficiencies observed in the final step of the Protocol. Preliminary calculations of chemical consumption rates and sludge generation rates will also be presented. A determination of the need for another treatment process – for example ion exchange, activated carbon, or activated silica adsorption – to achieve the desired effluent quality will also be completed and a recommendation for further testing, if necessary, will be presented.

3.4 Schedule

The treatability testing described in this Protocol will be initiated immediately after review of this protocol by the DNR. Collection and preparation of the test water mixes will be completed in approximately two weeks of the time that representative Dunka stockpile leachate water can be effectively collected. After preparation of the test water, the testing work outlined in this Protocol will be completed in approximately two weeks for each waste stream. The laboratory analysis will be completed in approximately two to three weeks from the date of delivery to the laboratory. The draft treatability testing report will be prepared within two weeks of receipt of the analytical data from the laboratory.

The data evaluation and the treatability testing results will be presented in the RS45 Wastewater Treatability Testing Report.

Table 1

Preliminary Wastewater Modeling Results, Water Quality Criteria, and Dunka Stockpile Leach Water (all units in mg/L, except where noted)

Water Source	Potential Water Quality Criteria	Non-Reactive Stockpile	Reactive Stockpile
Data Source		Scale-Up from Humidity Cells	Run-off from Dunka Piles
pH (su)	6.5-8.5	7.0	6.3-8.4
Chloride	100	22	
Sulfate	250	119	150-2000
Aluminium	0.125	8	
Antimony	0.031	0.5	
Arsenic	0.053	0.1	
Cadmium	0.0042	0.0019	
Calcium		185	300-350
Chromium	0.152	0.013	
Cobalt	0.005	0.005	0.02-0.4
Copper	0.017	0.087	0.04-1.0
Iron	0.3	0.82	0.05-0.7
Lead	0.0077	0.0029	
Magnesium		44	200-450
Manganese	0.05	0.048	
Mercury	0.0000013	0.001	
Nickel	0.094	0.017	0.2-11.0
Potassium		37	
Selenium	0.005	0.009454	
Sodium		296	
Thallium	0.00056	0.00095	
Zinc	0.216	0.13	0.06-1.6

Table 2

Proposed Target Concentration for Waste Rock and Lean Ore Treatability Testing Waters

	Proposed Target Range for Non-Reactive Waste Rock Test Water	Proposed Target Range for Lean Ore Test Water
Parameter		
pH (pH units)	6.5-7.5	7.0-8.0
Chloride	10-30	20-150
Sulfate	50-300	200-2000
Aluminium	2-8	4-80
Antimony	0.01-0.5	0.05-1.0
Arsenic	0.001-0.1	0.01-1.0
Cadmium	0.0002-0.002	0.002-0.020
Calcium	20-200	200-400
Chromium	0.002-0.02	0.02-0.20
Cobalt	0.001-0.01	0.01-0.4
Copper	0.01-0.1	0.1-1.0
Iron	0.5-1.0	0.5-2.0
Lead	0.001-0.003	0.003-0.03
Magnesium	10-100	100-500
Manganese	0.02-0.1	0.1-0.5
Mercury	0.000001-0.00001	0.00001-0.0001
Nickel	0.02-1.0	1.0-10.0
Potassium	10-50	50-200
Selenium	0.001-0.01	0.01-0.10
Sodium	50-300	100-500
Thallium	0.0005-0.001	0.001-0.010
Zinc	0.10-0.30	0.2-2.0

Note: Units are in mg/L unless noted otherwise.

Table 3

Analytical Parameters, Methods Reporting Limits and Method Detection Limits

Parameter	Method	RL (µg/L except where noted)	MDL (µg/L except where noted)
List 1			
Metals			
Copper	EPA 200.8	0.1	0.03
Mercury	EPA 1631	1 ng/L	0.06 ng/L
Nickel	EPA 200.8	0.2	0.06
Zinc	EPA 200.8	0.5	0.3
List 2			
Metals			
Aluminum	EPA 200.8	2	0.7
Iron	EPA 6010B	20	20
Magnesium	EPA 6010B	20	9
Manganese	EPA 200.8	0.05	0.02
Arsenic	EPA 200.8	0.5	0.2
Cadmium	EPA 200.8	0.02	0.02
Chromium	EPA 200.8	0.2	0.06
Lead	EPA 200.8	0.02	0.009
Cobalt	EPA 200.8	0.02	0.01
Antimony	EPA 200.8	0.05	0.02
Selenium	EPA 200.8	1	0.2
Silver	EPA 200.8	0.02	0.009
Thallium	EPA 200.8	0.02	0.004
General Parameters			
Sulfate	EPA 300.0	200	90
Calcium	EPA 6010B	50	20
Potassium	EPA 6010B	2000	700
Sodium	EPA 6010B	100	60
pH	EPA 150.1	NA	NA
Alkalinity	SM 2320B	2 mg/L	1 mg/L
Bicarbonate	SM 2320B	2 mg/L	1 mg/L
Carbonate	SM 2320B	2 mg/L	1 mg/L
Chemical Oxygen Demand	EPA 410.2	5 mg/L	2 mg/L
Total Organic Carbon	EPA 415.1	500	100
Total Suspended Solids	EPA 160.2	5 mg/L	NA
Total Kjeldahl Nitrogen	EPA 351.4	100	4
Ammonia	EPA 350.1/350.3	50/200	20/20
Sulfide	EPA 376.1	2 mg/L	300
Sulfite	EPA 377.1/9030	2/0.1 mg/L	0.4/0.05 mg/L
Hydroxide	SM 2320B	2 mg/L	1 mg/L
Chloride	EPA 300.0	200	30
Total Sulfur	EPA 300.0M	70	

RL Reporting Limit
MDL Method Detection Limit

Table 4

Laboratory Sample Containers, Preservation and Holding Times

Parameter/Media	Container	Preservative	Holding Time
Environmental Samples			
Metals (except Hg water)	500ml Plastic	HNO3, Cool 4 ºC	180 days
Mercury -water	250ml Plastic	Cool 4 ºC	48 hours to preserve in the lab
COD/TOC	500ml Plastic	H2SO4 pH <2, Cool 4 ºC	28 days
TSS	1 Liter Plastic	Cool 4 ºC	7 days
Chloride	250ml Plastic	Cool 4 ºC	28 days
Total Sulfur	500ml Plastic	Cool 4 ºC	28 days
Alkalinity (Bicarbonate/ Carbonate/Hydroxide)	500ml Plastic	Cool 4 ºC	14 days
Sulfate	250ml Plastic	Cool 4 ºC	28 days
Sulfide	1 Liter Glass	NaOH, Cool 4 ºC	7 days
pH	100ml Plastic	Cool 4 ºC	Immediate
Sulfite	125ml Plastic	Cool 4 ºC	Immediate
TKN	1 Liter Plastic	H2SO4 pH <2, Cool 4 ºC	28 days
Ammonia	1 Liter Plastic	H2SO4 pH <2, Cool 4 ºC	28 days

Standard Operating Procedures for the
Collection of Wastewater Samples

Purpose
To describe the collection of wastewater samples from a process basin, stream, or bench-scale test.

Applicability
This procedure applies to the collection of wastewater samples by the sampling technician(s).

References
- Procedures for Ground Water Monitoring, Minnesota Pollution Control Agency Guidelines, December 1986.
- Quality Assurance Manual: Groundwater and Surface Water Sampling Procedures, Barr Engineering Co.;
- American Water Works Association: Pocket Guide to Water Sampling;
- Environmental Sampling, A Summary, the Radian Corporation.

Definitions
Headspace: The air space between the container top and the water sample level.
Holding Time: Period of time between sample collection and when the sample is analyzed.
Sample Preservation: The stability of analytes depends upon how well the samples are preserved.

Discussion
Wastewater stations will include locations designated in the plan.
To account for potential variability at any sampling location, sample should be integrated from top to bottom in the middle of the location.
Samples collected in shallow water (less than 3 feet deep) should be collected at mid-depth, holding the container under the surface until filled. The mouth of the container should face the flow.
When sampling shallow areas, collection should begin at the furthest downstream location and move upstream so that any disturbances caused by sampling will not affect the quality of the water sampled. When sampling deeper waters, such as rivers, collection should begin first at the upstream point, next to the downstream point, and finally to the sampling point closest to the apparent source of discharge, minimizing contaminants clinging to the sample apparatus.
All unpreserved sample containers will be rinsed three times with sample wastewater prior to collection as a precautionary measure to be sure containers are uncontaminated. Preserved sample containers should be filled from a separate sample container that is rinsed and filled following the procedures for the collection of unpreserved grab samples.
Caution will be exercised in filling preserved containers to prevent loss of the preservative.

Container Selection
Container volume, type, and preservative are important considerations in sample collection.
Container volume must be adequate to meet laboratory requirements for quality control, split samples, or repeat examinations. The container type or construction varies with the analysis required: (1) septum-sealed 40-ml glass vial is used for volatile organic compounds; (2) semi volatile analysis usually requires a glass container (note—amber-tinted glass prevents sunlight from affecting the sample); (3) polyethylene containers are used for general parameters, metals, and inorganics. The analytical laboratory will preserve the containers before shipment. Preservation and shelf life vary; contact the laboratory to determine if an on-hand container is still useful.

Responsibilities

The Field Operations/QA Officer or the environmental technician(s) will order the sample containers prior to the sampling event. The environmental technician(s) is also responsible for proper collection of samples, sample identification, quality control procedures, sample filtering, and documentation.

Procedure

Wastewater Sampling

1. Approximately one week before the sampling event, the sample containers should be ordered from the laboratory.
2. Before leaving for the site, account for all the containers.
3. Prepare sampling containers by filling out the label with the following information:
   - Project number
   - Location identification
   - Individual collecting the samples
   - Date and time of collection
   - Sample analysis (if required by the lab)

   Note: Use an indelible permanent pen to avoid ink bleeding (Pilot permanent SC-UF).
4. Put on sampling gloves to protect the sample and skin.

   Note: New sampling gloves should be used for each location.
5. Remove cap from the first sample container.
6. Fill sampling container (do not overfill).
7. Continue the process until all sampling containers are filled. Samples should be collected and containerized in order of the parameters' sensitivity to volatilization and using the specific procedures required for each sample type as summarized below:
   a. Volatile organic compounds—Use caution because concentrated acid may be present. Do not rinse glass vials. Hold bottle in one hand, the cap right side up in the other. Pour slowly, avoiding air bubbles and overfilling the vial. Cap tightly, invert the bottle, and tap gently. If any air bubbles appear in the vial, discard and collect sample in a new vial. After collecting the required number of vials, insert them in a zip-lock plastic bag and place in a cooler with ice.
   b. Semivolatile organic compounds—Fill container slowly with a minimum headspace and cap tightly. Do not rinse glass containers. Place container directly in a cooler with ice.
   c. Filtered Metals—Select the appropriate Corning filter size, either 250-ml or 500-ml volume (see Standard Operating Procedures for filtering groundwater samples). Pour filtered sample into metals sample container, minimizing headspace and avoiding spillage. Use caution handling metals containers because of nitric acid. Place directly in a cooler with ice.
   d. Other Organics—Containers may contain acid, use caution when handling. Fill containers appropriately, minimizing headspace and avoiding spillage. Place container directly in a cooler with ice.
   e. General Chemistry—Containers may or may not contain acid, use caution when handling. For general chemistry parameters collected in unpreserved containers, rinse the container three times with the sample water prior to final sample collection to ensure containers are uncontaminated.
8. After all of the samples are collected, place the sample containers in the sampling cooler with ice.

Documentation

The technician(s) will document the wastewater sampling event, including the type and number of bottles, on the field log data sheet, field log cover sheet, and field log data reports, and chain-of-custody record. The analysis for each bottle and the laboratory used will be documented on the chain-of-custody record. The sampling request form will document which sampling containers are used for which wells.

Standard Operating Procedures for Documentation on a Chain-of-Custody

Purpose

To describe how a Chain-of-Custody should be documented properly.

Applicability

These procedures apply any time a Chain-of-Custody is required.

Definitions

Chain-of-Custody: This document shows traceable possession of samples from the time they are obtained until they are introduced as evidence in legal proceedings.

References

Groundwater sampling guidelines and groundwater and surface water sampling procedures by Barr Engineering Company.

Discussion

The Chain-of-Custody is the most important sampling document; it must be filled out accurately and completely every time.

Responsibilities

The environmental technician(s)/sampling technician(s) are responsible for accurate and complete documentation on the Chain-of-Custody.

Procedure

Writing a Chain-of-Custody

1. The Chain-of-Custody should be completed prior to leaving the sampling location.
2. Complete one Chain-of-Custody or more as needed for each cooler of samples.
3. The Chain-of-Custody form must be completed with the following information:
    a. Project number
    b. Sample identification
    c. Date and time of sample collection
    d. Container type and number
    e. Whether the sample is a grab, composite, or blank sample
    f. Project manager
    g. Project contract
    h. Laboratory
    i. Analysis required
    j. Signature of sampler(s)
    k. Signature of transferee
    l. Date and time of transfer
    m. Method of transport and any shipping numbers
4. The Chain-of-Custody should always accompany the cooler of samples.
    a. Distribution of the Chain-of-Custody pages: pages one (white) and two (yellow) go to the laboratory, page three (pink) goes to the lab coordinator, and the fourth page (gold) is the field copy.

Documentation

The Chain-of-Custody form is the documented proof of possession of samples collected. This is documented by samplers collecting the samples and the laboratory receiving the samples.

Standard Operating Procedures for Transporting Samples to the Laboratory

Purpose

To describe the procedures necessary for personal delivery or shipment of samples to analytical laboratories.

Applicability

This procedure applies to the transportation of ground and surface water samples to the appropriate laboratory.

Definitions

Environmental Samples. Water samples not regulated by the U.S. Department of Transportation.
Hazardous Material. Regulations for packing, marking, labeling, and shipping of hazardous materials are governed by the U.S. DOT.

References

- Quality Assurance Manual: Groundwater and Surface Water Sampling Procedures, Barr Engineering Co.;
- Procedures for Ground Water Monitoring: MPCA Guidelines, January 1983.

Discussion

Maintaining proper sample temperatures (4°C) and delivering samples to the laboratory within 24 to 48 hours are primary concerns.

Responsibilities

The environmental technician(s) shall ensure the security, temperature, and packaging of water samples during shipment.

Procedure

Packaging of Groundwater Samples. Place samples in an ice cooler, carefully pack glass containers to avoid breakage. (Note: Bubble-wrap is the preferred packing material.) Add enough ice secured in double-bagged ziplock baggies, to maintain a constant temperature at 4°C until the samples arrive at the laboratory. Complete the chain-of-custody, signing relinquished by and date, and include required copies with the samples (see Standard Operating Procedure for chain-of-custody record).
Personal Delivery. The samples are delivered to the laboratory by the sampling technician(s). The chain-of-custody record is signed and dated by the laboratory representative.
Local Courier. The same procedures are followed as above; i.e., the chain-of-custody record is signed and dated and the top two copies are sent with the samples. The ice cooler is then secured with strapping tape and a courier form is filled out for the designated laboratory. The cooler is then left in the services area for pickup.
Overnight Courier. Follow the procedures above, replacing the courier form with the Federal Express form. Date, project number, type of delivery desired, weight, and number of coolers should be included. Be sure the cooler will not leak. Federal Express will not ship a leaking container. Account for all samples before shipping and compare to the chain of custody (see Standard Operating Procedure for chain-of-custody record).

QA/QC

Ship samples during times when the laboratory will be able to accept and quickly analyze them. Avoid sending samples during holidays and weekends.

Record

Copies of the chain-of-custody, Federal Express forms, and sample analysis are copied and included in site files and reports. This is all documented by the sampling technician(s).

Attachment C2

Wastewater Treatability Study Report

RS45 ATTACHMENT C2:
WASTEWATER TREATABILITY STUDY REPORT
MINE SITE PROCESS WATER
NORTHMET PROJECT

Prepared By:

CEMI
Canadian Environmental & Metallurgical Inc.

6927 Antrim Avenue
Burnaby, BC, V5J 4M5

March 2007

TABLE OF CONTENTS

LIST OF TABLES

LIST OF APPENDICES

1.0 OBJECTIVE

The primary objective of this treatability study was to demonstrate the viability of chemical precipitation using lime to treat Dunka Seep water. The testing was conducted to determine the effectiveness of chemical precipitation, in particular the High Density Sludge (HDS) process, to meet the process water quality targets. Additionally, the results of this testing will be used to estimate reagent requirements and sludge generation rates and provide potential design parameters for a pilot scale study.

This report presents the method and results for this wastewater treatability study. The methods used were based on the Wastewater Treatability Study Protocol (Attachment C1 to RS45), which was submitted to the DNR for review prior to the initiation of this testing program.

1.1 The HDS Process

The effective removal of base metals in a chemically stable form in the HDS process is primarily the result of the formation of co-precipitates with iron on the surfaces of the recycled sludge particles. The chemical stability of the precipitate is favourably influenced by a high iron to total metals ratio in the treatment plant feed. Typically, a sludge recycle loop is used to increase this ratio. However, a simple recycle is sometimes not sufficient to change metal ratios and, in extreme examples, iron may have to be added. Otherwise, the storage site for the sludge produced must allow for the possibility of long-term instability. In all cases, the oxidation of ferrous iron to ferric iron is the principal oxygen-consuming reaction, and oxygen transfer into solution may well be controlling the reaction and hence the reactor tank sizing.

Design plant throughput is also influenced by the volume of water to be treated. For example, seasonal changes will determine variations in run-off, much of which may have to be treated. Increased flow may be accompanied by a dilution of contaminants, both acid and metal, and the resulting plant influent may require reduced oxidation and/or residence time, thus compensating for the increased flow.

The near-complete precipitation of the metals as hydroxides in the neutralization process proceeds according to the following reactions:

$$M^{++} + SO_4^{=} + Ca^{++} + 2(OH)^{-} + 2H_2O \rightarrow M(OH)_2 + CaSO_4{\bullet}2H_2O$$

$$2M^{+++} + 3(SO_4)^{=} + 3Ca^{++} + 6(OH)^{-} + 6H_2O \rightarrow 2M(OH)_3 + 3CaSO_4{\bullet}2H_2O$$

As implied by the equations above, the products of these reactions are metal hydroxide precipitates and calcium sulfate (gypsum). If the sulfate concentration of the wastewater is high enough, there will be sufficient gypsum produced to exceed its solubility and it will precipitate with the sludge.

The main features of the HDS process can be summarized as follows: Lime [$Ca(OH)_2$] and recycled sludge are added to the lime-sludge mix tank at the head of the process, providing the main neutralization agent. This mixture is discharged to the rapid mix tank where it is mixed with influent, thereby achieving neutralization. This mixture is fed to the main lime reactor where a combination of aggressive aeration and high shear agitation ensures optimum process chemistry and subsequent clarifier performance. The discharge from the lime reactor is treated with flocculant in the flocculation tank. In the final step, the clarifier separates the treated effluent from the sludge, a portion of which is recycled to the head of the process.

The HDS process is normally operated at a pH between 9.0 and 9.5, as most metals encountered will precipitate at or below this concentration of hydroxide ions. Oxidation of ferrous to ferric iron takes place rapidly at this pH, with air being the most common oxidizing agent.

For efficiency, the process relies on sludge recycle from the treated effluent. In most plants this is achieved in a thickener-style clarifier, which provides pumpable sludge in the underflow as the separated solids product. Recycling sludge from a settling pond or from filters are alternatives but they may present handling problems.

1.2 Advantages of the HDS Process

The HDS process has many advantages over other lime precipitation systems. The most important of these is a substantial reduction in sludge volume resulting from an increase in sludge density. An increase from 5 percent solids to 40 percent solids is typical of HDS systems; this reduces the volume of sludge produced by over 95 percent. The resulting reduction in sludge disposal costs increases the cost effectiveness of the process. In addition to reduced sludge volume and superior sludge density, there is an increase in sludge stability, both chemically and physically. Within a few days of deposition, the sludge can drain to in excess of 65 percent solids and possesses enough physical stability to support the heavy equipment on the surface of the impoundment area. Chemically the sludge has shown excellent stability characteristics at mining sites in British Columbia, Canada and at numerous other sites. Following twenty-five years of impoundment at one facility, there has been no contamination of the surrounding groundwater or any other evidence of metal reversion.

Other advantages of the HDS process include:

- A high quality effluent is produced,
- The process is easily automated,
- HDS is a proven technology, and
- Operating plants consist of standard equipment available from many competitive manufacturers, which reduces the need for large spare parts inventories,
- Lower neutralization costs than conventional lime treatment.

2.0 EXPERIMENTAL APPROACH

The testing work described in this report was conduced in accordance with the Work Plan (RS45 Attachment C1). Two containers (5 gallons each) containing water collected from Dunka Mine Pit near the NorthMet Mine Site were shipped to CEMI in May 2006 for bench-scale testing. The feed sample was shaken and 250 mL aliquot was taken for head analysis. The sample was filtered through a 0.45 micron membrane filter and analyzed for pH, conductivity, alkalinity and sulfate at CEMI, metal analysis at Maxxam Analytics located in Vancouver, BC and low-level mercury analysis at CAS in Washington.

2.1 Testing Program

The testing program consisted of three steps. The first step consists of a preliminary screening procedure to evaluate lime dosage rates. Aliquots of 500 mL of the feed water were added to five 1-liter beakers. Lime was added in different dosages to yield a final pH range from 8.0 to 10.0 (in 0.5 pH increments). Rapid mixing was used and pH was maintained at the desired level with addition of lime. After 60 minutes of high agitation allowing time for oxidation, flocculant was added and solution was allowed to settle for 60 minutes. During the settling period, samples were collected for total metal analysis after 15 minutes, 30 minutes and 60 minutes of settling. At the conclusion of the settling period, the solution was filtered, filter cake was dried and weighed to determine solids generation and the filtrate was sent to Maxxam Analytics in Vancouver, Canada for dissolved metal analysis and CAS in Washington for low-level mercury analysis.

In the second step of the test program, the lime dosage rate that provided the best effluent quality in the first step was used and rapid mixing and settling conditions were altered to determine the affect of longer or shorter reaction and settling times on effluent water quality. At the completion of the tests, the solution was filtered and submitted for metal analysis as described in step one.

Once results of the first and second steps were available, a large batch of water was treated using the best combination of lime dosage rate and mixing scenarios that provided the best effluent quality with lowest mass of sludge and shortest operating time.

The treatment was carried out in the following manner:

A 1.0 liter sample of the contaminated water was neutralized to the pH selected in the initial screening tests with lime slurry, followed by flocculant addition, settling, and decanting the overflow in order to recycle sludge. The required amount of lime was then added to the settled sludge and the sludge/lime was well mixed followed by another 1.0 liter of the contaminated water being added to this mixture. The slurry was agitated for reaction time determined in the initial tests. This procedure was repeated 10 times. The overflow from the final cycle was filtered and submitted for chemical analysis.

3.0 RESULTS & DISCUSSION

3.1 Feed Sample

Table 1, below, summarizes the dissolved metals contained in the feed water.

Table 1. Feed Characterization

	Units	**Process Water Quality Target**	**Feed**
Aluminum (Al)	mg/L	0.125	0.017
Arsenic (As)	mg/L	0.010	0.001
Boron (B)	mg/L	0.5	0.402
Cadmium (Cd) – HD	mg/L	0.004	0.002
Chromium (Cr) – HD	mg/L	0.100	<0.002
Cobalt (Co)	mg/L	0.005	**0.0673**
Copper (Cu) – HD	mg/L	0.030	**0.281**
Iron (Fe)	mg/L	0.3	<0.005
Manganese (Mn)	mg/L	0.05	**1.68**
Nickel (Ni) – HD	mg/L	0.100	**1.48**
Selenium (Se)	mg/L	0.005	<0.005
Zinc (Zn) – HD	mg/L	0.388	**0.52**
Mercury (Hg)	ug/L	0.0013	<0.05
Low-Level Mercury	ug/L	0.0013	**0.0031**

Notes:
Process Water Quality Targets as defined in RS29T
HD- Process water quality target for hardness dependent parameters based on 400 mg/L hardness.
Bold – Exceeds process water quality target

As indicated in the above table, the primary metals of concern are cobalt, copper, manganese, nickel, zinc, and mercury.

Table 2, below, summarizes the additional parameters measured at the CEMI facilities.

Table 2. Feed Chemistry

Parameter	pH	Conductivity us/cm	Acidity @ pH 8.3	Alkalinity mg $CaCO_3$/L
Feed	7.77	3129	9.6	101.6

3.2 Neutralization Test

The feed sample was neutralized to pH 8.0, 8.5, 9.0, 9.5 and 10.0 using hydrated lime with the lime being added as a 5 percent slurry. For each test, a 500 mL sample was neutralized to the selected pH while being vigorously agitated. The neutralized sample was agitated for 60 minutes while maintaining the selected pH by adding additional reagent when necessary. After 60 minutes, flocculant was added and solution was allowed to settle for 60 minutes. The samples were then filtered through a 0.45 micron membrane filter and submitted for analysis. The following table summarizes the results of the neutralization tests.

Table 3. Neutralization Results

	Units	**Process Water Quality Target**	**Feed**	**pH 8.0**	**pH 8.5**	**pH 9.0**	**pH 9.5**	**pH 10.0**
pH		6.5-8.5	7.77	8.03	8.54	9.01	9.61	9.96
Aluminum (Al)	mg/L	0.125	0.017	0.011	0.009	0.003	<0.002	<0.002
Arsenic (As)	mg/L	0.01	0.001	<0.001	0.003	<0.001	0.001	<0.001
Boron (B)	mg/L	0.5	0.402	0.403	0.41	0.397	0.383	0.372
Cadmium (Cd) HD	mg/L	0.004	0.002	0.0019	0.0015	0.0002	0.0002	0.0002
Calcium (Ca)	mg/L		285	289	304	294	265	279
Chromium (Cr) HD	mg/L	0.100	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Cobalt (Co)	mg/L	0.005	**0.0673**	**0.0675**	**0.0629**	**0.0403**	0.0022	<0.0002
Copper (Cu) HD	mg/L	0.030	**0.281**	**0.21**	**0.11**	0.028	0.009	0.007
Iron (Fe)	mg/L	0.3	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Magnesium (Mg)	mg/L		360	361	366	357	353	356
Manganese (Mn)	mg/L	0.05	**1.68**	**1.66**	**1.6**	**0.909**	**0.104**	0.0011
Nickel (Ni) HD	mg/L	0.100	**1.48**	**1.51**	**1.43**	**1.11**	**0.244**	0.013
Selenium (Se)	mg/L	0.005	<0.005	<0.005	<0.005	<0.005	<0.005	**0.007**
Zinc (Zn) HD	mg/L	0.388	**0.52**	**0.456**	0.224	0.01	<0.005	<0.005
Mercury (Hg)	ug/L	0.0013	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Low-Level Mercury	ug/L	0.0013	**0.0031**	**0.0079**	**0.0041**	**0.0046**	**0.0054**	**0.0060**

Notes:
Process Water Quality Targets as defined in RS29T
HD- Process water quality target for hardness dependent parameters based on 400 mg/L hardness.
Bold – Exceeds process water quality target

Based on the test data summarized in Table 3 above, it was determined that neutralization at pH 10.0 would be required to meet the process water quality targets, specifically for manganese and nickel concentration. At pH 10, the mercury concentration was still slightly above the process water quality target, and selenium, which had not been detected in the feed was also slightly above the target.

3.2.1 Reagent Requirements

The lime usage in the bench-scale testing is summarized in Table 4. The lime usage requirement was very difficult to measure at a bench-scale level as lime consumed was extremely low. In order to determine more reliable lime consumption data, a pilot-scale study is highly recommended.

Table 4. Lime Requirement

	Units	**Feed**	**pH 8.0**	**pH 8.5**	**pH 9.0**	**pH 9.5**	**pH 10.0**
pH		7.77	8.03	8.54	9.01	9.61	9.96
5% $Ca(OH)_2$	mL		0.75	1.40	4.65	5.90	7.60
$Ca(OH)_2$	g/L		0.04	0.07	0.23	0.30	0.38

3.2.2 Sludge Generation

The dissolved metals content in the feed was very low to generate enough sludge during the bench scale testing for any testing. The sludge generated during the neutralization was observed to be white in colour and increased with pH. Detailed results are provided in the Appendix.

3.3 Altering Mixing and Settling Time

Altering of mixing and settling times was evaluated to understand the impact of retention time on the effluent quality. This phase of the testing program was conducted at pH 10.0 based on the results of the first phase of the work, which showed a pH of 10 was necessary to remove manganese and nickel.

Table 5. Impact of retention time on effluent quality

	Units	**Process Water Quality Target**	**Feed**	**pH 10.0 30min RT**	**pH 10.0 60min RT**	**pH 10.0 90min RT**
pH		6.5-8.5	7.77	10.04	9.96	9.97
Aluminum (Al)	mg/L	0.125	0.017	0.006	<0.002	0.003
Arsenic (As)	mg/L	0.010	0.001	<0.001	<0.001	<0.001
Boron (B)	mg/L	0.5	0.402	0.259	0.372	0.223
Cadmium (Cd) – HD	mg/L	0.004	0.002	<0.0001	0.0002	<0.0001
Calcium (Ca)	mg/L		285	341	279	320
Chromium (Cr) – HD	mg/L	0.100	<0.002	<0.001	<0.002	<0.001
Cobalt (Co)	mg/L	0.005	**0.0673**	0.0005	<0.0002	<0.0005
Copper (Cu) – HD	mg/L	0.030	**0.281**	0.012	0.007	0.01
Iron (Fe)	mg/L	0.3	<0.005	<0.005	<0.005	<0.005
Magnesium (Mg)	mg/L		360	372	356	356
Manganese (Mn)	mg/L	0.05	**1.68**	0.006	0.0011	<0.001
Nickel (Ni) – HD	mg/L	0.100	**1.48**	<0.008	0.013	<0.008
Selenium (Se)	mg/L	0.005	<0.005	<0.001	**0.007**	<0.001
Sodium (Na)	mg/L		51.9	52.4	52.2	49.9
Zinc (Zn) – HD	mg/L	0.388	**0.52**	<0.005	<0.005	<0.005
Mercury (Hg)	ug/L	0.0013	<0.05	<0.05	<0.05	<0.05
Low-Level Mercury	ug/L	0.0013	**0.0031**	**0.0061**	**0.0060**	**0.0033**

Notes:
Process Water Quality Targets as defined in RS29T
HD- Process water quality target for hardness dependent parameters based on 400 mg/L hardness.
Bold – Exceeds process water quality target

The results summarized in Table 5 show that a retention time of 30 minutes to 90 minutes provides very similar effluent quality. To meet process water quality targets for most of the metals, a retention time of 60 minutes is suitable for design purposes. However, as indicated in the above table, the concentrations of mercury, manganese, and boron are lower with longer reaction time. In contrast, the concentration of copper increased slightly with a longer reaction time, although it was still below the process water quality target.

Due to low solids generation, it was not possible to generate a settling curve because the low solids content made it very difficult to detect an interface. Instead of interface measurement, 20 mL samples were drawn from the surface for total metal analysis after 30 minutes and 60 minutes. The samples were acidified and submitted for analysis.

Table 6. Settling Data – 30 minute neutralization

Total Metals	Units	**Process Water Quality Target**	**Feed**	**pH 10.0 30min RT 30min Set**	**pH 10.0 30min RT 60min Set**
Aluminum (Al)	mg/L	0.125	0.017	0.036	0.02
Arsenic (As)	mg/L	0.010	0.001	<0.001	<0.001
Boron (B)	mg/L	0.5	0.402	0.285	0.254
Cadmium (Cd) - HD	mg/L	0.004	0.002	0.0005	0.0003
Calcium (Ca)	mg/L		285	326	308
Chromium (Cr) - HD	mg/L	0.100	<0.002	<0.001	<0.001
Cobalt (Co)	mg/L	0.005	**0.0673**	0.0205	0.012
Copper (Cu) - HD	mg/L	0.030	**0.281**	**0.0962**	**0.0594**
Iron (Fe)	mg/L	0.3	<0.005	0.007	<0.005
Magnesium (Mg)	mg/L		360	341	328
Manganese (Mn)	mg/L	0.05	**1.68**	**0.422**	**0.235**
Nickel (Ni) - HD	mg/L	0.100	**1.48**	**0.372**	**0.215**
Selenium (Se)	mg/L	0.005	<0.005	<0.001	0.002
Sodium (Na)	mg/L		51.9	52.1	50.4
Zinc (Zn) - HD	mg/L	0.388	**0.52**	0.142	0.077

Notes:
Process Water Quality Targets as defined in RS29T
HD- Process water quality target for hardness dependent parameters based on 400 mg/L hardness.
Bold – Exceeds process water quality target

Table 7. Settling Data – 60 minute neutralization

Total Metals	Units	**Process Water Quality Target**	**Feed**	**pH 10.0 60min RT 30min Set**	**pH 10.0 60min RT 60min Set**
Aluminum (Al)	mg/L	0.125	0.017	0.048	0.023
Arsenic (As)	mg/L	0.01	0.001	<0.001	<0.001
Boron (B)	mg/L	0.5	0.402	0.308	0.37
Cadmium (Cd) - HD	mg/L	0.004	0.002	0.0003	0.0001
Calcium (Ca)	mg/L		285	251	290
Chromium (Cr) - HD	mg/L	0.100	<0.002	<0.001	<0.001
Cobalt (Co)	mg/L	0.005	**0.0673**	**0.0117**	**0.0052**
Copper (Cu) - HD	mg/L	0.030	**0.281**	**0.0684**	**0.036**
Iron (Fe)	mg/L	0.3	<0.005	0.015	0.01
Magnesium (Mg)	mg/L		360	293	352
Manganese (Mn)	mg/L	0.05	**1.68**	**0.183**	**0.097**
Nickel (Ni) - HD	mg/L	0.100	**1.48**	**0.175**	0.098
Selenium (Se)	mg/L	0.005	<0.005	**0.006**	**0.007**
Sodium (Na)	mg/L		51.9	43.4	52.1
Zinc (Zn) - HD	mg/L	0.388	**0.52**	0.065	0.03

Notes:
Process Water Quality Targets as defined in RS29T
HD- Process Water quality target for hardness dependent parameters based on 400 mg/L hardness.
Bold – Exceeds process water quality target

Table 8. Settling Data – 90 minute neutralization

Total Metals	Units	**Process Water Quality Target**	**Feed**	**pH 10.0 90min RT 30min Set**	**pH 10.0 90min RT 60min Set**
Aluminum (Al)	mg/L	0.125	0.017	0.041	0.024
Arsenic (As)	mg/L	0.01	0.001	<0.001	<0.001
Boron (B)	mg/L	0.5	0.402	0.289	0.275
Cadmium (Cd) - HD	mg/L	0.004	0.002	0.0008	0.0005
Calcium (Ca)	mg/L		285	324	327
Chromium (Cr) - HD	mg/L	0.100	<0.002	0.002	0.002
Cobalt (Co)	mg/L	0.005	**0.0673**	**0.0332**	**0.0223**
Copper (Cu) - HD	mg/L	0.030	**0.281**	**0.137**	**0.0952**
Iron (Fe)	mg/L	0.3	<0.005	0.01	<0.005
Magnesium (Mg)	mg/L		360	337	350
Manganese (Mn)	mg/L	0.05	**1.68**	**0.697**	**0.468**
Nickel (Ni) - HD	mg/L	0.100	**1.48**	**0.614**	**0.418**
Selenium (Se)	mg/L	0.005	<0.005	0.002	0.001
Sodium (Na)	mg/L		51.9	51	53.5
Zinc (Zn) - HD	mg/L	0.388	**0.52**	0.231	0.155

Notes:
Process Water Quality Targets as defined in RS29T
HD- Process water quality target for hardness dependent parameters based on 400 mg/L hardness.
Bold – Exceeds process water quality target

The results summarized in the above Tables 6 through 8 show that settling may be a concern for full-scale operation if sufficient solids are note generated to form a floc, as was the case in this testing. The reported concentrations of several metals above the process water quality target suggests that the methods used at the laboratory scale for this experiment did not provide adequate time to separate the solids from the water.

3.4 HDS Simulation

From previous testing results, it was decided to conduct the HDS simulation with 60 minute retention time at pH 10.0 and using 1-liter feed sample.

The following table provides the results of the bench scale HDS simulations at the pH 10.0. The individual neutralization tests and the HDS simulations only provide an indication of effluent quality that can be achieved with a proper HDS process where the recycle solids significantly improves precipitation kinetics through catalysed reactions.

Table 9. HDS simulation at pH 10.0

	Units	**Process Water Quality Target**	**Feed**	**pH 10.0 60min RT 10th Cycle**
Aluminum (Al)	mg/L	0.125	0.017	0.003
Arsenic (As)	mg/L	0.010	0.001	0.0007
Boron (B)	mg/L	0.5	0.402	0.366
Cadmium (Cd) - HD	mg/L	0.004	0.002	0.00004
Calcium (Ca)	mg/L		285	311
Chromium (Cr) - HD	mg/L	0.100	<0.002	<0.0002
Cobalt (Co)	mg/L	0.005	**0.0673**	<0.00002
Copper (Cu) - HD	mg/L	0.030	**0.281**	0.0064
Iron (Fe)	mg/L	0.3	<0.005	<0.005
Magnesium (Mg)	mg/L		360	373
Manganese (Mn)	mg/L	0.05	**1.68**	0.00096
Nickel (Ni) - HD	mg/L	0.100	**1.48**	0.0076
Selenium (Se)	mg/L	0.005	<0.005	0.0022
Sodium (Na)	mg/L		51.9	54.4
Zinc (Zn) - HD	mg/L	0.388	**0.52**	0.0017
Low-Level Hg	ug/L	0.0013	**0.0031**	**0.0034**

Notes:
Process Water Quality Targets as defined in RS29T
HD- Process water quality target for hardness dependent parameters based on 400 mg/L hardness.
Bold – Exceeds process water quality target

The results summarized in Table 9 show that, with the exception of mercury, the HDS simulation achieved effluent concentrations that were well below all the process water quality targets for metals. A comparison of these results to the previous tables suggests that the metal removal efficiency for all metals, with the exception of mercury, was improved with the use of sludge recycle.

4.0 CONCLUSIONS & RECOMMENDATIONS

This study was a preliminary bench-scale investigation of potential water treatment needs for the NorthMet Project. Wastewater from the Dunka Seep (near the proposed project site) was treated using conventional chemical precipitation (lime neutralization) treatment. The results presented in this report are representative of the samples received at the Canadian Environmental and Metallurgical Inc. laboratory in Vancouver, BC.

Based on the test data presented in this report, the following conclusions can be made:

- Metals of concern can be removed using chemical precipitation with lime, specifically High Density Sludge (HDS) process.
- Neutralization at pH 10.0 with 60 minute retention time is required to meet the discharge criteria.
- Effluent quality improved with recycle of solids.

Based on the results of the testwork, following are some of the recommendations:

- Bench-scale testing with iron salt addition could be conducted to further improve effluent quality by increasing the iron to total metals ratio.
- If the water chemistry is expected to be significantly different, then it is recommended to conduct bench-scale testwork with different feed water.
- An on-site pilot-scale study program would aid in the determination of important parameters for design (reagent consumption and effluent quality).

APPENDIX A:
Neutralization Process Worksheet

Neutralization Testing Workbook

Project Polymet
Project No. 0610
Date May 9, 2006

Test ID T1 - pH 8

Volume 1000 mL
Initial pH 7.27

% Lime ~~10%~~ 5%
Lime Vol. 0.75

Target pH 8.0
Final pH 8.03

Sludge Generation 0.01 g

Other Testwork -

Analysis MAXXAM
CAS (low Hg)

Notes/Comments
2mL of E-10 added
60 min settling and sample
taken after 0 min, 30min
and 60 min

Test ID T2 - pH 9.0

Volume 1000 mL
Initial pH 7.34

% Lime 5%
Lime Vol. 4.65

Target pH 9.0
Final pH 9.01

Sludge Generation 0.09 g

Other Testwork -

Analysis same

Notes/Comments
same

Neutralization Testing Workbook

Project	Polymet
Project No.	0610
Date	May 9, 2006

Test ID	T3 - pH 10
Volume	1000 mL
Initial pH	7.36
% Lime	5%
Lime Vol.	7.60
Target pH	10.0
Final pH	9.96
Sludge Generation	0.32 g
Other Testwork	-
Analysis	MAXXAM CAS

Notes/Comments

·2mL of E10 added

· 60 min settling time

Test ID	T4 - pH 8.5
Volume	1000 mL
Initial pH	7.24
% Lime	5%
Lime Vol.	1.40
Target pH	8.5
Final pH	8.54
Sludge Generation	0.042 g
Other Testwork	-
Analysis	Same

Notes/Comments

Same

3 of 3

Neutralization Testing Workbook

Project: Polymet
Project No.: 0610
Date: May 9, 2006

Test ID: T5 - pH 9.5

Volume: 1000 mL
Initial pH: 7.26

% Lime: 5%
Lime Vol.: 5.90

Target pH: 9.5
Final pH: 9.61

Sludge Generation: 0.24g

Other Testwork: -

Analysis: MAXXAM
CAS

Notes/Comments

- 2mL of E10 added
- 60 min settling time

Test ID

Volume
Initial pH

% Lime
Lime Vol.

Target pH
Final pH

Sludge Generation

Other Testwork

Analysis

Notes/Comments

1 of 1

Neutralization Testing Workbook

Project: Polymer
Project No.: 0610
Date: June 7, 2006

(Retention Time)

Test ID	T6 - pH10 - 30 min	Test ID	T7 - pH10 - 90 min
Volume	1000 mL	Volume	1000 mL
Initial pH	7.35	Initial pH	7.37
% Lime	5%	% Lime	5%
Lime Vol.	7.55 mL	Lime Vol.	7.80 ml
Target pH	10.0	Target pH	10.0
Final pH	10.04	Final pH	9.97
Sludge Generation	-	Sludge Generation	-
Other Testwork	-	Other Testwork	-
Analysis	MAXXAM CAS	Analysis	MAXXAM CAS
Notes/Comments	• 2mL of E10 Added • samples taken after 30 min 60 min and 90 min of settling	Notes/Comments	SAME

APPENDIX B:
MAXXAM Analysis Report

Table 1
Laboratory Report Sample Identification and Corresponding Test Condition
Wastewater Treatability Study
Mine Site Process Water
NorthMet Project

Sample ID	Test Conditions
25392	Feed (Table 1)
25393	pH 8.0; 60min Retention Time; Dissolved Metals (Table 3)
25396	pH 9.0; 60min Retention Time; Dissolved Metals (Table 3)
25399	pH 10.0; 60min Retention Time; Dissolved Metals (Table 3 and Table 5)
25403	pH 8.5; 60min Retention Time; Dissolved Metals (Table 3)
25406	pH 9.5; 60min Retention Time; Dissolved Metals (Table 3)
25434	pH 10.0; 30min Retention Time; Dissolved Metals (Table 5)
25438	pH 10.0; 90min Retention Time; Dissolved Metals (Table 5)
25435	pH 10.0; 30min Retention Time; Total Metals; 30min Settling (Table 6)
25436	pH 10.0; 30min Retention Time; Total Metals; 60min Settling (Table 6)
25400	pH 10.0; 60min Retention Time; Total Metals; 30min Settling (Table 7)
25401	pH 10.0; 60min Retention Time; Total Metals; 60min Settling (Table 7)
25439	pH 10.0; 90min Retention Time; Total Metals; 30min Settling (Table 8)
25440	pH 10.0; 90min Retention Time; Total Metals; 60min Settling (Table 8)
25424	HDS Simulation; pH 10.0, 10th Cycle

Your P.O. #: 129
Your Project #: 0610
Your C.O.C. #: 08186697

Attention: Rik Vos
CEMI
6927 Antrim Ave.
Burnaby, BC
CANADA V5J 4M5

Report Date: 2007/03/13
This report supersedes all previous reports

CERTIFICATE OF ANALYSIS

MAXXAM JOB #: A623586
Received: 2006/06/07, 11:20

Sample Matrix: Water
Samples Received: 1

Analyses	Quantity	Date Extracted	Date Analyzed	Laboratory Method	Analytical Method
Hardness (calculated as CaCO3)	1	N/A	2006/06/08		
Elements by ICP-AES (dissolved)	1	2006/06/07	2006/06/07	BRN SOP-00040 V1.0	Based on EPA 6010B
Elements by ICPMS (dissolved) (1)	1	2006/06/06	2006/06/06	BRN SOP-00042 V1.0	Based on EPA 200.8

* RPDs calculated using raw data. The rounding of final results may result in the apparent difference.

(1) SCC/CAEAL

Encryption Key

Please direct all questions regarding this Certificate of Analysis to your Project Manager.

ELAINE COUSINS, CS Manager
Email: elaine.cousins@maxxamanalytics.com
Phone# (604) 444-4808 Ext:276

==
Maxxam has procedures in place to guard against improper use of the electronic signature and have the required "signatories", as per section 5.10.2 of ISO/IEC 17025:2005(E), signing the reports.   SCC and CAEAL have approved this reporting process and electronic report format.

Total cover pages: 1

Maxxam Job #: A623586
Report Date: 2007/03/13

CEMI
Client Project #: 0610
Site Reference:
Your P.O. #: 129
Sampler Initials:

RESULTS OF CHEMICAL ANALYSES OF WATER

Maxxam ID		B55196		
Sampling Date				
COC Number		08186697		
	Units	**25424**	**RDL**	**QC Batch**
Misc. Inorganics				
Dissolved Hardness (CaCO3)	mg/L	2310	0.5	1158317

RDL = Reportable Detection Limit

CEMI
Maxxam Job #: A623586
Report Date: 2007/03/13
Client Project #: 0610
Site Reference:
Your P.O. #: 129
Sampler Initials:

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B55196		
Sampling Date				
COC Number		08186697		
	Units	**25424**	**RDL**	**QC Batch**
Dissolved Metals by ICP				
Dissolved Boron (B)	mg/L	0.366	0.008	1157007
Dissolved Calcium (Ca)	mg/L	311	0.05	1157007
Dissolved Iron (Fe)	mg/L	<0.005	0.005	1157007
Dissolved Magnesium (Mg)	mg/L	373	0.05	1157007
Dissolved Phosphorus (P)	mg/L	<0.1	0.1	1157007
Dissolved Silicon (Si)	mg/L	4.74	0.05	1157007
Dissolved Sodium (Na)	mg/L	54.4	0.05	1157007
Dissolved Sulphur (S)	mg/L	766	0.1	1157007
Dissolved Zirconium (Zr)	mg/L	<0.005	0.005	1157007
Dissolved Metals by ICPMS				
Dissolved Aluminum (Al)	ug/L	3.0	0.2	1155980
Dissolved Antimony (Sb)	ug/L	0.07	0.05	1155980
Dissolved Arsenic (As)	ug/L	0.7	0.1	1155980
Dissolved Barium (Ba)	ug/L	7.43	0.02	1155980
Dissolved Beryllium (Be)	ug/L	<0.05	0.05	1155980
Dissolved Bismuth (Bi)	ug/L	<0.05	0.05	1155980
Dissolved Cadmium (Cd)	ug/L	0.04	0.01	1155980
Dissolved Chromium (Cr)	ug/L	<0.2	0.2	1155980
Dissolved Cobalt (Co)	ug/L	<0.02	0.02	1155980
Dissolved Copper (Cu)	ug/L	6.4	0.1	1155980
Dissolved Lead (Pb)	ug/L	0.07	0.02	1155980
Dissolved Lithium (Li)	ug/L	41.6	0.2	1155980
Dissolved Manganese (Mn)	ug/L	0.96	0.02	1155980
Dissolved Molybdenum (Mo)	ug/L	1.04	0.02	1155980
Dissolved Nickel (Ni)	ug/L	7.6	0.5	1155980
Dissolved Potassium (K)	ug/L	6400	50	1155980
Dissolved Selenium (Se)	ug/L	2.2	0.5	1155980
Dissolved Silver (Ag)	ug/L	<0.01	0.01	1155980
Dissolved Strontium (Sr)	ug/L	789	0.01	1155980
Dissolved Thallium (Tl)	ug/L	0.05	0.05	1155980
Dissolved Tin (Sn)	ug/L	<0.05	0.05	1155980
Dissolved Titanium (Ti)	ug/L	5.9	0.5	1155980

RDL = Reportable Detection Limit

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B55196		
Sampling Date				
COC Number		08186697		
	Units	**25424**	**RDL**	**QC Batch**

Dissolved Uranium (U)	ug/L	0.88	0.01	1155980
Dissolved Vanadium (V)	ug/L	0.65	0.05	1155980
Dissolved Zinc (Zn)	ug/L	1.7	0.5	1155980

RDL = Reportable Detection Limit

Maxxam Job #: A623586
Report Date: 2007/03/13

CEMI
Client Project #: 0610
Site Reference:
Your P.O. #: 129
Sampler Initials:

General Comments

Results relate only to the items tested.

CEMI
Attention: Rik Vos
Client Project #: 0610
P.O. #: 129
Site Reference:

Quality Assurance Report

Maxxam Job Number: VA623586

QA/QC Batch Num	Init	QC Type	Parameter	Date Analyzed yyyy/mm/dd	Value	Recovery	Units	QC Limits
1155980	AA1	MATRIX SPIKE	Dissolved Arsenic (As)	2006/06/06		107	%	75 - 125
			Dissolved Cadmium (Cd)	2006/06/06		106	%	75 - 125
			Dissolved Chromium (Cr)	2006/06/06		104	%	75 - 125
			Dissolved Cobalt (Co)	2006/06/06		103	%	75 - 125
			Dissolved Copper (Cu)	2006/06/06		106	%	75 - 125
			Dissolved Lead (Pb)	2006/06/06		103	%	75 - 125
			Dissolved Selenium (Se)	2006/06/06		111	%	75 - 125
			Dissolved Thallium (Tl)	2006/06/06		101	%	75 - 125
			Dissolved Zinc (Zn)	2006/06/06		107	%	75 - 125
		SPIKE	Dissolved Arsenic (As)	2006/06/06		98	%	75 - 125
			Dissolved Cadmium (Cd)	2006/06/06		101	%	75 - 125
			Dissolved Chromium (Cr)	2006/06/06		109	%	75 - 125
			Dissolved Cobalt (Co)	2006/06/06		107	%	75 - 125
			Dissolved Copper (Cu)	2006/06/06		104	%	75 - 125
			Dissolved Lead (Pb)	2006/06/06		105	%	75 - 125
			Dissolved Selenium (Se)	2006/06/06		95	%	75 - 125
			Dissolved Thallium (Tl)	2006/06/06		103	%	75 - 125
			Dissolved Zinc (Zn)	2006/06/06		91	%	75 - 125
		BLANK	Dissolved Aluminum (Al)	2006/06/06	<0.2		ug/L	
			Dissolved Antimony (Sb)	2006/06/06	<0.05		ug/L	
			Dissolved Arsenic (As)	2006/06/06	<0.1		ug/L	
			Dissolved Barium (Ba)	2006/06/06	<0.02		ug/L	
			Dissolved Beryllium (Be)	2006/06/06	<0.05		ug/L	
			Dissolved Bismuth (Bi)	2006/06/06	<0.05		ug/L	
			Dissolved Cadmium (Cd)	2006/06/06	<0.01		ug/L	
			Dissolved Chromium (Cr)	2006/06/06	<0.2		ug/L	
			Dissolved Cobalt (Co)	2006/06/06	<0.02		ug/L	
			Dissolved Copper (Cu)	2006/06/06	<0.1		ug/L	
			Dissolved Lead (Pb)	2006/06/06	<0.02		ug/L	
			Dissolved Lithium (Li)	2006/06/06	<0.2		ug/L	
			Dissolved Manganese (Mn)	2006/06/06	<0.02		ug/L	
			Dissolved Molybdenum (Mo)	2006/06/06	<0.02		ug/L	
			Dissolved Nickel (Ni)	2006/06/06	<0.5		ug/L	
			Dissolved Potassium (K)	2006/06/06	<50		ug/L	
			Dissolved Selenium (Se)	2006/06/06	<0.5		ug/L	
			Dissolved Silver (Ag)	2006/06/06	<0.01		ug/L	
			Dissolved Strontium (Sr)	2006/06/06	<0.01		ug/L	
			Dissolved Thallium (Tl)	2006/06/06	<0.05		ug/L	
			Dissolved Tin (Sn)	2006/06/06	<0.05		ug/L	
			Dissolved Titanium (Ti)	2006/06/06	<0.5		ug/L	
			Dissolved Uranium (U)	2006/06/06	<0.01		ug/L	
			Dissolved Vanadium (V)	2006/06/06	<0.05		ug/L	
			Dissolved Zinc (Zn)	2006/06/06	<0.5		ug/L	
		RPD	Dissolved Aluminum (Al)	2006/06/06	0.6		%	25
			Dissolved Antimony (Sb)	2006/06/06	1.5		%	25
			Dissolved Arsenic (As)	2006/06/06	NC		%	25
			Dissolved Barium (Ba)	2006/06/06	1.9		%	25
			Dissolved Beryllium (Be)	2006/06/06	NC		%	25
			Dissolved Bismuth (Bi)	2006/06/06	NC		%	25
			Dissolved Cadmium (Cd)	2006/06/06	NC		%	25
			Dissolved Chromium (Cr)	2006/06/06	NC		%	25
			Dissolved Cobalt (Co)	2006/06/06	NC		%	25
			Dissolved Copper (Cu)	2006/06/06	4.1		%	25
			Dissolved Lead (Pb)	2006/06/06	NC		%	25
			Dissolved Lithium (Li)	2006/06/06	NC		%	25

CEMI
Attention: Rik Vos
Client Project #: 0610
P.O. #: 129
Site Reference:

Quality Assurance Report (Continued)

Maxxam Job Number: VA623586

QA/QC Batch Num	Init	QC Type	Parameter	Date Analyzed yyyy/mm/dd	Value	Recovery	Units	QC Limits
1155980	AA1	RPD	Dissolved Manganese (Mn)	2006/06/06	2.0		%	25
			Dissolved Molybdenum (Mo)	2006/06/06	NC		%	25
			Dissolved Nickel (Ni)	2006/06/06	NC		%	25
			Dissolved Potassium (K)	2006/06/06	NC		%	25
			Dissolved Selenium (Se)	2006/06/06	NC		%	25
			Dissolved Silver (Ag)	2006/06/06	NC		%	25
			Dissolved Strontium (Sr)	2006/06/06	2.9		%	25
			Dissolved Thallium (Tl)	2006/06/06	NC		%	25
			Dissolved Tin (Sn)	2006/06/06	NC		%	25
			Dissolved Titanium (Ti)	2006/06/06	NC		%	25
			Dissolved Uranium (U)	2006/06/06	NC		%	25
			Dissolved Vanadium (V)	2006/06/06	7.4		%	25
			Dissolved Zinc (Zn)	2006/06/06	NC		%	25
1157007	KL1	BLANK	Dissolved Boron (B)	2006/06/07	0.010,	RDL=0.008	mg/L	
			Dissolved Calcium (Ca)	2006/06/07	<0.05		mg/L	
			Dissolved Iron (Fe)	2006/06/07	<0.005		mg/L	
			Dissolved Magnesium (Mg)	2006/06/07	<0.05		mg/L	
			Dissolved Phosphorus (P)	2006/06/07	<0.1		mg/L	
			Dissolved Silicon (Si)	2006/06/07	<0.05		mg/L	
			Dissolved Sodium (Na)	2006/06/07	<0.05		mg/L	
			Dissolved Sulphur (S)	2006/06/07	<0.1		mg/L	
			Dissolved Zirconium (Zr)	2006/06/07	<0.005		mg/L	
		RPD	Dissolved Calcium (Ca)	2006/06/07	0.07		%	25
			Dissolved Magnesium (Mg)	2006/06/07	2.2		%	25

NC = Non-calculable
RPD = Relative Percent Difference

Maxxam Analytics Inc

Calgary: 2021-41st Ave. NE, T2E 6P2. Ph: (403) 291-3077, Fax: (403) 291-9468, Toll free: (800) 386-7247
Edmonton: 9619 - 42 Ave, T6E 5R2. Ph: (780) 465-1212, Fax: (780) 450-4187, Toll free: (877) 465-8889
Burnaby: 8577 Commerce Court, V5A 4N5 Ph: (604) 444-4808, Fax (604) 444-4511, Toll free: (800) 440-480l

08186697

ANALYTICAL REQUEST FORM

Page 1 of 1

Invoice To: Require Report? Yes ☒ No ☐

Company Name: CEMI
Contact Name: Rik Vos
Address:
PC:
Phone / Fax#: Ph: 604-264-5536 Fax: 604-264-5535

Report To: A 623586
CEMI
Prab Bhatia
PC:
Ph: 604-264-5536 Fax: 604-264-5535

PO# / AFE#: 129
Quotation #: A60050
Project #: 0610
Proj. Name:
Location:
Sampler's Initials:

REGULATORY REQUIREMENTS:

- ☐ AT1 - Soil Contamination
- ☐ CCME
- ☐ CCME FWAL
- ☐ Regulatory Limits to appear on Final report
- ☐ PST
- ☐ CDWQG
- ☐ G50

REPORT DISTRIBUTION:

- ☒ Mail
- ☒ PDF
- ☒ Email: prab@cemi.bc.ca
- ☐ Fax
- ☒ Excel
- ☐ Other:

SERVICE REQUESTED:

- ☒ RUSH (Please ensure you contact the lab)
  Date Required: 24-hr RUSH
- ☐ REGULAR Turnaround

METALS: (WATERS)

☐ Total ☐ Extractable ☒ Dissolved

ANALYSIS REQUESTED

	Sample Identification	Matrix	Date/Time Sampled	Sample Type Grab/Comp	Hold > 60 Days	Sample Container #	LLICPMS	LLICPMS WO/Hg	REGICPMS	REGICPMS WO/Hg	REGICPMS WO/Hg - TOT												
1	25424 B55196			GRAB				X						Dissolved Metals - Filtered & HNO_3 added									
2				GRAB																			
3				GRAB																			
4				GRAB																			
5				GRAB																			
6				GRAB																			
7				GRAB																			
8				GRAB																			
9				GRAB																			
10				GRAB																			
11				GRAB																			
12				GRAB																			

** For water samples, please indicate if sample container has been preserved (P) and/or filtered (F).

Relinquished By: R DIXON
Signature: R.S. Dixon
Date/Time: JUNE 6/06

Received
June 7/06.
11:20 am.
DUE-
JUNE 8/06

Temperature
22.

C of C #

COMMENTS/SPECIAL INSTRUCTIONS:

FCD - 0026 Chain of Custody R4 - April 11, 2005

Maxxam Analytics Inc

Driven by service and Science
www.maxxamanalytics.com

Your P.O. #: 88
Your Project #: 0610
Your C.O.C. #: 08186192

Attention: Rik Vos
CEMI
6927 Antrim Ave.
Burnaby, BC
CANADA V5J 4M5

Report Date: 2007/03/13
This report supersedes all previous reports

CERTIFICATE OF ANALYSIS

MAXXAM JOB #: A619312
Received: 2006/05/11, 15:00

Sample Matrix: Water
\# Samples Received: 2

Analyses	Quantity	Date Extracted	Date Analyzed	Laboratory Method	Analytical Method
Hardness (calculated as CaCO3)	2	N/A	2006/05/15		
Mercury (Dissolved)	2	2006/05/16	2006/05/17	BRN SOP-00044 V1.0	Based on EPA 245.1
Elements by ICP-AES (dissolved)	2	2006/05/15	2006/05/15	BRN SOP-00040 V1.0	Based on EPA 6010B
Elements by ICPMS (dissolved) (1)	2	2006/05/16	2006/05/16	BRN SOP-00042 V1.0	Based on EPA 200.8

* RPDs calculated using raw data. The rounding of final results may result in the apparent difference.

(1) SCC/CAEAL

Encryption Key

Please direct all questions regarding this Certificate of Analysis to your Project Manager.

ELAINE COUSINS, CS Manager
Email: elaine.cousins@maxxamanalytics.com
Phone# (604) 444-4808 Ext:276

==
Maxxam has procedures in place to guard against improper use of the electronic signature and have the required "signatories", as per section 5.10.2 of ISO/IEC 17025:2005(E), signing the reports. SCC and CAEAL have approved this reporting process and electronic report format.

Total cover pages: 1

Maxxam Job #: A619312
Report Date: 2007/03/13

CEMI
Client Project #: 0610
Site Reference:
Your P.O. #: 88
Sampler Initials:

RESULTS OF CHEMICAL ANALYSES OF WATER

Maxxam ID		B28806	B28807		
Sampling Date					
COC Number		08186192	08186192		
	Units	**25403**	**25406**	**RDL**	**QC Batch**
Misc. Inorganics					
Dissolved Hardness (CaCO3)	mg/L	2260	2120	0.5	1133469

RDL = Reportable Detection Limit

Maxxam Job #: A619312
Report Date: 2007/03/13

CEMI
Client Project #: 0610
Site Reference:
Your P.O. #: 88
Sampler Initials:

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B28806	B28807		
Sampling Date					
COC Number		08186192	08186192		
	Units	**25403**	**25406**	**RDL**	**QC Batch**

Low Level Elements					
Dissolved Mercury (Hg)	ug/L	<0.05	<0.05	0.05	1135004
Dissolved Metals by ICP					
Dissolved Boron (B)	mg/L	0.410	0.383	0.008	1134064
Dissolved Calcium (Ca)	mg/L	304	265	0.05	1134064
Dissolved Iron (Fe)	mg/L	<0.005	<0.005	0.005	1134064
Dissolved Magnesium (Mg)	mg/L	366	353	0.05	1134064
Dissolved Phosphorus (P)	mg/L	<0.1	<0.1	0.1	1134064
Dissolved Silicon (Si)	mg/L	9.35	8.34	0.05	1134064
Dissolved Sodium (Na)	mg/L	52.6	51.1	0.05	1134064
Dissolved Sulphur (S)	mg/L	770	745	0.1	1134064
Dissolved Zirconium (Zr)	mg/L	<0.005	<0.005	0.005	1134064
Dissolved Metals by ICPMS					
Dissolved Aluminum (Al)	ug/L	9	<2	2	1135123
Dissolved Antimony (Sb)	ug/L	<0.5	<0.5	0.5	1135123
Dissolved Arsenic (As)	ug/L	3	1	1	1135123
Dissolved Barium (Ba)	ug/L	13.2	5.2	0.2	1135123
Dissolved Beryllium (Be)	ug/L	<0.5	<0.5	0.5	1135123
Dissolved Bismuth (Bi)	ug/L	<0.5	<0.5	0.5	1135123
Dissolved Cadmium (Cd)	ug/L	1.5	0.2	0.1	1135123
Dissolved Chromium (Cr)	ug/L	<2	<2	2	1135123
Dissolved Cobalt (Co)	ug/L	62.9	2.2	0.2	1135123
Dissolved Copper (Cu)	ug/L	110	9	1	1135123
Dissolved Lead (Pb)	ug/L	0.6	<0.2	0.2	1135123
Dissolved Lithium (Li)	ug/L	40	37	2	1135123
Dissolved Manganese (Mn)	ug/L	1600	104	0.2	1135123
Dissolved Molybdenum (Mo)	ug/L	1.0	1.2	0.2	1135123
Dissolved Nickel (Ni)	ug/L	1430	244	5	1135123
Dissolved Potassium (K)	ug/L	7040	7790	500	1135123
Dissolved Selenium (Se)	ug/L	<5	<5	5	1135123
Dissolved Silver (Ag)	ug/L	<0.1	<0.1	0.1	1135123
Dissolved Strontium (Sr)	ug/L	833	691	0.1	1135123
Dissolved Thallium (Tl)	ug/L	<0.5	<0.5	0.5	1135123

RDL = Reportable Detection Limit

Maxxam Job #: A619312
Report Date: 2007/03/13

CEMI
Client Project #: 0610
Site Reference:
Your P.O. #: 88
Sampler Initials:

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B28806	B28807		
Sampling Date					
COC Number		08186192	08186192		
	Units	**25403**	**25406**	**RDL**	**QC Batch**
Dissolved Tin (Sn)	ug/L	<0.5	<0.5	0.5	1135123
Dissolved Titanium (Ti)	ug/L	<5	<5	5	1135123
Dissolved Uranium (U)	ug/L	4.4	1.7	0.1	1135123
Dissolved Vanadium (V)	ug/L	<0.5	<0.5	0.5	1135123
Dissolved Zinc (Zn)	ug/L	224	<5	5	1135123

RDL = Reportable Detection Limit

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER) Comments

Sample B28806-01 Elements by ICPMS (dissolved): MDL raised due to sample dilution.

Sample B28807-01 Elements by ICPMS (dissolved): MDL raised due to sample dilution.

Results relate only to the items tested.

CEMI
Attention: Rik Vos
Client Project #: 0610
P.O. #: 88
Site Reference:

Quality Assurance Report

Maxxam Job Number: VA619312

QA/QC Batch Num	Init	QC Type	Parameter	Date Analyzed yyyy/mm/dd	Value	Recovery	Units	QC Limits
1134064	KL1	BLANK	Dissolved Boron (B)	2006/05/15	<0.008		mg/L	
			Dissolved Calcium (Ca)	2006/05/15	<0.05		mg/L	
			Dissolved Iron (Fe)	2006/05/15	<0.005		mg/L	
			Dissolved Magnesium (Mg)	2006/05/15	<0.05		mg/L	
			Dissolved Phosphorus (P)	2006/05/15	<0.1		mg/L	
			Dissolved Silicon (Si)	2006/05/15	<0.05		mg/L	
			Dissolved Sodium (Na)	2006/05/15	<0.05		mg/L	
			Dissolved Sulphur (S)	2006/05/15	<0.1		mg/L	
			Dissolved Zirconium (Zr)	2006/05/15	<0.005		mg/L	
		RPD	Dissolved Boron (B)	2006/05/15	NC		%	25
			Dissolved Calcium (Ca)	2006/05/15	0.1		%	25
			Dissolved Iron (Fe)	2006/05/15	NC		%	25
			Dissolved Magnesium (Mg)	2006/05/15	0.3		%	25
			Dissolved Phosphorus (P)	2006/05/15	NC		%	25
			Dissolved Silicon (Si)	2006/05/15	0.2		%	25
			Dissolved Sodium (Na)	2006/05/15	0.4		%	25
			Dissolved Sulphur (S)	2006/05/15	0.2		%	25
			Dissolved Zirconium (Zr)	2006/05/15	NC		%	25
1135004	AA1	MATRIX SPIKE	Dissolved Mercury (Hg)	2006/05/17		101	%	70 - 130
		QC STANDARD	Dissolved Mercury (Hg)	2006/05/17		100	%	80 - 120
		SPIKE	Dissolved Mercury (Hg)	2006/05/17		95	%	80 - 120
		BLANK	Dissolved Mercury (Hg)	2006/05/17	<0.05		ug/L	
		RPD	Dissolved Mercury (Hg)	2006/05/17	NC		%	25
1135123	DJ	MATRIX SPIKE	Dissolved Arsenic (As)	2006/05/16		96	%	75 - 125
			Dissolved Cadmium (Cd)	2006/05/16		106	%	75 - 125
			Dissolved Chromium (Cr)	2006/05/16		109	%	75 - 125
			Dissolved Cobalt (Co)	2006/05/16		109	%	75 - 125
			Dissolved Copper (Cu)	2006/05/16		112	%	75 - 125
			Dissolved Lead (Pb)	2006/05/16		98	%	75 - 125
			Dissolved Selenium (Se)	2006/05/16		98	%	75 - 125
			Dissolved Thallium (Tl)	2006/05/16		95	%	75 - 125
			Dissolved Zinc (Zn)	2006/05/16		104	%	75 - 125
		SPIKE	Dissolved Arsenic (As)	2006/05/16		105	%	75 - 125
			Dissolved Cadmium (Cd)	2006/05/16		105	%	75 - 125
			Dissolved Chromium (Cr)	2006/05/16		112	%	75 - 125
			Dissolved Cobalt (Co)	2006/05/16		111	%	75 - 125
			Dissolved Copper (Cu)	2006/05/16		115	%	75 - 125
			Dissolved Lead (Pb)	2006/05/16		100	%	75 - 125
			Dissolved Selenium (Se)	2006/05/16		108	%	75 - 125
			Dissolved Thallium (Tl)	2006/05/16		96	%	75 - 125
			Dissolved Zinc (Zn)	2006/05/16		115	%	75 - 125
		BLANK	Dissolved Aluminum (Al)	2006/05/16	<0.2		ug/L	
			Dissolved Antimony (Sb)	2006/05/16	<0.05		ug/L	
			Dissolved Arsenic (As)	2006/05/16	<0.1		ug/L	
			Dissolved Barium (Ba)	2006/05/16	<0.02		ug/L	
			Dissolved Beryllium (Be)	2006/05/16	<0.05		ug/L	
			Dissolved Bismuth (Bi)	2006/05/16	<0.05		ug/L	
			Dissolved Cadmium (Cd)	2006/05/16	<0.01		ug/L	
			Dissolved Chromium (Cr)	2006/05/16	<0.2		ug/L	
			Dissolved Cobalt (Co)	2006/05/16	<0.02		ug/L	
			Dissolved Copper (Cu)	2006/05/16	<0.1		ug/L	
			Dissolved Lead (Pb)	2006/05/16	<0.02		ug/L	
			Dissolved Lithium (Li)	2006/05/16	0.2, RDL=0.2		ug/L	
			Dissolved Manganese (Mn)	2006/05/16	<0.02		ug/L	
			Dissolved Molybdenum (Mo)	2006/05/16	<0.02		ug/L	

CEMI
Attention: Rik Vos
Client Project #: 0610
P.O. #: 88
Site Reference:

Quality Assurance Report (Continued)

Maxxam Job Number: VA619312

QA/QC Batch Num	Init	QC Type	Parameter	Date Analyzed yyyy/mm/dd	Value	Recovery	Units	QC Limits
1135123	DJ	BLANK	Dissolved Nickel (Ni)	2006/05/16	<0.5		ug/L	
			Dissolved Potassium (K)	2006/05/16	<50		ug/L	
			Dissolved Selenium (Se)	2006/05/16	<0.5		ug/L	
			Dissolved Silver (Ag)	2006/05/16	<0.01		ug/L	
			Dissolved Strontium (Sr)	2006/05/16	<0.01		ug/L	
			Dissolved Thallium (Tl)	2006/05/16	<0.05		ug/L	
			Dissolved Tin (Sn)	2006/05/16	<0.05		ug/L	
			Dissolved Titanium (Ti)	2006/05/16	<0.5		ug/L	
			Dissolved Uranium (U)	2006/05/16	<0.01		ug/L	
			Dissolved Vanadium (V)	2006/05/16	<0.05		ug/L	
			Dissolved Zinc (Zn)	2006/05/16	<0.5		ug/L	
		RPD	Dissolved Aluminum (Al)	2006/05/16	2.8		%	25
			Dissolved Antimony (Sb)	2006/05/16	NC		%	25
			Dissolved Arsenic (As)	2006/05/16	1.4		%	25
			Dissolved Barium (Ba)	2006/05/16	0.7		%	25
			Dissolved Beryllium (Be)	2006/05/16	NC		%	25
			Dissolved Bismuth (Bi)	2006/05/16	NC		%	25
			Dissolved Cadmium (Cd)	2006/05/16	1.5		%	25
			Dissolved Chromium (Cr)	2006/05/16	3.6		%	25
			Dissolved Cobalt (Co)	2006/05/16	2.0		%	25
			Dissolved Copper (Cu)	2006/05/16	4.8		%	25
			Dissolved Lead (Pb)	2006/05/16	1.2		%	25
			Dissolved Lithium (Li)	2006/05/16	NC		%	25
			Dissolved Manganese (Mn)	2006/05/16	3.5		%	25
			Dissolved Molybdenum (Mo)	2006/05/16	17.5		%	25
			Dissolved Nickel (Ni)	2006/05/16	4.1		%	25
			Dissolved Potassium (K)	2006/05/16	NC		%	25
			Dissolved Selenium (Se)	2006/05/16	NC		%	25
			Dissolved Silver (Ag)	2006/05/16	NC		%	25
			Dissolved Strontium (Sr)	2006/05/16	4.5		%	25
			Dissolved Thallium (Tl)	2006/05/16	NC		%	25
			Dissolved Tin (Sn)	2006/05/16	0.2		%	25
			Dissolved Titanium (Ti)	2006/05/16	NC		%	25
			Dissolved Uranium (U)	2006/05/16	NC		%	25
			Dissolved Vanadium (V)	2006/05/16	NC		%	25
			Dissolved Zinc (Zn)	2006/05/16	2.9		%	25

NC = Non-calculable
RPD = Relative Percent Difference

Maxxam Analytics Inc

Calgary: 2021-41st Ave. NE, T2E 6P2 Ph: (403) 291-3077, Fax: (403) 291-9468, Toll free: (800) 386-7247
Edmonton: 9619 - 42 Ave, T6E 5R2 Ph: (780) 465-1212, Fax: (780) 450-4187, Toll free: (877) 465-8889
Burnaby: 8577 Commerce Court, V5A 4N5 Ph: (604) 444-4808, Fax (604) 444-4511, Toll free: (800) 440-4808

08186192

ANALYTICAL REQUEST FORM

Page 1 of 1

Invoice To: Require Report? Yes ☒ No ☐
Company Name: CEMI
Contact Name: Rik Vos
Address:
PC
Phone / Fax#: Ph 604-264-5536 Fax 604-264-5535

Report To: A619312
CEMI
Prab Bhatia
PC
Ph 604-264-5536 Fax 604-264-5535

PO# / AFE#: 88
Quotation #: A60050
Project # : 0610
Proj. Name:
Location:
Sampler's Initials:

REGULATORY REQUIREMENTS:
- ☐ AT1 - Soil Contamination
- ☐ CCME
- ☐ CCME FWAL
- ☐ Regulatory Limits to appear on Final report
- ☐ PST
- ☐ CDWQG
- ☐ G50

REPORT DISTRIBUTION:
- ☒ Mail
- ☒ PDF
- ☒ Email: prab@cemi.bc.ca
- ☐ Fax
- ☒ Excel
- ☐ Other:

SERVICE REQUESTED:
- ☐ RUSH (Please ensure you contact the lab)
  Date Required:
- ☒ REGULAR Turnaround

METALS: (WATERS) ☐ Total ☐ Extractable ☒ Dissolved

ANALYSIS REQUESTED

	Sample Identification	Matrix	Date/Time Sampled	Sample Type Grab/Comp	Hold > 60 Days	Sample Container #	LLICPMS	LLICPMS WO/Hg	REGICPMS	REGICPMS WO/Hg	REGICPMS WO/Hg - TOT	
1	25403	B528806		GRAB			X					Dissolved Metals - Filtered & HNO$_3$ added
2	25406	07		GRAB			X					Dissolved Metals - Filtered & HNO$_3$ added
3				GRAB								
4				GRAB								
5				GRAB								
6				GRAB								
7				GRAB								
8				GRAB								
9				GRAB								
10				GRAB								
11				GRAB								
12				GRAB								

** For water samples, please indicate if sample container has been preserved (P) and/or filtered (F).

Relinquished By:
Date/Time:
Signature:

Received
May 11, 2006
1500

Temperature
20, 20

C of C #

COMMENTS/SPECIAL INSTRUCTIONS:

FCD - 0026 Chain of Custody R4 - April 11, 2005

Your P.O. #: 83
Your Project #: 0610
Your C.O.C. #: 08186188

Attention: Rik Vos
CEMI
6927 Antrim Ave.
Burnaby, BC
CANADA V5J 4M5

Report Date: 2007/03/13
This report supersedes all previous reports

CERTIFICATE OF ANALYSIS

MAXXAM JOB #: A619315
Received: 2006/05/11, 15:00

Sample Matrix: Water
Samples Received: 4

Analyses	Quantity	Date Extracted	Date Analyzed	Laboratory Method	Analytical Method
Hardness (calculated as CaCO3)	4	N/A	2006/05/15		
Mercury (Dissolved)	4	2006/05/16	2006/05/17	BRN SOP-00044 V1.0	Based on EPA 245.1
Elements by ICP-AES (dissolved)	4	2006/05/15	2006/05/15	BRN SOP-00040 V1.0	Based on EPA 6010B
Elements by ICPMS (dissolved) (1)	4	2006/05/16	2006/05/16	BRN SOP-00042 V1.0	Based on EPA 200.8

* RPDs calculated using raw data. The rounding of final results may result in the apparent difference.

(1) SCC/CAEAL

Encryption Key

Please direct all questions regarding this Certificate of Analysis to your Project Manager.

ELAINE COUSINS, CS Manager
Email: elaine.cousins@maxxamanalytics.com
Phone# (604) 444-4808 Ext:276

==
Maxxam has procedures in place to guard against improper use of the electronic signature and have the required "signatories", as per section 5.10.2 of ISO/IEC 17025:2005(E), signing the reports. SCC and CAEAL have approved this reporting process and electronic report format.

Total cover pages: 1

CEMI
Maxxam Job #: A619315
Client Project #: 0610
Report Date: 2007/03/13
Site Reference:
Your P.O. #: 83
Sampler Initials:

RESULTS OF CHEMICAL ANALYSES OF WATER

Maxxam ID		B28818	B28819	B28820	B28821		
Sampling Date							
COC Number		08186188	08186188	08186188	08186188		
	Units	**25392**	**25393**	**25396**	**25399**	**RDL**	**QC Batch**
Misc. Inorganics							
Dissolved Hardness (CaCO3)	mg/L	2190	2210	2200	2160	0.5	1133469

RDL = Reportable Detection Limit

CEMI
Maxxam Job #: A619315
Report Date: 2007/03/13

Client Project #: 0610
Site Reference:
Your P.O. #: 83
Sampler Initials:

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B28818	B28819	B28820	B28821		
Sampling Date							
COC Number		08186188	08186188	08186188	08186188		
	Units	**25392**	**25393**	**25396**	**25399**	**RDL**	**QC Batch**
Low Level Elements							
Dissolved Mercury (Hg)	ug/L	<0.05	<0.05	<0.05	<0.05	0.05	1135004
Dissolved Metals by ICP							
Dissolved Boron (B)	mg/L	0.402	0.403	0.397	0.372	0.008	1134064
Dissolved Calcium (Ca)	mg/L	285	289	294	279	0.05	1134064
Dissolved Iron (Fe)	mg/L	<0.005	<0.005	<0.005	<0.005	0.005	1134064
Dissolved Magnesium (Mg)	mg/L	360	361	357	356	0.05	1134064
Dissolved Phosphorus (P)	mg/L	<0.1	<0.1	<0.1	<0.1	0.1	1134064
Dissolved Silicon (Si)	mg/L	9.33	9.32	9.06	6.86	0.05	1134064
Dissolved Sodium (Na)	mg/L	51.9	52.0	51.2	52.2	0.05	1134064
Dissolved Sulphur (S)	mg/L	739	717	749	750	0.1	1134064
Dissolved Zirconium (Zr)	mg/L	<0.005	<0.005	<0.005	<0.005	0.005	1134064
Dissolved Metals by ICPMS							
Dissolved Aluminum (Al)	ug/L	17	11	3	<2	2	1135123
Dissolved Antimony (Sb)	ug/L	<0.5	<0.5	<0.5	<0.5	0.5	1135123
Dissolved Arsenic (As)	ug/L	1	<1	<1	<1	1	1135123
Dissolved Barium (Ba)	ug/L	12.4	13.0	10.2	7.0	0.2	1135123
Dissolved Beryllium (Be)	ug/L	<0.5	<0.5	<0.5	<0.5	0.5	1135123
Dissolved Bismuth (Bi)	ug/L	<0.5	<0.5	<0.5	<0.5	0.5	1135123
Dissolved Cadmium (Cd)	ug/L	2.0	1.9	0.2	0.2	0.1	1135123
Dissolved Chromium (Cr)	ug/L	<2	<2	<2	<2	2	1135123
Dissolved Cobalt (Co)	ug/L	67.3	67.5	40.3	<0.2	0.2	1135123
Dissolved Copper (Cu)	ug/L	281	210	28	7	1	1135123
Dissolved Lead (Pb)	ug/L	<0.2	0.3	<0.2	<0.2	0.2	1135123
Dissolved Lithium (Li)	ug/L	39	40	38	41	2	1135123
Dissolved Manganese (Mn)	ug/L	1680	1660	909	1.1	0.2	1135123
Dissolved Molybdenum (Mo)	ug/L	0.8	0.9	1.4	2.7	0.2	1135123
Dissolved Nickel (Ni)	ug/L	1480	1510	1110	13	5	1135123
Dissolved Potassium (K)	ug/L	6880	7190	7280	7200	500	1135123
Dissolved Selenium (Se)	ug/L	<5	<5	<5	7	5	1135123
Dissolved Silver (Ag)	ug/L	<0.1	<0.1	<0.1	<0.1	0.1	1135123
Dissolved Strontium (Sr)	ug/L	799	813	793	757	0.1	1135123
Dissolved Thallium (Tl)	ug/L	<0.5	<0.5	<0.5	<0.5	0.5	1135123

RDL = Reportable Detection Limit

Maxxam Job #: A619315
Report Date: 2007/03/13

CEMI
Client Project #: 0610
Site Reference:
Your P.O. #: 83
Sampler Initials:

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B28818	B28819	B28820	B28821		
Sampling Date							
COC Number		08186188	08186188	08186188	08186188		
	Units	**25392**	**25393**	**25396**	**25399**	**RDL**	**QC Batch**
Dissolved Tin (Sn)	ug/L	<0.5	<0.5	<0.5	<0.5	0.5	1135123
Dissolved Titanium (Ti)	ug/L	<5	<5	<5	<5	5	1135123
Dissolved Uranium (U)	ug/L	4.4	4.5	4.1	0.4	0.1	1135123
Dissolved Vanadium (V)	ug/L	<0.5	<0.5	<0.5	<0.5	0.5	1135123
Dissolved Zinc (Zn)	ug/L	520	456	10	<5	5	1135123

RDL = Reportable Detection Limit

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER) Comments

Sample B28818-01 Elements by ICPMS (dissolved): MDL raised due to sample dilution.

Sample B28819-01 Elements by ICPMS (dissolved): MDL raised due to sample dilution.

Sample B28820-01 Elements by ICPMS (dissolved): MDL raised due to sample dilution.

Sample B28821-01 Elements by ICPMS (dissolved): MDL raised due to sample dilution.

Results relate only to the items tested.

CEMI
Attention: Rik Vos
Client Project #: 0610
P.O. #: 83
Site Reference:

Quality Assurance Report

Maxxam Job Number: VA619315

QA/QC Batch Num	Init	QC Type	Parameter	Date Analyzed yyyy/mm/dd	Value	Recovery	Units	QC Limits
1134064	KL1	BLANK	Dissolved Boron (B)	2006/05/15	<0.008		mg/L	
			Dissolved Calcium (Ca)	2006/05/15	<0.05		mg/L	
			Dissolved Iron (Fe)	2006/05/15	<0.005		mg/L	
			Dissolved Magnesium (Mg)	2006/05/15	<0.05		mg/L	
			Dissolved Phosphorus (P)	2006/05/15	<0.1		mg/L	
			Dissolved Silicon (Si)	2006/05/15	<0.05		mg/L	
			Dissolved Sodium (Na)	2006/05/15	<0.05		mg/L	
			Dissolved Sulphur (S)	2006/05/15	<0.1		mg/L	
			Dissolved Zirconium (Zr)	2006/05/15	<0.005		mg/L	
		RPD	Dissolved Boron (B)	2006/05/15	NC		%	25
			Dissolved Calcium (Ca)	2006/05/15	0.1		%	25
			Dissolved Iron (Fe)	2006/05/15	NC		%	25
			Dissolved Magnesium (Mg)	2006/05/15	0.3		%	25
			Dissolved Phosphorus (P)	2006/05/15	NC		%	25
			Dissolved Silicon (Si)	2006/05/15	0.2		%	25
			Dissolved Sodium (Na)	2006/05/15	0.4		%	25
			Dissolved Sulphur (S)	2006/05/15	0.2		%	25
			Dissolved Zirconium (Zr)	2006/05/15	NC		%	25
1135004	AA1	MATRIX SPIKE	Dissolved Mercury (Hg)	2006/05/17		101	%	70 - 130
		QC STANDARD	Dissolved Mercury (Hg)	2006/05/17		100	%	80 - 120
		SPIKE	Dissolved Mercury (Hg)	2006/05/17		95	%	80 - 120
		BLANK	Dissolved Mercury (Hg)	2006/05/17	<0.05		ug/L	
		RPD	Dissolved Mercury (Hg)	2006/05/17	NC		%	25
1135123	DJ	MATRIX SPIKE	Dissolved Arsenic (As)	2006/05/16		96	%	75 - 125
			Dissolved Cadmium (Cd)	2006/05/16		106	%	75 - 125
			Dissolved Chromium (Cr)	2006/05/16		109	%	75 - 125
			Dissolved Cobalt (Co)	2006/05/16		109	%	75 - 125
			Dissolved Copper (Cu)	2006/05/16		112	%	75 - 125
			Dissolved Lead (Pb)	2006/05/16		98	%	75 - 125
			Dissolved Selenium (Se)	2006/05/16		98	%	75 - 125
			Dissolved Thallium (Tl)	2006/05/16		95	%	75 - 125
			Dissolved Zinc (Zn)	2006/05/16		104	%	75 - 125
		SPIKE	Dissolved Arsenic (As)	2006/05/16		105	%	75 - 125
			Dissolved Cadmium (Cd)	2006/05/16		105	%	75 - 125
			Dissolved Chromium (Cr)	2006/05/16		112	%	75 - 125
			Dissolved Cobalt (Co)	2006/05/16		111	%	75 - 125
			Dissolved Copper (Cu)	2006/05/16		115	%	75 - 125
			Dissolved Lead (Pb)	2006/05/16		100	%	75 - 125
			Dissolved Selenium (Se)	2006/05/16		108	%	75 - 125
			Dissolved Thallium (Tl)	2006/05/16		96	%	75 - 125
			Dissolved Zinc (Zn)	2006/05/16		115	%	75 - 125
		BLANK	Dissolved Aluminum (Al)	2006/05/16	<0.2		ug/L	
			Dissolved Antimony (Sb)	2006/05/16	<0.05		ug/L	
			Dissolved Arsenic (As)	2006/05/16	<0.1		ug/L	
			Dissolved Barium (Ba)	2006/05/16	<0.02		ug/L	
			Dissolved Beryllium (Be)	2006/05/16	<0.05		ug/L	
			Dissolved Bismuth (Bi)	2006/05/16	<0.05		ug/L	
			Dissolved Cadmium (Cd)	2006/05/16	<0.01		ug/L	
			Dissolved Chromium (Cr)	2006/05/16	<0.2		ug/L	
			Dissolved Cobalt (Co)	2006/05/16	<0.02		ug/L	
			Dissolved Copper (Cu)	2006/05/16	<0.1		ug/L	
			Dissolved Lead (Pb)	2006/05/16	<0.02		ug/L	
			Dissolved Lithium (Li)	2006/05/16	0.2, RDL=0.2		ug/L	
			Dissolved Manganese (Mn)	2006/05/16	<0.02		ug/L	
			Dissolved Molybdenum (Mo)	2006/05/16	<0.02		ug/L	

CEMI
Attention: Rik Vos
Client Project #: 0610
P.O. #: 83
Site Reference:

Quality Assurance Report (Continued)

Maxxam Job Number: VA619315

QA/QC Batch Num Init	QC Type	Parameter	Date Analyzed yyyy/mm/dd	Value	Recovery	Units	QC Limits
1135123 DJ	BLANK	Dissolved Nickel (Ni)	2006/05/16	<0.5		ug/L	
		Dissolved Potassium (K)	2006/05/16	<50		ug/L	
		Dissolved Selenium (Se)	2006/05/16	<0.5		ug/L	
		Dissolved Silver (Ag)	2006/05/16	<0.01		ug/L	
		Dissolved Strontium (Sr)	2006/05/16	<0.01		ug/L	
		Dissolved Thallium (Tl)	2006/05/16	<0.05		ug/L	
		Dissolved Tin (Sn)	2006/05/16	<0.05		ug/L	
		Dissolved Titanium (Ti)	2006/05/16	<0.5		ug/L	
		Dissolved Uranium (U)	2006/05/16	<0.01		ug/L	
		Dissolved Vanadium (V)	2006/05/16	<0.05		ug/L	
		Dissolved Zinc (Zn)	2006/05/16	<0.5		ug/L	
	RPD	Dissolved Aluminum (Al)	2006/05/16	2.8		%	25
		Dissolved Antimony (Sb)	2006/05/16	NC		%	25
		Dissolved Arsenic (As)	2006/05/16	1.4		%	25
		Dissolved Barium (Ba)	2006/05/16	0.7		%	25
		Dissolved Beryllium (Be)	2006/05/16	NC		%	25
		Dissolved Bismuth (Bi)	2006/05/16	NC		%	25
		Dissolved Cadmium (Cd)	2006/05/16	1.5		%	25
		Dissolved Chromium (Cr)	2006/05/16	3.6		%	25
		Dissolved Cobalt (Co)	2006/05/16	2.0		%	25
		Dissolved Copper (Cu)	2006/05/16	4.8		%	25
		Dissolved Lead (Pb)	2006/05/16	1.2		%	25
		Dissolved Lithium (Li)	2006/05/16	NC		%	25
		Dissolved Manganese (Mn)	2006/05/16	3.5		%	25
		Dissolved Molybdenum (Mo)	2006/05/16	17.5		%	25
		Dissolved Nickel (Ni)	2006/05/16	4.1		%	25
		Dissolved Potassium (K)	2006/05/16	NC		%	25
		Dissolved Selenium (Se)	2006/05/16	NC		%	25
		Dissolved Silver (Ag)	2006/05/16	NC		%	25
		Dissolved Strontium (Sr)	2006/05/16	4.5		%	25
		Dissolved Thallium (Tl)	2006/05/16	NC		%	25
		Dissolved Tin (Sn)	2006/05/16	0.2		%	25
		Dissolved Titanium (Ti)	2006/05/16	NC		%	25
		Dissolved Uranium (U)	2006/05/16	NC		%	25
		Dissolved Vanadium (V)	2006/05/16	NC		%	25
		Dissolved Zinc (Zn)	2006/05/16	2.9		%	25

NC = Non-calculable
RPD = Relative Percent Difference

Maxxam Analytics Inc

Calgary: 2021-41st Ave. NE. T2E 6P2. Ph: (403) 291-3077, Fax: (403) 291-9468, Toll free: (800) 386-7247
Edmonton: 9619 - 42 Ave, T6E 5R2. Ph: (780) 465-1212, Fax: (780) 450-4187, Toll free: (877) 465-8889
Burnaby: 8577 Commerce Court, V5A 4N5 Ph: (604) 444-4808, Fax (604) 444-4511, Toll free: (800) 440-4808

08186188

ALYTICAL REQUEST FORM

Page 1 of 1

Invoice To: Require Report? Yes ☒ No ☐

Company Name: CEMI
Contact Name: Rik Vos
Address:
PC:
Phone / Fax#: Ph 604-264-5536 Fax 604-264-5535

Report To: A619315
CEMI
Prab Bhatia
PC:
Ph 604-264-5536 Fax 604-264-5535

PO# / AFE#: 83
Quotation #: A60050
Project # : 0610
Proj. Name:
Location:
Sampler's Initials:

REGULATORY REQUIREMENTS:
- ☐ AT1 - Soil Contamination
- ☐ CCME
- ☐ CCME FWAL
- ☐ Regulatory Limits to appear on Final report
- ☐ PST
- ☐ CDWQG
- ☐ G50

REPORT DISTRIBUTION:
- ☒ Mail
- ☒ PDF
- ☒ Email: prab@cemi.bc.ca
- ☐ Fax
- ☒ Excel
- ☐ Other:

SERVICE REQUESTED:
- ☐ RUSH (Please ensure you contact the lab)
  Date Required:
- ☒ REGULAR Turnaround

METALS: (WATERS)
☐ Total ☐ Extractable ☒ Dissolved

ANALYSIS REQUESTED

	Sample Identification	Matrix	Date/Time Sampled	Sample Type Grab/Comp	Hold > 60 Days	Sample Container #	LLICPMS	LLICPMS WO/Hg	REGICPMS	REGICPMS WO/Hg	REGICPMS WO/Hg - TOT			
1	25392	B28818		GRAB			X							Dissolved Metals - Filtered & HNO_3 added
2	25393	19		GRAB			X							Dissolved Metals - Filtered & HNO_3 added
3	25396	20		GRAB			X							Dissolved Metals - Filtered & HNO_3 added
4	25399	21		GRAB			X							Dissolved Metals - Filtered & HNO_3 added
5				GRAB										
6				GRAB										
7				GRAB										
8				GRAB										
9				GRAB										
10				GRAB										
11				GRAB										
12				GRAB										

** For water samples, please indicate if sample container has been preserved (P) and/or filtered (F).

Relinquished By:
Signature:
Date/Time:

Received
May 11, 2006
1500

Temperature
20, 20, 21

C of C #

COMMENTS/SPECIAL INSTRUCTIONS:

FCD - 0026 Chain of Custody R4 - April 11, 2005

Your P.O. #: 145
Your Project #: 0610
Your C.O.C. #: 08186201

Attention: Rik Vos
CEMI
6927 Antrim Ave.
Burnaby, BC
CANADA V5J 4M5

Report Date: 2006/06/15

CERTIFICATE OF ANALYSIS

MAXXAM JOB #: A624486
Received: 2006/06/12, 13:46

Sample Matrix: Water
Samples Received: 8

Analyses	Quantity	Date Extracted	Date Analyzed	Laboratory Method	Analytical Method
Hardness (calculated as CaCO3)	2	N/A	2006/06/12		
Mercury (Dissolved)	2	2006/06/13	2006/06/13	ING143 Rev.6.2	Based on EPA 245.1
Mercury (Total)	6	2006/06/13	2006/06/13	ING143 Rev.6.2	Based on EPA 245.1
Elements by ICP-AES (dissolved)	2	2006/06/09	2006/06/12	ING101 Rev.4.0	Based on EPA 6010B
Elements by ICPMS (dissolved) (1)	2	2006/06/12	2006/06/12	ING111 Rev. 1.9	Based on EPA 200.8
Elements by ICPMS (total) (1)	6	N/A	2006/06/13	ING111 Rev. 1.9	Based on EPA 200.8
Elements by ICP-AES (total)	6	N/A	2006/06/13	ING101 Rev 4.0	Based on EPA 6010B

(1) SCC/CAEAL

Encryption Key

Please direct all questions regarding this Certificate of Analysis to your Project Manager.

ELAINE COUSINS, CS Manager
Email: elaine.cousins@maxxamanalytics.com
Phone# (604) 444-4808 Ext:276

==

Maxxam has procedures in place to guard against improper use of the electronic signature and have the required "signatories", as per section 5.10.2 of ISO/IEC 17025:2005(E), signing the reports. SCC and CAEAL have approved this reporting process and electronic report format.

Total cover pages: 1

Maxxam Job #: A624486
Report Date: 2006/06/15

CEMI
Client Project #: 0610
Site Reference:
Your P.O. #: 145
Sampler Initials:

RESULTS OF CHEMICAL ANALYSES OF WATER

Maxxam ID		B61028	B61031		
Sampling Date					
COC Number		08186201	08186201		
	Units	**25434**	**25438**	**RDL**	**QC Batch**
Misc. Inorganics					
Dissolved Hardness (CaCO3)	mg/L	2400	2300	0.5	1161944

RDL = Reportable Detection Limit

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B61026	B61027	B61028	B61029		
Sampling Date							
COC Number		08186201	08186201	08186201	08186201		
	Units	**25400**	**25401**	**25434**	**25435**	**RDL**	**QC Batch**
Dissolved Metals by ICP							
Dissolved Barium (Ba)	mg/L			0.009		0.001	1160347
Dissolved Beryllium (Be)	mg/L			<0.0002		0.0002	1160347
Dissolved Bismuth (Bi)	mg/L			<0.05		0.05	1160347
Dissolved Boron (B)	mg/L			0.259		0.008	1160347
Dissolved Calcium (Ca)	mg/L			341		0.05	1160347
Dissolved Iron (Fe)	mg/L			<0.005		0.005	1160347
Dissolved Magnesium (Mg)	mg/L			372		0.05	1160347
Dissolved Manganese (Mn)	mg/L			0.006		0.001	1160347
Dissolved Molybdenum (Mo)	mg/L			<0.005		0.005	1160347
Dissolved Nickel (Ni)	mg/L			<0.008		0.008	1160347
Dissolved Phosphorus (P)	mg/L			<0.1		0.1	1160347
Dissolved Potassium (K)	mg/L			8		1	1160347
Dissolved Silicon (Si)	mg/L			3.84		0.05	1160347
Dissolved Sodium (Na)	mg/L			52.4		0.05	1160347
Dissolved Strontium (Sr)	mg/L			0.718		0.001	1160347
Dissolved Sulphur (S)	mg/L			732		0.1	1160347
Dissolved Tin (Sn)	mg/L			<0.02		0.02	1160347
Dissolved Titanium (Ti)	mg/L			<0.003		0.003	1160347
Dissolved Vanadium (V)	mg/L			<0.005		0.005	1160347
Dissolved Zinc (Zn)	mg/L			<0.005		0.005	1160347
Dissolved Zirconium (Zr)	mg/L			<0.005		0.005	1160347
Dissolved Metals by ICPMS							
Dissolved Aluminum (Al)	ug/L			6		1	1162126
Dissolved Antimony (Sb)	ug/L			<1		1	1162126
Dissolved Arsenic (As)	ug/L			<1		1	1162126
Dissolved Cadmium (Cd)	ug/L			<0.1		0.1	1162126
Dissolved Chromium (Cr)	ug/L			<1		1	1162126
Dissolved Cobalt (Co)	ug/L			0.5		0.5	1162126
Dissolved Copper (Cu)	ug/L			12.0		0.2	1162126
Dissolved Lead (Pb)	ug/L			<0.5		0.5	1162126
Dissolved Lithium (Li)	ug/L			40		2	1162126
Dissolved Selenium (Se)	ug/L			<1		1	1162126

RDL = Reportable Detection Limit

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B61026	B61027	B61028	B61029		
Sampling Date							
COC Number		08186201	08186201	08186201	08186201		
	Units	**25400**	**25401**	**25434**	**25435**	**RDL**	**QC Batch**
Dissolved Silver (Ag)	ug/L			<0.1		0.1	1162126
Dissolved Thallium (Tl)	ug/L			<0.1		0.1	1162126
Dissolved Uranium (U)	ug/L			0.7		0.1	1162126
Mercury by CVAA							
Dissolved Mercury (Hg)	ug/L			<0.05		0.05	1162561
Total Mercury (Hg)	ug/L	<0.05	<0.05		<0.05	0.05	1162627
Total Metals by ICP							
Total Barium (Ba)	mg/L	0.007	0.008		0.009	0.001	1163103
Total Beryllium (Be)	mg/L	<0.0002	<0.0002		<0.0002	0.0002	1163103
Total Bismuth (Bi)	mg/L	<0.05	<0.05		<0.05	0.05	1163103
Total Boron (B)	mg/L	0.308	0.370		0.285	0.008	1163103
Total Calcium (Ca)	mg/L	251	290		326	0.05	1163103
Total Iron (Fe)	mg/L	0.015	0.010		0.007	0.005	1163103
Total Magnesium (Mg)	mg/L	293	352		341	0.05	1163103
Total Manganese (Mn)	mg/L	0.183	0.097		0.422	0.001	1163103
Total Molybdenum (Mo)	mg/L	<0.005	<0.005		<0.005	0.005	1163103
Total Nickel (Ni)	mg/L	0.175	0.098		0.372	0.008	1163103
Total Phosphorus (P)	mg/L	<0.1	<0.1		<0.1	0.1	1163103
Total Potassium (K)	mg/L	6	7		7	1	1163103
Total Silicon (Si)	mg/L	6.12	7.06		5.39	0.05	1163103
Total Sodium (Na)	mg/L	43.4	52.1		52.1	0.05	1163103
Total Strontium (Sr)	mg/L	0.600	0.696		0.710	0.001	1163103
Total Sulphur (S)	mg/L	724	701		720	0.1	1163103
Total Tin (Sn)	mg/L	<0.02	<0.02		<0.02	0.02	1163103
Total Titanium (Ti)	mg/L	<0.003	<0.003		<0.003	0.003	1163103
Total Vanadium (V)	mg/L	<0.005	<0.005		<0.005	0.005	1163103
Total Zinc (Zn)	mg/L	0.065	0.030		0.142	0.005	1163103
Total Zirconium (Zr)	mg/L	<0.005	<0.005		<0.005	0.005	1163103
Total Metals by ICPMS							
Total Aluminum (Al)	ug/L	48	23		36	1	1163412
Total Antimony (Sb)	ug/L	<1	<1		<1	1	1163412
Total Arsenic (As)	ug/L	<1	<1		<1	1	1163412
Total Cadmium (Cd)	ug/L	0.3	0.1		0.5	0.1	1163412

RDL = Reportable Detection Limit

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B61026	B61027	B61028	B61029		
Sampling Date							
COC Number		08186201	08186201	08186201	08186201		
	Units	**25400**	**25401**	**25434**	**25435**	**RDL**	**QC Batch**
Total Chromium (Cr)	ug/L	<1	<1		<1	1	1163412
Total Cobalt (Co)	ug/L	11.7	5.2		20.5	0.5	1163412
Total Copper (Cu)	ug/L	68.4	36.0		96.2	0.2	1163412
Total Lead (Pb)	ug/L	<0.5	<0.5		<0.5	0.5	1163412
Total Lithium (Li)	ug/L	45	44		43	2	1163412
Total Selenium (Se)	ug/L	6	7		<1	1	1163412
Total Silver (Ag)	ug/L	<0.1	0.1		<0.1	0.1	1163412
Total Thallium (Tl)	ug/L	<0.1	<0.1		<0.1	0.1	1163412
Total Uranium (U)	ug/L	1.0	0.7		1.7	0.1	1163412

RDL = Reportable Detection Limit

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B61030	B61031	B61032	B61033		
Sampling Date							
COC Number		08186201	08186201	08186201	08186201		
	Units	**25436**	**25438**	**25439**	**25440**	**RDL**	**QC Batch**
Dissolved Metals by ICP							
Dissolved Barium (Ba)	mg/L		0.008			0.001	1160347
Dissolved Beryllium (Be)	mg/L		<0.0002			0.0002	1160347
Dissolved Bismuth (Bi)	mg/L		<0.05			0.05	1160347
Dissolved Boron (B)	mg/L		0.223			0.008	1160347
Dissolved Calcium (Ca)	mg/L		320			0.05	1160347
Dissolved Iron (Fe)	mg/L		<0.005			0.005	1160347
Dissolved Magnesium (Mg)	mg/L		356			0.05	1160347
Dissolved Manganese (Mn)	mg/L		<0.001			0.001	1160347
Dissolved Molybdenum (Mo)	mg/L		<0.005			0.005	1160347
Dissolved Nickel (Ni)	mg/L		<0.008			0.008	1160347
Dissolved Phosphorus (P)	mg/L		<0.1			0.1	1160347
Dissolved Potassium (K)	mg/L		7			1	1160347
Dissolved Silicon (Si)	mg/L		2.99			0.05	1160347
Dissolved Sodium (Na)	mg/L		49.9			0.05	1160347
Dissolved Strontium (Sr)	mg/L		0.675			0.001	1160347
Dissolved Sulphur (S)	mg/L		702			0.1	1160347
Dissolved Tin (Sn)	mg/L		<0.02			0.02	1160347
Dissolved Titanium (Ti)	mg/L		<0.003			0.003	1160347
Dissolved Vanadium (V)	mg/L		<0.005			0.005	1160347
Dissolved Zinc (Zn)	mg/L		<0.005			0.005	1160347
Dissolved Zirconium (Zr)	mg/L		<0.005			0.005	1160347
Dissolved Metals by ICPMS							
Dissolved Aluminum (Al)	ug/L		3			1	1162126
Dissolved Antimony (Sb)	ug/L		<1			1	1162126
Dissolved Arsenic (As)	ug/L		<1			1	1162126
Dissolved Cadmium (Cd)	ug/L		<0.1			0.1	1162126
Dissolved Chromium (Cr)	ug/L		<1			1	1162126
Dissolved Cobalt (Co)	ug/L		<0.5			0.5	1162126
Dissolved Copper (Cu)	ug/L		10.0			0.2	1162126
Dissolved Lead (Pb)	ug/L		<0.5			0.5	1162126
Dissolved Lithium (Li)	ug/L		41			2	1162126
Dissolved Selenium (Se)	ug/L		<1			1	1162126

RDL = Reportable Detection Limit

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B61030	B61031	B61032	B61033		
Sampling Date							
COC Number		08186201	08186201	08186201	08186201		
	Units	**25436**	**25438**	**25439**	**25440**	**RDL**	**QC Batch**
Dissolved Silver (Ag)	ug/L		<0.1			0.1	1162126
Dissolved Thallium (Tl)	ug/L		<0.1			0.1	1162126
Dissolved Uranium (U)	ug/L		0.8			0.1	1162126
Mercury by CVAA							
Dissolved Mercury (Hg)	ug/L		<0.05			0.05	1162561
Total Mercury (Hg)	ug/L	<0.05		<0.05	<0.05	0.05	1162627
Total Metals by ICP							
Total Barium (Ba)	mg/L	0.008		0.009	0.009	0.001	1163103
Total Beryllium (Be)	mg/L	<0.0002		<0.0002	<0.0002	0.0002	1163103
Total Bismuth (Bi)	mg/L	<0.05		<0.05	<0.05	0.05	1163103
Total Boron (B)	mg/L	0.254		0.289	0.275	0.008	1163103
Total Calcium (Ca)	mg/L	308		324	327	0.05	1163103
Total Iron (Fe)	mg/L	<0.005		0.010	<0.005	0.005	1163103
Total Magnesium (Mg)	mg/L	328		337	350	0.05	1163103
Total Manganese (Mn)	mg/L	0.235		0.697	0.468	0.001	1163103
Total Molybdenum (Mo)	mg/L	<0.005		<0.005	<0.005	0.005	1163103
Total Nickel (Ni)	mg/L	0.215		0.614	0.418	0.008	1163103
Total Phosphorus (P)	mg/L	<0.1		<0.1	<0.1	0.1	1163103
Total Potassium (K)	mg/L	7		7	7	1	1163103
Total Silicon (Si)	mg/L	4.51		5.82	5.03	0.05	1163103
Total Sodium (Na)	mg/L	50.4		51.0	53.5	0.05	1163103
Total Strontium (Sr)	mg/L	0.679		0.696	0.719	0.001	1163103
Total Sulphur (S)	mg/L	719		720	731	0.1	1163103
Total Tin (Sn)	mg/L	<0.02		<0.02	<0.02	0.02	1163103
Total Titanium (Ti)	mg/L	<0.003		<0.003	<0.003	0.003	1163103
Total Vanadium (V)	mg/L	<0.005		<0.005	<0.005	0.005	1163103
Total Zinc (Zn)	mg/L	0.077		0.231	0.155	0.005	1163103
Total Zirconium (Zr)	mg/L	<0.005		<0.005	<0.005	0.005	1163103
Total Metals by ICPMS							
Total Aluminum (Al)	ug/L	20		41	24	1	1163412
Total Antimony (Sb)	ug/L	<1		<1	<1	1	1163412
Total Arsenic (As)	ug/L	<1		<1	<1	1	1163412
Total Cadmium (Cd)	ug/L	0.3		0.8	0.5	0.1	1163412

RDL = Reportable Detection Limit

Maxxam Job #: A624486
Report Date: 2006/06/15

CEMI
Client Project #: 0610
Site Reference:
Your P.O. #: 145
Sampler Initials:

ELEMENTS BY ATOMIC SPECTROSCOPY (WATER)

Maxxam ID		B61030	B61031	B61032	B61033		
Sampling Date							
COC Number		08186201	08186201	08186201	08186201		
	Units	**25436**	**25438**	**25439**	**25440**	**RDL**	**QC Batch**
Total Chromium (Cr)	ug/L	<1		2	2	1	1163412
Total Cobalt (Co)	ug/L	12.0		33.2	22.3	0.5	1163412
Total Copper (Cu)	ug/L	59.4		137	95.2	0.2	1163412
Total Lead (Pb)	ug/L	<0.5		<0.5	<0.5	0.5	1163412
Total Lithium (Li)	ug/L	44		41	41	2	1163412
Total Selenium (Se)	ug/L	2		2	1	1	1163412
Total Silver (Ag)	ug/L	<0.1		<0.1	<0.1	0.1	1163412
Total Thallium (Tl)	ug/L	<0.1		<0.1	<0.1	0.1	1163412
Total Uranium (U)	ug/L	1.3		2.4	1.8	0.1	1163412

RDL = Reportable Detection Limit

General Comments

Results relate only to the items tested.

Quality Assurance Report

Maxxam Job Number: VA624486

QA/QC Batch Num Init	QC Type	Parameter	Date Analyzed yyyy/mm/dd	Value	Recovery	Units	QC Limits
1160347 KL1	MATRIX SPIKE	Dissolved Manganese (Mn)	2006/06/12		97	%	80 - 120
		Dissolved Zinc (Zn)	2006/06/12		101	%	80 - 120
	SPIKE	Dissolved Manganese (Mn)	2006/06/12		104	%	80 - 120
		Dissolved Zinc (Zn)	2006/06/12		104	%	80 - 120
	BLANK	Dissolved Barium (Ba)	2006/06/12	<0.001		mg/L	
		Dissolved Beryllium (Be)	2006/06/12	<0.0002		mg/L	
		Dissolved Bismuth (Bi)	2006/06/12	<0.05		mg/L	
		Dissolved Boron (B)	2006/06/12	<0.008		mg/L	
		Dissolved Calcium (Ca)	2006/06/12	<0.05		mg/L	
		Dissolved Iron (Fe)	2006/06/12	<0.005		mg/L	
		Dissolved Magnesium (Mg)	2006/06/12	<0.05		mg/L	
		Dissolved Manganese (Mn)	2006/06/12	<0.001		mg/L	
		Dissolved Molybdenum (Mo)	2006/06/12	<0.005		mg/L	
		Dissolved Nickel (Ni)	2006/06/12	<0.008		mg/L	
		Dissolved Phosphorus (P)	2006/06/12	<0.1		mg/L	
		Dissolved Potassium (K)	2006/06/12	<1		mg/L	
		Dissolved Silicon (Si)	2006/06/12	<0.05		mg/L	
		Dissolved Sodium (Na)	2006/06/12	<0.05		mg/L	
		Dissolved Strontium (Sr)	2006/06/12	<0.001		mg/L	
		Dissolved Sulphur (S)	2006/06/12	<0.1		mg/L	
		Dissolved Tin (Sn)	2006/06/12	<0.02		mg/L	
		Dissolved Titanium (Ti)	2006/06/12	<0.003		mg/L	
		Dissolved Vanadium (V)	2006/06/12	<0.005		mg/L	
		Dissolved Zinc (Zn)	2006/06/12	<0.005		mg/L	
		Dissolved Zirconium (Zr)	2006/06/12	<0.005		mg/L	
	RPD	Dissolved Calcium (Ca)	2006/06/12	0.6		%	25
		Dissolved Magnesium (Mg)	2006/06/12	0.4		%	25
1162126 DJ	MATRIX SPIKE	Dissolved Arsenic (As)	2006/06/12		105	%	75 - 125
		Dissolved Cadmium (Cd)	2006/06/12		106	%	75 - 125
		Dissolved Chromium (Cr)	2006/06/12		108	%	75 - 125
		Dissolved Cobalt (Co)	2006/06/12		103	%	75 - 125
		Dissolved Copper (Cu)	2006/06/12		106	%	75 - 125
		Dissolved Lead (Pb)	2006/06/12		97	%	75 - 125
		Dissolved Selenium (Se)	2006/06/12		115	%	75 - 125
		Dissolved Thallium (Tl)	2006/06/12		94	%	75 - 125
	SPIKE	Dissolved Arsenic (As)	2006/06/12		105	%	75 - 125
		Dissolved Cadmium (Cd)	2006/06/12		101	%	75 - 125
		Dissolved Chromium (Cr)	2006/06/12		109	%	75 - 125
		Dissolved Cobalt (Co)	2006/06/12		105	%	75 - 125
		Dissolved Copper (Cu)	2006/06/12		110	%	75 - 125
		Dissolved Lead (Pb)	2006/06/12		99	%	75 - 125
		Dissolved Selenium (Se)	2006/06/12		104	%	75 - 125
		Dissolved Thallium (Tl)	2006/06/12		95	%	75 - 125
	BLANK	Dissolved Aluminum (Al)	2006/06/12	<1		ug/L	
		Dissolved Antimony (Sb)	2006/06/12	<1		ug/L	
		Dissolved Arsenic (As)	2006/06/12	<1		ug/L	
		Dissolved Cadmium (Cd)	2006/06/12	<0.1		ug/L	
		Dissolved Chromium (Cr)	2006/06/12	<1		ug/L	
		Dissolved Cobalt (Co)	2006/06/12	<0.5		ug/L	
		Dissolved Copper (Cu)	2006/06/12	<0.2		ug/L	
		Dissolved Lead (Pb)	2006/06/12	<0.5		ug/L	
		Dissolved Lithium (Li)	2006/06/12	<2		ug/L	
		Dissolved Selenium (Se)	2006/06/12	<1		ug/L	
		Dissolved Silver (Ag)	2006/06/12	<0.1		ug/L	
		Dissolved Thallium (Tl)	2006/06/12	<0.1		ug/L	
		Dissolved Uranium (U)	2006/06/12	<0.1		ug/L	

Quality Assurance Report (Continued)

Maxxam Job Number: VA624486

QA/QC Batch Num Init	QC Type	Parameter	Date Analyzed yyyy/mm/dd	Value	Recovery	Units	QC Limits
1162126 DJ	RPD	Dissolved Antimony (Sb)	2006/06/12	NC		%	25
		Dissolved Arsenic (As)	2006/06/12	NC		%	25
		Dissolved Cadmium (Cd)	2006/06/12	NC		%	25
		Dissolved Cobalt (Co)	2006/06/12	NC		%	25
		Dissolved Copper (Cu)	2006/06/12	NC		%	25
		Dissolved Lead (Pb)	2006/06/12	NC		%	25
		Dissolved Selenium (Se)	2006/06/12	NC		%	25
		Dissolved Silver (Ag)	2006/06/12	NC		%	25
		Dissolved Thallium (Tl)	2006/06/12	NC		%	25
		Dissolved Uranium (U)	2006/06/12	8.9		%	25
1162561 GS2	MATRIX SPIKE	Dissolved Mercury (Hg)	2006/06/13		112	%	70 - 130
	QC STANDARD	Dissolved Mercury (Hg)	2006/06/13		100	%	80 - 120
	SPIKE	Dissolved Mercury (Hg)	2006/06/13		109	%	80 - 120
	BLANK	Dissolved Mercury (Hg)	2006/06/13	<0.05		ug/L	
	RPD	Dissolved Mercury (Hg)	2006/06/13	NC		%	25
1162627 GS2	MATRIX SPIKE	Total Mercury (Hg)	2006/06/13		114	%	70 - 130
	QC STANDARD	Total Mercury (Hg)	2006/06/13		98	%	N/A
	SPIKE	Total Mercury (Hg)	2006/06/13		105	%	80 - 120
	BLANK	Total Mercury (Hg)	2006/06/13	<0.05		ug/L	
	RPD	Total Mercury (Hg)	2006/06/13	NC		%	25
1163103 KL1	MATRIX SPIKE	Total Manganese (Mn)	2006/06/13		108	%	80 - 120
		Total Zinc (Zn)	2006/06/13		110	%	80 - 120
	SPIKE	Total Manganese (Mn)	2006/06/13		102	%	80 - 120
		Total Zinc (Zn)	2006/06/13		101	%	80 - 120
	BLANK	Total Barium (Ba)	2006/06/13	<0.001		mg/L	
		Total Beryllium (Be)	2006/06/13	<0.0002		mg/L	
		Total Bismuth (Bi)	2006/06/13	<0.05		mg/L	
		Total Boron (B)	2006/06/13	<0.008		mg/L	
		Total Calcium (Ca)	2006/06/13	<0.05		mg/L	
		Total Iron (Fe)	2006/06/13	<0.005		mg/L	
		Total Magnesium (Mg)	2006/06/13	<0.05		mg/L	
		Total Manganese (Mn)	2006/06/13	<0.001		mg/L	
		Total Molybdenum (Mo)	2006/06/13	<0.005		mg/L	
		Total Nickel (Ni)	2006/06/13	<0.008		mg/L	
		Total Phosphorus (P)	2006/06/13	<0.1		mg/L	
		Total Potassium (K)	2006/06/13	<1		mg/L	
		Total Silicon (Si)	2006/06/13	<0.05		mg/L	
		Total Sodium (Na)	2006/06/13	<0.05		mg/L	
		Total Strontium (Sr)	2006/06/13	<0.001		mg/L	
		Total Sulphur (S)	2006/06/13	<0.1		mg/L	
		Total Tin (Sn)	2006/06/13	<0.02		mg/L	
		Total Titanium (Ti)	2006/06/13	<0.003		mg/L	
		Total Vanadium (V)	2006/06/13	<0.005		mg/L	
		Total Zinc (Zn)	2006/06/13	<0.005		mg/L	
		Total Zirconium (Zr)	2006/06/13	<0.005		mg/L	
	RPD	Total Barium (Ba)	2006/06/13	9.5		%	25
		Total Beryllium (Be)	2006/06/13	NC		%	25
		Total Bismuth (Bi)	2006/06/13	NC		%	25
		Total Boron (B)	2006/06/13	14.5		%	25
		Total Calcium (Ca)	2006/06/13	9.6		%	25
		Total Iron (Fe)	2006/06/13	9.3		%	25
		Total Magnesium (Mg)	2006/06/13	9.6		%	25
		Total Manganese (Mn)	2006/06/13	9.6		%	25
		Total Molybdenum (Mo)	2006/06/13	NC		%	25
		Total Nickel (Ni)	2006/06/13	NC		%	25
		Total Phosphorus (P)	2006/06/13	NC		%	25

Quality Assurance Report (Continued)

Maxxam Job Number: VA624486

QA/QC Batch Num Init	QC Type	Parameter	Date Analyzed yyyy/mm/dd	Value	Recovery	Units	QC Limits
1163103 KL1	RPD	Total Potassium (K)	2006/06/13	NC		%	25
		Total Silicon (Si)	2006/06/13	9.2		%	25
		Total Sodium (Na)	2006/06/13	9.6		%	25
		Total Strontium (Sr)	2006/06/13	9.2		%	25
		Total Sulphur (S)	2006/06/13	8.6		%	25
		Total Tin (Sn)	2006/06/13	NC		%	25
		Total Titanium (Ti)	2006/06/13	NC		%	25
		Total Vanadium (V)	2006/06/13	NC		%	25
		Total Zinc (Zn)	2006/06/13	NC		%	25
		Total Zirconium (Zr)	2006/06/13	NC		%	25
1163412 DJ	MATRIX SPIKE	Total Arsenic (As)	2006/06/13		103	%	75 - 125
		Total Cadmium (Cd)	2006/06/13		100	%	75 - 125
		Total Chromium (Cr)	2006/06/13		111	%	75 - 125
		Total Cobalt (Co)	2006/06/13		108	%	75 - 125
		Total Copper (Cu)	2006/06/13		105	%	75 - 125
		Total Lead (Pb)	2006/06/13		111	%	75 - 125
		Total Selenium (Se)	2006/06/13		97	%	75 - 125
		Total Thallium (Tl)	2006/06/13		113	%	75 - 125
	SPIKE	Total Arsenic (As)	2006/06/13		98	%	75 - 125
		Total Cadmium (Cd)	2006/06/13		93	%	75 - 125
		Total Chromium (Cr)	2006/06/13		109	%	75 - 125
		Total Cobalt (Co)	2006/06/13		105	%	75 - 125
		Total Copper (Cu)	2006/06/13		105	%	75 - 125
		Total Lead (Pb)	2006/06/13		112	%	75 - 125
		Total Selenium (Se)	2006/06/13		94	%	75 - 125
		Total Thallium (Tl)	2006/06/13		108	%	75 - 125
	BLANK	Total Aluminum (Al)	2006/06/13	<1		ug/L	
		Total Antimony (Sb)	2006/06/13	<1		ug/L	
		Total Arsenic (As)	2006/06/13	<1		ug/L	
		Total Cadmium (Cd)	2006/06/13	<0.1		ug/L	
		Total Chromium (Cr)	2006/06/13	<1		ug/L	
		Total Cobalt (Co)	2006/06/13	<0.5		ug/L	
		Total Copper (Cu)	2006/06/13	<0.2		ug/L	
		Total Lead (Pb)	2006/06/13	<0.5		ug/L	
		Total Lithium (Li)	2006/06/13	<2		ug/L	
		Total Selenium (Se)	2006/06/13	<1		ug/L	
		Total Silver (Ag)	2006/06/13	<0.1		ug/L	
		Total Thallium (Tl)	2006/06/13	<0.1		ug/L	
		Total Uranium (U)	2006/06/13	<0.1		ug/L	
	RPD	Total Aluminum (Al)	2006/06/13	5.7		%	25
		Total Antimony (Sb)	2006/06/13	NC		%	25
		Total Arsenic (As)	2006/06/13	NC		%	25
		Total Chromium (Cr)	2006/06/13	NC		%	25
		Total Cobalt (Co)	2006/06/13	NC		%	25
		Total Copper (Cu)	2006/06/13	NC		%	25
		Total Lead (Pb)	2006/06/13	NC		%	25
		Total Lithium (Li)	2006/06/13	5.5		%	25
		Total Selenium (Se)	2006/06/13	NC		%	25
		Total Silver (Ag)	2006/06/13	NC		%	25
		Total Thallium (Tl)	2006/06/13	NC		%	25
		Total Uranium (U)	2006/06/13	NC		%	25

N/A = Not Applicable
NC = Non-calculable
RPD = Relative Percent Difference

APPENDIX C:
CAS Analysis Report

1317 South 13th Avenue P.O. Box 479 Kelso, Washington 98626 (360) 577-7222 (360) 636-1068 fax

Columbia Analytical Services INC.
An Employee - Owned Company

July 12, 2006 Service Request No: K0604871

Rik Vos
Canadian Environmental and Metallurgical Inc.
6927 Antrim Avenue
Burnaby, BC V5J 4M5

RE: Low level Hg

Dear Rik:

Enclosed are the results of the sample(s) submitted to our laboratory on June 14, 2006. For your reference, these analyses have been assigned our service request number K0604871.

All analyses were performed according to our laboratory's quality assurance program. The test results meet requirements of the NELAC standards except as noted in the case narrative report. All results are intended to be considered in their entirety, and Columbia Analytical Services, Inc. (CAS) is not responsible for use of less than the complete report. Results apply only to the items submitted to the laboratory for analysis and individual items (samples) analyzed, as listed in the report.

Please call if you have any questions. My extension is 3358.

Respectfully submitted,

Columbia Analytical Services, Inc.

Lynda Huckestein
Lynda Huckestein
Client Services Manager

LH/lmb

Page 1 of 10

Acronyms

ASTM	American Society for Testing and Materials
A2LA	American Association for Laboratory Accreditation
CARB	California Air Resources Board
CAS Number	Chemical Abstract Service registry Number
CFC	Chlorofluorocarbon
CFU	Colony-Forming Unit
DEC	Department of Environmental Conservation
DEQ	Department of Environmental Quality
DHS	Department of Health Services
DOE	Department of Ecology
DOH	Department of Health
EPA	U. S. Environmental Protection Agency
ELAP	Environmental Laboratory Accreditation Program
GC	Gas Chromatography
GC/MS	Gas Chromatography/Mass Spectrometry
LUFT	Leaking Underground Fuel Tank
M	Modified
MCL	Maximum Contaminant Level is the highest permissible concentration of a substance allowed in drinking water as established by the USEPA.
MDL	Method Detection Limit
MPN	Most Probable Number
MRL	Method Reporting Limit
NA	Not Applicable
NC	Not Calculated
NCASI	National Council of the Paper Industry for Air and Stream Improvement
ND	Not Detected
NIOSH	National Institute for Occupational Safety and Health
PQL	Practical Quantitation Limit
RCRA	Resource Conservation and Recovery Act
SIM	Selected Ion Monitoring
TPH	Total Petroleum Hydrocarbons
tr	Trace level is the concentration of an analyte that is less than the PQL but greater than or equal to the MDL.

Inorganic Data Qualifiers

*	The result is an outlier. See case narrative.
#	The control limit criteria is not applicable. See case narrative.
B	The analyte was found in the associated method blank at a level that is significant relative to the sample result.
E	The result is an estimate amount because the value exceeded the instrument calibration range.
J	The result is an estimated concentration that is less than the MRL but greater than or equal to the MDL.
U	The compound was analyzed for, but was not detected ("Non-detect") at or above the MRL/MDL.
i	The MRL/MDL has been elevated due to a matrix interference.
X	See case narrative.

Metals Data Qualifiers

#	The control limit criteria is not applicable. See case narrative.
B	The result is an estimated concentration that is less than the MRL but greater than or equal to the MDL.
E	The percent difference for the serial dilution was greater than 10%, indicating a possible matrix interference in the sample.
M	The duplicate injection precision was not met.
N	The Matrix Spike sample recovery is not within control limits. See case narrative.
S	The reported value was determined by the Method of Standard Additions (MSA).
U	The compound was analyzed for, but was not detected ("Non-detect") at or above the MRL/MDL.
W	The post-digestion spike for furnace AA analysis is out of control limits, while sample absorbance is less than 50% of spike absorbance.
i	The MRL/MDL has been elevated due to a matrix interference.
X	See case narrative.
*	The duplicate analysis not within control limits. See case narrative.
+	The correlation coefficient for the MSA is less than 0.995.

Organic Data Qualifiers

*	The result is an outlier. See case narrative.
#	The control limit criteria is not applicable. See case narrative.
A	A tentatively identified compound, a suspected aldol-condensation product.
B	The analyte was found in the associated method blank at a level that is significant relative to the sample result.
C	The analyte was qualitatively confirmed using GC/MS techniques, pattern recognition, or by comparing to historical data.
D	The reported result is from a dilution.
E	The result is an estimate amount because the value exceeded the instrument calibration range.
J	The result is an estimated concentration that is less than the MRL but greater than or equal to the MDL.
N	The result is presumptive. The analyte was tentatively identified, but a confirmation analysis was not performed.
P	The GC or HPLC confirmation criteria was exceeded. The relative percent difference is greater than 40% between the two analytical results (25% for CLP Pesticides).
U	The compound was analyzed for, but was not detected ("Non-detect") at or above the MRL/MDL.
i	The MRL/MDL has been elevated due to a chromatographic interference.
X	See case narrative.

Additional Petroleum Hydrocarbon Specific Qualifiers

F	The chromatographic fingerprint of the sample matches the elution pattern of the calibration standard.
L	The chromatographic fingerprint of the sample resembles a petroleum product, but the elution pattern indicates the presence of a greater amount of lighter molecular weight constituents than the calibration standard.
H	The chromatographic fingerprint of the sample resembles a petroleum product, but the elution pattern indicates the presence of a greater amount of heavier molecular weight constituents than the calibration standard.
O	The chromatographic fingerprint of the sample resembles an oil, but does not match the calibration standard.
Y	The chromatographic fingerprint of the sample resembles a petroleum product eluting in approximately the correct carbon range, but the elution pattern does not match the calibration standard.
Z	The chromatographic fingerprint does not resemble a petroleum product.

COLUMBIA ANALYTICAL SERVICES, INC.

Analytical Report

Client:	Canadian Environmental and Metallurgical Inc.	**Service Request:**	K0604871
Project:	Low level Hg	**Date Collected:**	NA
Sample Matrix:	Water	**Date Received:**	06/14/06

Mercury, Dissolved

Prep Method:	METHOD	Units:	ng/L
Analysis Method:	1631E	Basis:	NA
Test Notes:			

Sample Name	Lab Code	MRL	Dilution Factor	Date Extracted	Date Analyzed	Result	Result Notes
25392	K0604871-001	1.0	1	06/14/06	07/11/06	3.1	
25393	K0604871-002	1.0	1	06/14/06	07/11/06	7.9	
25396	K0604871-003	1.0	1	06/14/06	07/11/06	4.6	
25399	K0604871-004	1.0	1	06/14/06	07/11/06	6.0	
25403	K0604871-005	1.0	1	06/14/06	07/11/06	4.1	
25406	K0604871-006	1.0	1	06/14/06	07/11/06	5.4	
25424	K0604871-007	1.0	1	06/14/06	07/11/06	3.4	
25434	K0604871-008	1.0	1	06/14/06	07/11/06	6.1	
25438	K0604871-009	1.0	1	06/14/06	07/11/06	3.3	
Method Blank 1	K0604871-MB1	1.0	1	06/14/06	07/11/06	ND	
Method Blank 2	K0604871-MB2	1.0	1	06/14/06	07/11/06	ND	
Method Blank 3	K0604871-MB3	1.0	1	06/14/06	07/11/06	ND	

COLUMBIA ANALYTICAL SERVICES, INC.

QA/QC Report

Client:	Canadian Environmental and Metallurgical Inc.	**Service Request:**	K0604871
Project:	Low level Hg	**Date Collected:**	NA
Sample Matrix:	Water	**Date Received:**	06/14/06
		Date Extracted:	06/14/06
		Date Analyzed:	07/11/06

Matrix Spike/Duplicate Matrix Spike Summary
Dissolved Metals

Sample Name:	25392		Units:	ng/L
Lab Code:	K0604871-001MS,	K0604871-001DMS	Basis:	NA
Test Notes:				

									Percent Recovery				
Analyte	**Prep Method**	**Analysis Method**	**MRL**	**Spike Level MS**	**Spike Level DMS**	**Sample Result**	**Spike Result MS**	**Spike Result DMS**	**MS**	**DMS**	**CAS Acceptance Limits**	**Relative Percent Difference**	**Result Notes**
Mercury	METHOD	1631E	1.0	50	50	3.1	52.9	53.8	100	101.4	71-125	2	

COLUMBIA ANALYTICAL SERVICES, INC.

QA/QC Report

Client:	Canadian Environmental and Metallurgical Inc.	**Service Request:**	K0604871
Project:	Low level Hg	**Date Collected:**	NA
LCS Matrix:	Water	**Date Received:**	NA
		Date Extracted:	06/14/06
		Date Analyzed:	07/11/06

Ongoing Precision and Recovery (OPR) Sample Summary
Total Metals

Sample Name: Ongoing Precision and Recovery (Initial)

Units: ng/L
Basis: NA

Test Notes:

Analyte	**Prep Method**	**Analysis Method**	**True Value**	**Result**	**Percent Recovery**	**CAS Percent Recovery Acceptance Limits**	**Result Notes**
Mercury	METHOD	1631E	5.00	5.81	116	77-123	

QA/QC Report

Client:	Canadian Environmental and Metallurgical Inc.	**Service Request:**	K0604871
Project:	Low level Hg	**Date Collected:**	NA
LCS Matrix:	Water	**Date Received:**	NA
		Date Extracted:	06/14/06
		Date Analyzed:	07/11/06

Ongoing Precision and Recovery (OPR) Sample Summary
Total Metals

Sample Name: Ongoing Precision and Recovery (Final)

Units: ng/L
Basis: NA

Test Notes:

Analyte	**Prep Method**	**Analysis Method**	**True Value**	**Result**	**Percent Recovery**	**CAS Percent Recovery Acceptance Limits**	**Result Notes**
Mercury	METHOD	1631E	5.00	5.44	109	77-123	

COLUMBIA ANALYTICAL SERVICES, INC.

QA/QC Report

Client:	Canadian Environmental and Metallurgical Inc.	**Service Request:**	K0604871
Project:	Low level Hg	**Date Collected:**	NA
LCS Matrix:	Water	**Date Received:**	NA
		Date Extracted:	06/14/06
		Date Analyzed:	07/11/06

Quality Control Sample (QCS) Summary
Total Metals

Sample Name:	Quality Control Sample	Units:	ng/L
		Basis:	NA

Test Notes:

Analyte	**Prep Method**	**Analysis Method**	**True Value**	**Result**	**Percent Recovery**	**CAS Percent Recovery Acceptance Limits**	**Result Notes**
Mercury	METHOD	1631E	5.00	5.34	107	77-123	

TO: COLUMBIA ANALYTICAL SERVICES 1317 S. 13th AVE KELSO, WA 98626 ATTN: ABBIE SPIELMAN	Date: June 9, 2006 Purchase Order No. 41074
SHIP TO: **CEMI** **1636 West 75th Ave.** **Vancouver, BC** **V6P 6G2**	**Tel: 604-264-5536** **Fax: 604-264-5535** **email: cemilab@cemi** **www.cemi.bc.ca**

Materials and/or Services requested on this Release Form are subject to the terms and conditions included and described on the Purchase Order referenced above.

ITEM	**QUANTITY**	**DESCRIPTION**
1	9	SAMPLE ID:
		25392, 25393, 25396,
		25399, 25403, 25406,
		25424, 25434, 25438
		*All FOR LOW-LEVEL MERCURY
		ANALYSIS

Requested by: PRAB

Date required by: ____________

Project Code : 0610 Polymet WTP

Quotation # : ____________

LYNDA

Columbia Analytical Services Inc.
Cooler Receipt and Preservation Form

PC 4871

Project/Client CEMI Service Request K06

Cooler received on 6/14/06 and opened on 6/14/06 by

1. Were custody seals on outside of coolers? Y [✓ N]
   If yes, how many and where?
2. Were custody seals intact? Y [✓ N]
3. Were signature and date present on the custody seals? Y [✓ N]
4. Is the shipper's airbill available and filed? If no, record airbill number: 7280753605 [✓ Y] N
5. COC#

COC#				
Temperature of cooler(s) upon receipt: (°C)	10.9	10.2	11.3	12.4
Temperature Blank: (°C)	14.5	9.6	12.9	11.8

Were samples hand delivered on the same day as collection? Y [✓ N]

6. Were custody papers properly filled out (ink, signed, etc.)? [✓ Y] [✓ N] 1.
7. Type of packing material present bags - thawed gelpacks
8. **Did all bottles arrive in good condition (unbroken)?** [✓ Y] N
9. Were all bottle labels complete (i.e analysis, preservation, etc.)? [✓ Y] N
10. Did all bottle labels and tags agree with custody papers? [✓ Y] N
11. **Were the correct types of bottles used for the tests indicated?** [✓ Y] N
12. Were all of the preserved bottles received at the lab with the appropriate pH? [✓ Y] N
13. Were VOA vials checked for absence of air bubbles, and if present, noted below? ~~Y N~~
14. Were the 1631 Mercury bottles checked for absence of air bubbles, and if present, noted below? 2. [✓ Y] N
15. Did the bottles originate from CAS/K or a branch laboratory? ~~Y~~ [✓ N] 3.
16. **Are CWA Microbiology samples received with >1/2 the 24hr. hold time remaining from collection?** ~~Y N~~
17. Was C12/Res negative? ~~Y N~~

Explain any discrepancies: 1. Coc not signed - all sample I.D.'s ok. 2. headspace all

3. bottles are from Clean

RESOLUTION:

Samples that required preservation or received out of temperature:

Sample ID	Reagent	Volume	Lot Number	Bottle Type	Rec'd out of Temperature	Initials

Appendix D

Review of Dunka Wetlands Treatment Performance

Appendix D

Review of Dunka Treatment Wetland Performance

Table of Contents

List of Tables

List of Figures

1.0 LTVSMC Dunka Mine Background

LTVSMC conducted an open pit taconite mining operation at the Dunka Mine north of Babbitt, Minnesota. This operation resulted in the mining of a considerable amount of surface and rock overburden, which was stockpiled on the site. In the 1970s, surface water seeps from these stockpiles presented water quality issues due to elevated levels of copper, zinc, cobalt, nickel, and sulfate. These water quality issues are also of concern for NorthMet.

At the Dunka Mine, constructed wetlands treat several of the seeps prior to discharge in accordance with an existing NPDES permit. The site also has a lime precipitation unit capable of treating 350 gpm of wastewater as a backup treatment option. Operational data for four of the wetland treatment systems has been summarized and is discussed in the context of wetland treatment performance in the following sections. In previous work (Eger et al., 2000[1]), long-term performance of two of the wetlands (SD005 and SD009) was evaluated based on measurement of metals concentrations in wetland sediments/media. This work builds upon the results reported in the Eger study, using data collected from 2000 through 2005. Performance of each of the four constructed wetlands was evaluated by comparing influent and effluent concentrations of target constituents. Additionally, mass balances were performed and the storage capacity of each wetland was computed for various constituents. It should be noted that mass balances were performed assuming equal volumetric inflow and outflow from the wetland. In actuality, the inflow and outflow differ due to precipitation received by the wetland, groundwater inputs, and evapotranspiration in the wetland.

2.0 Treatment Wetland Performance Data

2.1 Dunka Mine Seep 051 (SD005) Treatment Performance

The wetland receiving water from Seep 051 is approximately 1.8 ha in area and consists of sequential wetland cells separated by earthen berms. Some of the berms are “underflow” berms (Eger et al., 2000), which implies that some of the cells are operated as vertical, sub-surface flow (SSF) wetlands. The wetland substrate is *Sphagnum* peat, and the system is vegetated with emergent wetland plants (mostly cattail). Portions of the wetland cells are submerged, while other portions are not.

This wetland has been very effective in removing metals, providing a net sink for nickel, copper, zinc, and cobalt for the duration of the study period and accumulating approximately 89, 4.5, 2.3, and

---

[1] References cited in Appendix D are listed in Section 8 of RS29T.

1.0 lb/ha for each of these metals, respectively (Figure D1). Complete removal of copper (Figure D2), and cobalt (Figure D3) was typically achieved throughout the treatment season. Zinc removal was typically complete (Figure D4), although effluent zinc concentrations were more variable than copper and cobalt. Nickel removal was variable (Figure D5), generally greater than 50 percent, and showed seasonal variability with minimum effluent concentrations occurring around August.

The trends in copper, zinc, nickel, and cobalt accumulation were similar, suggesting that all four metals are removed by the same mechanism in the wetland. Copper, cobalt, and zinc were removed more completely by the wetland than nickel. This is consistent with the relative magnitudes of the solubility products for these metal sulfides (see Table 5 of the RS29T report).

The wetland also transformed non-metal parameters including sulfate, calcium, and magnesium. Sulfate removal (Figure D6) was highly variable, generally poor, and showed no apparent seasonal trends. The wetland acted as an overall source for sulfate (Figure D7), releasing 30,000 pounds of sulfate per hectare of wetland area over the 5-year study period. It may also be possible that the wetland received other sulfate inputs (i.e., surface or sub-surface flows) that were not quantified over this period. The wetland acted as a sink for calcium and magnesium (Figure D7), accumulating 22,000 and 17,000 lb/ha of these parameters, respectively. The rates of calcium and magnesium accumulation were relatively constant throughout the study period. Copper, nickel, zinc, and cobalt accumulated differently from calcium and magnesium, suggesting that calcium and magnesium accumulate via a different mechanism. It is likely that calcium and magnesium retention occurs via ion exchange/plant uptake, while copper, cobalt, zinc, and nickel retention occurs via sulfide precipitation.

The sulfate-releasing behavior of the wetland apparently confounds the notion of metals removal via sulfide precipitation. However, only a small fraction of the available sulfur in the waste stream was required to precipitate the metals. Thus, the apparent sulfate-releasing behavior of the wetland may be an artifact of the assumption that inflow equals outflow. It may also be possible that the wetland received other sulfate inputs (i.e., surface or sub-surface flows) that were not quantified over this period.

2.2 Dunka Mine Seep 041 (SD007) Treatment Performance

The wetland receiving water from Seep 041 is approximately 2.5 ha in area.

The wetland acted as a net sink for cobalt, copper, and zinc, but was a net source for nickel from February 2002 through the end of the study (Figure D8). Copper, zinc, and cobalt accumulated to 9.3, 12.4, and 1.1 lb/ha, respectively. Nickel released from the wetland amounted to 35 lb/ha. As shown in the graphs, copper and cobalt removal in this wetland (Figures D9 and D10, respectively) was generally greater than 30 percent, but was subject to significant seasonal variation. Minimum effluent copper and cobalt concentrations occurred around August. Zinc removal was highly variable and, in many instances poor (Figure D11). No seasonal trends with respect to zinc removal are apparent. Nickel removal was very poor, with effluent nickel concentrations often exceeding the input (Figure D12).

Sulfate removal was highly variable and showed no apparent seasonal trends (Figure D13). The wetland was a net sink of sulfate (Figure D14), accumulating 10,000 lbs/ha. On two occasions (February 2002 and September 2002) sulfate was released from the wetland. While the wetland accumulated calcium and magnesium (Figure D14, 9,600 lb/ha and 8,600 lb/ha, respectively), the accumulation rates were more erratic than observed at Seep 051 wetland.

As with the Seep 051 wetland, metal sulfide precipitation is likely the primary removal mechanism in this wetland. The onset of nickel release coincided with a release of sulfate around February 2002. While the reason for impaired sulfate-reducing activity is unknown, a subsequent reduction in sulfide concentrations in the wetland may have resulted in the preferential release of nickel over the other metals. This is consistent with the differences in the solubility products of the metal sulfides outlined in Table 5 of the RS29T report. Despite the apparent recovery of sulfate-reducing activity, the wetland continued to act as a nickel source. Elevated concentrations of iron (data not shown) were also detected in wetland effluent concurrent with the onset of nickel release.

While copper, cobalt, and zinc were retained in the wetland, their removal from the seepage stream was less complete than observed at the Seep 051 wetland. This may be reflective of sulfide-limiting conditions within the wetland.

2.3 Dunka Mine Seep 043 (SD008) Treatment Performance

The wetland receiving water from Seep 043 is about 1.1 ha in area.

The wetland acted as a sink for nickel, copper, and cobalt, accumulating 13, 12.8, and 4.1 lb/ha of these metals, respectively (Figure D15). However, the wetland acted as a source of zinc in the amount of 31 lb/ha. Copper and cobalt removal in this wetland was generally complete (Figures D16 and D17, respectively). No seasonal variations in copper or cobalt removal were observed. Zinc and nickel removal (Figures D18 and D19, respectively) was variable. Zinc and nickel removal exhibited seasonal trends, with minimum effluent concentrations occurring around August.

Sulfate removal was highly variable (Figure D20), with no discernable seasonal trends. The wetland was a net sink for sulfate until June 2003, when it became a net source (Figure D21). Overall, the wetland released 2,500 pounds of sulfate per hectare over the course of the study period. The wetland was a source of calcium in the amount of 1,200 lb/ha, and a sink for 500 lb/ha of magnesium (Figure D20).

This wetland differs from Seep 051 and Seep 041 in that it is a source of calcium and zinc. Moreover, the zinc release apparently is not associated with a concomitant release of sulfate. This may be indicative of a groundwater input.

2.4 Dunka Mine Seep 044 (SD009) Treatment Performance

The wetland receiving water from Seep 044 is about 0.92 ha in area and is a constructed peat bed with limestone.

The wetland acted as a net sink for copper, cobalt, and zinc, which accumulated to 161, 30, and 167 lb/ha, respectively (Figure D22). Removal was variable for all metals, but copper, cobalt, and zinc removal was more complete than nickel removal (Figures D23, D24, D25, and D26, respectively). The wetland was at steady state with respect to nickel until February 2003, at which time it became a net nickel source, releasing a total of 110 pounds of nickel per hectare.

Sulfate removal was poor (Figure D27). The wetland was a source of sulfate in the amount of 52,000 lb/ha and a net sink for calcium and magnesium at 18,000 and 16,500 lb/ha, respectively (Figure D28).

This wetland again demonstrates the selective release of nickel over other metals concomitant with the release of sulfate. This may be indicative of sulfide-limiting conditions within the wetland.

3.0 Conclusions

The performances of four constructed wetlands used at the Dunka Mine for mine drainage treatment were evaluated. All four wetlands were able to effectively remove copper and cobalt. Three of the four wetlands effectively removed zinc. Two of the four wetlands effectively removed nickel.

Sulfate mass balance results for the wetlands may be of limited value. It does not seem likely that as much as 5 tons of sulfur per year could be released per hectare of wetland area. Sulfate release could be correlated with nickel release in some cases, but not in others.

All four wetlands were sinks for magnesium, and three wetlands were sinks for calcium. The calcium and magnesium storage capacity of the wetlands is considerable and may be related to uptake by vegetation and ion exchange with wetland substrate. This observation may be important, as Minnesota surface water standards for metals are hardness-dependent. In the case of the Dunka Mine wetlands, however, total hardness in wetland effluents is still near the 400 mg/L maximum value for computation of the metal standards.

3.1 Design Considerations Applied to the Dunka Mine Wetlands

Table D1 summarizes the estimated sulfate reduction rates and corresponding carbon utilization rates necessary to provide sulfide for metals removal by the Dunka Mine constructed wetlands. The sulfate received by these wetlands was significantly in excess of that required to precipitate the metals. This excess sulfate can still reduced by the sulfate-reducing bacteria nonetheless, and therefore exerts an additional annual carbon demand in the wetland. The total carbon demand exerted by sulfate in the wetland is also tabulated in Table D1.

Table D1 Sulfate Reduction and Carbon Utilization Requirements for Metals Removal by the Dunka Mine Wetlands

Wetland	Required Sulfate Reduction Rate, mol/ha/d	Carbon Required for Sulfate Reduction to bind metals mol/ha/d	Total Carbon Demand for Complete Sulfate Reduction, mol/ha/d	Typical Available Carbon Supply (Vymazal, 1995, 40 percent refractory) mol/ha/d
SD005	6.6	13.2	3,500	1,400
SD007	22	44	2,300	1,400
SD008	5.2	10.3	1,600	1,400
SD009	6.7	13.4	2,600	1,400

3.1.1 Successes

Wetland SD005 successfully accumulated copper, cobalt, nickel, and zinc. This wetland has emergent wetland vegetation (cattails) in addition to peat material. Metals removal occurred despite the fact that this wetland was apparently a source of sulfate. Although the carbon demand for wetland SD005 was high (3,500 mol C/ha/d), it was within the range reported for primary productivity of freshwater wetlands (958 to 6,712 mol C/ha/d, Brinson et al., 1981).

Wetland SD008 successfully accumulated copper, cobalt, and nickel. This wetland was also a sink for sulfate. This wetland had the lowest carbon demand of the Dunka Mine constructed wetlands studied (1,600 mol C/ha/d), and is similar to the typical design value for carbon supply rates (1,400 mol/ha/d, Vymazal, 1995).

3.1.2 Failures

Wetland SD009, a peatland, exhibited nickel-releasing behavior. Peatlands are characterized by a relatively low rate of primary production (~27 moles C/ha/d, Worrall et al., 2003). This is significantly less than the range reported for other types of freshwater wetlands (958 to 6,712 moles C/ha/d, Brinson et al., 1981). While the carbon demand exerted by sulfate in wetland SD009 (2,600 mol C/ha/d) can be reasonably supplied by most freshwater wetlands, it likely cannot be supplied by a peatland. Thus, carbon-limiting conditions in wetland SD009 likely resulted in a decrease in sulfate reducing activity, a decrease in porewater sulfide concentration, and subsequent dissolution of nickel sulfides.

While wetland SD007 initially exhibited nickel-storing behavior, a sudden release of nickel occurred during the study period. Wetland SD007 was also characterized by a much higher required sulfate reduction rate than the other wetlands. While the onset of nickel release from wetland SD007 corresponded with a small release of sulfate, the wetland continued to release nickel despite the apparent recovery of sulfate-reducing activity. While influent iron concentrations are unknown, elevated effluent iron concentrations were observed concurrent with nickel release. Thus, mobilization of iron within the wetland or changes in iron inputs may have also interfered with nickel retention.

The release of calcium and zinc from wetland SD008 is inconsistent with any of the other wetlands. The reason for this behavior is unknown.

3.1.3 Lessons Learned

A careful review of the results from operation of the wetland treatment systems for the Dunka Mine suggest that peat alone may not provide sufficient carbon to support metals removal via sulfide precipitation. Also, nickel removal is typically the limiting factor for design. Iron inputs to the wetland may interfere with nickel retention. Wetland SD005 appears to be most effective at removing metals from the seepage stream, thus a similar design may be most effective at NorthMet.

Figures

Figure D1: Cumulative Metals Storage
SD005

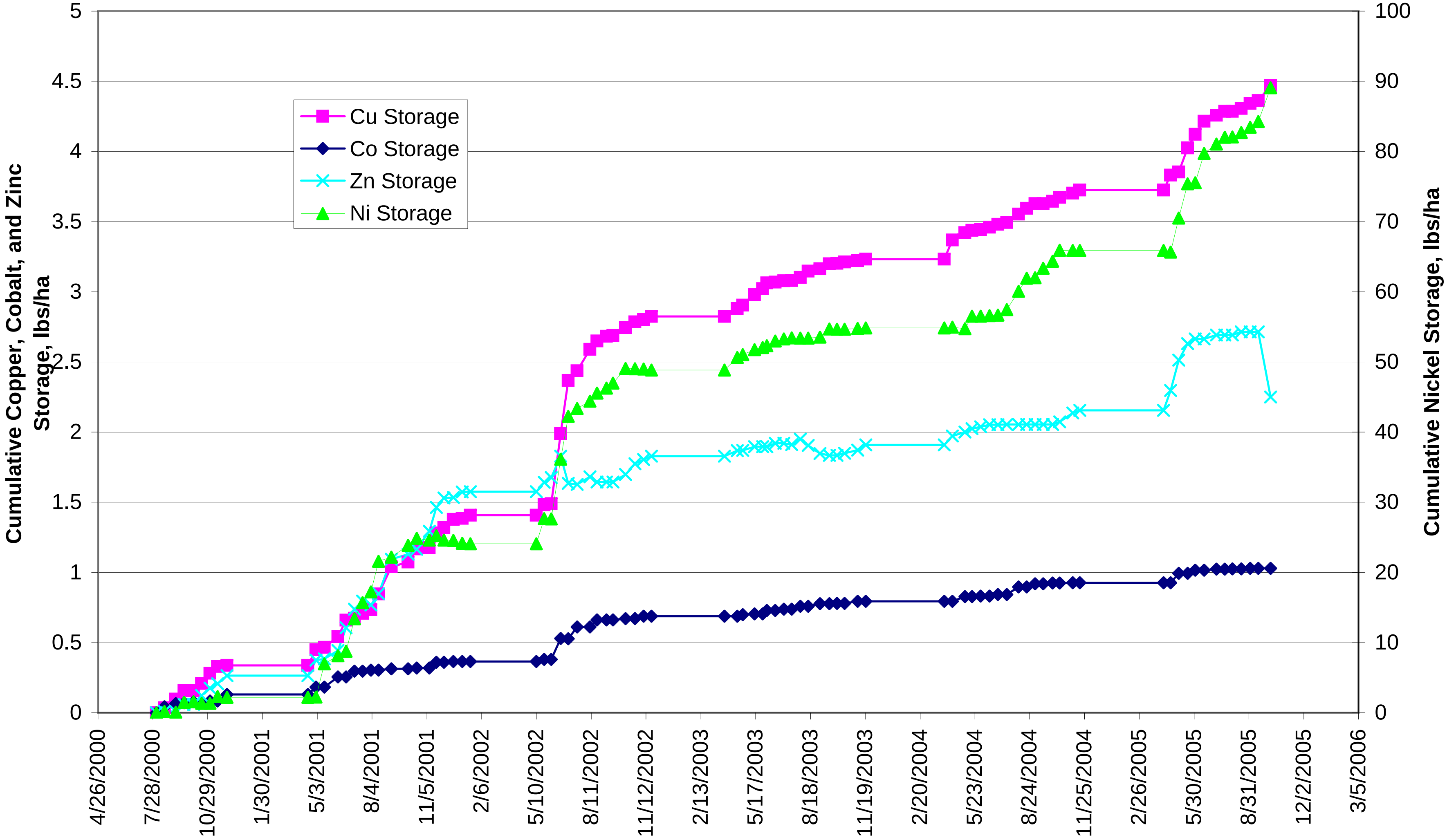


Figure D2: Influent and Effluent Copper Concentrations
SD005

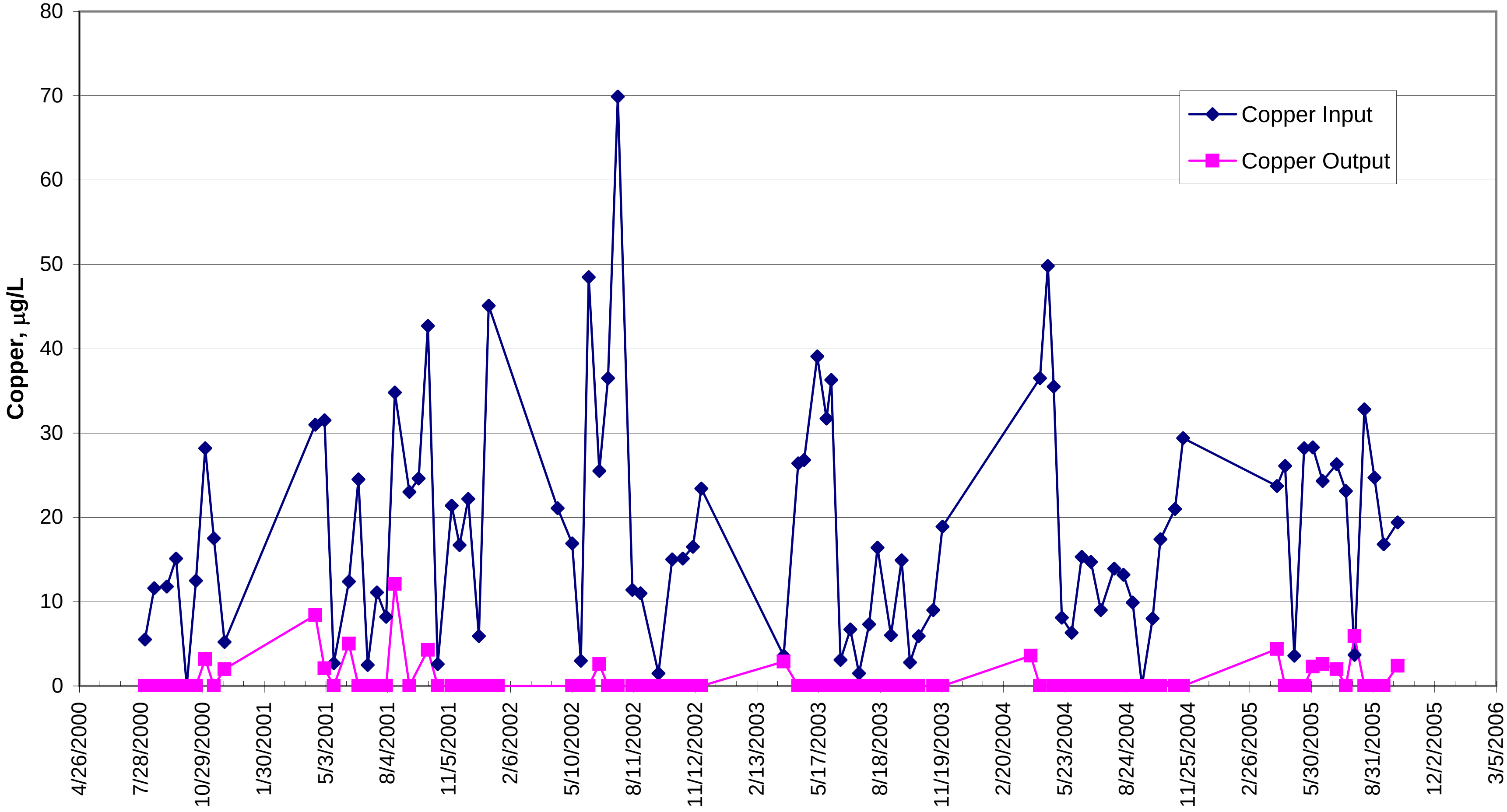


Figure D3: Influent and Effluent Cobalt Concentrations
SD005

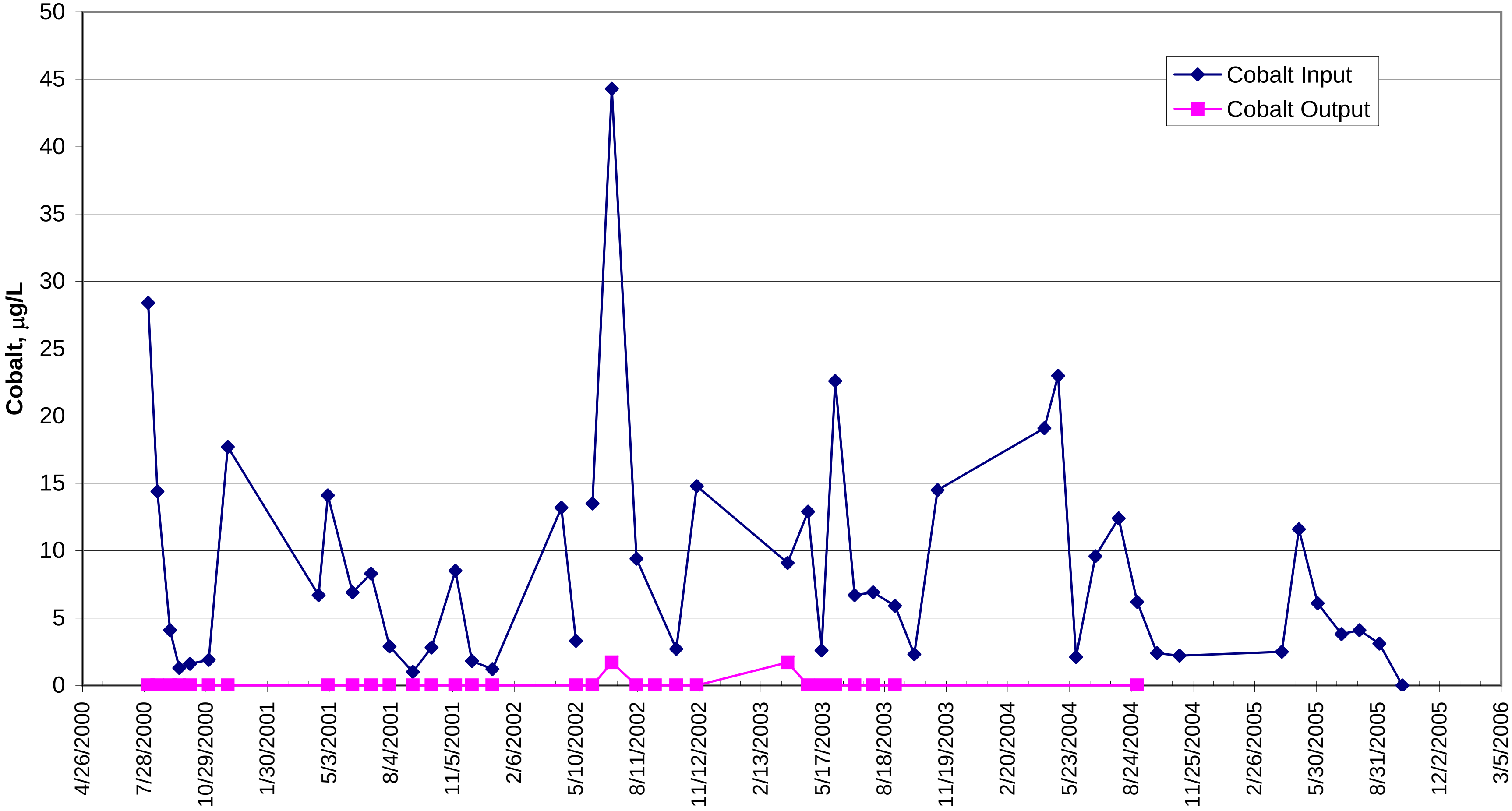


Figure D4: Influent and Effluent Zinc Concentrations SD005

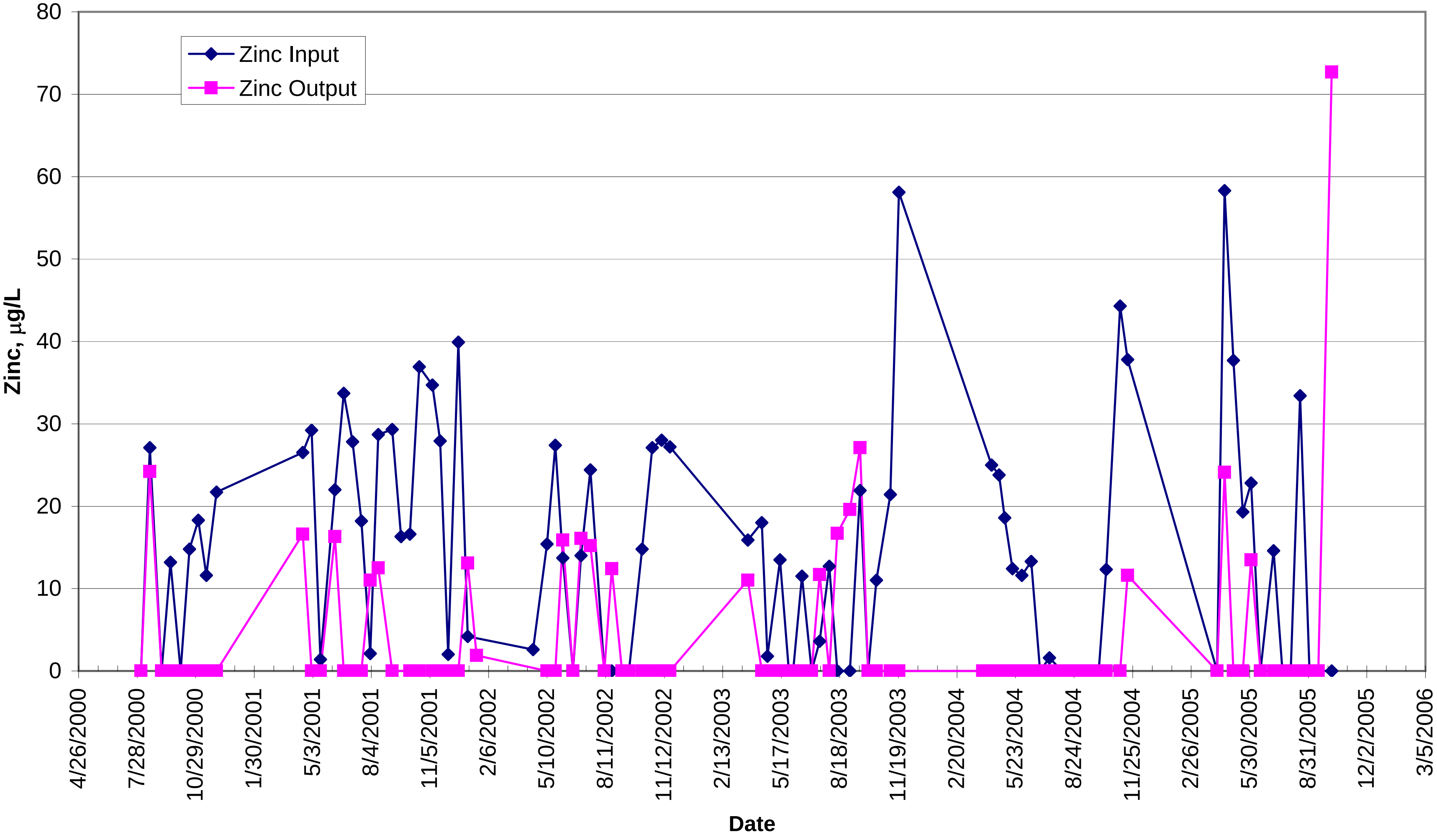


Figure D5: Influent and Effluent Nickel Concentrations SD005

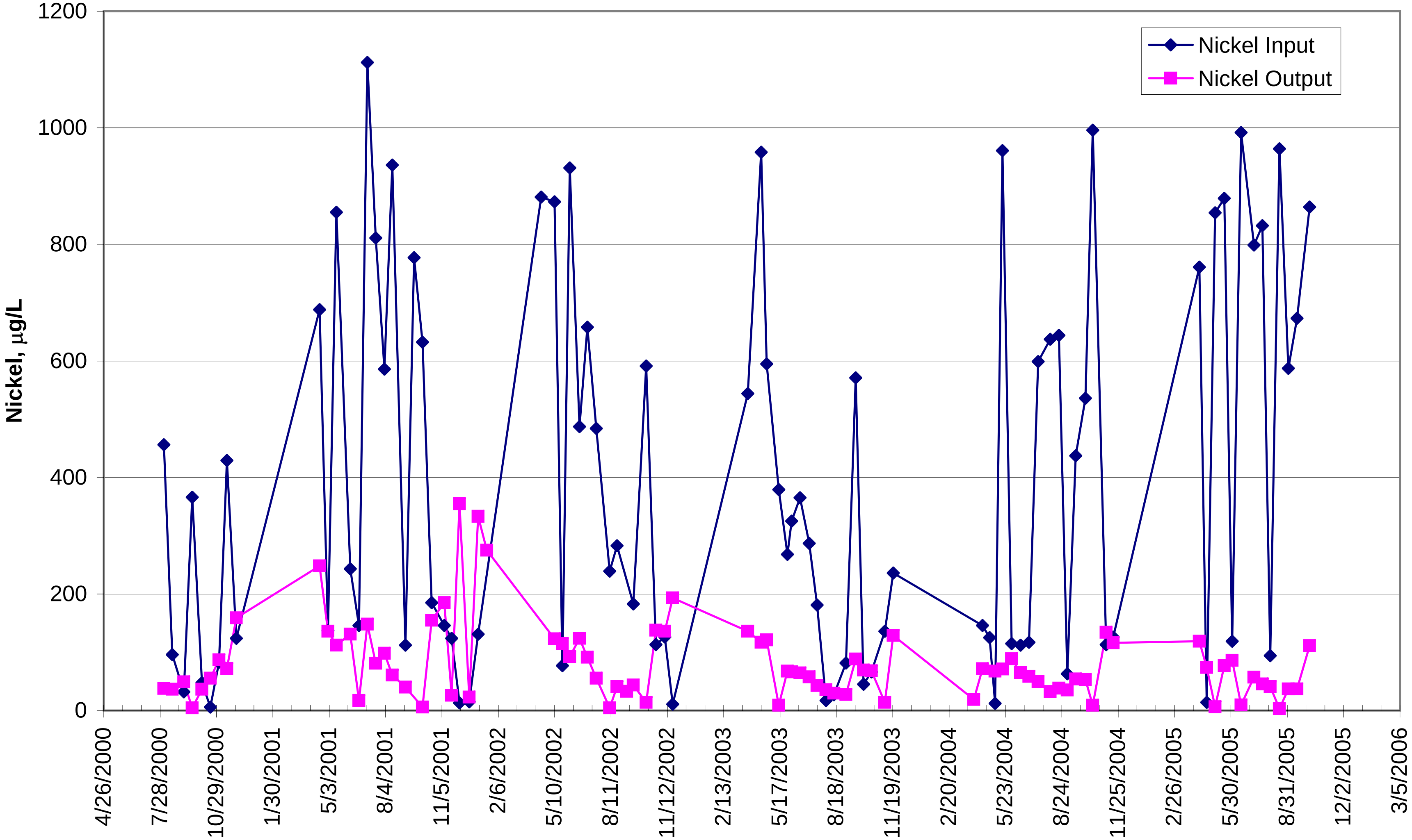


Figure D6: Influent and Effluent Sulfate Concentrations
SD005

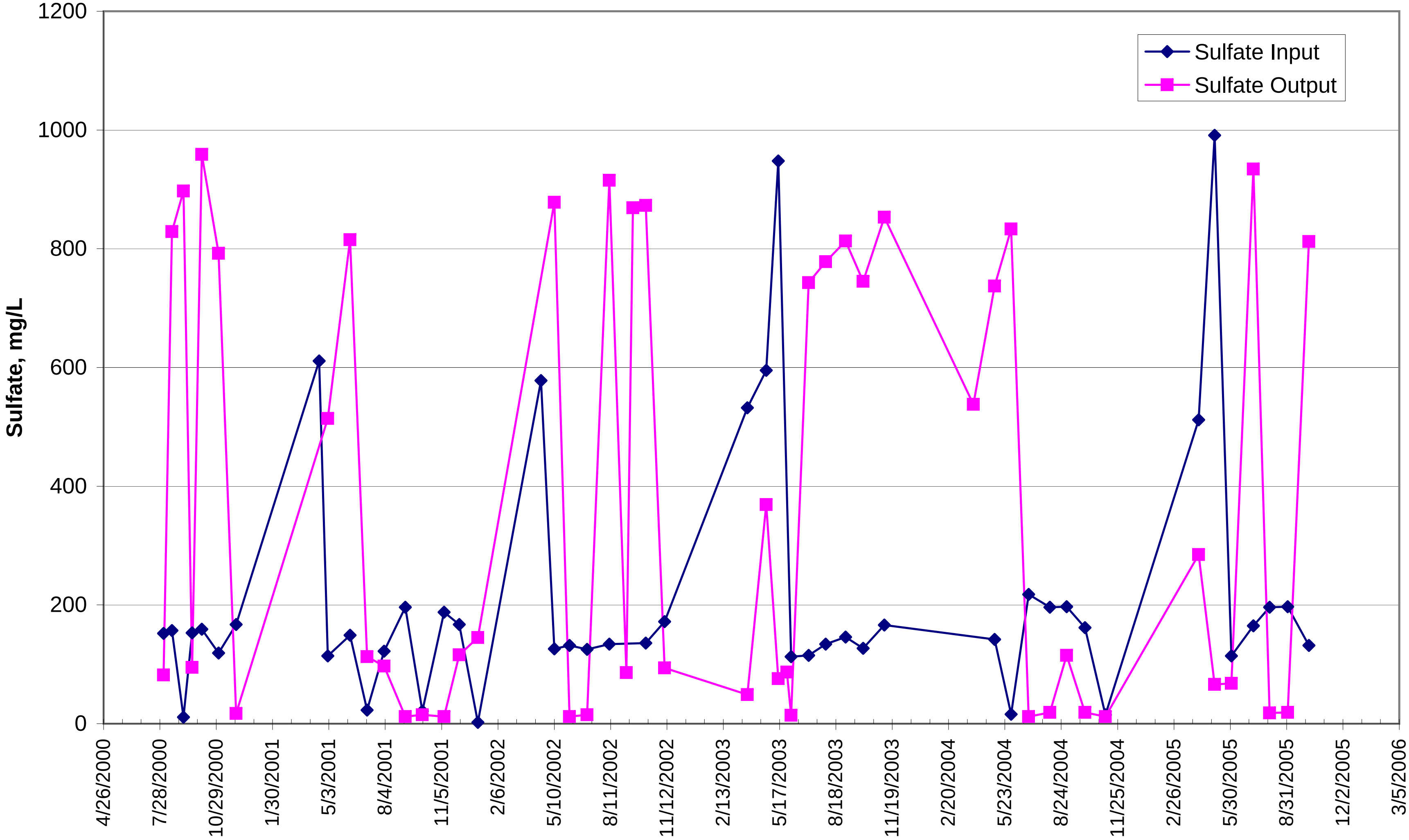


Figure D7: Calcium, Magnesium, and Sulfate Storage
SD005

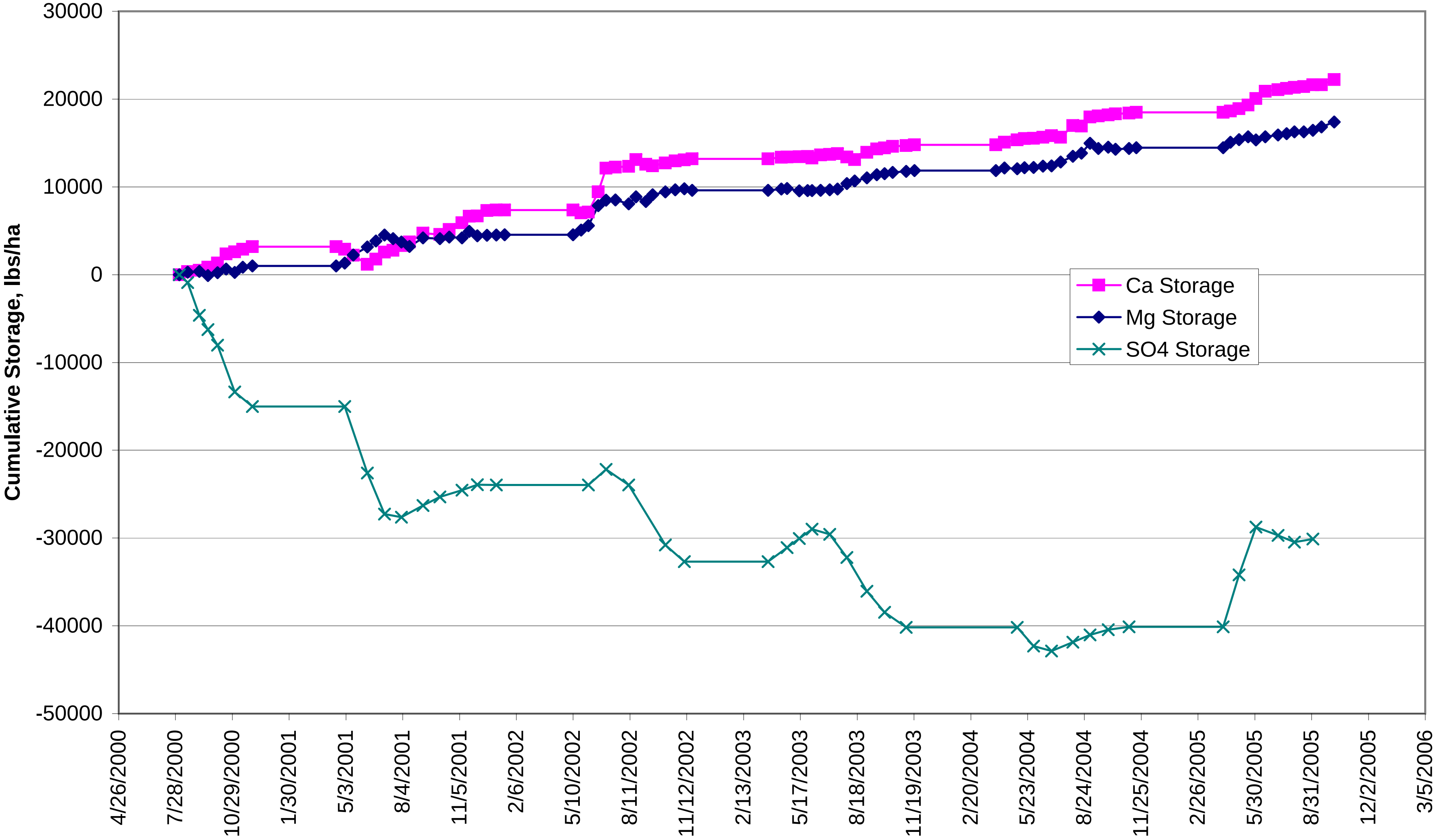


Figure D8: Cumulative Metals Storage
SD007

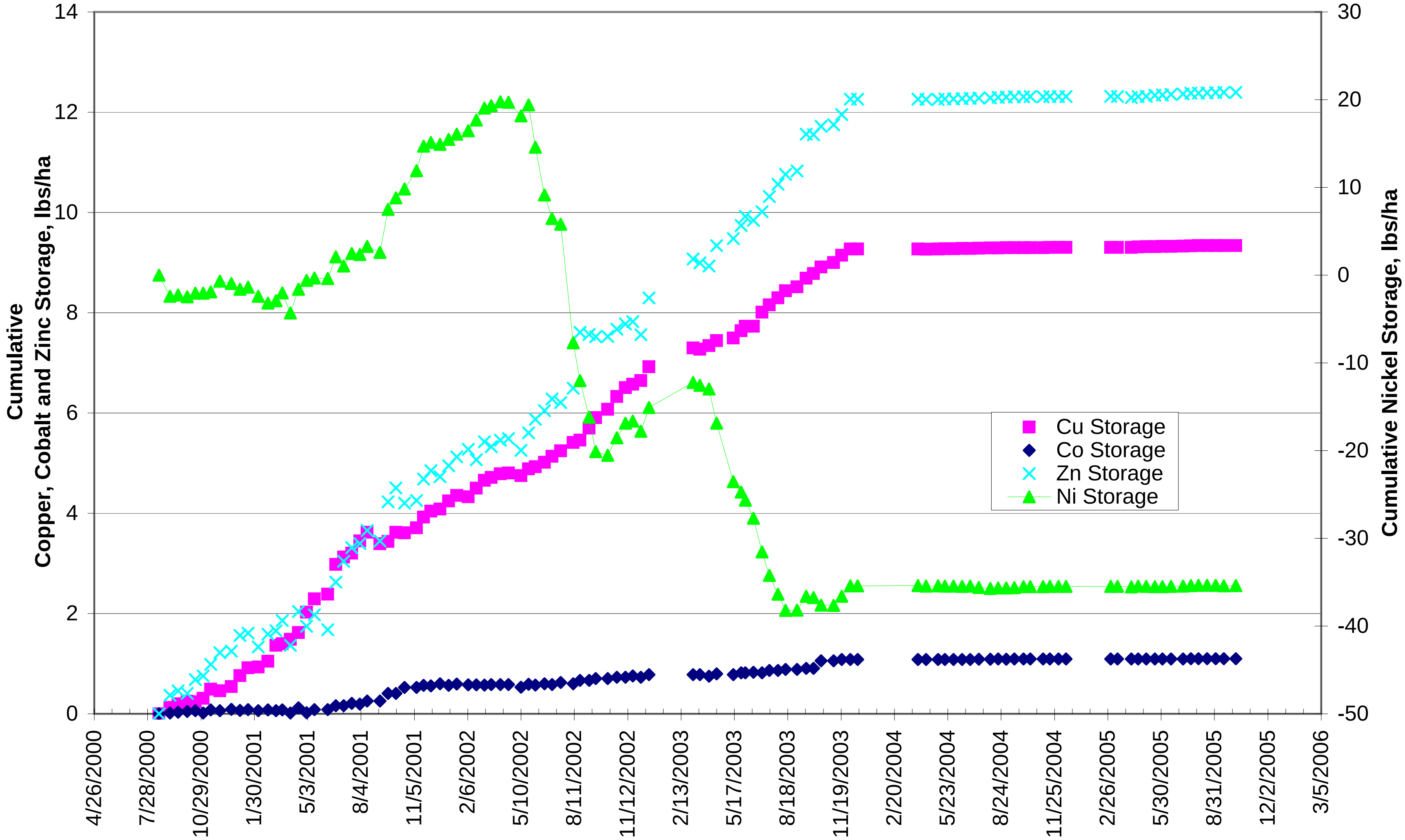


Figure D9: Influent and Effluent Copper Concentrations
SD007

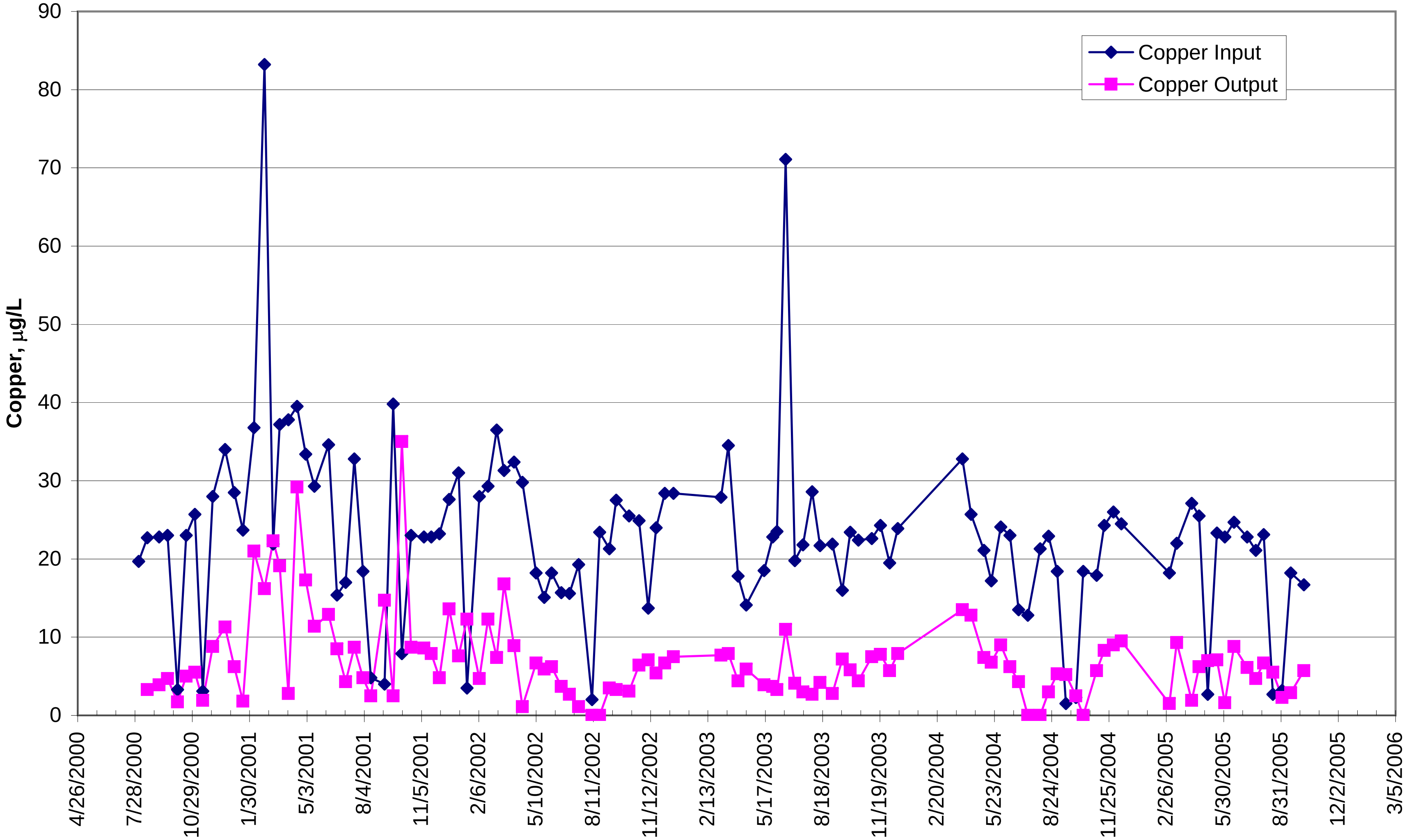
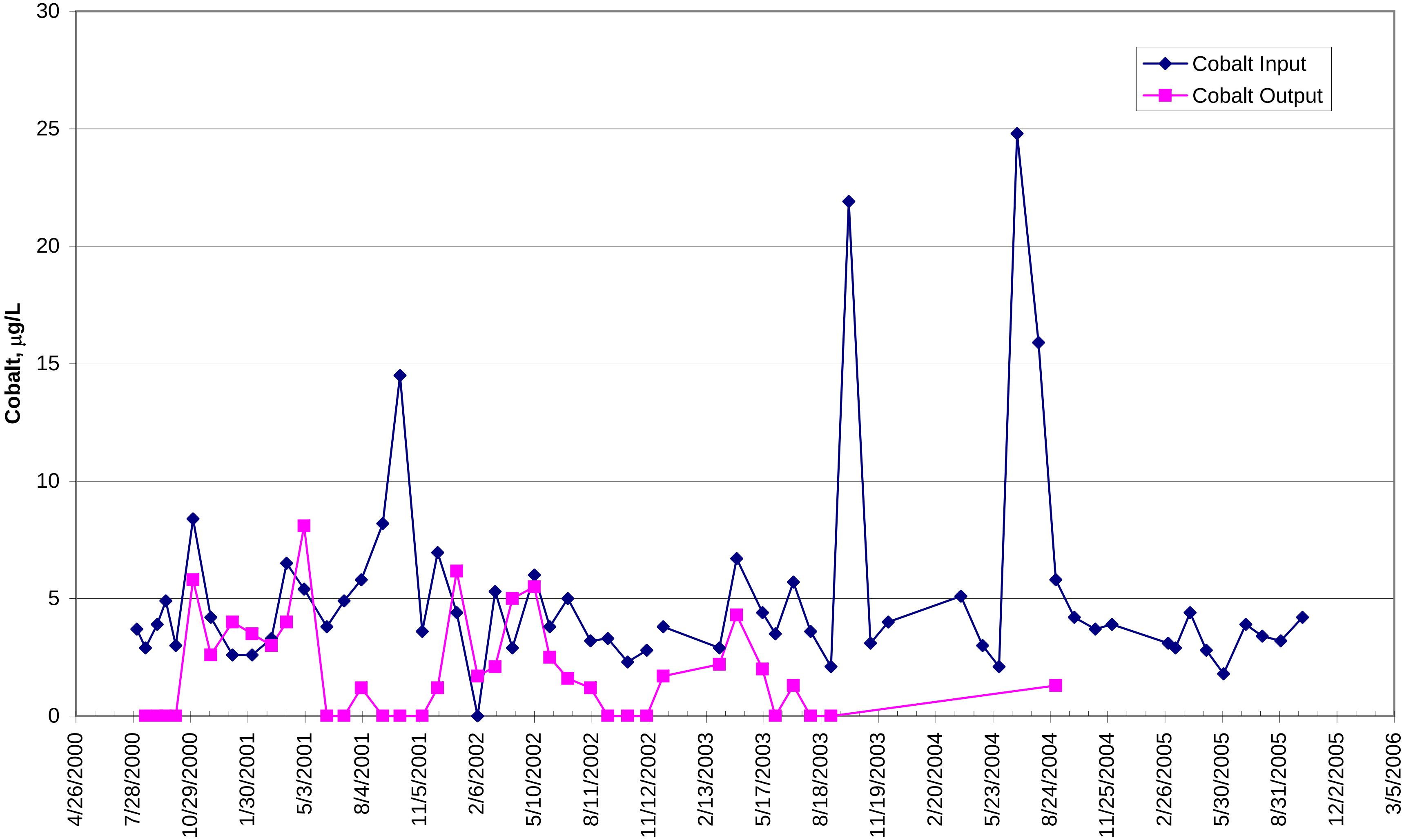


Figure D10: Influent and Effluent Cobalt Concentrations
SD007



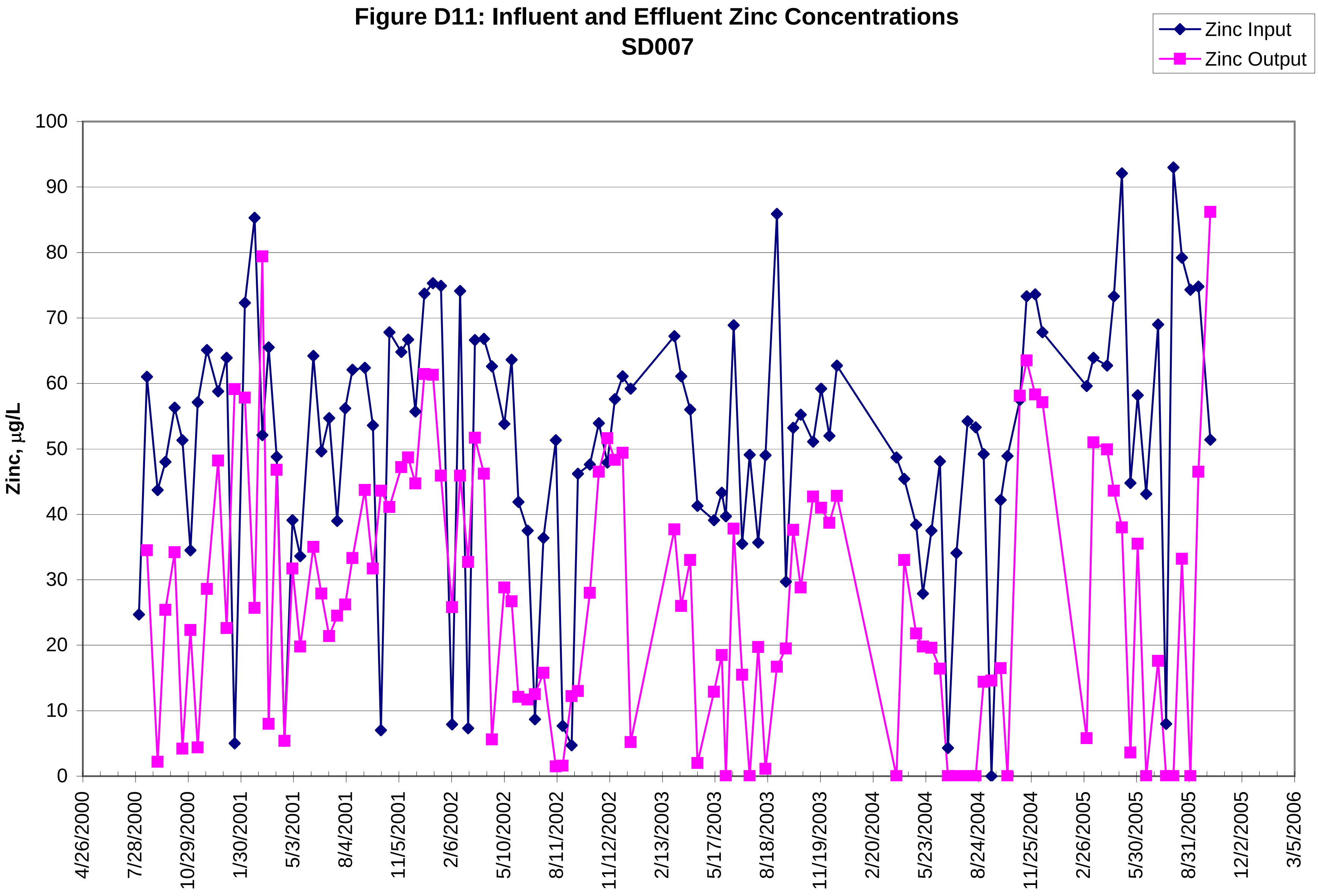


Figure D11: Influent and Effluent Zinc Concentrations
SD007
Zinc Input
Zinc Output
Zinc, µg/L
100
90
80
70
60
50
40
30
20
10
0
4/26/2000
7/28/2000
10/29/2000
1/30/2001
5/3/2001
8/4/2001
11/5/2001
2/6/2002
5/10/2002
8/11/2002
11/12/2002
2/13/2003
5/17/2003
8/18/2003
11/19/2003
2/20/2004
5/23/2004
8/24/2004
11/25/2004
2/26/2005
5/30/2005
8/31/2005
12/2/2005
3/5/2006

Figure D12: Influent and Effluent Nickel Concentrations
SD007

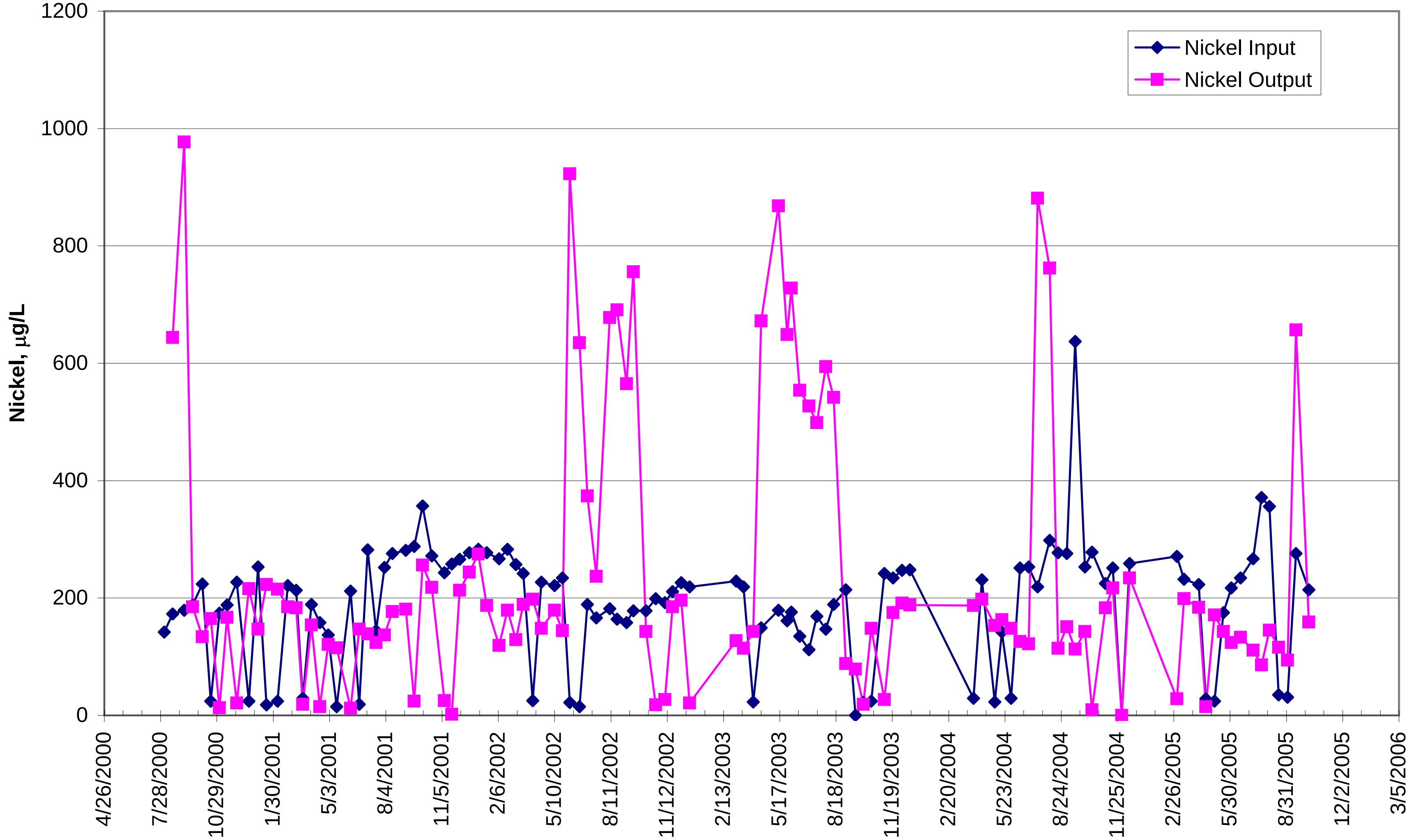


Figure D13: Influent and Effluent Sulfate Concentrations
SD007

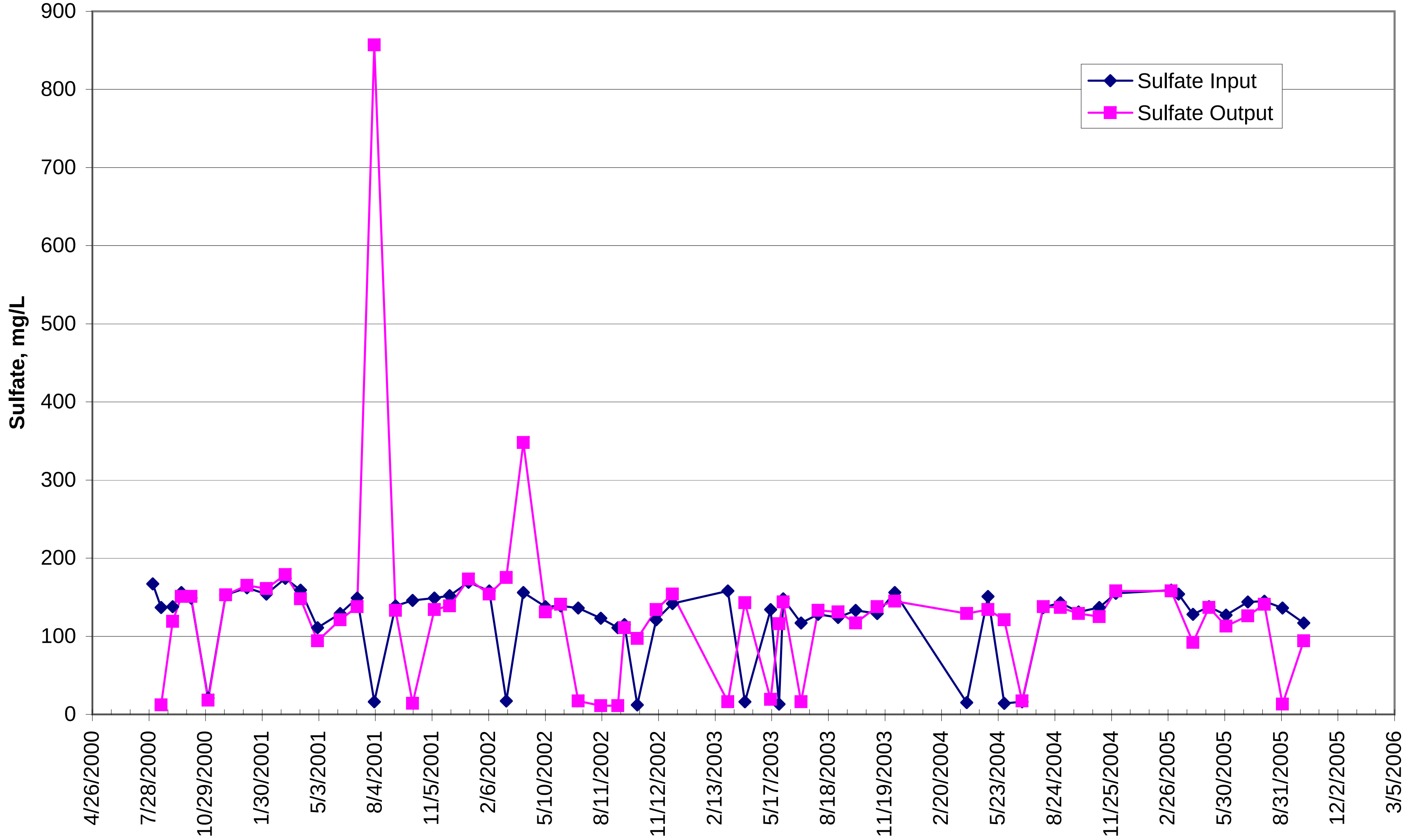


Figure D14: Calcium, Magnesium, and Sulfate Storage
SD007

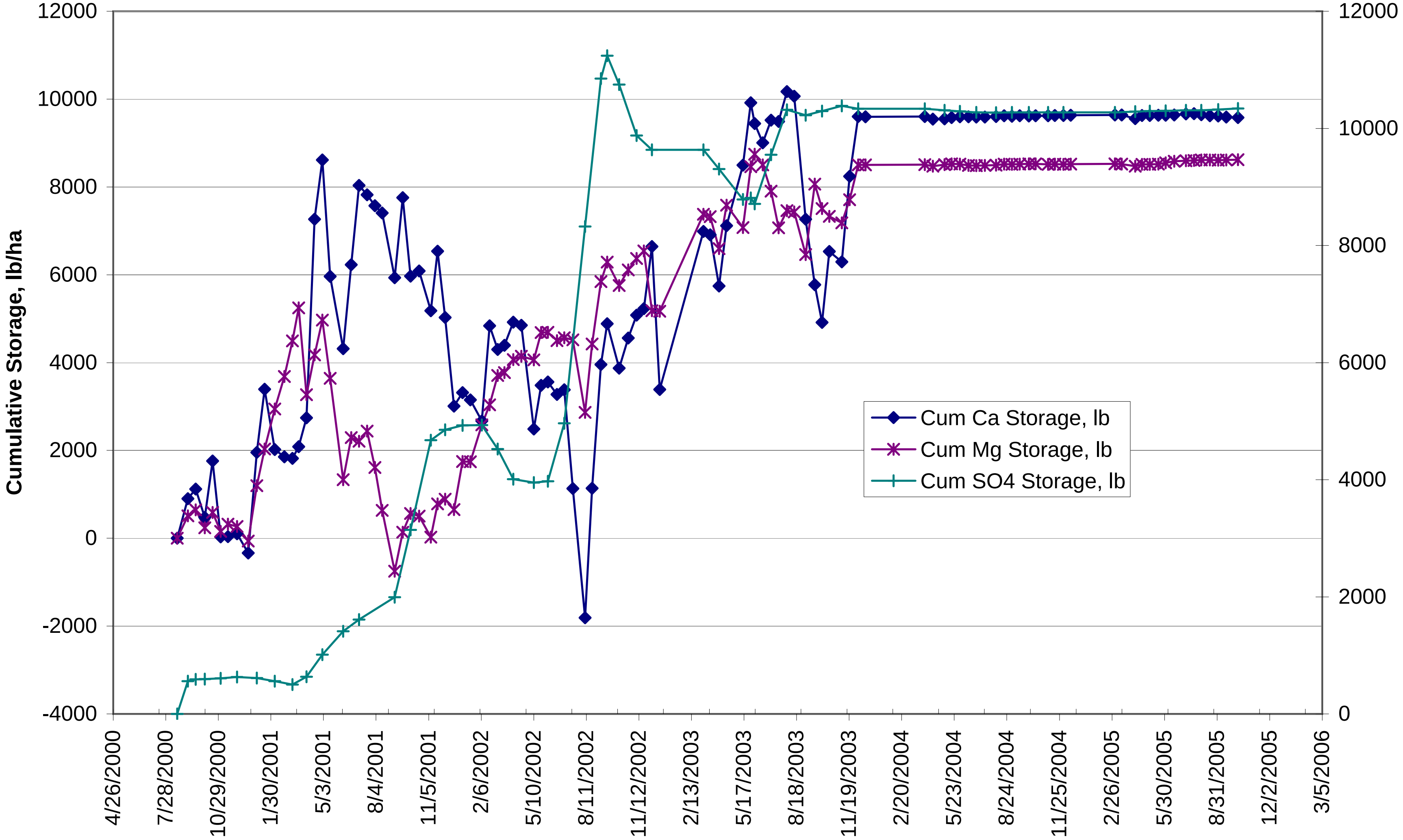


Figure D15: Cumulative Metals Storage
SD008

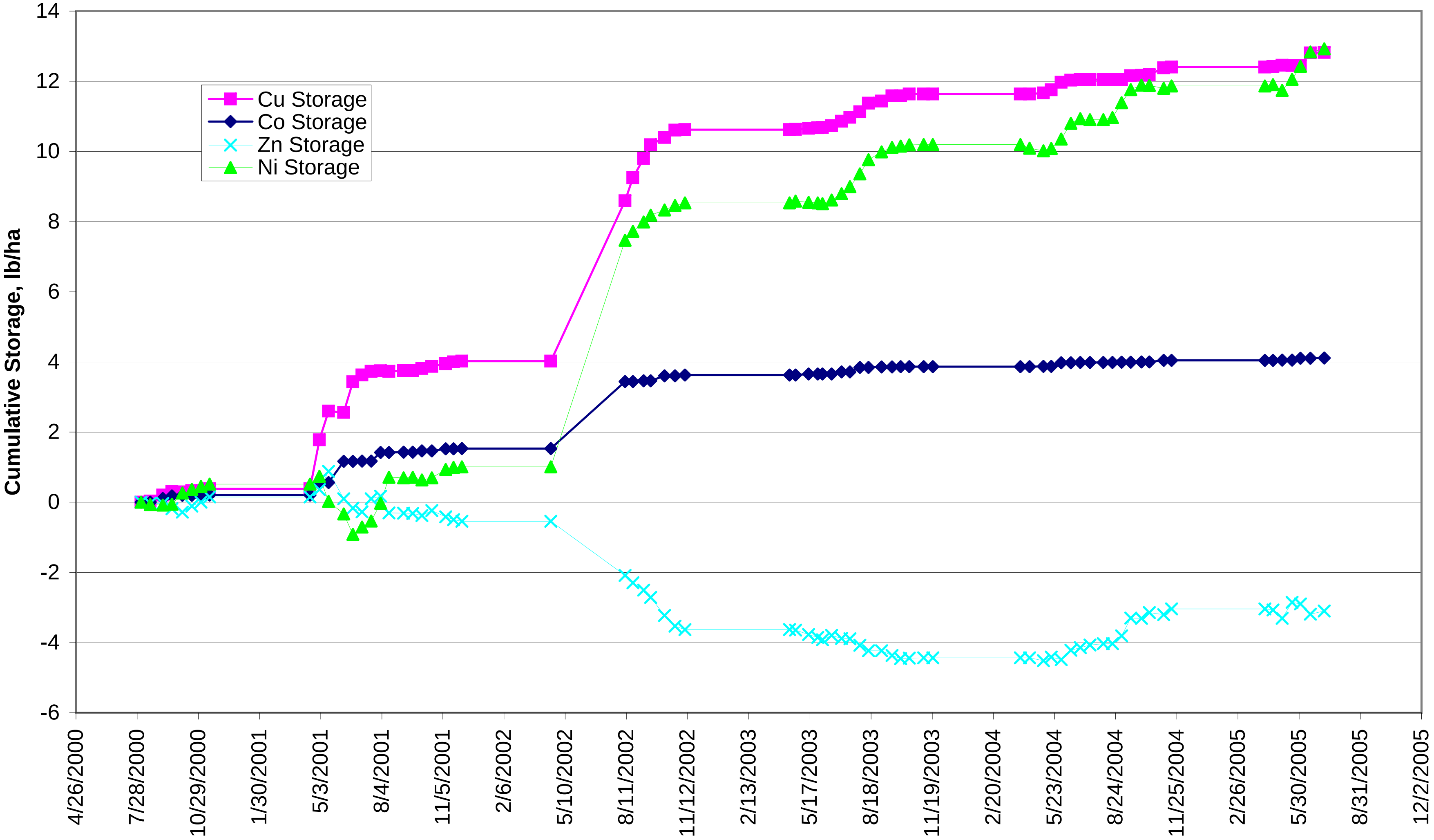


Figure D16: Influent and Effluent Copper Concentrations SD008

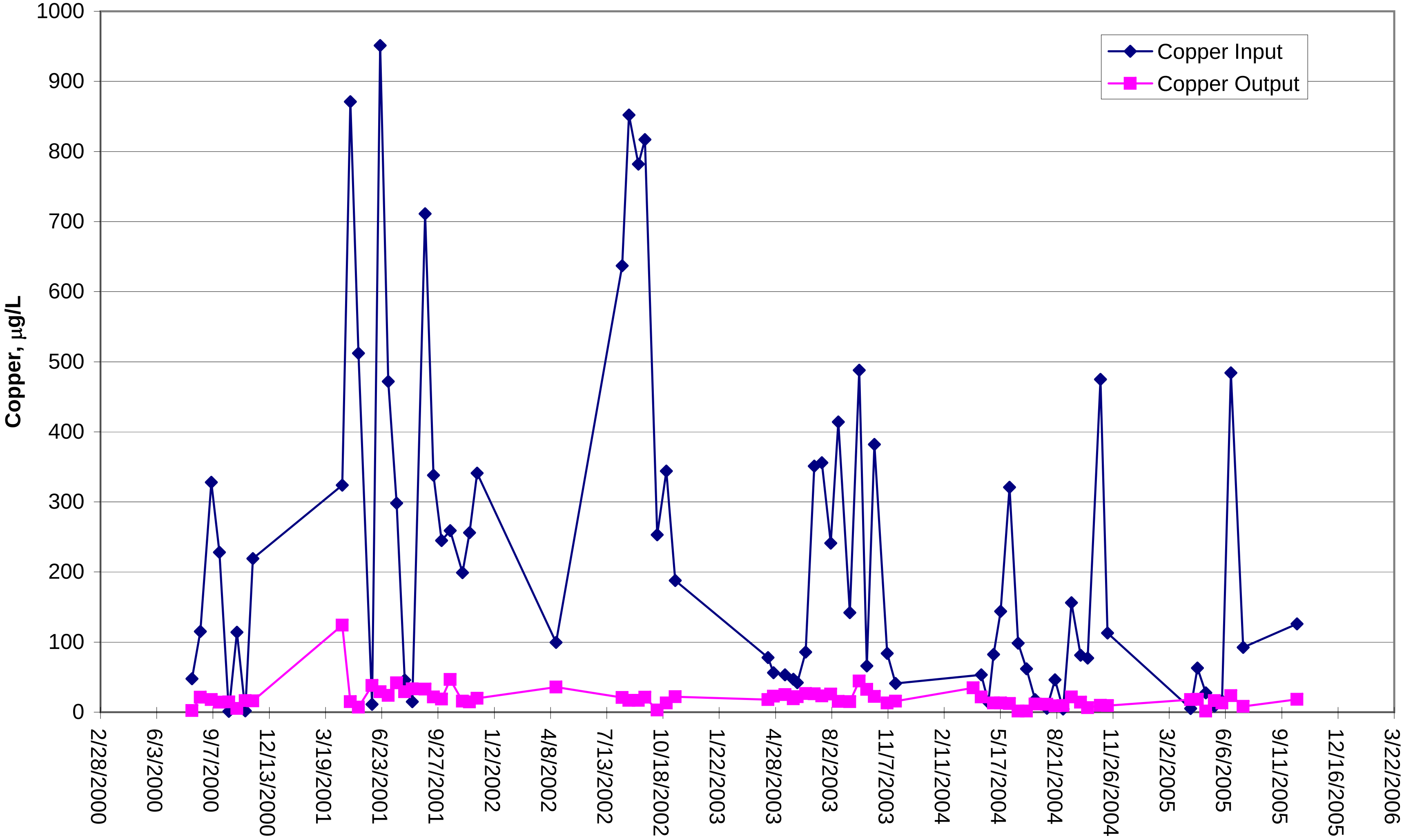


Figure D17: Influent and Effluent Cobalt Concentrations
SD008

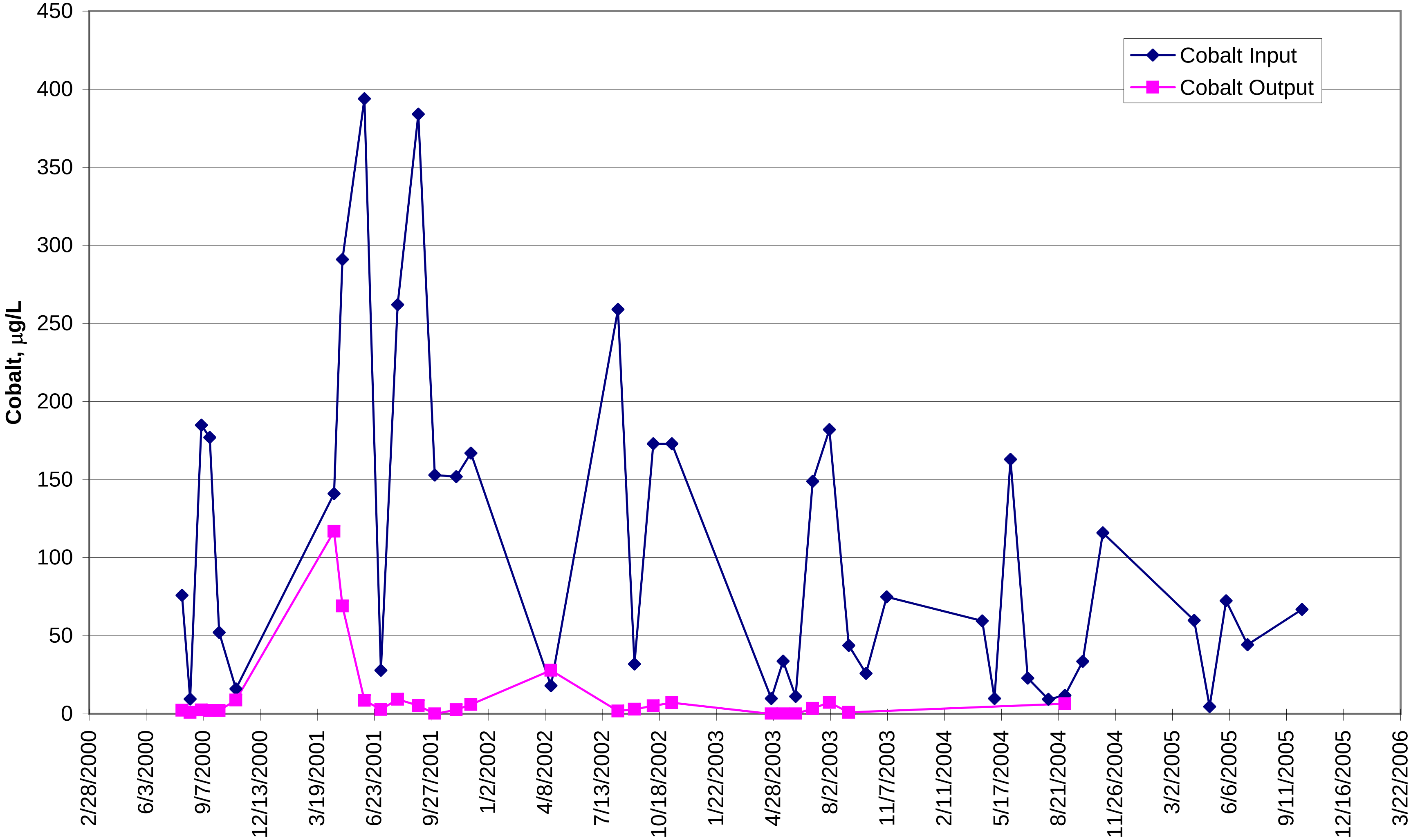


Figure D18: Influent and Effluent Zinc Concentrations
SD008

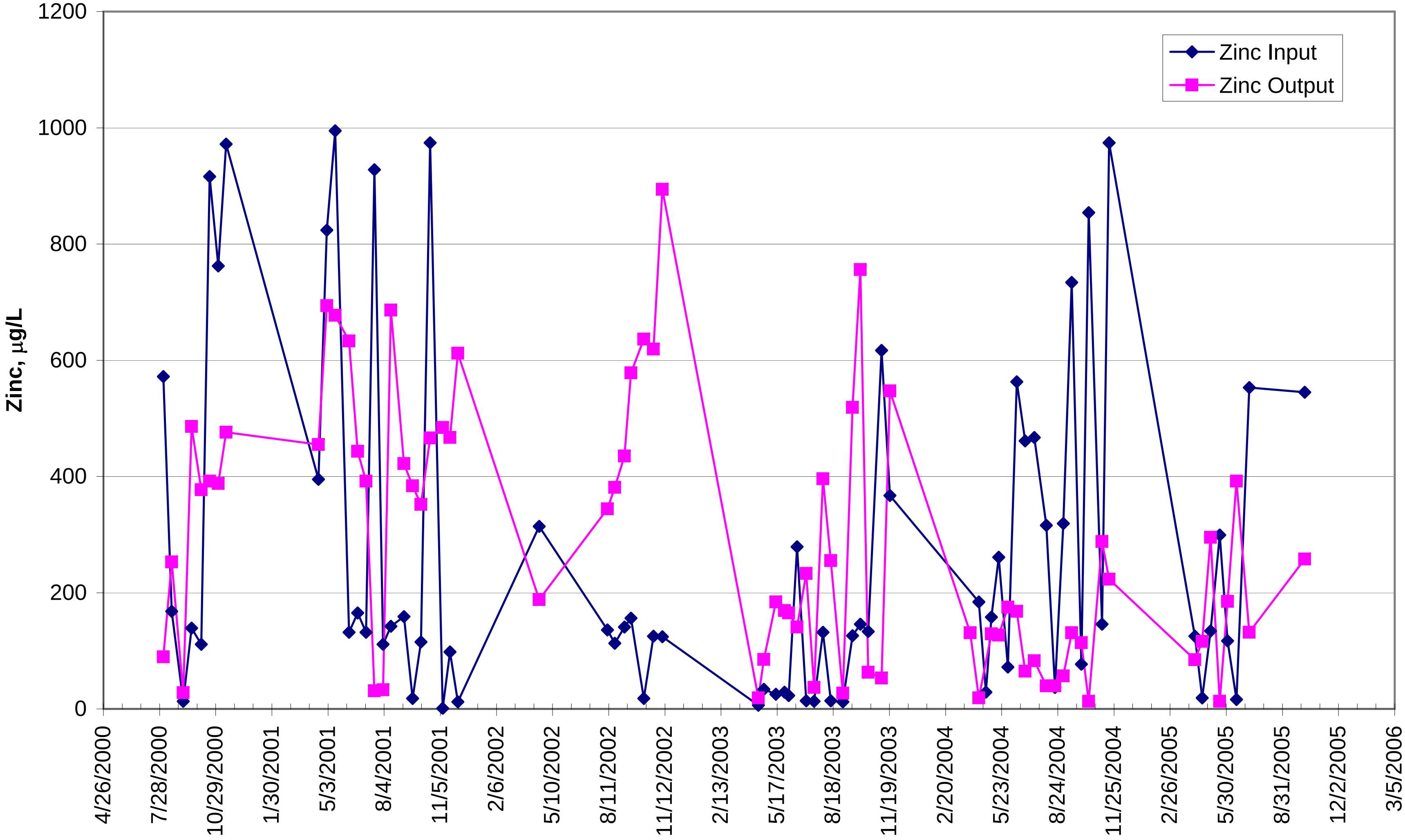


Figure D19: Influent and Effluent Nickel Concentrations
SD008

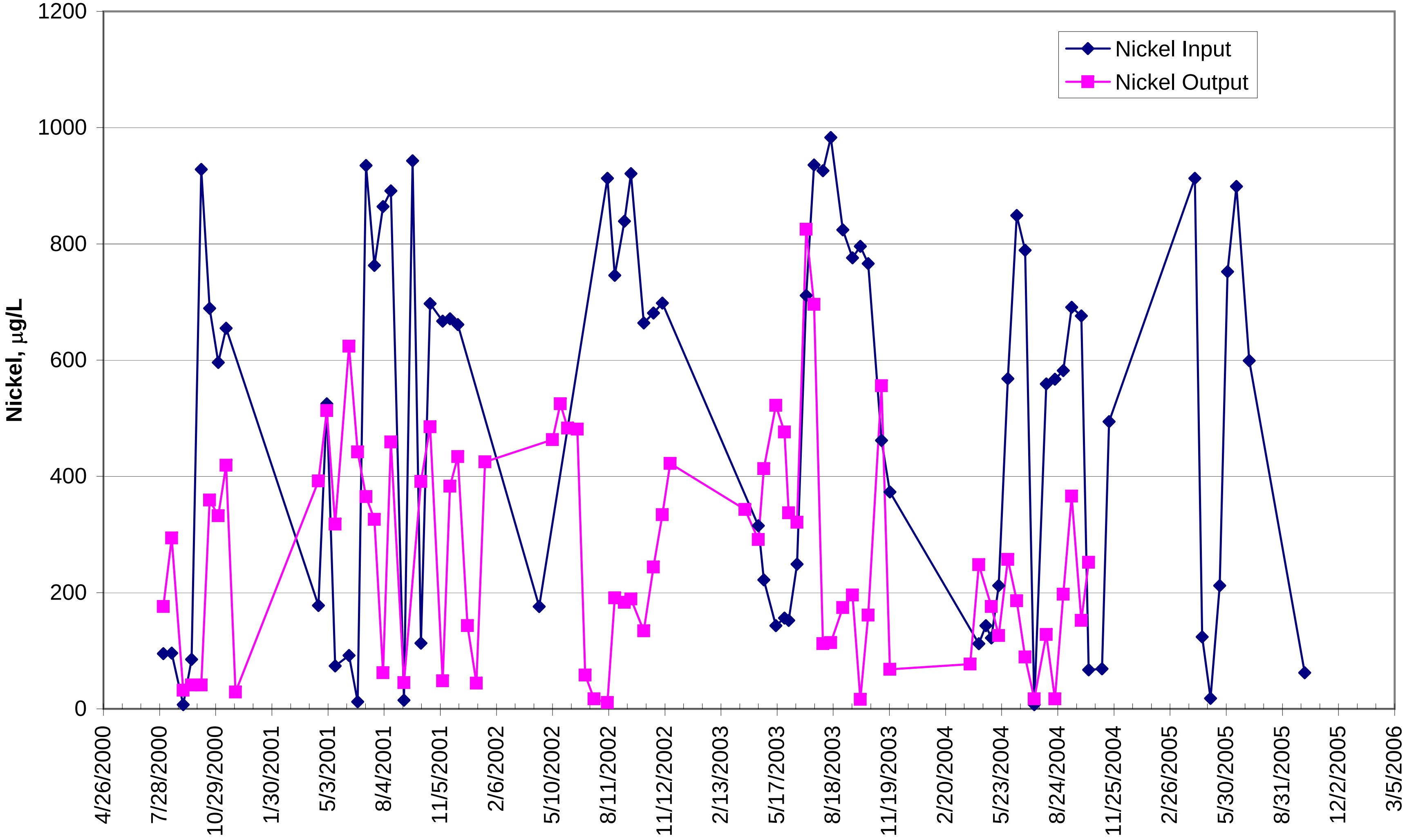


Figure D20: Influent and Effluent Sulfate Concentrations
SD008

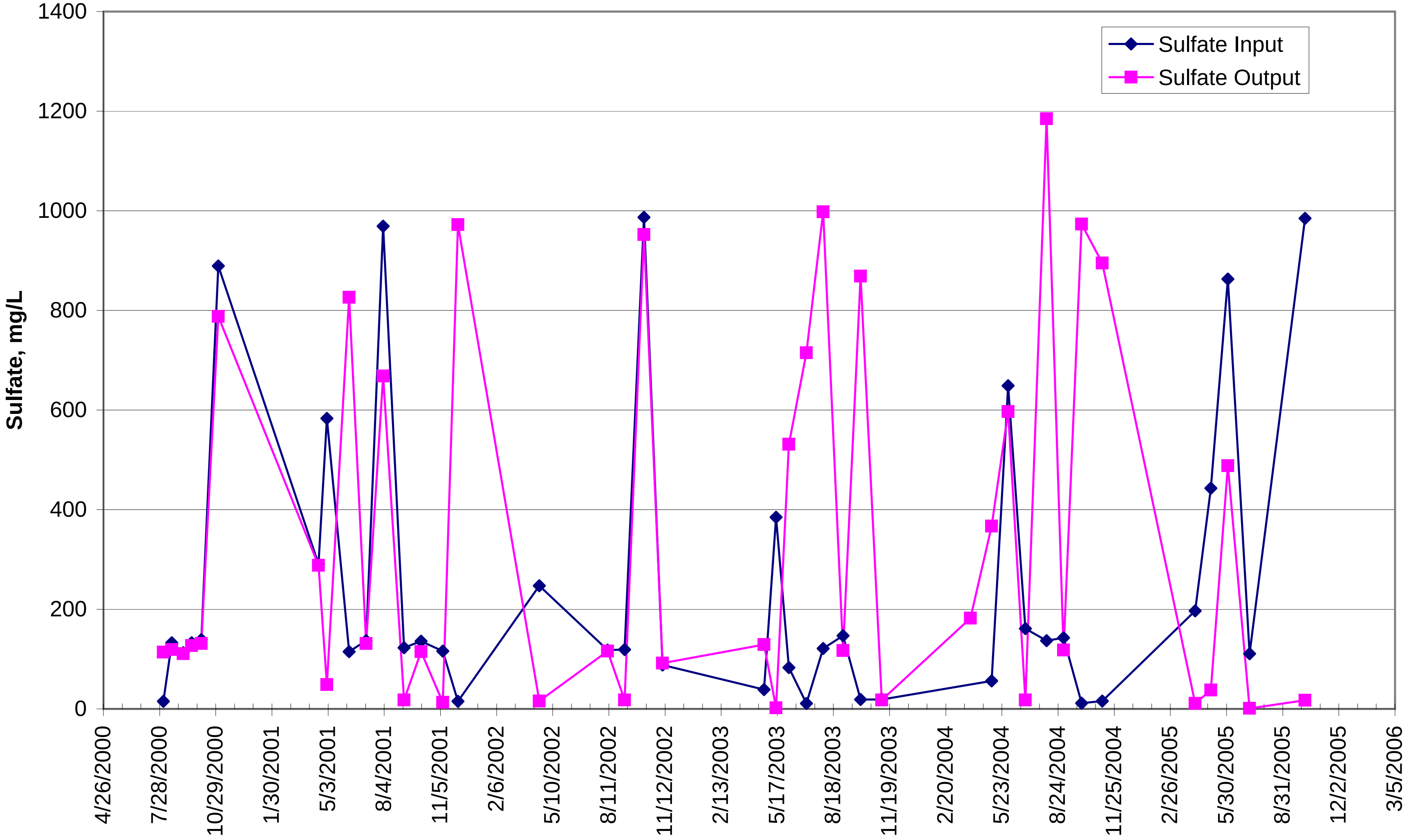


Figure D21: Calcium, Magnesium, and Sulfate Storage
SD008

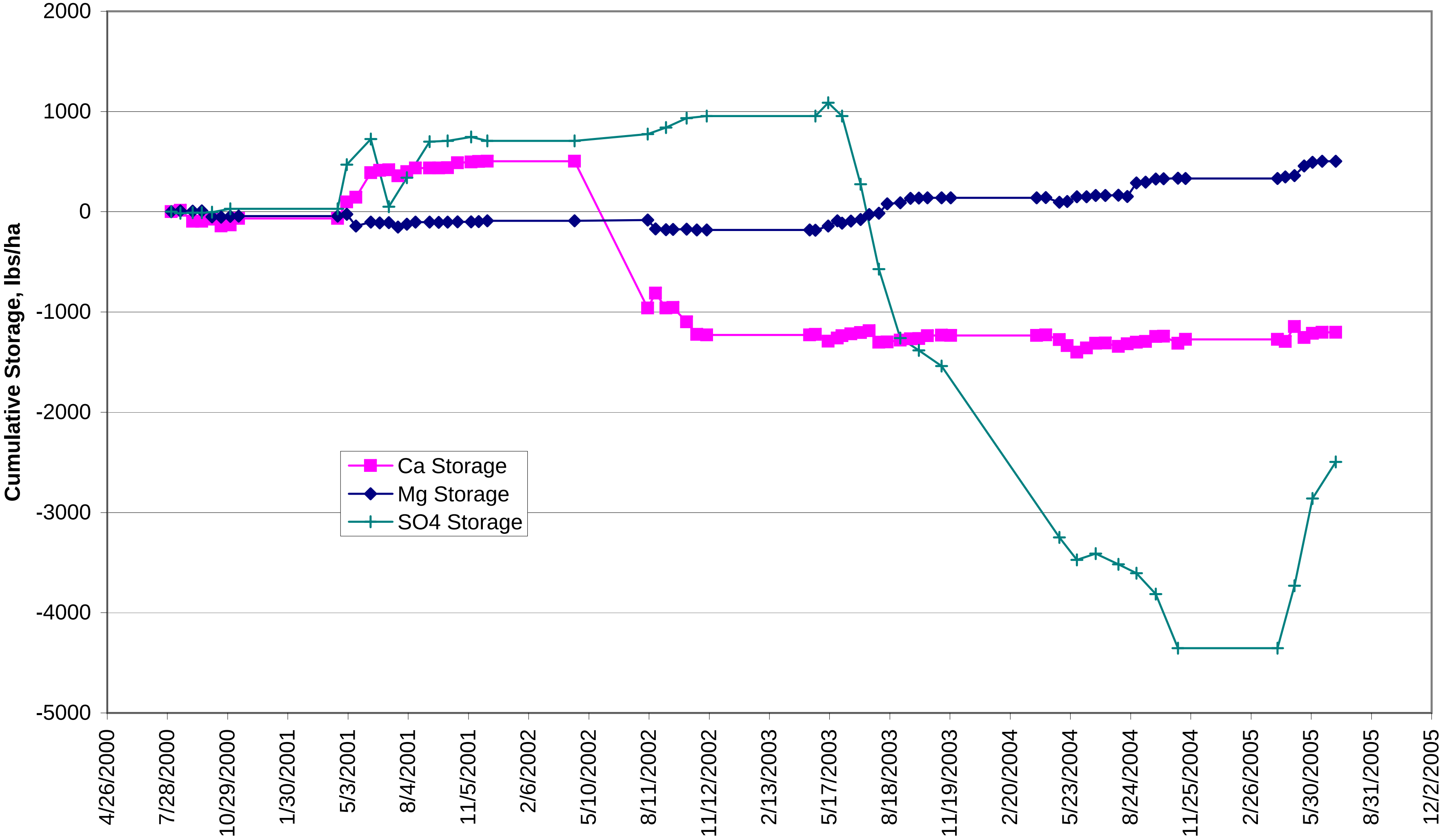


Figure D22: Cumulative Metals Storage
SD009

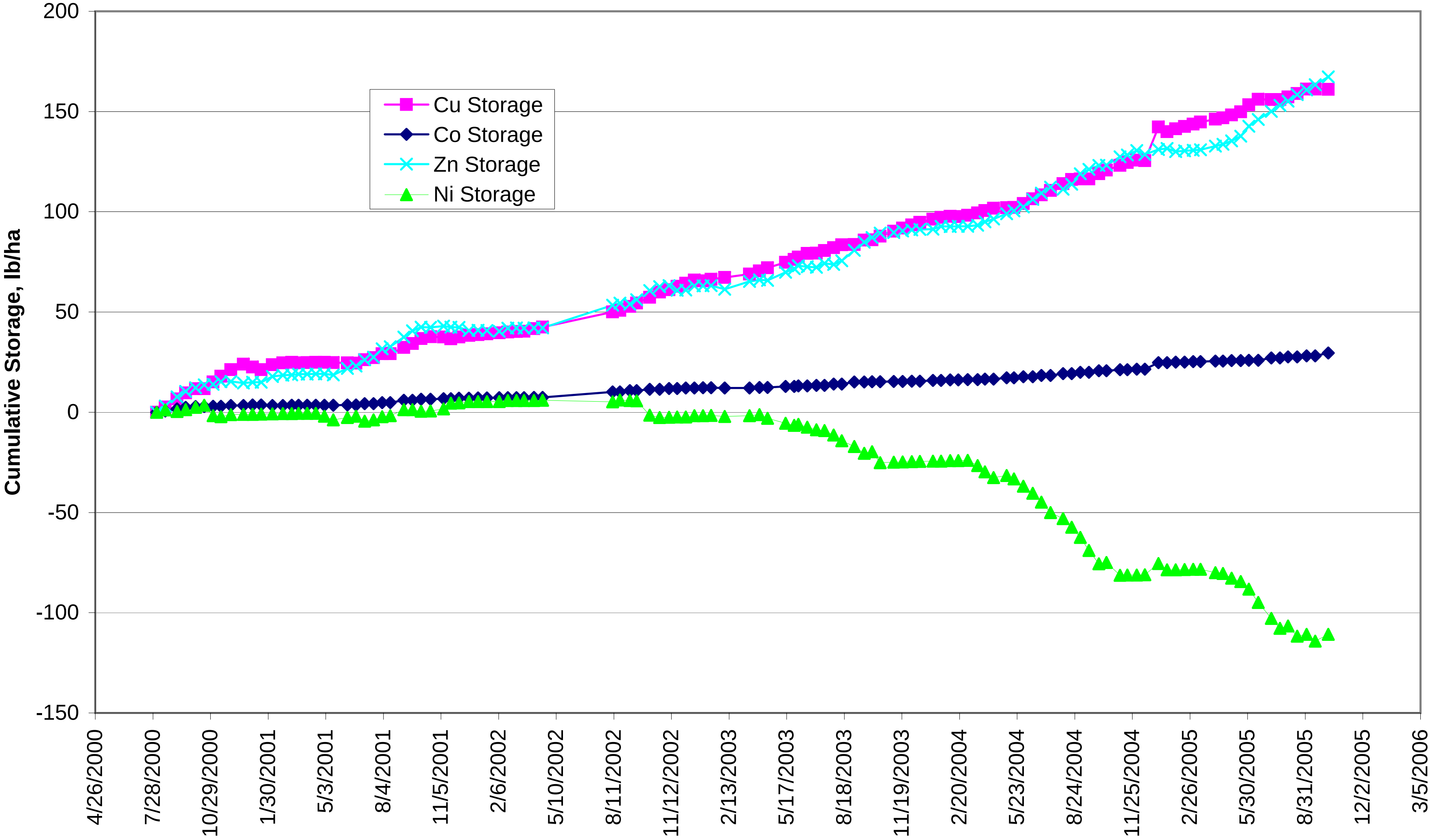


Figure D23: Influent and Effluent Copper Concentrations
SD009

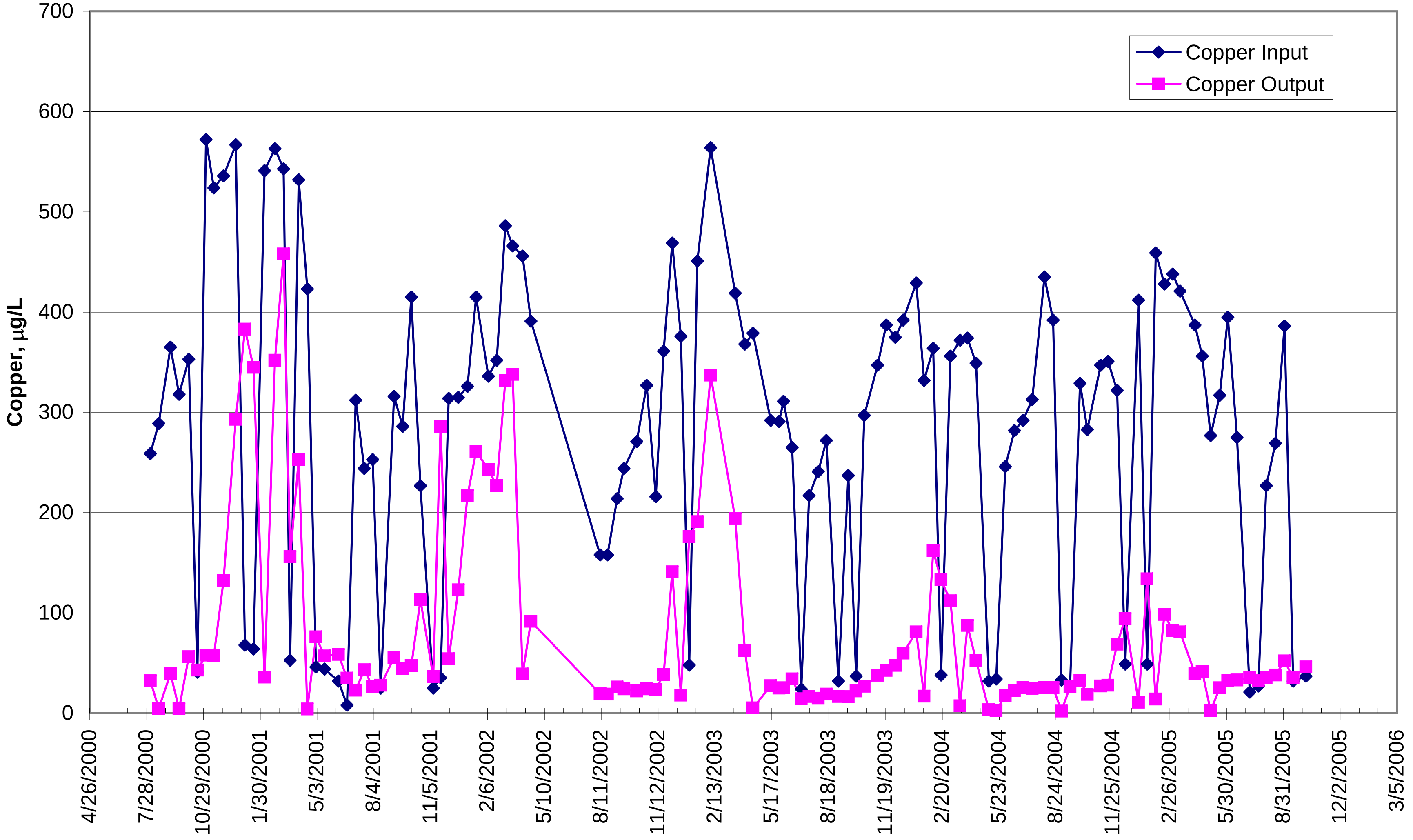


Figure D24: Influent and Effluent Cobalt Concentrations
SD009

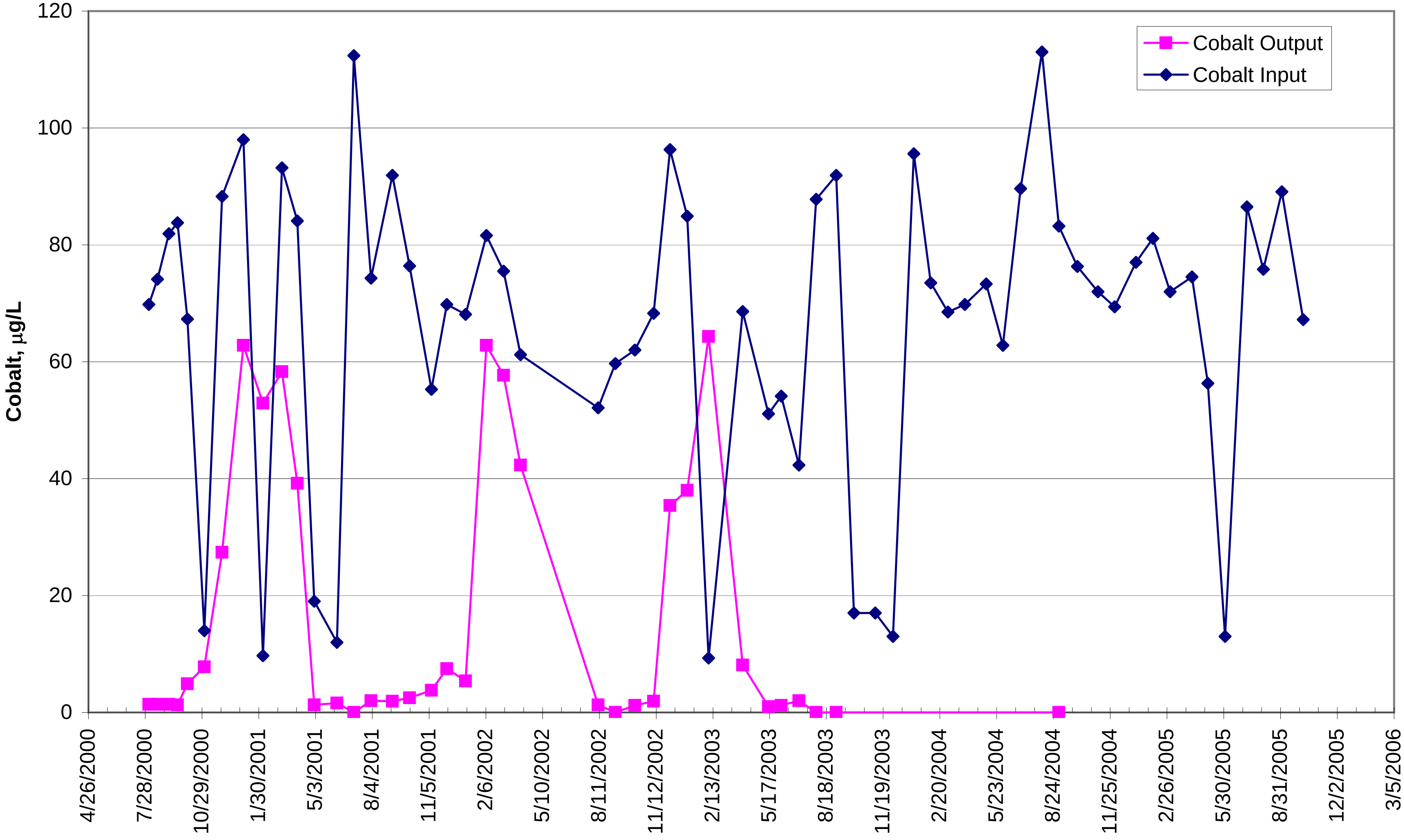


Figure D25: Influent and Effluent Zinc Concentrations
SD005

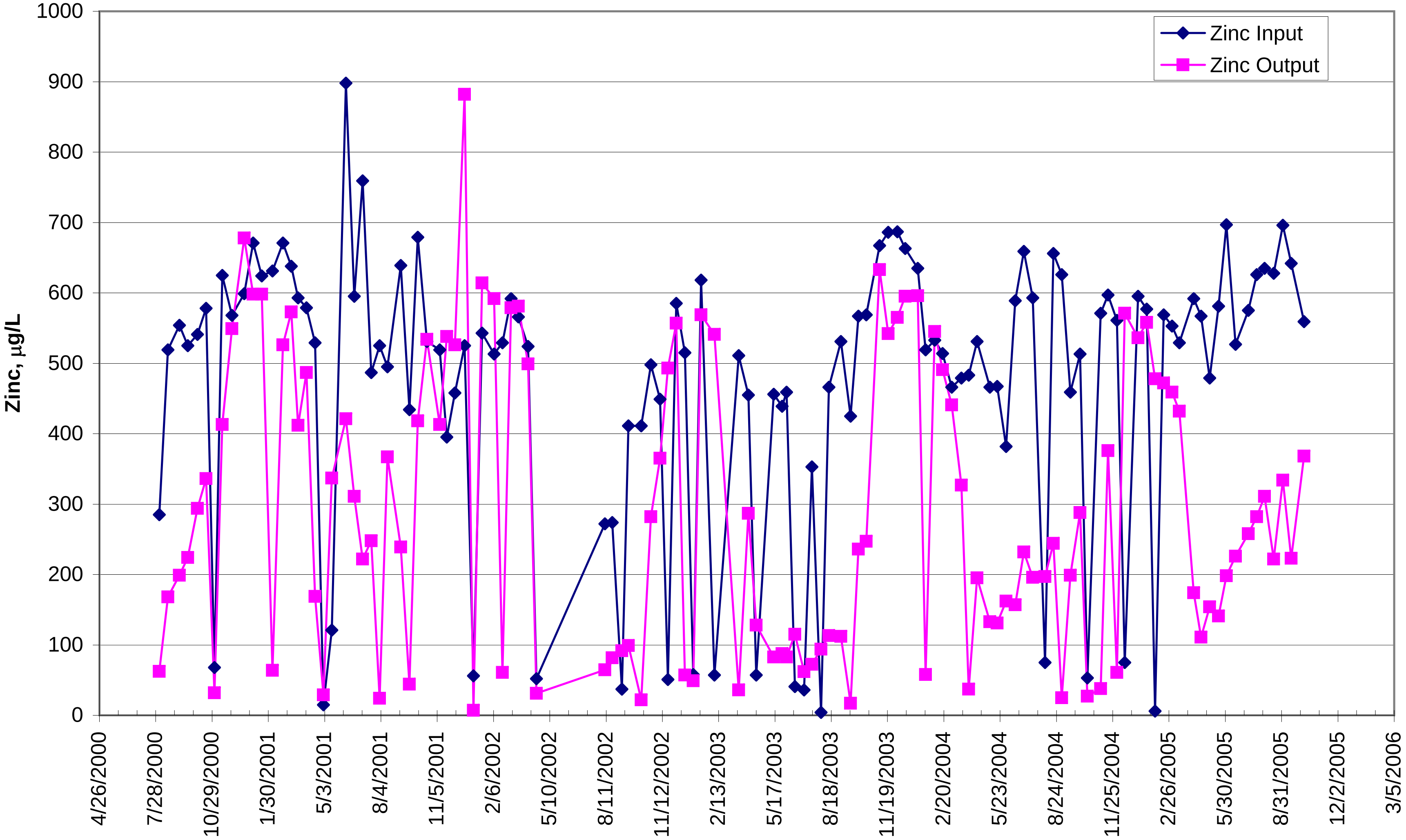


Figure D26: Influent and Effluent Nickel Concentrations
SD009

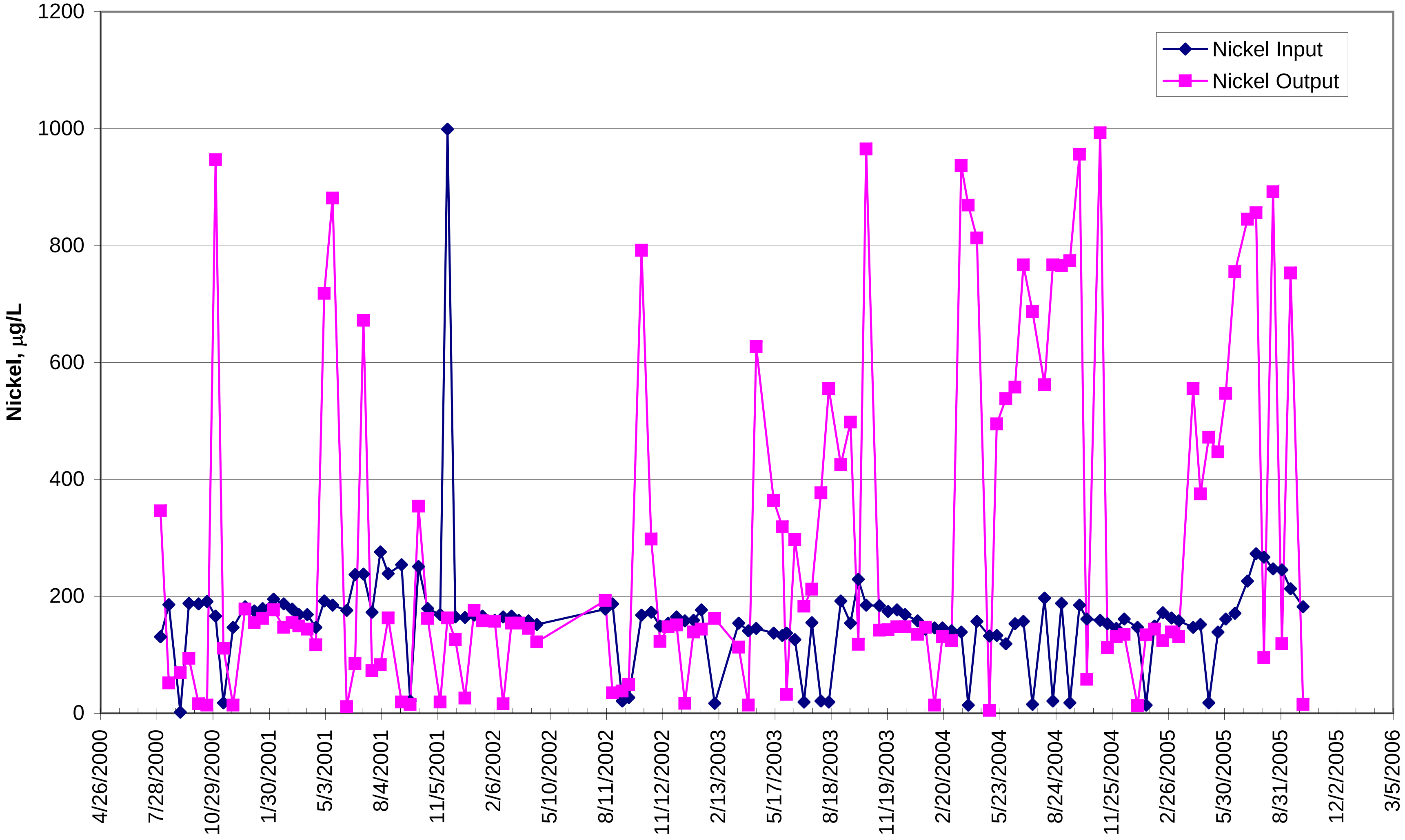


Figure D27: Influent and Effluent Sulfate Concentrations
SD009

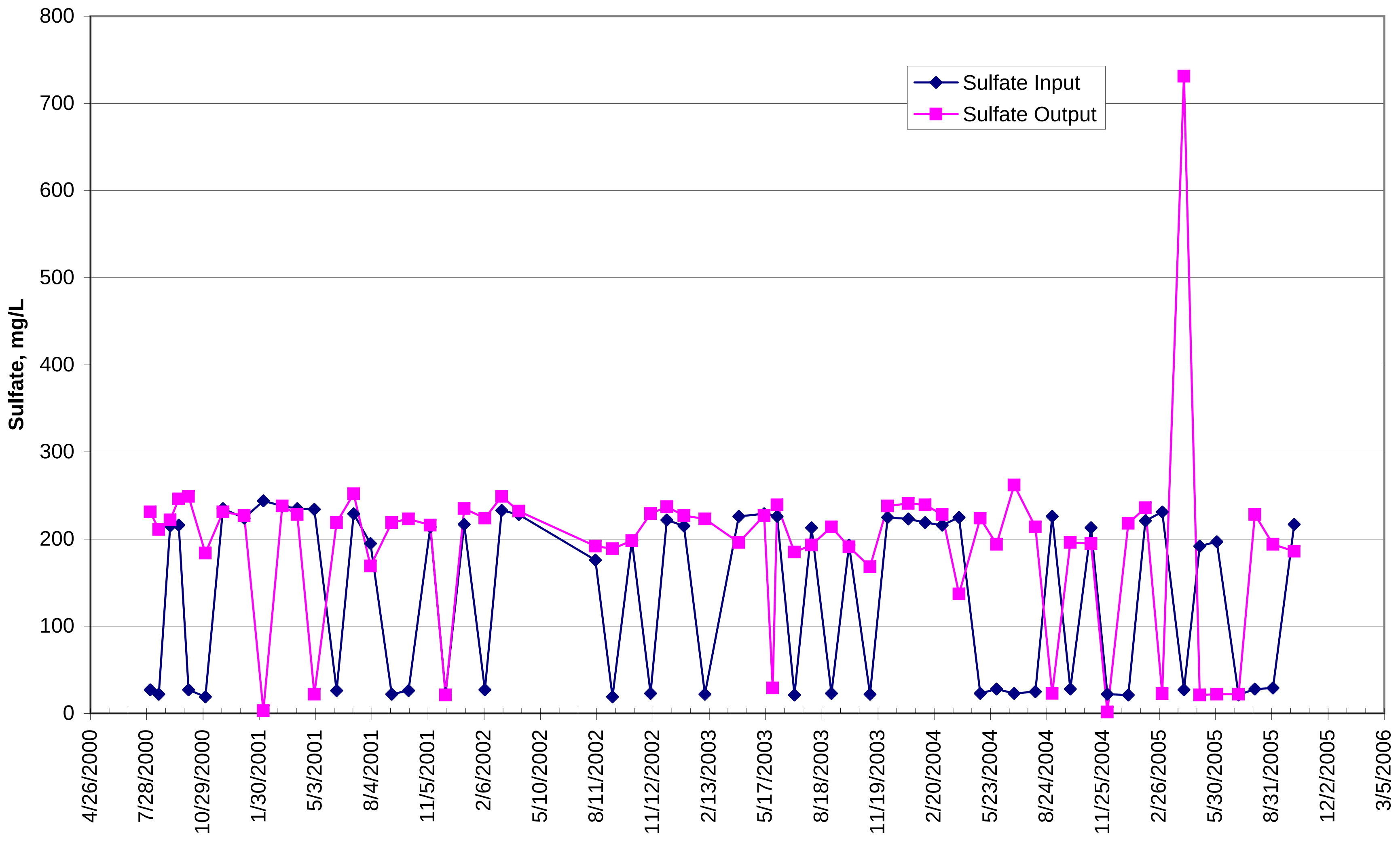
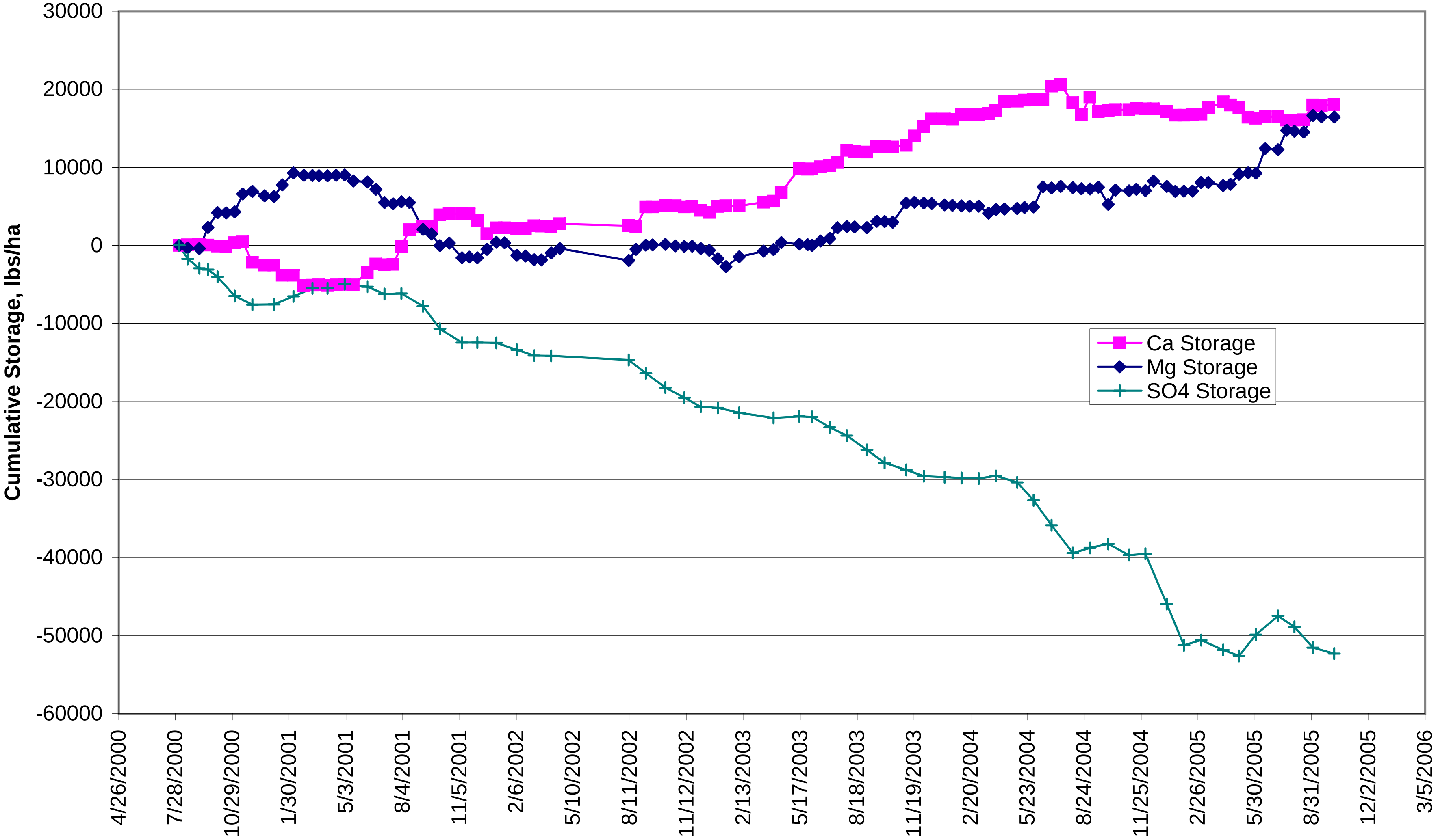


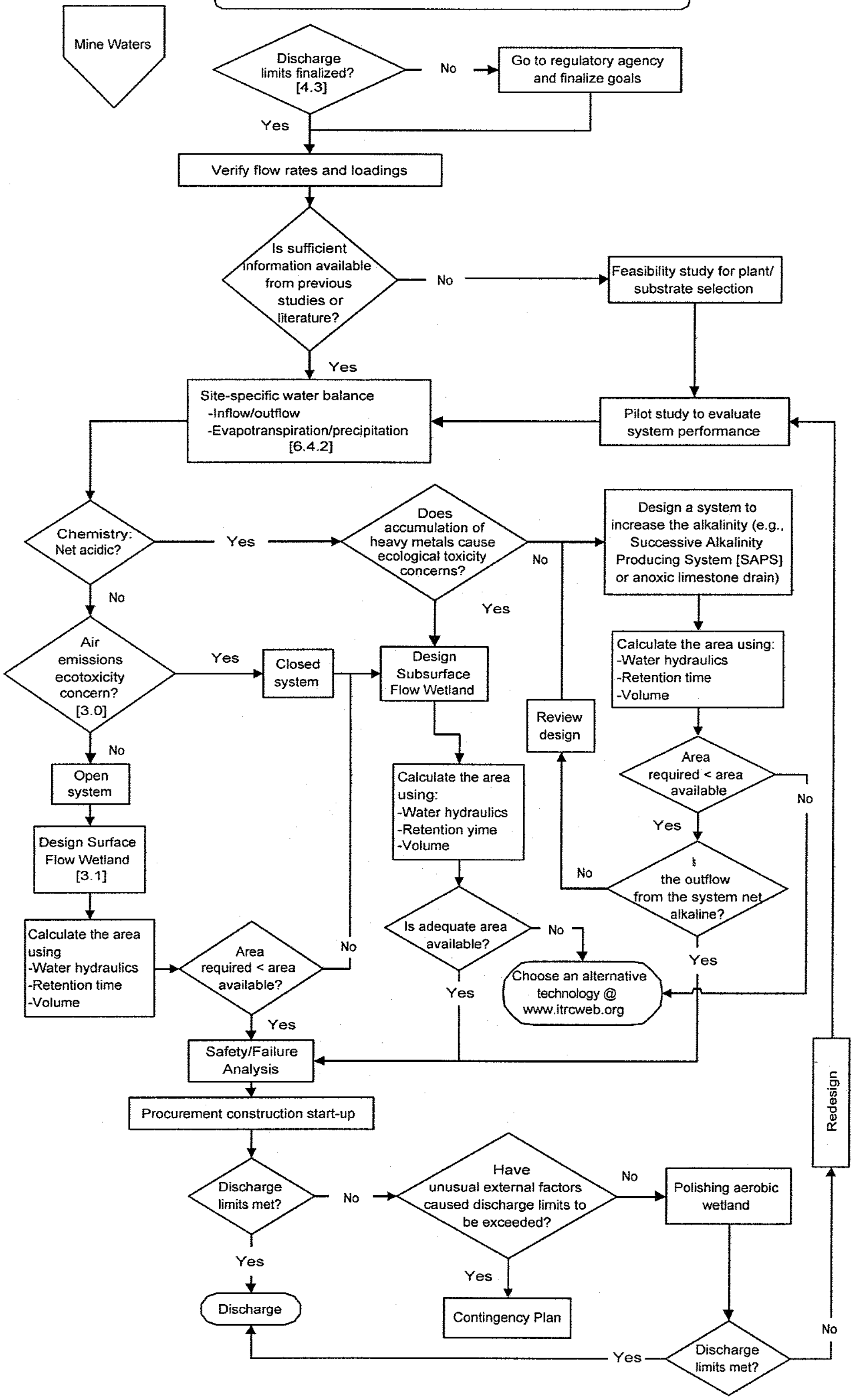
Figure D28: Calcium, Magnesium, and Sulfate Storage
SD009



Appendix E

Decision Tree for Treatment Wetlands

Figure 5-4. Mine Waters Decision Tree



Appendix F

Detailed Cost Estimates for Mine Site Wastewater Treatment Alternatives

Table F-1

Cost Estimate for 1,300 gpm Stage 1 and 3,000 gpm Stage 2 Mine Site Water Treatment-Hydroxide Precipitation

NorthMet Project

Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	USACE EM 1110-1-4012
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Hydroxide Precipitation						
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Stage 2 Hydroxide Precipitation						
Reaction Chambers	LS	$603,000	1		$603,000	USACE EM 1110-1-4012
Clarifier	LS	$1,200,000	1		$1,200,000	USACE EM 1110-1-4012
Sludge Holding Tanks (for both stages)	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Filter Press (for both stages)	LS	$3,600,000	1		$3,600,000	EPA, 1976, pressing gypsum, hydroxide, and carbonate sludge
Recarbonation (inc. calcite clarifier)	LS	$1,300,000	1		$1,300,000	EPA, 1976
Sub-total for Treatment Equipment					$8,109,000	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	600		$90,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	5,000		$500,000	
Pumps	LS	$200,000	1		$200,000	
Piping, Sch.40, 10"	LF	$25	1,000		$25,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	600		$6,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$1,661,800	1		$1,661,800	Previous Project Experience
Sub-total for Pumping/Piping ,Electrical, and Controls					$2,732,800	
Sub-Total: Line 1 Capital Costs					$10,842,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$1,626,000	1		$1,626,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$2,321,000	
TOTAL: Capital, Engineering & Administration					**$13,163,000**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 2 person years)	HR	$50	4,000	$200,000		Previous Project Experience
Treatment Equipment Maintenance (2% of equipment cost)	LS	$162,180	1	$162,180		Previous Project Experience
Pumping O & M	LS	$10,000	1	$10,000		Previous Project Experience (Approx 200 Hrs/month)
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 400 HP average annual usage
Chemical Usage - Lime	Ton	$86	1,150	$98,900		400 mg/L lime Dosage from Preliminary CEMI Report + 2,688 mg/L for gypsum removal @ 170 gpm (yr 10 average, stage 1)
Sludge Trucking to Residue Pile	Ton	$10	19,000	$190,000		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$775,680**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$775,680**	**$13,163,000**
Net Present Value (20 years @ 5%)		**$22,830,000**
Contingency (20 percent)		**$4,566,000**
Total Cost		**$27,396,000**

Table F-2

Cost Estimate for 1,300 gpm Stage 1 and 3,000 gpm Stage 2 Mine Site Water Treatment-Sulfide Precipitation
NorthMet Project
Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	USACE EM 1110-1-4012
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Hydroxide Precipitation						
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Recarbonation (inc. calcite clarifier)	LS	$565,000	1		$565,000	EPA, 1976
Stage 1 Sulfide Precipitation						
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Stage 2 Sulfide Precipitation						
Reaction Chambers (includes pH adjust and chemical feed)	LS	$603,000	1		$603,000	USACE EM 1110-1-4012
Clarifier	LS	$1,200,000	1		$1,200,000	USACE EM 1110-1-4012
Quenching Tank	LS	$200,000	1		$200,000	
Sludge Holding Tanks (both stages)	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Filter Press (both stages)	LS	$3,600,000	1		$3,600,000	EPA, 1976, pressing gypsum, hydroxide, and carbonate sludge
Sub-total for Treatment Equipment					$8,380,000	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	1,000		$150,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	6,000		$600,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	1,000		$25,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	600		$6,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$1,696,000	1		$1,696,000	Previous Project Experience
Sub-total for Pumping/Piping ,Electrical, and Controls					$2,827,000	
Sub-Total: Line 1 Capital Costs					$11,207,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$1,681,000	1		$1,681,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$2,376,000	
TOTAL: Capital, Engineering & Administration					**$13,583,000**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 2 person years)	HR	$50	4,000	$200,000		Previous Project Experience
Treatment Equipment Maintenance (2% of equipment cost)	LS	$167,600	1	$167,600		
Pumping O & M	LS	$10,000	1	$10,000		Previous Project Experience (Approx 200 Hrs/month)
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 400 HP average annual usage
Chemical Usage -NaHS	Ton	$900	6	$5,400		15 mg/L NaHS dosage
Chemical Usage-Lime	Ton	$86	1,150	$98,900		400 mg/L lime Dosage from Preliminary CEMI Report + 2,688 mg/L for gypsum removal @ 170 gpm (yr 10 average, stage 1)
Chemical Usage-FeCl2	Ton	$100	10	$1,000		Quench entire NaHS dosage
Sludge Trucking to Hydromet facility	Ton	$10	19,000	$190,000		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$787,500**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$787,500**	**$13,583,000**
Net Present Value (20 years @ 5%)		**$23,397,000**
Contingency (20 percent)		**$4,679,000**
Total Cost		**$28,076,000**

Table F-3
Cost Estimate for 1,300 gpm Stage 1 and 3,000 gpm Stage 2 Mine Site Water Treatment-Carbonate Precipitation
NorthMet Project
Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	USACE EM 1110-1-4012
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Hydroxide Precipitation						
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Stage 1 Carbonate Precipitation						
Reaction Chambers	LS	$587,000	1		$587,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Stage 2 Carbonate Precipitation						
Reaction Chambers	LS	$603,000	1		$603,000	USACE EM 1110-1-4012
Clarifier	LS	$1,200,000	1		$1,200,000	USACE EM 1110-1-4012
Sludge Holding Tanks (for both stages)	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Filter Press (for both stages)	LS	$3,600,000	1		$3,600,000	EPA, 1976, pressing gypsum, hydroxide, and carbonate sludge
Sub-total for Treatment Equipment					$7,911,000	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	350		$52,500	Means, Previous Project Experience
Treatment Buildings	SF	$100	3,500		$350,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	800		$20,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	300		$3,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$1,602,200	1		$1,602,200	Previous Project Experience
Sub-total for Pumping/Piping ,Electrical, and Controls					$2,377,700	
Sub-Total: Line 1 Capital Costs					$10,289,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$1,543,000	1		$1,543,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$2,238,000	
TOTAL: Capital, Engineering & Administration					**$12,527,000**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 1.5 person years)	HR	$50	3,200	$160,000		Previous Project Experience
Treatment Equipment Maintenance (2% of equipment cost)	LS	$158,220	1	$158,220		
Pumping O & M	LS	$10,000	1	$10,000		Previous Project Experience (Approx 200 Hrs/month)
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 400 HP average annual usage
Chemical Usage-Lime	Ton	$86	1,150	$98,900		
Chemical Usage - Soda Ash	Ton	$269	2,186	$588,024		Dose to precipitate non-Mg species, Vendor price quote
Sludge Trucking to Residue Pile	Ton	$10	19,000	$190,000		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$1,319,744**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$1,319,744**	**$12,527,000**
Net Present Value (20 years @ 5%)		**$28,974,000**
Contingency (20 percent)		**$5,795,000**
Total Cost		**$34,769,000**

Table F-4

Cost Estimate for 1,300 gpm Stage 1 and 3,000 gpm Stage 2 Mine Site Water Treatment-FeS Precipitation

NorthMet Project

Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	USACE EM 1110-1-4012
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Hydroxide Precipitation						
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Recarbonation (inc. calcite clarifier)	LS	$565,000	1		$565,000	EPA, 1976
Stage 1 FeS Precipitation						
Reaction Chambers	LS	$436,500	1		$436,500	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Stage 2 FeS Precipitation						
Reaction Chambers (includes pH adjust and chemical feed)	LS	$904,500	1		$904,500	USACE EM 1110-1-4012
Clarifier	LS	$1,200,000	1		$1,200,000	USACE EM 1110-1-4012
Sludge Holding Tanks	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Filter Press	LS	$3,600,000	1		$3,600,000	EPA 1976, pressing gypsum, hydroxide, and carbonate sludge
Sub-total for Treatment Equipment					$8,627,000	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	1,000		$150,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	6,000		$600,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	800		$20,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	300		$3,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$1,745,400	1		$1,745,400	Previous Project Experience
Sub-total for Pumping/Piping ,Electrical, and Controls					$2,868,400	
Sub-Total: Line 1 Capital Costs					$11,495,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$1,724,000	1		$1,724,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$2,419,000	
TOTAL: Capital, Engineering & Administration					$13,914,000	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 2 person years)	HR	$50	4,000	$200,000		Previous Project Experience
Treatment Equipment Maintenance (2% of equipment cost)	LS	$172,540	1	$172,540		
Pumping O & M	LS	$10,000	1	$10,000		Previous Project Experience (Approx 200 Hrs/month)
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 400 HP average annual usage
Chemical Usage-Lime	Ton	$86	1,150	$98,900		400 mg/L lime Dosage from Preliminary CEMI Report + 2,688 mg/L for gypsum removal @ 170 gpm (yr 10 average, stage 1)
Chemical Usage -FeSO4	Ton	$343	381	$130,882		1:1 stoichiometric ratio of Fe:S
Chemical Usage-NaHS	Ton	$900	562	$505,476		4 times stoichiometric requirement
Sludge Trucking to Hydromet Facility	Ton	$10	19,000	$190,000		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$1,422,398**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$1,422,398**	**$13,914,000**
Net Present Value (20 years @ 5%)		**$31,640,000**
Contingency (20 percent)		**$6,328,000**
Total Cost		**$37,968,000**

Table F-5

Cost Estimate for 1,300 gpm Stage 1 and 3,000 gpm Stage 2 Mine Site Water Treatment-CaS Precipitation

NorthMet Project

Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	USACE EM 1110-1-4012
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Hydroxide Precipitation						
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Recarbonation	LS	$565,000	1		$565,000	EPA, 1976
Stage 1 CaS Precipitation						
Reaction Chambers	LS	$436,500	1		$436,500	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Stage 2 CaS Precipitation						
Reaction Chambers (includes pH adjust and chemical feed)	LS	$904,500	1		$904,500	USACE EM 1110-1-4012
Clarifier	LS	$1,200,000	1		$1,200,000	USACE EM 1110-1-4012
Sludge Holding Tanks	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Filter Press	LS	$3,600,000	1		$3,600,000	USACE EM 1110-1-4012
Sub-total for Treatment Equipment					$8,627,000	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	1,000		$150,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	6,000		$600,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	800		$20,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	300		$3,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$1,745,400	1		$1,745,400	Previous Project Experience
Sub-total for Pumping/Piping ,Electrical, and Controls					$2,868,400	
Sub-Total: Line 1 Capital Costs					$11,495,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$1,724,000	1		$1,724,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$2,419,000	
TOTAL: Capital, Engineering & Administration					**$13,914,000**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 1 person years)	HR	$50	4,000	$200,000		Previous Project Experience
Treatment Equipment Maintenance (2% of equipment cost)	LS	$172,540	1	$172,540		
Pumping O & M	LS	$5,000	1	$5,000		Previous Project Experience (Approx 100 Hrs/month)
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 400 HP average annual usage
Chemical Usage -Lime	Ton	$86	1,290	$110,975		1:1 stoichiometric ratio of S:Ca + 400 mg/L lime Dosage from Preliminary CEMI Report + 2,688 mg/L for gypsum removal @ 170 gpm (yr 10 average, stage 1)
Chemical Usage-NaHS	Ton	$900	140	$126,369		15 mg/L NaHS dosage
Sludge Trucking to Hydromet Facility	Ton	$10	19,000	$190,000		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$919,484**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$919,484**	**$13,914,000**
Net Present Value (20 years @ 5%)		**$25,373,000**
Contingency (20 percent)		**$5,075,000**
Total Cost		**$30,448,000**

Table F-6
Cost Estimate for 1,300 gpm Stage 1 and 3,000 gpm Stage 2Mine Site Water Treatment-Nanofiltration
NorthMet Project
Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Hydroxide Precipitation						
Reaction Chambers	LS	$244,440	1		$244,440	USACE EM 1110-1-4012
Clarifier	LS	$432,600	1		$432,600	USACE EM 1110-1-4012
Stage 1 Nanofiltration						
Nanofiltration Unit	LS	$1,900,000	1		$1,900,000	Vendor Quote, assumes nanofiltration of 1,090 gpm of Stage 1 flow
Stage 2 Hydroxide Precipitation						
Reaction Chambers	LS	$500,000	1		$500,000	USACE EM 1110-1-4012
Clarifier	LS	$1,000,000	1		$1,000,000	USACE EM 1110-1-4012
Sludge Storage Tanks	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Filter Press	LS	$3,600,000	1		$3,600,000	
Recarbonation (inc. calcite clarifier)	LS	$1,300,000	1		$1,300,000	EPA, 1976
Sub-total for Treatment Equipment					$9,577,040	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	300		$45,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	3,000		$300,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	800		$20,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	300		$3,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$1,935,408	1		$1,935,408	Previous Project Experience
Sub-total for Pumping/Piping ,Electrical, and Controls					$2,653,408	
Sub-Total: Line 1 Capital Costs					$12,230,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$1,835,000	1		$1,835,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$2,530,000	
TOTAL: Capital, Engineering & Administration					**$14,760,000**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 2 person years)	HR	$50	4,000	$200,000		Previous Project Experience
Pumping O & M	LS	$10,000	1	$10,000		Previous Project Experience (Approx 200 Hrs/month)
Nanofiltration Unit O&M	1000 GAL	$1.00	572,904	$572,900		Vendor Estimate
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 400 HP average annual usage
Chemical Usage-Lime	Ton	$86	1,150	$98,900		400 mg/L lime Dosage from Preliminary CEMI Report + 2,688 mg/L for gypsum removal @ 170 gpm (yr 10 average, stage 1)
Sludge Trucking to Residue Pile	Ton	$10	19,000	$190,000		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$1,186,400**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$1,186,400**	**$14,760,000**
Net Present Value (20 years @ 5%)		**$32,997,000**
Contingency (20 percent)		**$6,599,000**
Total Cost		**$39,596,000**

Table F-7

Cost Estimate for 1,300 gpm Stage 1 and 1,700 gpm Stage 2 Mine Site Water Treatment-Nanofiltration

NorthMet Project

Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Hydroxide Precipitation						
Reaction Chambers	LS	$244,440	1		$244,440	USACE EM 1110-1-4012
Clarifier	LS	$432,600	1		$432,600	USACE EM 1110-1-4012
Sludge Storage Tanks	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Filter Press	LS	$3,600,000	1		$3,600,000	
Recarbonation (inc. calcite clarifier)	LS	$565,000	1		$565,000	EPA, 1976
Stage 2 Nanofiltration						
Nanofiltration Unit	LS	$3,000,000	1		$3,000,000	Vendor Quote, assumes nanofiltration of 1,700 gpm of Stage 2 flow
		Sub-total for Treatment Equipment			$8,442,040	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	300		$45,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	3,000		$300,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	800		$20,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	300		$3,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$1,708,408	1		$1,708,408	Previous Project Experience
	Sub-total for Pumping/Piping ,Electrical, and Controls				$2,426,408	
Sub-Total: Line 1 Capital Costs					$10,868,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$1,630,000	1		$1,630,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$2,325,000	
<u>TOTAL: Capital, Engineering & Administration</u>					**<u>$13,193,000</u>**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 2 person years)	HR	$50	4,000	$200,000		Previous Project Experience
Pumping O & M	LS	$10,000	1	$10,000		Previous Project Experience (Approx 200 Hrs/month)
Nanofiltration Unit O&M	1000 GAL	$0.90	893,520	$804,200		Vendor Estimate
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 400 HP average annual usage
Chemical Usage-Lime	Ton	$86	1,150	$98,900		400 mg/L lime Dosage from Preliminary CEMI Report + 2,688 mg/L for gypsum removal @ 170 gpm (yr 10 average, stage 1)
Sludge Trucking to Residue Pile	Ton	$10	19,000	$190,000		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$1,417,700**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$1,417,700**	**$13,193,000**
Net Present Value (20 years @ 5%)		**$30,860,000**
Contingency (20 percent)		**$6,172,000**
Total Cost		**$37,032,000**

Table F-8
Cost Estimate for 1,300 gpm Stage 1 and 3,000 gpm Stage 2 Mine Site Water Treatment-Reverse Osmosis
NorthMet Project
Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Hydroxide Precipitation						
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Stage 1 + Stage 2 Reverse Osmosis						
Pre-Treatment (Ultrafiltration)	LS	$7,197,400	1		$7,197,400	Vendor Quote
RO Unit	LS	$3,932,600	1		$3,932,600	Vendor Quote
RO Element-Clean in place skid	LS	$15,000	1		$15,000	Vendor Quote
Brine Treatment-Lime Reactor	LS	$102,000	1		$102,000	USACE EM 1110-1-4012, assumes 35% reject
Brine Treatment-Clarifier	LS	$415,000	1		$415,000	USACE EM 1110-1-4012, assumes 35% reject
Sludge Storage Tanks	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Filter Press	LS	$3,600,000	1		$3,600,000	EPA, 1976
Sub-total for Treatment Equipment					$16,668,000	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	300		$45,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	3,000		$300,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	800		$20,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	300		$3,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$3,353,600	1		$3,353,600	Previous Project Experience
Sub-total for Pumping/Piping ,Electrical, and Controls					$4,071,600	
Sub-Total: Line 1 Capital Costs					$20,740,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$3,111,000	1		$3,111,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$3,806,000	
TOTAL: Capital, Engineering & Administration					**$24,546,000**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 2 person years)	HR	$50	4,000	$200,000		Previous Project Experience
Pumping O & M	LS	$5,000	1	$5,000		Previous Project Experience (Approx 100 Hrs/month)
Reverse Osmosis Unit O&M	1000 GAL	$1.10	1,559,981	$1,716,000		Vendor Estimate
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 400 HP average annual usage
Chemical Usage-Lime	Ton	$86	1,150	$98,900		400 mg/L lime Dosage from Preliminary CEMI Report + 2,688 mg/L for gypsum removal @ 170 gpm (yr 10 average, stage 1)
Sludge Trucking to Residue Pile	Ton	$10	19,000	$190,000		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$2,324,500**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$2,324,500**	**$24,546,000**
Net Present Value (20 years @ 5%)		**$53,514,000**
Contingency (20 percent)		**$10,703,000**
Total Cost		**$64,217,000**

Table F-9
Cost Estimate for 1,300 gpm Stage 1 and 3,000 gpm Stage 2 Mine Site Water Treatment-Ion Exchange
NorthMet Project
Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Ion Exchange						
Pre-Treatment (Prefilter)	LS	$100,000	1		$100,000	
Pre-Treatment (Carbon Filtration)	CF	$21	13985		$290,194	
Ion Exchange Resin	CF	$200	27971		$5,594,100	Capacity for 1-month of flow, duplicate vessels, 0.5# metals/cf resin
Resin Vessels	EA	$10,000	6		$60,000	5,000-gal SS tanks
Regen Lime Precipitation Reactor	LS	$20,000	1		$20,000	
Regen Lime Precipitation Clarifier	LS	$50,000	1		$50,000	
Stage 1 Lime Precipitation						
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Stage 2 Lime Precipitation						
Reaction Chambers	LS	$603,000	1		$603,000	USACE EM 1110-1-4012
Clarifier	LS	$1,200,000	1		$1,200,000	USACE EM 1110-1-4012
Sludge Holding Tanks (for both stages)	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Filter Press (for both stages)	LS	$3,600,000	1		$3,600,000	EPA 1976 pressing gypsum, hydroxide, and carbonate sludge
Recarbonation (inc. calcite clarifier)	LS	$1,300,000	1		$1,300,000	EPA, 1976
		Sub-total for Treatment Equipment			$14,223,294	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	300		$45,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	3,000		$300,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	800		$20,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	300		$3,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$2,864,659	1		$2,864,659	Previous Project Experience
	Sub-total for Pumping/Piping ,Electrical, and Controls				$3,582,659	
Sub-Total: Line 1 Capital Costs					$17,806,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$2,671,000	1		$2,671,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$3,366,000	
TOTAL: Capital, Engineering & Administration					**$21,172,000**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 1.5 person years)	HR	$50	3,200	$160,000		Previous Project Experience
Pumping O & M	LS	$5,000	1	$5,000		Previous Project Experience (Approx 100 Hrs/month)
Resin Replacement	CF	$200.00	2,797	$559,400		Assume replacement of 10 percent per year
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 200 HP average annual usage
Chemical Costs	Ton	$100.00	1,300	$130,000		Acid Regen
Carbon Replacement	Ton	$1,695.00	175	$296,300		
Chemical Usage-Lime	Ton	$86	1,150	$98,900		400 mg/L lime Dosage from Preliminary CEMI Report + 2,688 mg/L for gypsum removal @ 170 gpm (yr 10 average, stage 1)
Sludge Trucking to Residue Pile	Ton	$10	19,000	$190,000		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$1,554,200**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$1,554,200**	**$21,172,000**
Net Present Value (20 years @ 5%)		**$40,540,000**
Contingency (20 percent)		**$8,108,000**
Total Cost		**$48,648,000**

Table F-10

Cost Estimate for 1,300 gpm Stage 1 and 1,700 gpm Stage 2 Mine Site Water Treatment-Constructed Wetland

NorthMet Project

Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	Previous project experience, (1)
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Hydroxide Precipitation						
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Recarbonation (inc. calcite clarifier)	LS	$565,000	1		$565,000	EPA, 1976
Sludge Storage	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Filter Press	LS	$3,600,000	1		$3,600,000	
Stage 2 Wetland Treatment						
Constructed Wetland-Earthwork	AC	$5,000	200		$1,000,000	Previous project experience, IWA 2004
Constructed Wetland-Liner	AC	$65,000	200		$13,000,000	Previous project experience, IWA 2004
Constructed Wetland-Drainage Gravel (6-inch)	AC	$12,000	200		$2,400,000	Previous project experience, IWA 2004
Constructed Wetland-Bed Media (1-meter depth, 50% compost, 50% onsite granular)	AC	$60,000	200		$12,000,000	Previous project experience, IWA 2004
Constructed Wetland-Vegetation	AC	$30,000	200		$6,000,000	Previous project experience, IWA 2004
		Sub-total for Treatment Equipment			$39,971,000	
Treatment Process Pumping and Piping						
Plumbing	AC	$3,200	600		$1,920,000	Previous project experience, IWA 2004
Concrete foundations	CY	$150	200		$30,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	2,000		$200,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	1,000		$25,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	600		$6,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$161,200	1		$161,200	Previous Project Experience
Control Structures	LS	$4,000,000	1		$4,000,000	Previous project experience, IWA 2004
	Sub-total for Pumping/Piping ,Electrical, and Controls				$6,692,200	
Sub-Total: Line 1 Capital Costs					$46,663,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$6,999,000	1		$6,999,000	Previous Project Experience
Construction Management	MO	$35,000	10		$350,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$7,904,000	
TOTAL: Capital, Engineering & Administration					**$54,567,000**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 0.5 person years)	HR	$50	1,067	$53,333		Previous Project Experience
Treatment Equipment Maintenance (2% of Stage 1 cost)	LS	$21,120	1	$21,120		Previous Project Experience
Pumping O & M	LS	$10,000	1	$10,000		Previous Project Experience (Approx 200 Hrs/month)
Leachate Trucking from Residue Pile	Gal					
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 200 HP average annual usage
Chemical Usage - Lime	Ton	$86	1,150	$98,900		400 mg/L lime Dosage from Preliminary CEMI Report + 2,688 mg/L for gypsum removal @ 170 gpm (yr 10 average, stage 1)
Sludge Trucking to Residue Pile	Ton	$10	19,000	$190,000		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$487,953**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$487,953**	**$54,567,000**
Net Present Value (20 years @ 5%)		**$60,648,000**
Contingency (20 percent)		**$12,130,000**
Total Cost		**$72,778,000**

Table F-11

Cost Estimate for 1,300 gpm Stage 1 and 3,000 gpm Stage 2 Mine Site Water Treatment-Biological Treatment of Stage 1

NorthMet Project

Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	USACE EM 1110-1-4012
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Biological Sulfate Removal						
Bioreactor	LS	$1,100,000	1		$1,100,000	EPA, 1976
Clarifier	LS	$984,000	1		$984,000	EPA, 1976
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Reaeration	LS	$200,000	1		$200,000	
Sludge Holding Tanks (Biosolids)	LS	$240,000	1		$240,000	7 days' storage @ $1 per gallon
Sludge Holding Tanks (FeS Sludge)	LS	$200,000	1		$200,000	7 days' storage @ $1 per gallon
Filter Press	LS	$4,600,000	1		$4,600,000	EPA, 1976
Sub-total for Treatment Equipment					$8,380,000	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	1,000		$150,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	6,000		$600,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	800		$20,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	300		$3,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$1,696,000	1		$1,696,000	Previous Project Experience
Sub-total for Pumping/Piping ,Electrical, and Controls					$2,819,000	
Sub-Total: Line 1 Capital Costs					$11,199,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$1,680,000	1		$1,680,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$2,375,000	
TOTAL: Capital, Engineering & Administration					**$13,574,000**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 2 person years)	HR	$50	4,000	$200,000		Previous Project Experience
Treatment Equipment Maintenance (2% of equipment cost)	LS	$167,600	1	$167,600		
Pumping O & M	LS	$10,000	1	$10,000		Previous Project Experience (Approx 200 Hrs/month)
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 400 HP average annual usage
Chemical Usage-ethanol	Ton	$607	1,067	$647,669		0.4 lb ethanol per lb sulfate
Chemical Usage-Nitrogen (28-0-0)	Ton	$800	73	$58,400		0.14 lb N per lb sludge
Chemical Usage-Phosphorus (0-46-0)	Ton	$1,280	16	$19,968		0.03 lb P per lb sludge
FeCl2	Ton	$100	3,540	$354,000		1:1 stoichiometric ratio of Fe:S
Biosolids Trucking and Disposal	Ton	$35	2,600	$91,000		20 percent solids, local tipping
FeS Sludge-Trucking to Hydromet	Ton	$10.00	11,324	$113,240		20 percent solids, 15 mile round trip
TOTAL: Annual Costs				**$1,776,477**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$1,776,477**	**$13,574,000**
Net Present Value (20 years @ 5%)		**$35,712,000**
Contingency (20 percent)		**$7,142,000**
Total Cost		**$42,854,000**

Table F-12

Cost Estimate for 1,300 gpm Stage 1 and 3,000 gpm Stage 2 Mine Site Process Water Treatment-Biological Treatment of Stage 2

NorthMet Project

Polymet Inc., Hoyt Lakes, MN

Item	Unit	Estimated Unit Cost	Estimated Quantity	Annual Cost	Capital Cost	Basis for Cost Estimate
Capital Costs						
Treatment						
Flow Equalization	LS	$200,000	1		$200,000	USACE EM 1110-1-4012
Preaeration	LS	$50,000	1		$50,000	
Stage 1 Hydroxide Precipitation						
Reaction Chambers	LS	$291,000	1		$291,000	USACE EM 1110-1-4012
Clarifier	LS	$515,000	1		$515,000	USACE EM 1110-1-4012
Recarbonation (Incl. Clarifier)	LS	$1,300,000	1		$1,300,000	EPA, 1976
Sludge Holding Tanks (Gypsum, calcite)	LS	$350,000	1		$350,000	7 days' storage @ $1 per gallon
Stage 2 Biological Sulfate Removal						
Bioreactor	LS	$2,300,000	1		$2,300,000	EPA, 1976
Clarifier	LS	$1,600,000	1		$1,600,000	EPA, 1976
Reaction Chambers	LS	$603,000	1		$603,000	USACE EM 1110-1-4012
Clarifier	LS	$1,200,000	1		$1,200,000	USACE EM 1110-1-4012
Reaeration	LS	$200,000	1		$200,000	
Sludge Holding Tanks (Biosolids)	LS	$50,000	1		$50,000	7 days' storage @ $1 per gallon
Sludge Holding Tanks (FeS)	LS	$6,800	1		$6,800	7 days' storage @ $1 per gallon
Filter Press	LS	$3,600,000	1		$3,600,000	EPA, 1976
Sub-total for Treatment Equipment					$12,265,800	
Treatment Process Pumping and Piping						
Concrete foundations	CY	$150	1,000		$150,000	Means, Previous Project Experience
Treatment Buildings	SF	$100	6,000		$600,000	
Pumps	LS	$100,000	1		$100,000	
Piping, Sch.40, 10"	LF	$25	800		$20,000	Means, Previous Project Experience
Piping, Sch.40, 4"	LF	$10	300		$3,000	Means, Previous Project Experience
Installation labor	HR	$50	5,000		$250,000	Assume 10 person Crew for 12 Weeks
Electrical Service Installation and Controls (20% of Treatment Equipment Cost)	LS	$2,473,160	1		$2,473,160	Previous Project Experience
Sub-total for Pumping/Piping ,Electrical, and Controls					$3,596,160	
Sub-Total: Capital Costs					$15,862,000	
Engineering & Administration						
Pilot Testing	LS	$500,000	1		$500,000	Previous Project Experience
Treatment Design (15 % of Total Capital Cost)	LS	$2,379,000	1		$2,379,000	Previous Project Experience
Construction Management	MO	$35,000	4		$140,000	Previous Project Experience (Approx 100 Hrs/month)
Full Scale Technical Assistance and Start-Up	LS	$55,000	1		$55,000	Previous Project Experience
Sub-total: Engineering & Administration					$3,074,000	
TOTAL: Capital, Engineering & Administration					**$18,936,000**	
Operations & Maintenance Costs						
Project Management	LS	$10,000	1	$10,000		Previous Project Experience
Operating Labor (assumes 2 person years)	HR	$50	4,000	$200,000		Previous Project Experience
Treatment Equipment Maintenance (2% of equipment cost)	LS	$245,316	1	$245,316		
Pumping O & M	LS	$10,000	1	$10,000		Previous Project Experience (Approx 200 Hrs/month)
Electrical Costs (~400 HP average over the year)	KW-HR	$0.04	2,614,000	$104,600		$0.04 per KWH, 400 HP average annual usage
Chemical Usage-Ethanol	Ton	$607	213	$129,291		0.4 lb ethanol per lb sulfate
Chemical Usage-Nitrogen (28-0-0)	Ton	$800	15	$12,000		0.14 lb N per lb sludge
Chemical Usage-Phosphorus (0-46-0)	Ton	$1,280	3	$3,994		0.03 lb P per lb sludge
FeCl2	Ton	$100	121	$12,100		1:1 stoichiometric ratio of Fe:S
Chemical Usage-Lime	Ton	$86	1,150	$98,900		400 mg/L lime Dosage from Preliminary CEMI Report + 2,688 mg/L for gypsum removal @ 170 gpm (yr 10 average, stage 1)
Biological Sludge Trucking and Disposal	Ton	$35	520	$18,200		20 percent solids, local tipping fee
FeS sludge Trucking to Hydromet	Ton	$10.00	388	$3,880		20 percent solids, 15 mi trip to hydromet
Gypsum/Calcite Sludge Trucking to Residue Pile	Ton	$10.00	19,000	$190,000		
TOTAL: Annual Costs				**$1,038,281**		

	Annual Cost	Capital Cost
TOTAL: Wastewater Treatment - Estimated Cost	**$1,038,281**	**$18,936,000**
Net Present Value (20 years @ 5%)		**$31,875,000**
Contingency (20 percent)		**$6,375,000**
Total Cost		**$38,250,000**

Appendix G

WWTF Treatment Estimates

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Stage 2: Nanofiltration
Influent Streams [1]

Category 1 and 2 Stockpile		Year				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	85.8	99.6	50.1	120.6	120.6
Alkalinity	mg/L	0.67	72.5	72.5	72.5	72.5
Hardness	mg/L	0.48	1157	1729	1729	1729
F	mg/L	0.0040	9.73	55.1	27.6	27.6
Cl	mg/L	0.058	40.1	84.3	0.0	0.0
SO_4	mg/L	0.35	845	2340	2340	2340
Al	mg/L	0.013	1.68	1.68	1.68	1.68
As	mg/L	0.00067	0.71	0.71	0.71	0.71
Ba	mg/L	0.0013	0.19	0.19	0.19	0.19
Be	mg/L	0.000015	0.00020	0.00020	0.00020	0.00020
B	mg/L	0.00059	0.76	0.76	0.76	0.76
Cd	mg/L	0.0000030	0.00018	0.00018	0.00018	0.00018
Ca	mg/L	0.15	359	540	540	540
Cr	mg/L	0.000016	0.0015	0.0015	0.0015	0.0015
Co	mg/L	0.0000080	0.019	0.052	0.052	0.052
Cu	mg/L	0.00013	0.092	0.092	0.092	0.092
Fe	mg/L	0.0023	0.81	0.81	0.81	0.81
Pb	mg/L	0.0000095	0.023	0.053	0.053	0.053
Mg	mg/L	0.026	63.4	93.0	93.0	93.0
Mn	mg/L	0.00015	0.35	0.75	0.75	0.75
Hg	mg/L	6.81E-07	6.00E-06	6.00E-06	6.00E-06	6.00E-06
Mo	mg/L	0.0000041	0.0051	0.0051	0.0051	0.0051
Ni	mg/L	0.000037	0.089	0.51	0.25	0.25
PO_4	mg/L	0.0030	0.20	0.20	0.20	0.20
K	mg/L	0.11	49.0	49.0	49.0	49.0
Se	mg/L	0.000016	0.0029	0.0029	0.0029	0.0029
SiO_2	mg/L	0.16	8.65	8.65	8.65	8.65
Ag	mg/L	0.0000038	0.00070	0.00070	0.00070	0.00070
Na	mg/L	0.22	543	681	681	681
Tl	mg/L	0.0000015	0.000020	0.000020	0.000020	0.000020
Zn	mg/L	0.00020	0.090	0.090	0.090	0.090
NO_3	mg-N/L	0.00075	0.52	1.09	0.0	0.0
NH_4	mg-N/L	0.00075	0.52	1.09	0.0	0.0

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

East Pit Dewatering		**Year**				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	201	774	820	0.0	0.0
Alkalinity	mg/L	60.6	64.3	63.9	0.0	0.0
Hardness	mg/L	93.5	73.1	77.4	0.0	0.0
F	mg/L	0.26	0.26	0.26	0.0	0.0
Cl	mg/L	1.30	1.31	1.31	0.0	0.0
SO_4	mg/L	94.9	41.5	50.9	0.0	0.0
Al	mg/L	0.60	0.28	0.33	0.0	0.0
As	mg/L	0.033	0.012	0.016	0.0	0.0
Ba	mg/L	0.027	0.017	0.019	0.0	0.0
Be	mg/L	0.00038	0.00028	0.00030	0.0	0.0
B	mg/L	0.13	0.10	0.10	0.0	0.0
Cd	mg/L	0.00068	0.00056	0.00053	0.0	0.0
Ca	mg/L	23.7	16.2	17.8	0.0	0.0
Cr	mg/L	0.0011	0.0011	0.0011	0.0	0.0
Co	mg/L	0.012	0.010	0.0092	0.0	0.0
Cu	mg/L	0.0094	0.0050	0.0059	0.0	0.0
Fe	mg/L	2.84	2.46	2.19	0.0	0.0
Pb	mg/L	0.0016	0.0013	0.0013	0.0	0.0
Mg	mg/L	8.38	7.95	8.04	0.0	0.0
Mn	mg/L	0.075	0.056	0.057	0.0	0.0
Hg	mg/L	5.08E-06	2.76E-06	3.07E-06	0.0	0.0
Mo	mg/L	0.0046	0.0047	0.0047	0.0	0.0
Ni	mg/L	0.16	0.13	0.12	0.0	0.0
PO_4	mg/L	0.0	0.0	0.0	0.0	0.0
K	mg/L	3.28	1.29	1.65	0.0	0.0
Se	mg/L	0.0020	0.0020	0.0020	0.0	0.0
SiO_2	mg/L	0.0	0.0	0.0	0.0	0.0
Ag	mg/L	0.00092	0.00095	0.00095	0.0	0.0
Na	mg/L	21.9	6.66	9.77	0.0	0.0
Tl	mg/L	0.0017	0.0019	0.0018	0.0	0.0
Zn	mg/L	0.18	0.16	0.14	0.0	0.0
NO_3	mg-N/L	0.085	0.093	0.092	0.0	0.0
NH_4	mg-N/L	0.085	0.093	0.092	0.0	0.0

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

West Pit Dewatering/ Haul Roads/ Central Pit		**Year**				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	125	170	263	604	960
Alkalinity	mg/L	52.2	42.7	42.3	53.7	60.5
Hardness	mg/L	115	197	210	138	102
F	mg/L	0.26	0.25	0.25	0.26	0.26
Cl	mg/L	1.27	1.24	1.25	1.28	1.30
SO_4	mg/L	161	356	381	202	107
Al	mg/L	1.13	2.15	2.25	1.22	0.65
As	mg/L	0.075	0.15	0.15	0.083	0.043
Ba	mg/L	0.061	0.084	0.084	0.052	0.032
Be	mg/L	0.00045	0.00081	0.00085	0.00053	0.00037
B	mg/L	0.15	0.27	0.28	0.18	0.13
Cd	mg/L	0.00044	0.00083	0.00086	0.00054	0.00038
Ca	mg/L	33.9	62.4	66.6	40.7	27.1
Cr	mg/L	0.0011	0.0012	0.0012	0.0011	0.0011
Co	mg/L	0.0057	0.0086	0.0087	0.0061	0.0041
Cu	mg/L	0.020	0.033	0.035	0.021	0.012
Fe	mg/L	0.56	1.43	1.37	0.83	0.61
Pb	mg/L	0.0015	0.0024	0.0025	0.0018	0.0014
Mg	mg/L	7.33	10.1	10.7	8.99	8.35
Mn	mg/L	0.074	0.13	0.14	0.087	0.057
Hg	mg/L	6.00E-06	6.00E-06	6.00E-06	6.00E-06	6.00E-06
Mo	mg/L	0.0033	0.0037	0.0039	0.0042	0.0046
Ni	mg/L	0.068	0.11	0.11	0.072	0.045
PO_4	mg/L	0.0	0.0	0.0	0.0	0.0
K	mg/L	7.76	13.4	14.0	7.70	3.98
Se	mg/L	0.0019	0.0021	0.0021	0.0021	0.0020
SiO_2	mg/L	0.0	0.0	0.0	0.0	0.0
Ag	mg/L	0.00070	0.00071	0.00074	0.00083	0.00091
Na	mg/L	46.4	101	108	56.2	28.5
Tl	mg/L	0.0010	0.00088	0.00093	0.0013	0.0017
Zn	mg/L	0.029	0.062	0.056	0.041	0.037
NO_3	mg-N/L	0.051	0.043	0.045	0.067	0.082
NH_4	mg-N/L	0.051	0.043	0.045	0.067	0.082

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Loadout		**Year**				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	6.05	6.05	6.05	6.05	6.05
Alkalinity	mg/L	7.34	7.34	7.34	7.34	7.34
Hardness	mg/L	34.7	34.7	34.7	34.7	34.7
F	mg/L	0.058	0.058	0.058	0.058	0.058
Cl	mg/L	0.16	0.16	0.16	0.16	0.16
SO_4	mg/L	32.0	32.0	32.0	32.0	32.0
Al	mg/L	0.023	0.023	0.023	0.023	0.023
As	mg/L	0.0019	0.0019	0.0019	0.0019	0.0019
Ba	mg/L	0.0083	0.0083	0.0083	0.0083	0.0083
Be	mg/L	0.00014	0.00014	0.00014	0.00014	0.00014
B	mg/L	0.015	0.015	0.015	0.015	0.015
Cd	mg/L	0.000031	0.000031	0.000031	0.000031	0.000031
Ca	mg/L	10.3	10.3	10.3	10.3	10.3
Cr	mg/L	0.00014	0.00014	0.00014	0.00014	0.00014
Co	mg/L	0.0040	0.0040	0.0040	0.0040	0.0040
Cu	mg/L	0.0074	0.0074	0.0074	0.0074	0.0074
Fe	mg/L	0.010	0.010	0.010	0.010	0.010
Pb	mg/L	0.00011	0.00011	0.00011	0.00011	0.00011
Mg	mg/L	2.16	2.16	2.16	2.16	2.16
Mn	mg/L	0.032	0.032	0.032	0.032	0.032
Hg	mg/L	6.00E-06	6.00E-06	6.00E-06	6.00E-06	6.00E-06
Mo	mg/L	0.000048	0.000048	0.000048	0.000048	0.000048
Ni	mg/L	0.080	0.08	0.08	0.080	0.080
PO_4	mg/L	0.021	0.021	0.021	0.021	0.021
K	mg/L	1.47	1.47	1.47	1.47	1.47
Se	mg/L	0.00016	0.00016	0.00016	0.00016	0.00016
SiO_2	mg/L	1.67	1.67	1.67	1.67	1.67
Ag	mg/L	0.000035	0.000035	0.000035	0.000035	0.000035
Na	mg/L	1.52	1.52	1.52	1.52	1.52
Tl	mg/L	0.000014	0.000014	0.000014	0.000014	0.000014
Zn	mg/L	0.0030	0.0030	0.0030	0.0030	0.0030
NO_3	mg-N/L	0.0021	0.0021	0.0021	0.0021	0.0021
NH_4	mg-N/L	0.0021	0.0021	0.0021	0.0021	0.0021

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Stage 2 Combined Influent		**Year**				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	418	1050	1139	731	1086
Alkalinity	mg/L	45.0	61.3	59.0	56.4	61.5
Hardness	mg/L	79.9	196	180	400	282
F	mg/L	0.20	1.16	2.67	4.77	3.30
Cl	mg/L	1.02	4.98	4.94	1.06	1.15
SO_4	mg/L	94	169	228	554	355
Al	mg/L	0.63	0.72	0.83	1.28	0.76
As	mg/L	0.038	0.10	0.078	0.19	0.12
Ba	mg/L	0.032	0.044	0.041	0.074	0.049
Be	mg/L	0.00032	0.00036	0.00042	0.00048	0.00035
B	mg/L	0.11	0.19	0.17	0.28	0.20
Cd	mg/L	0.00046	0.00056	0.00059	0.00047	0.00035
Ca	mg/L	21.7	56.2	52.0	123	83.9
Cr	mg/L	0.00087	0.0011	0.0011	0.0012	0.0011
Co	mg/L	0.0075	0.011	0.011	0.014	0.009
Cu	mg/L	0.011	0.018	0.016	0.032	0.021
Fe	mg/L	1.53	2.12	1.93	0.82	0.63
Pb	mg/L	0.0012	0.0035	0.0039	0.010	0.0071
Mg	mg/L	6.26	13.5	12.4	22.8	17.7
Mn	mg/L	0.059	0.10	0.11	0.20	0.13
Hg	mg/L	4.47E-06	3.61E-06	3.89E-06	6.00E-06	6.00E-06
Mo	mg/L	0.0032	0.0046	0.0045	0.0043	0.0046
Ni	mg/L	0.10	0.13	0.13	0.10	0.07
PO_4	mg/L	0.0009	0.019	0.009	0.033	0.022
K	mg/L	3.94	7.79	6.58	14.5	9.0
Se	mg/L	0.0015	0.0021	0.0021	0.0022	0.0021
SiO_2	mg/L	0.06	0.83	0.39	1.44	0.97
Ag	mg/L	0.00065	0.00089	0.00089	0.00080	0.00088
Na	mg/L	24.5	72.8	61.9	159	101
Tl	mg/L	0.0011	0.0015	0.0015	0.0011	0.0015
Zn	mg/L	0.095	0.14	0.12	0.049	0.043
NO_3	mg-N/L	0.065	0.15	0.15	0.0	0.0
NH_4	mg-N/L	0.065	0.15	0.15	0.0	0.0

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Stage 2 Effluent [5]		Year				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	376	945	1025	658	978
Alkalinity	mg/L	2.62	3.47	3.37	3.47	3.78
Hardness	mg/L	4.99	11.2	10.5	23.8	17.4
F	mg/L	0.012	0.065	0.15	0.27	0.19
Cl	mg/L	0.059	0.28	0.28	0.066	0.072
SO_4	mg/L	5.76	9.64	13.1	32.2	21.3
Al	mg/L	0.035	0.040	0.047	0.072	0.043
As	mg/L	0.0022	0.0056	0.0044	0.010	0.0066
Ba	mg/L	0.0019	0.0025	0.0024	0.0045	0.0031
Be	mg/L	0.000020	0.000021	0.000025	0.000033	0.000026
B	mg/L	0.0061	0.011	0.010	0.016	0.012
Cd	mg/L	0.000026	0.000032	0.000033	0.000028	0.000021
Ca	mg/L	1.37	3.21	3.02	7.29	5.17
Cr	mg/L	0.000050	0.000064	0.000064	0.000072	0.000070
Co	mg/L	0.00048	0.00063	0.00066	0.00094	0.00071
Cu	mg/L	0.00071	0.0010	0.0010	0.0021	0.0015
Fe	mg/L	0.085	0.12	0.11	0.046	0.035
Pb	mg/L	0.000068	0.00020	0.00022	0.00057	0.00040
Mg	mg/L	0.38	0.77	0.71	1.36	1.09
Mn	mg/L	0.0038	0.0056	0.0063	0.012	0.0090
Hg	mg/L	6.24E-07	5.52E-07	5.87E-07	1.39E-06	1.15E-06
Mo	mg/L	0.00018	0.00025	0.00025	0.00024	0.00026
Ni	mg/L	0.0067	0.0077	0.0085	0.0093	0.0077
PO_4	mg/L	0.00038	0.0012	0.00076	0.0028	0.0023
K	mg/L	0.24	0.45	0.38	0.87	0.57
Se	mg/L	0.000088	0.00012	0.00012	0.00013	0.00013
SiO_2	mg/L	0.030	0.061	0.043	0.16	0.14
Ag	mg/L	0.000037	0.000049	0.000050	0.000046	0.000051
Na	mg/L	1.39	4.06	3.46	8.89	5.67
Tl	mg/L	0.000063	0.000084	0.000086	0.000063	0.000082
Zn	mg/L	0.0053	0.0077	0.0067	0.0029	0.0025
NO_3	mg-N/L	0.0037	0.0084	0.0082	0.0	0.0
NH_4	mg-N/L	0.0037	0.0084	0.0082	0.0	0.0

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Stage 1: Chemical Precipitation
Influent Streams [1]

Category 3 Stockpile		Year				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	3.79	14.7	25.3	34.4	10.0
Alkalinity	mg/L	72.5	72.5	72.5	72.5	72.5
Hardness	mg/L	1145	1729	5419	5436	5436
F	mg/L	3.29	9.70	12.2	17.0	85.5
Cl	mg/L	19.1	12.9	5.74	8.41	53.5
SO_4	mg/L	1539	2340	9600	9600	9600
Al	mg/L	1.68	1.68	83.0	83.0	83.0
As	mg/L	0.71	0.71	0.71	0.71	0.71
Ba	mg/L	0.19	0.19	0.19	0.19	0.19
Be	mg/L	0.00020	0.00020	0.0023	0.0023	0.0023
B	mg/L	0.73	0.76	0.76	0.76	0.76
Cd	mg/L	0.00018	0.00018	0.0149	0.0149	0.0149
Ca	mg/L	371	540	480	480	480
Cr	mg/L	0.0015	0.0015	0.0015	0.0015	0.0015
Co	mg/L	0.052	0.052	15.4	24.0	44.0
Cu	mg/L	0.092	0.092	21.8	33.9	202
Fe	mg/L	0.81	0.81	28.7	44.7	235
Pb	mg/L	0.0092	0.027	0.053	0.053	0.053
Mg	mg/L	53.1	93.0	1026	1030	1030
Mn	mg/L	0.75	0.75	47.0	47.0	47.0
Hg	mg/L	6.00E-06	6.00E-06	6.00E-06	6.00E-06	6.00E-06
Mo	mg/L	0.0051	0.0051	0.0051	0.0051	0.0051
Ni	mg/L	0.86	0.86	182	284	762
PO_4	mg/L	0.20	0.20	0.20	0.20	0.20
K	mg/L	49.0	49.0	38.0	38.0	38.0
Se	mg/L	0.0029	0.0029	0.0029	0.0029	0.0029
SiO_2	mg/L	8.65	8.65	3.88	3.88	3.88
Ag	mg/L	0.00070	0.00070	0.00070	0.00070	0.00070
Na	mg/L	267	681	338	338	338
Tl	mg/L	0.000020	0.000020	0.000060	0.000060	0.000060
Zn	mg/L	0.090	0.090	10.5	16.4	26
NO_3	mg-N/L	0.20	0.14	0.060	0.088	0.56
NH_4	mg-N/L	0.20	0.14	0.060	0.088	0.56

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Category 3 LO Stockpile		**Year**				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	22.7	36.7	33.7	26.2	22.5
Alkalinity	mg/L	72.5	72.5	72.5	72.5	72.5
Hardness	mg/L	1432	1729	5436	5436	5436
F	mg/L	4.11	13.13	28.1	68.2	107
Cl	mg/L	23.8	9.82	17.7	61.4	31.5
SO_4	mg/L	1925	2340	9600	9600	9600
Al	mg/L	1.68	1.68	83.0	83.0	83.0
As	mg/L	0.71	0.71	0.71	0.71	0.71
Ba	mg/L	0.19	0.19	0.19	0.19	0.19
Be	mg/L	0.00020	0.00020	0.0023	0.0023	0.0023
B	mg/L	0.76	0.76	0.76	0.76	0.76
Cd	mg/L	0.00018	0.00018	0.015	0.015	0.015
Ca	mg/L	465	540	480	480	480
Cr	mg/L	0.0015	0.0015	0.0015	0.0015	0.0015
Co	mg/L	0.052	0.052	38.5	44.0	44.0
Cu	mg/L	0.092	0.092	54.3	136	202
Fe	mg/L	0.81	0.81	71.7	180	235
Pb	mg/L	0.012	0.037	0.053	0.053	0.053
Mg	mg/L	66.4	93.0	1030	1030	1030
Mn	mg/L	0.75	0.75	47.0	47.0	47.0
Hg	mg/L	6.00E-06	6.00E-06	6.00E-06	6.00E-06	6.00E-06
Mo	mg/L	0.0051	0.0051	0.0051	0.0051	0.0051
Ni	mg/L	0.86	0.86	455	762	762
PO_4	mg/L	0.20	0.20	0.20	0.20	0.20
K	mg/L	49.0	49.0	38.0	38.0	38.0
Se	mg/L	0.0029	0.0029	0.0029	0.0029	0.0029
SiO_2	mg/L	8.65	8.65	3.88	3.88	3.88
Ag	mg/L	0.00070	0.00070	0.00070	0.00070	0.00070
Na	mg/L	334	681	338	338	338
Tl	mg/L	0.000020	0.000020	0.000060	0.000060	0.000060
Zn	mg/L	0.090	0.090	26.0	26.0	26.0
NO_3	mg-N/L	0.25	0.10	0.19	0.65	0.33
NH_4	mg-N/L	0.25	0.10	0.19	0.65	0.33

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Category 4 Stockpile		**Year**				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	2.87	22.9	25.8	23.3	0.92
Alkalinity	mg/L	4.61	20.3	47.4	63.5	72.5
Hardness	mg/L	602	2644	4891	5436	5436
F	mg/L	0.20	0.20	0.20	0.20	0.20
Cl	mg/L	6.51	11.2	5.63	0.28	16.1
SO_4	mg/L	3107	9600	9600	9600	9600
Al	mg/L	22.7	83.0	83.0	83.0	83.0
As	mg/L	0.044	0.19	0.45	0.61	0.71
Ba	mg/L	0.19	0.19	0.19	0.19	0.19
Be	mg/L	0.0023	0.0023	0.0023	0.0023	0.0023
B	mg/L	0.76	0.76	0.76	0.76	0.76
Cd	mg/L	0.015	0.015	0.015	0.015	0.015
Ca	mg/L	97.3	427	480	480	480
Cr	mg/L	0.0015	0.0015	0.0015	0.0015	0.0015
Co	mg/L	2.39	10.5	24.6	32.9	44.0
Cu	mg/L	0.29	1.29	3.03	4.06	107
Fe	mg/L	235	235	235	235	235
Pb	mg/L	0.053	0.053	0.053	0.053	0.053
Mg	mg/L	87.4	384	898	1030	1030
Mn	mg/L	7.67	33.7	47.0	47.0	47.0
Hg	mg/L	6.00E-06	6.00E-06	6.00E-06	6.00E-06	6.00E-06
Mo	mg/L	0.0016	0.0051	0.0051	0.0051	0.0051
Ni	mg/L	34.9	153	358	480	762
PO_4	mg/L	0.20	0.20	0.20	0.20	0.20
K	mg/L	38.0	38.0	38.0	38.0	38.0
Se	mg/L	0.0029	0.0029	0.0029	0.0029	0.0029
SiO_2	mg/L	3.88	3.88	3.88	3.88	3.88
Ag	mg/L	0.00070	0.00070	0.00070	0.00070	0.00070
Na	mg/L	45.4	199	338	338	338
Tl	mg/L	0.000060	0.000060	0.000060	0.000060	0.000060
Zn	mg/L	26.0	26.0	26.0	26.0	26.0
NO_3	mg-N/L	0.092	0.16	0.080	0.0040	0.23
NH_4	mg-N/L	0.092	0.16	0.080	0.0040	0.23

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Lean Ore Surge Pile		**Year**				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	35.0	35.0	35.0	35.0	35.0
Alkalinity	mg/L	0.40	6.68	9.62	25.8	20.7
Hardness	mg/L	51.9	872	1255	3207	2702
F	mg/L	0.18	0.20	0.20	0.20	0.20
Cl	mg/L	0.62	0.56	1.41	0.27	1.75
SO_4	mg/L	268	4499	6475	9600	9600
Al	mg/L	1.96	32.9	47.3	83.0	83.0
As	mg/L	0.0038	0.06	0.09	0.25	0.20
Ba	mg/L	0.028	0.19	0.19	0.19	0.19
Be	mg/L	0.0023	0.0023	0.0023	0.0023	0.0023
B	mg/L	0.11	0.76	0.76	0.76	0.76
Cd	mg/L	0.015	0.015	0.015	0.015	0.015
Ca	mg/L	8.38	141	203	480	436
Cr	mg/L	0.00066	0.0015	0.0015	0.0015	0.0015
Co	mg/L	0.21	3.47	4.99	13.4	10.7
Cu	mg/L	0.025	0.43	0.61	1.65	1.32
Fe	mg/L	50.6	235	235	235	235
Pb	mg/L	0.0061	0.053	0.053	0.053	0.053
Mg	mg/L	7.53	127	182	488	392
Mn	mg/L	0.66	11.1	16.0	42.8	34.4
Hg	mg/L	6.00E-06	6.00E-06	6.00E-06	6.00E-06	6.00E-06
Mo	mg/L	0.00014	0.0023	0.0033	0.0051	0.0051
Ni	mg/L	3.00	50.5	72.7	195	156
PO_4	mg/L	0.097	0.20	0.20	0.20	0.20
K	mg/L	8.22	38.0	38.0	38.0	38.0
Se	mg/L	0.0029	0.0029	0.0029	0.0029	0.0029
SiO_2	mg/L	3.88	3.88	3.88	3.88	3.88
Ag	mg/L	0.00015	0.00070	0.00070	0.00070	0.00070
Na	mg/L	3.91	65.8	94.6	254	204
Tl	mg/L	0.000060	0.000060	0.000060	0.000060	0.000060
Zn	mg/L	3.19	26.0	26.0	26.0	26.0
NO_3	mg-N/L	0.0079	0.0072	0.018	0.0035	0.022
NH_4	mg-N/L	0.0079	0.0072	0.018	0.0035	0.022

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Stage 2 Brine [5]		**Year**				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	41.8	105	114	73.1	109
Alkalinity	mg/L	427	582	560	536	585
Hardness	mg/L	759	1860	1715	3801	2681
F	mg/L	1.94	11.0	25.4	45.3	31.3
Cl	mg/L	9.7	47.3	47.0	10.1	10.9
SO_4	mg/L	898	1602	2165	5259	3369
Al	mg/L	5.98	6.80	7.91	12.2	7.20
As	mg/L	0.36	0.95	0.75	1.76	1.11
Ba	mg/L	0.30	0.42	0.39	0.71	0.47
Be	mg/L	0.0031	0.0034	0.0040	0.0045	0.0033
B	mg/L	1.01	1.78	1.65	2.64	1.93
Cd	mg/L	0.0044	0.0054	0.0056	0.0045	0.0034
Ca	mg/L	206	534	494	1167	797
Cr	mg/L	0.0082	0.011	0.011	0.011	0.011
Co	mg/L	0.071	0.10	0.10	0.13	0.09
Cu	mg/L	0.10	0.17	0.16	0.31	0.20
Fe	mg/L	14.6	20.2	18.3	7.81	5.95
Pb	mg/L	0.011	0.034	0.037	0.097	0.067
Mg	mg/L	59.5	129	117	217	168
Mn	mg/L	0.56	0.92	1.01	1.86	1.27
Hg	mg/L	4.24E-05	3.43E-05	3.70E-05	5.70E-05	5.49E-05
Mo	mg/L	0.030	0.043	0.043	0.041	0.044
Ni	mg/L	0.94	1.19	1.28	0.97	0.65
PO_4	mg/L	0.009	0.18	0.08	0.32	0.21
K	mg/L	37.5	74.0	62.5	137	85.1
Se	mg/L	0.015	0.020	0.020	0.021	0.020
SiO_2	mg/L	0.53	7.9	3.70	13.7	9.2
Ag	mg/L	0.0062	0.0084	0.0084	0.0076	0.0084
Na	mg/L	233	692	588	1509	957
Tl	mg/L	0.011	0.014	0.015	0.011	0.014
Zn	mg/L	0.90	1.31	1.14	0.47	0.41
NO_3	mg-N/L	0.62	1.42	1.39	0.0	0.0
NH_4	mg-N/L	0.62	1.42	1.39	0.0	0.0

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Stage 1 Combined Influent		Year					Removal Rate
Parameter	Units	1	5	10	15	20	
Flow	gpm	106	214	234	192	177	NA
Alkalinity	mg/L	187	306	298	239	376	0% [4]
Hardness	mg/L	679	1751	2934	4407	3205	0% [4]
F	mg/L	1.83	8.35	17.8	29.7	37.7	75% [2]
Cl	mg/L	10.0	27.0	26.9	13.8	14.2	0% [4]
SO_4	mg/L	992	3106	5507	7947	5776	[3]
Al	mg/L	4.03	18.0	41.1	56.0	36.5	99% [2]
As	mg/L	0.32	0.67	0.61	1.01	0.85	50% [3]
Ba	mg/L	0.18	0.30	0.29	0.39	0.36	0% [4]
Be	mg/L	0.0021	0.0023	0.0031	0.0031	0.0029	0% [4]
B	mg/L	0.64	1.26	1.19	1.48	1.48	5% [3]
Cd	mg/L	0.0071	0.0067	0.010	0.011	0.0078	0% [4]
Ca	mg/L	199	460	445	742	666	0% [4]
Cr	mg/L	0.0039	0.0060	0.0059	0.0052	0.0072	0% [4]
Co	mg/L	0.17	1.75	10.7	16.8	10.5	99.8% [3]
Cu	mg/L	0.079	0.31	10.7	25.6	38.0	99.5% [2]
Fe	mg/L	28.9	73.5	83.5	107	94.4	99.9% [2]
Pb	mg/L	0.011	0.039	0.045	0.070	0.062	0% [4]
Mg	mg/L	44.4	147	443	622	375	95% [2]
Mn	mg/L	0.83	6.04	19.9	29.1	16.5	99.9% [3]
Hg	mg/L	2.04E-05	1.99E-05	2.11E-05	2.54E-05	3.73E-05	0% [4]
Mo	mg/L	0.013	0.023	0.023	0.019	0.029	0% [4]
Ni	mg/L	2.51	25.4	136	249	175	99.9% [3]
PO_4	mg/L	0.09	0.19	0.14	0.24	0.21	50% [2]
K	mg/L	30.7	58.3	50.0	75.8	66.9	0% [4]
Se	mg/L	0.0075	0.011	0.011	0.010	0.013	0% [4]
SiO_2	mg/L	3.75	6.99	3.79	7.6	7.1	0% [4]
Ag	mg/L	0.0027	0.0045	0.0045	0.0033	0.0054	0% [4]
Na	mg/L	175	534	424	769	691	0% [4]
Tl	mg/L	0.0043	0.0071	0.0071	0.0041	0.0086	0% [4]
Zn	mg/L	2.13	7.68	12.2	14.6	10.3	90% [3]
NO_3	mg-N/L	0.31	0.74	0.72	0.11	0.080	0% [4]
NH_4	mg-N/L	0.31	0.74	0.72	0.11	0.080	0% [4]

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Stage 1 Effluent		Year				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	106	214	234	192	177
Alkalinity	mg/L	187	306	298	239	376
Hardness	mg/L	679	1751	2934	4407	3205
F	mg/L	1.83	2.09	4.45	7.42	9.43
Cl	mg/L	10.0	27.0	26.9	13.8	14.2
SO_4	mg/L	992	1500	1500	1500	1500
Al	mg/L	0.040	0.18	0.41	0.56	0.36
As	mg/L	0.16	0.33	0.30	0.51	0.43
Ba	mg/L	0.18	0.30	0.29	0.39	0.36
Be	mg/L	0.0021	0.0023	0.0031	0.0031	0.0029
B	mg/L	0.61	1.20	1.13	1.40	1.41
Cd	mg/L	0.0071	0.0067	0.010	0.011	0.0078
Ca	mg/L	199	460	445	742	666
Cr	mg/L	0.0039	0.0060	0.0059	0.0052	0.0072
Co	mg/L	0.00035	0.0035	0.021	0.034	0.021
Cu	mg/L	0.00040	0.0016	0.053	0.13	0.19
Fe	mg/L	0.029	0.074	0.084	0.11	0.094
Pb	mg/L	0.011	0.039	0.045	0.070	0.062
Mg	mg/L	2.22	7.35	22.2	31.1	18.8
Mn	mg/L	0.00083	0.0060	0.020	0.029	0.016
Hg	mg/L	2.04E-05	1.99E-05	2.11E-05	2.54E-05	3.73E-05
Mo	mg/L	0.013	0.023	0.023	0.019	0.029
Ni	mg/L	0.0025	0.025	0.14	0.25	0.18
PO_4	mg/L	0.045	0.10	0.072	0.12	0.10
K	mg/L	30.7	58.3	50.0	75.8	66.9
Se	mg/L	0.0075	0.011	0.011	0.010	0.013
SiO_2	mg/L	3.75	6.99	3.79	7.6	7.1
Ag	mg/L	0.0027	0.0045	0.0045	0.0033	0.0054
Na	mg/L	175	534	424	769	691
Tl	mg/L	0.0043	0.0071	0.0071	0.0041	0.0086
Zn	mg/L	0.21	0.77	1.2	1.5	1.0
NO_3	mg-N/L	0.31	0.74	0.72	0.11	0.080
NH_4	mg-N/L	0.31	0.74	0.72	0.11	0.080

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

Stages 1 and 2 Effluents		**Year**				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Flow	gpm	482	1159	1259	850	1155
Alkalinity	mg/L	43.0	59.3	58.0	56.5	60.6
Hardness	mg/L	153	333	553	1013	505
F	mg/L	0.41	0.44	0.95	1.88	1.60
Cl	mg/L	2.24	5.22	5.22	3.16	2.23
SO_4	mg/L	222	285	289	363	247
Al	mg/L	0.036	0.066	0.114	0.182	0.092
As	mg/L	0.037	0.066	0.060	0.12	0.071
Ba	mg/L	0.041	0.058	0.055	0.091	0.057
Be	mg/L	0.00047	0.00045	0.00060	0.00073	0.00046
B	mg/L	0.14	0.23	0.22	0.33	0.23
Cd	mg/L	0.0016	0.0013	0.0020	0.0025	0.0012
Ca	mg/L	44.8	87.5	85.0	173	106
Cr	mg/L	0.00089	0.0012	0.0012	0.0012	0.0012
Co	mg/L	0.00040	0.0011	0.0045	0.0082	0.0037
Cu	mg/L	0.00055	0.0011	0.011	0.030	0.030
Fe	mg/L	0.073	0.11	0.10	0.060	0.044
Pb	mg/L	0.0024	0.0074	0.0085	0.0161	0.0098
Mg	mg/L	0.76	1.97	4.67	8.00	3.71
Mn	mg/L	0.0027	0.0055	0.0085	0.015	0.009
Hg	mg/L	4.67E-06	3.83E-06	4.09E-06	6.00E-06	6.00E-06
Mo	mg/L	0.0031	0.0045	0.0045	0.0044	0.0046
Ni	mg/L	0.0048	0.010	0.031	0.061	0.030
PO_4	mg/L	0.010	0.018	0.014	0.029	0.017
K	mg/L	6.93	11.13	9.57	17.75	10.68
Se	mg/L	0.0017	0.0022	0.0022	0.0023	0.0022
SiO_2	mg/L	0.83	1.33	0.72	1.78	1.14
Ag	mg/L	0.00062	0.00087	0.00087	0.00079	0.00087
Na	mg/L	39.6	102.0	81.4	180	111
Tl	mg/L	0.00098	0.0014	0.0014	0.00097	0.0014
Zn	mg/L	0.051	0.15	0.23	0.33	0.16
NO_3	mg-N/L	0.071	0.14	0.14	0.024	0.012
NH_4	mg-N/L	0.071	0.14	0.14	0.024	0.012

Appendix G, Table G-1
WWTP Influent and Effluent Water Quality Projections
Flow Scenario: Low

CPS Effluent Flow		**Year**				
Parameter	**Units**	**1**	**5**	**10**	**15**	**20**
Overburden Flow	gpm	214	237	138	54	0
CPS Effluent Flow	gpm	696	1396	1397	903	1155
Alkalinity	mg/L	41.7	69.2	104	138	98.3
Hardness	mg/L	106	276	498	952	505
F	mg/L	0.28	0.36	0.85	1.77	1.60
Cl	mg/L	1.55	4.34	4.70	2.98	2.23
SO_4	mg/L	154	237	260	341	247
Al	mg/L	0.025	0.055	0.103	0.171	0.092
As	mg/L	0.026	0.055	0.054	0.12	0.071
Ba	mg/L	0.029	0.048	0.050	0.085	0.057
Be	mg/L	0.00033	0.00037	0.00054	0.00069	0.00046
B	mg/L	0.10	0.19	0.20	0.31	0.23
Cd	mg/L	0.0011	0.0010	0.0018	0.0023	0.0012
Ca	mg/L	150	150	150	150	150
Cr	mg/L	0.00062	0.0010	0.0010	0.0012	0.0012
Co	mg/L	0.00028	0.0009	0.0040	0.0077	0.0037
Cu	mg/L	0.00038	0.0009	0.010	0.028	0.030
Fe	mg/L	0.050	0.091	0.093	0.056	0.044
Pb	mg/L	0.0017	0.0061	0.0077	0.015	0.0098
Mg	mg/L	0.53	1.64	4.21	7.52	3.71
Mn	mg/L	0.0019	0.0046	0.0077	0.014	0.009
Hg	mg/L	3.24E-06	3.18E-06	3.69E-06	5.64E-06	6.00E-06
Mo	mg/L	0.0021	0.0038	0.0041	0.0042	0.0046
Ni	mg/L	0.0033	0.009	0.028	0.057	0.030
PO_4	mg/L	0.0069	0.015	0.012	0.027	0.017
K	mg/L	4.80	9.24	8.63	16.7	10.7
Se	mg/L	0.0012	0.0018	0.0019	0.0021	0.0022
SiO_2	mg/L	0.57	1.10	0.65	1.68	1.14
Ag	mg/L	0.00043	0.00072	0.00078	0.00074	0.00087
Na	mg/L	27.4	84.7	73.4	170	111
Tl	mg/L	0.00068	0.0011	0.0013	0.00091	0.0014
Zn	mg/L	0.035	0.12	0.21	0.31	0.16
NO_3	mg-N/L	0.049	0.12	0.13	0.022	0.012
NH_4	mg-N/L	0.049	0.12	0.13	0.022	0.012

Notes

[1] Concentrations based upon information presented in RS42 Appendix I.
[2] Removal efficiency based upon results of solubility modeling using the USGS Software PHREEQC.
[3] Removal efficiency based upon results of treatability study (RS45).
[4] Conservative engineering estimate.
[5] Stage 2 effluent based upon 90% water recovery and 95% mass removal.

Appendix H

Chemical Balance: Pilot Plant Flotation Process

Appendix H

Chemical Balance: Pilot Plant Flotation Process

Table of Contents

List of Tables

List of Figures

List of Attachments

1.0 Introduction

This appendix contains a summary of the work completed to develop a mathematical model that describes the water quality of the flotation process water during the operation of the pilot plant by Lakefield Research Limited in April 2006. The model was developed from a mass balance equation and used the operating parameters for the pilot plant and the analytical data from samples collected during the test run to estimate the potential solute loading from the flotation process. The pilot plant operating data were reported in the SGS Lakefield Research Project 11263-001 Report No. 1 dated July 5, 2006. Relevant portions of this report are included in Attachment H1. Analytical results for the process water flows, which were used in conjunction with the mass balance model to develop the chemical balance, are reported in the *Environmental Sampling and Analysis Flotation Process Optimization Test* Report prepared by Barr Engineering in July 2006. Relevant portions of this report are included in Attachment H2.

The following paragraphs present the development of the hydraulic balance for the pilot test and the development of the mass balance model for the pilot test. The approach presented in this appendix addressed the chemical balance of all pollutants measured during the pilot plant operation. This work was completed based upon agreement with the MDNR that this method was an acceptable approach. The final phase of this work compares the results of the pilot test to the proposed full-scale operation.

2.0 Pilot Plant Water Balance

The hydraulic operating data for the pilot plant water balance were obtained from SGS Lakefield Research Project 11263-001 Report No. 1 dated July 5, 2006 (pages 17-27) and addendums dated August 16, 2006 and August 17, 2006. The flotation pilot plant had a total system volume of 4,632 liters (11263-001 Table 7). Approximately 4,200 L of the total system volume was contained in two water recycle tanks. The bulk flotation circuit – which included all the pilot-scale processes where water was in contact with the ore, concentrate, or tailings – had a total volume of approximately 432 L.

The reported flow rate for the water inside the flotation pilot plant was 447 L/h (11263-001 Table 11). The system was operated with one inlet flow and two water losses. The inlet flow was make-up water at an average rate of 50.8 L/h (August 16 addendum corrected using August 17 addendum). Cake moisture losses in the tailings after filter pressing were 42.5 L/h (August 16 addendum). Water exiting the system into the concentrate surge tank was later decanted and added back into the system. This will not be done in the full-scale operation and may have resulted in potentially higher concentrations of some parameters as the pilot test compares to full-scale operations. After dewatering, the moisture content of the concentrate was an average of 52.9 percent, resulting in water losses of 8.3 L/h (August 17 addendum). No significant spillage was reported during the testing and evaporation during the test was considered minimal. Sample collection during the test removed approximately 70 liters of water, or an additional loss of less than 2 L/h.

Based on the total volume (4,632 L) of the system and the inlet water flow rate of 50.8 L/hr, the recycle ratio of the complete pilot system was 0.89. This system would need to be operated for 8.8 cycles to complete one full exchange of the process water, or approximately 91 hours. Because the operating time of the pilot system (for parcels PP-2 through PP-6) was 32 hours, this duration may have limited the potential maximum concentrations that may have been observed in the pilot system. However, because the active volume of the bulk flotation circuit alone is only 432 L, and the internal flow rate for this component of the pilot test was 447 L/hr, any mass transfer between the water and the solid phases in the water in these portions of the pilot test would be limited to fast reactions, and those reactions would be well-represented in the pilot plant. Long-term dissolution and equilibrium will need to be addressed in the water quality modeling for the tailings basin (work being completed by SRK).

3.0 Pilot Plant Mass Balance

To estimate the concentration of any substance in solution within the pilot plant process water, a mass balance equation was used. The mass balance considered the entire volume of the pilot plant to correspond to the analytical data collected during the pilot testing. Analytical data included the chemistry of the make-up water and the chemistry of the water that was recycled back to the storage tanks at the completion of the bulk flotation process. The basic form of the mass balance was as follows:

(Accumulation) = (Make-up water flow in) – (Tailings filter cake losses) – (Concentrate moisture losses) + (Mass transfer from ore) + (Reagent addition) (1)

This mass balance can also be expressed mathematically as follows:

$$V\frac{dC(t)}{dt} = F_F C_M - F_F C(t) + kV\left(C_s - C(t)\right) + \dot{m} \qquad (2)$$

where V is the internal volume of the flotation plant, C is the process water concentration, t is time, F_F is the make-up water flow (equal to the sum of the tailings filter cake losses and concentrate moisture losses), C_M is the concentration of solute in the make-up water, k is the mass transfer coefficient, C_s is the ultimate steady-state concentration within the system, and $\dot{m}$ is the addition rate of copper sulfate or some other reagent (if applicable). The mass transfer coefficient and the steady-state concentration are unknowns in this system. In this form, the mass transfer coefficient accounts for transfer to or from the solid phases in the system (concentrate, ore, and tailings).

Three assumptions were made in this mass balance. It was assumed that the only parameter that varied with time was the concentration of the solute. The process water composition was assumed to represent the composition of water lost in the tailings thickener filter cake and water lost as concentrate moisture. It was also assumed that the loss and reintroduction of water from the concentrate decant had no effect on the process water composition. Changing operating conditions (i.e., regrind rates) during pilot plant operation were not accounted for in analysis of the pilot plant data. However, the likely operating conditions for the full-scale plant are expected to be within the range of operating conditions used during the pilot plant operation.

Each component of the mass balance is responsible for a portion of the mass transfer to/from the system. This rate of loading is constant for the fresh water contribution and the reagent (copper sulfate) contribution, but the mass transfer from the solid phase to the liquid phase varies with time. Table H1 shows the mass loading of the system at the conclusion of the pilot plant run as an illustrative example. Copper sulfate addition is a significant contributor to the sulfate and copper loading in the system. At the conclusion of the pilot plant run, the system is expected to be near steady state; therefore the contribution of the mass transfer component to the rate of change in the process water concentration is less than during start-up due to the smaller concentration gradient.

Table H1 Loading to Process Water at the Conclusion of the Pilot Plant Run Due to Components of the Mass Balance

Species	Fresh water [mg/L/h]	$CuSO_4$ [mg/L/h]	Solid Phase [mg/L/h]
Alkalinity, total, mg/L	9.51E-01	--	7.78E-01
Chemical Oxygen Demand, mg/L	1.61E-01	--	4.54E+00
Chloride, mg/L	1.70E-01	--	4.67E-01
Phosphorus total, mg/L	1.10E-04	--	4.88E-03
Sulfate, mg/L	1.22E-01	1.53E+00	4.08E-01
Sulfur, mg/L	4.42E-02	--	5.31E-01
Aluminum, dissolved, mg/L	5.91E-02	--	2.80E+00
Antimony dissolved, mg/L	6.11E-04	--	5.50E-02

Table H1 Loading to Process Water at the Conclusion of the Pilot Plant Run Due to Components of the Mass Balance

Species	Fresh water [mg/L/h]	$CuSO_4$ [mg/L/h]	Solid Phase [mg/L/h]
Arsenic, dissolved, mg/L	5.48E-03	--	2.49E+00
Barium, dissolved, mg/L	3.22E-07	--	4.75E-05
Boron, dissolved, mg/L	1.09E-01	--	5.74E+00
Cadmium, dissolved, mg/L	2.66E-04	--	2.40E-02
Calcium, dissolved, mg/L	3.81E-01	--	-7.74E-02
Chromium, dissolved, mg/L	2.22E-03	--	2.00E-01
Cobalt, dissolved, mg/L	2.30E-06	--	-5.49E-08
Copper, dissolved, mg/L	2.30E-06	9.36E-01	-2.58E-06
Magnesium, dissolved, mg/L	3.86E-02	--	7.52E-02
Manganese, dissolved, mg/L	2.40E-02	--	1.09E+01
Molybdenum dissolved, mg/L	2.37E-06	--	2.63E-04
Nickel, dissolved, mg/L	1.49E-05	--	3.32E-05
Potassium, dissolved, mg/L	2.19E-02	--	2.00E-01
Selenium, dissolved, mg/L	1.10E-02	--	1.68E-02
Silicon, dissolved, mg/L	4.38E+01	--	5.72E+03
Sodium dissolved, mg/L	1.02E+02	--	2.95E+03
Zinc, dissolved, mg/L	7.00E-02	--	3.13E-01
Nitrate + Nitrite, mg/L	3.69E-03	--	3.40E-01
Nitrogen total kjeldahl, mg/L	4.02E-03	--	-7.30E-04
Phenol 4AAP, mg/L	1.83E-04	--	9.14E-05
Sulfite, mg/L	2.19E-02	--	2.14E-01
Surfactants MBAS, mg/L	6.58E-04	--	9.21E-03
pH, standard units	8.60E-02	--	7.07E-03
Tetrathionate, mg/L	2.19E-03	--	1.33E-02
Tetrathionate, filtered, mg/L	2.19E-03	--	3.68E-03
Thiosulphate, mg/L	2.19E-03	--	2.91E-01
Thiosulphate, filtered, mg/L	2.19E-03	--	1.48E-01
Trithionate, mg/L	2.19E-02	--	2.64E-01
Trithionate, filtered, mg/L	2.19E-02	--	1.14E-01

The steady-state concentration value for the pilot plant is dependent on the hydraulic retention time of the system and the kinetics of the mass transfer between the solid phases and the process water. In the case of a fast reaction, where the reaction time is significantly less than the hydraulic retention time of the system, the process water would reach a steady-state concentration before the entire system is flushed one time. In the case of a very slow reaction, where the time to chemical equilibrium is significantly longer than the hydraulic retention time, the steady-state concentration will be dependent on the hydraulic retention of the system. Modeling of this system through 32 hours will address all reactions where the mass transfer is not limited by the hydraulic retention of the pilot system. Any additional mass transfer, which would occur over a longer duration, will be addressed in the water quality modeling for the tailings basin.

Solving this differential equation for concentration as a function of time results in the following equation:

$$C(t)=\frac{F_F C_M + kVC_s + \dot{m}}{F_F + kV} + \left(C_O - \frac{F_F C_M + kVC_s + \dot{m}}{F_F + kV} \right) \exp\left[-\left(\frac{F_F + kV}{V} \right) t \right] \qquad (3)$$

where C_0 is the initial concentration of the system. The form of the equation was then reduced to a simple parametric model of the form:

$$C(t) = A + B \cdot \exp(D \cdot t) \qquad (4)$$

where *A*, *B*, and *D* are lumped parameters derived from the mass balance equation. As shown in equation number 3, the time dependence of concentration is non-linear in nature and cannot be simplified to a linear form due to unknown values within the parameter *A*.

3.1 Regression Analysis of Pilot Plant Solute Data

The MathCAD function ‘genfit’ was used to perform a non-linear regression of the pilot plant data fit to the form of Equation 4. In addition, the Matlab functions ‘nlinfit’, ‘nlpredci’, and ‘nlparci’ were used to cross-check the regression results and to obtain confidence intervals. Data from PP-1 were not used because that run was discontinuous from the subsequent runs and represented only start-up conditions. Table 1 of Attachment H2 contains a list of the tailings thickener overflow concentration data, which represents the process water. Table 2 of Attachment H2 contains a summary of the solute concentrations in the make-up water, which were averaged. The values used in the regression analyses for the parameters included in this memo are highlighted.

The regression provides values for the parameters *A*, *B*, and *D* for Equation 4. These values together with the known values in the expression of these parameters (in Equation 3) were then used to calculate values of the mass transfer coefficient and the steady-state concentration (*k* and C_s respectively) in the overall mass balance equation for the pilot plant.

An initial demonstration of the proposed chemical balance modeling approach was performed using the data sets for six solutes: sulfate (total), chloride (total), nickel (dissolved), copper (dissolved), calcium (dissolved), and magnesium (dissolved). The lines of the best-fit non-linear regression along with the pilot plant data points for each of these four analytes are shown in Figures H1 through H6. Total metal concentrations were not modeled. The curves shown on Figures H1 through H6 can be classified into two different shapes – increasing or decreasing. Sulfate (Figure H1), magnesium (Figure H5), and chloride (Figure H6) show increasing trends. Copper (Figure H2), nickel (Figure H3), and calcium (Figure H4) show decreasing trends.

Additional parameters have been modeled to give an overall picture of the process water composition. Solutes present only in low levels ("no-detect" laboratory results) were not modeled. Solutes with limited concentration data or little variation in data points (ammonia, total suspended solids, dissolved sulfite, carbon disulfide, methyl isobutyl alcohol) could not be successfully modeled with this regression technique due to non-convergence. Table H2 contains information on the concentration of these solutes. All other solutes were analyzed to identify the most appropriate model for each on a solute-by-solute basis.

Table H2 Concentration of Constituents Not Modeled Due to Insufficient Data Points or "No Detect" Readings

Parameter	Concentration [mg/L]
Alkalinity, (hydrox.) as @CaCO3, mg/L	<2
Bromide, mg/L	<0.2
Carbonate, mg/L	2 [1]
Cyanide	<0.01
Fluoride, mg/L	<0.4
Nitrogen, ammonia as N	0.9 [1]
Solids, total suspended, mg/L	862 [1]
Sulfide total, mg/L	<2
Sulfide, dissolved, mg/L	<2
Sulfite, dissolved, mg/L	3 [1]
Chlorine, mg/L	<0.1
Thiosalt, mg/L	<10
Thiosalt, filtered, mg/L	<10
Beryllium, dissolved	<0.00002
Iron, dissolved	<0.02
Lead, dissolved	<0.00002
Mercury, dissolved	0.0000018 [1]
Silver, dissolved	<0.00002
Thallium dissolved	<0.00002
Tin dissolved	<0.0001
Titanium dissolved	<0.01
1-Pentanol	<0.4
2-Pentanol	<0.1

Table H2 Concentration of Constituents Not Modeled Due to Insufficient Data Points or "No Detect" Readings

Parameter	Concentration [mg/L]
3-Pentanol	<0.1
Benzene	<0.0005
Carbon disulfide	0.00073 [1]
Ethyl benzene	<0.0005
Methyl isobutyl alcohol	0.0042 [1]
Toluene	<0.0005
Xylene m & p	<0.0005
Xylene o-	<0.0005

[1] Maximum detected value.

Thiosalts may be generated from processing sulfidic ores. The oxidation of thiosalts in tailings basins is sufficiently slow that the sulfuric acid generated can generally be neutralized. Thiosalts were below the detection level during pilot plant operation. Therefore, thiosalts are not expected to significantly contribute to acidity within the tailings basin or the process water loop.

Inspection of the data suggests that most parameters considered for this work appear to be near steady-state conditions by the completion of the pilot test (i.e., the concentrations are not changing with time). This implies that the kinetics of the dominant mass transfer processes for these chemical are faster than the hydraulic retention time of the pilot system. The estimated solute concentrations at the conclusion of the pilot plant run are shown in Table H3. For each additional parameter, the general shape of the regression curve (increasing or decreasing) is also noted in Table H3, in lieu of additional figures.

Table H3 Solute Concentrations in the Tailings Discharge at the Conclusion of the Pilot Plant Run

Species	Concentration [mg/L]	95% Confidence Interval [mg/L]	R^2 [1]	R^2 [2]	Increasing / Decreasing
Alkalinity, total, mg/L	157	(150, 165)	0.97	0.92	Increasing
Chemical Oxygen Demand, mg/L	429	(383, 474)	0.96	0.96	Increasing
Chloride, mg/L	52.4	(47.3, 57.4)	0.97	0.91	Increasing
Phosphorus total, mg/L	0.45	(0.27, 0.64)	0.66	0.63	Increasing
Sulfate, mg/L	125	(103, 147)	0.90	0.33	Increasing
Sulfur, mg/L	42.5	(36.5, 48.6)	0.89	0.47	Increasing
Aluminum, dissolved	0.128	(0.11, 0.15)	0.74	0.38	Increasing
Antimony dissolved	0.0032	(0.0028, 0.0035)	-0.77	-0.29	Increasing
Arsenic, dissolved	0.0053	(0.0046, 0.0061)	0.74	0.74	Increasing

Table H3 Solute Concentrations in the Tailings Discharge at the Conclusion of the Pilot Plant Run

Species	Concentration [mg/L]	95% Confidence Interval [mg/L]	$R^{2\,[1]}$	$R^{2\,[2]}$	Increasing / Decreasing
Barium, dissolved	0.0043	(0.0039, 0.0046)	0.90	0.86	Increasing
Boron, dissolved	0.15	(0.13, 0.17)	0.79	0.37	Increasing
Cadmium, dissolved	0.00011	(0.00009, 0.00012)	-0.11	-0.01	Increasing
Calcium, dissolved	19.3	(18.5, 20.1)	0.97	0.94	Decreasing
Chromium, dissolved	0.00032	(0.00025, 0.00038)	0.12	0.07	Decreasing
Cobalt, dissolved	0.00020	(0.00012, 0.00029)	0.00	**-0.47**	Decreasing
Copper, dissolved	0.00051	(0.00008, 0.00095)	0.54	0.15	Decreasing
Magnesium, dissolved	10.4	(9.7, 11)	0.89	0.78	Increasing
Manganese, dissolved	0.0058	(0.0055, 0.0061)	0.90	0.87	Increasing
Molybdenum dissolved	0.024	(0.019, 0.029)	0.63	**-0.57**	Increasing
Nickel, dissolved, mg/L	0.0043	(0.0037, 0.005)	0.59	0.59	Decreasing
Potassium, dissolved	20.3	(17.7, 22.8)	0.78	0.34	Increasing
Selenium, dissolved	0.0014	(0, 0.0028)	0.12	0.01	Decreasing
Silicon, dissolved	6.74	(6.44, 7.03)	0.85	0.84	Increasing
Sodium dissolved	108	(97, 119)	0.88	0.64	Increasing
Zinc, dissolved	0.0093	(-0.0117, 0.0303)	0.07	0.02	Increasing
Nitrate + Nitrite	0.56	(0.54, 0.59)	**-1.07**	-0.30	Increasing
Nitrogen total kjeldahl	0.30	(0.21, 0.39)	0.16	0.15	Increasing
Phenol 4AAP, mg/L	0.025	(0.01, 0.04)	-0.19	**-1.35**	Increasing
Sulfite, mg/L	2.88	(2.44, 3.33)	0.87	0.83	Increasing
Surfactants MBAS, mg/L	0.90	(0.53, 1.27)	0.63	0.08	Increasing
pH, standard units	8.48	(8.35, 8.62)	0.61	0.59	Increasing
Tetrathionate, mg/L	0.56	(0.33, 0.79)	0.73	0.51	Increasing
Tetrathionate, filtered, mg/L	0.39	(0.19, 0.59)	0.58	0.40	Increasing
Thiosulphate, mg/L	9.83	(8.16, 11.51)	0.94	0.82	Increasing
Thiosulphate, filtered, mg/L	9.89	(9.31, 10.47)	0.99	0.98	Increasing
Trithionate, mg/L	7.19	(5.17, 9.22)	0.86	0.54	Increasing
Trithionate, filtered, mg/L	6.80	(5.42, 8.18)	0.91	0.73	Increasing

[1] Comparison with line of zero slope at the average concentration.
[2] Comparison with linear regression model.

Confidence intervals for the non-linear model of each parameter were obtained using the regression software. Uncertainties of the parameters *A*, *B*, and *D* were given directly by the regression software. For the period of time covering the pilot plant operation, upper and lower 95 percent confidence intervals were also given directly by the regression software. Two correlation coefficients were developed to compare the non-linear regression model to a zero-slope line at the mean of the data points and a linear regression model, discussed below. This information is also shown in Table H3.

Correlation coefficients were developed to quantify the "goodness of fit" of the model, shown in Table H3.[1] For nonlinear regression, the fit of the model was compared to two linear models, a horizontal line and a linear regression as described below. Neither linear model has a theoretical basis for application in this type of process. However, the linear models provide a basis for evaluating the non-linear results obtained from the model.

One linear model was a horizontal (constant value) line at the mean of the data points. Mathematically, the correlation coefficient between the non-linear regression model and a horizontal line is defined as

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (C_i - C_{reg})^2}{\sum_{i=1}^{n} (C_i - \bar{C})^2} \tag{5}$$

where C_i is a concentration data point, $\bar{C}$ is the mean of the concentration data points, and C_{reg} is the concentration predicted by the model. When the value is equal to zero, the fit is no better than the linear model which simply uses the average value. This quantity can be less than zero, despite being identified as a "squared" value, if the fit of the linear model is superior to the proposed model.[2] In a few cases, the R^2 value is less than zero, which indicates that the proposed non-linear model does not provide the best fit to the data. In these cases, the most conservative model (highest modeled concentration at the end of the pilot plant) will be applied to estimate the process water quality.

The non-linear model was also compared to a linear regression model. A similar R^2 value was derived for comparison of the residuals of the nonlinear regression and the residuals of the linear regression. In a few cases (cobalt, molybdenum, nitrate+nitrite, and phenol 4AAP), the R^2 value is less than zero, which indicates that the proposed non-linear model does not provide the best fit to the data. In these cases, the most conservative model was applied to estimate the process water quality. Corrected results are presented in Table H4, and graphical results for these species are presented in Figures H7 through H10.

---

[1] http://www.graphpad.com/curvefit/goodness_of_fit.htm

[2] http://www.graphpad.com/curvefit/goodness_of_fit.htm

Water discharged from the full-scale flotation process will be directed to the tailings basin. This water will be reused in the process and not discharged to surface water. Additional modeling of the tailings basin water quality will be completed using the estimated water quality for the full-scale flotation process. As a preliminary estimate of the potential effect of the process water flows on the tailings basin water quality, the final estimated concentrations in Table H4 are compared to process water quality targets for the project as described in Section 3 of RS29T. Based on these process water quality targets, the process water entering the tailings basin from the flotation operation meets process water quality targets for all parameters except aluminum. However, it is expected that the dissolved aluminum analytical results are high due to the presence of aluminum in colloidal particles.

Table H4 Corrected Solute Concentrations from Table H3 and Process Water Quality Targets

Species	Concentration [mg/L]	95% Confidence Interval [mg/L]	Process Water Quality Targets [mg/L]
Alkalinity, total, mg/L	157	(150, 165)	NA
Chemical Oxygen Demand, mg/L	429	(383, 474)	NA
Chloride, mg/L	52.4	(47.3, 57.4)	230
Phosphorus total, mg/L	0.45	(0.27, 0.64)	NA
Sulfate, mg/L	125	(103, 147)	250
Sulfur, mg/L	42.5	(36.5, 48.6)	NA
Aluminum, dissolved	0.128	(0.11, 0.15)	0.125
Antimony dissolved	0.0032	(0.0028, 0.0035)	0.031
Arsenic, dissolved	0.0053	(0.0046, 0.0061)	0.050
Barium, dissolved	0.0043	(0.0039, 0.0046)	2.0
Boron, dissolved	0.15	(0.13, 0.17)	0.50
Cadmium, dissolved	0.00011	(0.00009, 0.00012)	0.004
Calcium, dissolved	19.3	(18.5, 20.1)	NA
Chromium, dissolved	0.00032	(0.00025, 0.00038)	0.10
Cobalt, dissolved	*0.00011*	*(0.00001, 0.00021)*	0.005
Copper, dissolved	0.00051	(0.00008, 0.00095)	0.030
Magnesium, dissolved	10.4	(9.7, 11)	NA
Manganese, dissolved	0.0058	(0.0055, 0.0061)	0.050
Molybdenum dissolved	*0.035*	*(0.030, 0.040)*	NA
Nickel, dissolved, mg/L	0.0043	(0.0037, 0.005)	0.100
Potassium, dissolved	20.3	(17.7, 22.8)	NA
Selenium, dissolved	0.0014	(0, 0.0028)	0.005
Silicon, dissolved	6.74	(6.44, 7.03)	NA
Sodium dissolved	108	(97, 119)	NA
Zinc, dissolved	0.0093	(-0.0117, 0.0303)	0.388
Nitrate + Nitrite	*0.53*	*(0.47, 0.59)*	10
Nitrogen total kjeldahl	0.30	(0.21, 0.39)	NA
Phenol 4AAP, mg/L	*0.033*	*(0.028, 0.037)*	0.123

Table H4 Corrected Solute Concentrations from Table H3 and Process Water Quality Targets

Species	Concentration [mg/L]	95% Confidence Interval [mg/L]	Process Water Quality Targets [mg/L]
Sulfite, mg/L	2.88	(2.44, 3.33)	NA
Surfactants MBAS, mg/L	0.90	(0.53, 1.27)	NA
pH, standard units	8.48	(8.35, 8.62)	6.5-8.5
Tetrathionate, mg/L	0.56	(0.33, 0.79)	NA
Tetrathionate, filtered, mg/L	0.39	(0.19, 0.59)	NA
Thiosulphate, mg/L	9.83	(8.16, 11.51)	NA
Thiosulphate, filtered, mg/L	9.89	(9.31, 10.47)	NA
Trithionate, mg/L	7.19	(5.17, 9.22)	NA
Trithionate, filtered, mg/L	6.80	(5.42, 8.18)	NA

[1] Comparison with line of zero slope at the average concentration.
[2] Comparison with linear regression model.

3.2 Charge Balance and Saturation Indices

The USGS model PHREEQC was used to perform a charge balance of the results and to calculate saturation indices for various parameters. Analytical data at the conclusion of the pilot plant run (Hour 31) and the model predictions at that time were chosen as representative data sets for analysis. There were minor parameters (i.e., thiosulfate) that PHREEQC did not have the capability to model and were not included. A summary of the results is shown in Table H5. The charge balance for each data set was within 20 percent of neutrality. A variety of surface chemistry issues, such as adsorption/desorption equilibria, and organic matter within the system are complications that PHREEQC does not adequately account for in its model. As a result, it is unlikely that the discrepancy in the charge balance can be closed through practical means. Complete PHREEQC modeling output files are available upon request.

Table H5 Summary of PHREEQC Modeling Results

Parameter	Analytical	Modeled
pH	7.979	7.956
pe	6.617	7.134
Activity of water	1	1
Ionic strength	9.05E-03	7.83E-03
Total alkalinity (eq/kg)	1.45E-03	1.44E-03
Electrical balance (eq)	2.45E-03	1.58E-03
Percent error, 100*(Cat-|An|)/(Cat+|An|)	17.84%	13.24%

The saturation indices provided by PHREEQC indicate high levels of aluminum dissolved in the system. Aluminum is not a desired product extracted as concentrate, but is present in the ore. Therefore, it is not unexpected that aluminum-containing species are at or near levels of saturation.

4.0 Conclusion of Analysis of Pilot Plant Flotation Data

The contribution of solute loading to the process water from contact with solids in the flotation process has been quantified using a mass balance model. The model is capable of predicting steady-state concentrations within an acceptable confidence interval. The non-linear regression model provides a superior fit to the pilot plant data compared to a linear regression model and a horizontal line at the mean of the data points for most solutes. For the other parameters, the most conservative model was applied to estimate the water quality of the process water. Modeling of the process water shows an acceptable charge balance and saturation characteristics.

5.0 Comparison of Pilot Plant and Proposed Full-Scale Operations

The operation of the full-scale plant will be different from the pilot scale plant in several areas. These differences will include the extent of weathering of the crude ore prior to processing, the ratio of water to ore in the flotation plant, reagent addition rates, water recycle ratio, differences in concentrate handling, make-up water source, and inclusion of the tailings basin in the flotation plant recycle loop. These differences may result in different mass loading rates in the full-scale plant, and ultimately different process water quality. Table H6 summarizes the operational parameters for the pilot scale and full-scale operation.

Table H6 Summary of Operational Parameters at Pilot and Full-Scale Operation

Stream	Pilot Plant	Full-Scale Plant	Units
Water Recycle Rate	447	2,231,030	L/h
Fresh Water Rate	50.8	250,000	L/h
Fraction of Water Recycled	0.89	0.89	L/L
Cycles (theoretical)	8.80	8.92	cycles
Internal Volume of Flotation Plant	4,632.5	5,201,000	L
Ore Rate	0.20	1,343	t/hr
CuSO4 Addition Rate	57	55	g/t
Process Water/Ore Mass Ratio	2.24	1.66	t/t
Cake Moisture Losses/Water To Tailings Basin	42.5	2,205,822	L/h
Water Exiting With Concentrate	8.31	25,200	L/h
Water From Tailings Basin	NA	1,785,006	L/h

To compare the results of the pilot plant operation to the expected full-scale operations, a parallel analysis of the contribution of pollutants to the process water from the ore was conducted by SRK using geochemical principles. Sulfate was used as a basis for comparison between the parallel analyses. SRK predicted that 0.60 tons per day of sulfate will be contributed to the process water from the ore at full-scale operation. Addition of copper sulfate would also contribute to the sulfate load in the process water. Using an addition ratio of 55 grams of copper sulfate per ton of ore processed at 32,000 tons per day of ore processed, 0.68 tons per day of sulfate will be contributed to the process water from the copper sulfate. Thus, a total of 1.28 tons per day of sulfate will be contributed to the process water from the flotation plant.

There are two goals for this discussion. The first goal is to demonstrate that this loading rate is consistent with what was observed during the pilot plant operation. The second goal is to assess which method is more conservative in predicting pollutant load to the tailings basin. To reach these goals, the mass loading calculated by SRK was converted to the scale of the pilot plant. The mass loading of sulfate was also calculated from the regression parameters derived in this memorandum.

The sulfate mass loading rate of 0.68 tons per day was scaled down by using the ore throughput rates of the pilot plant and the full-scale plant. The ratio between ore throughput rates is 1.50×10^{-4}, therefore, the equivalent mass loading at the pilot scale is 1.02×10^{-4} tons of sulfate per day.

The mass loading rate during pilot plant operation was dependent upon the concentration of the process water C, which is the basis for the mass transfer driving force. The concentration at which the mass loading rate is 1.02 x 10^{-4} tons of sulfate per day was back-calculated using the parameters derived from the regression. The mass transfer coefficient k is 0.07 h^{-1}, the ultimate steady-state concentration within the system C_S is 131 mg/L, and the internal volume used is 4632.5 L. The calculated value of C, the process water concentration for sulfate, is 117.9 mg/L when the loading rate is 1.02 x 10^{-4} tons of sulfate per day.

Above this concentration, the mass loading calculated using the methods presented in this memorandum will be less than predicted by SRK due to the decreased driving force. Below this concentration, the opposite is true. Regression analysis showed that the steady-state concentration of sulfate was 125 mg/L during pilot plant operation with an ultimate steady-state concentration C_S of 131 mg/L. As in the pilot plant, the time it takes to approach steady state will be very small relative to the total time of operation for the full-scale plant. Based on the existing sulfate concentrations in the tailings basin, it is expected that the process water concentration will be greater than 118 mg/L for a much greater period of time than it will be less than 118 mg/L. Therefore, the mass loading prediction by SRK should be conservative relative to the mass loading predicted by this memorandum, and may overestimate the sulfate load to the process water loop.

The prediction by SRK has been shown to be conservative, but not by a large margin. These independent methods of prediction, however, have similar results, which speaks to the validity of each. The methods and results presented in this memorandum strengthen the predictions of SRK.

It is likely that the pollutant loading of the process water from the ore may be greater in the full-scale plant than in the pilot plant for other reasons as well. For example, the ore used in the pilot plant was not subjected to the same treatment as the ore will be in the full-scale plant. Prior to the pilot test, the ore was kept in a covered building in larger fragments than is typical in a stockpile. Decreasing ore fragment size increases the surface area available for oxidation and its overall reactivity with water.

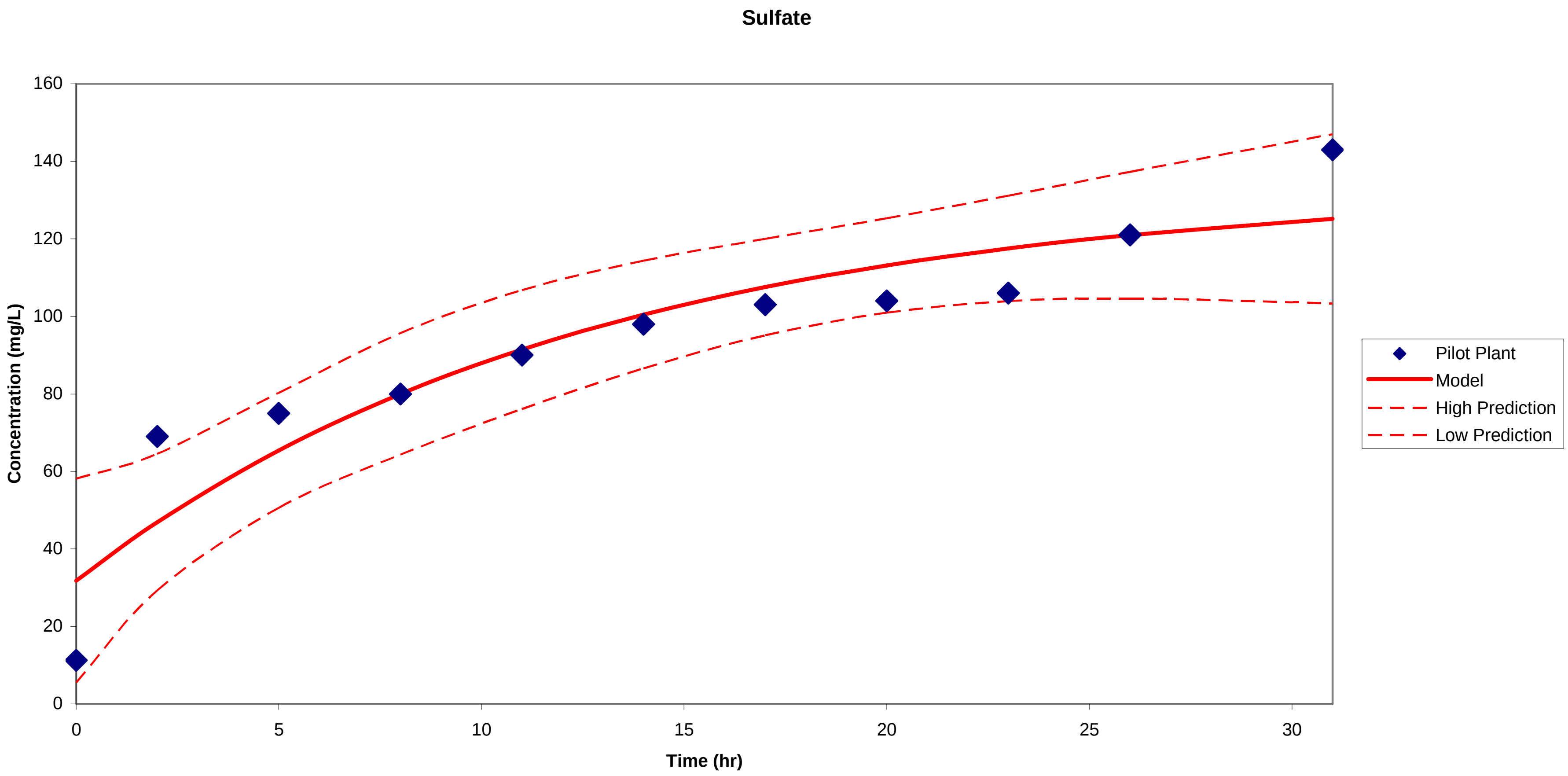


Figure H1 Regression Curve and Pilot Plant Data for Total Sulfate Concentration in the Process Water (R^2 = 0.90 compared to average model, R^2 = 0.33 compared to linear regression model)

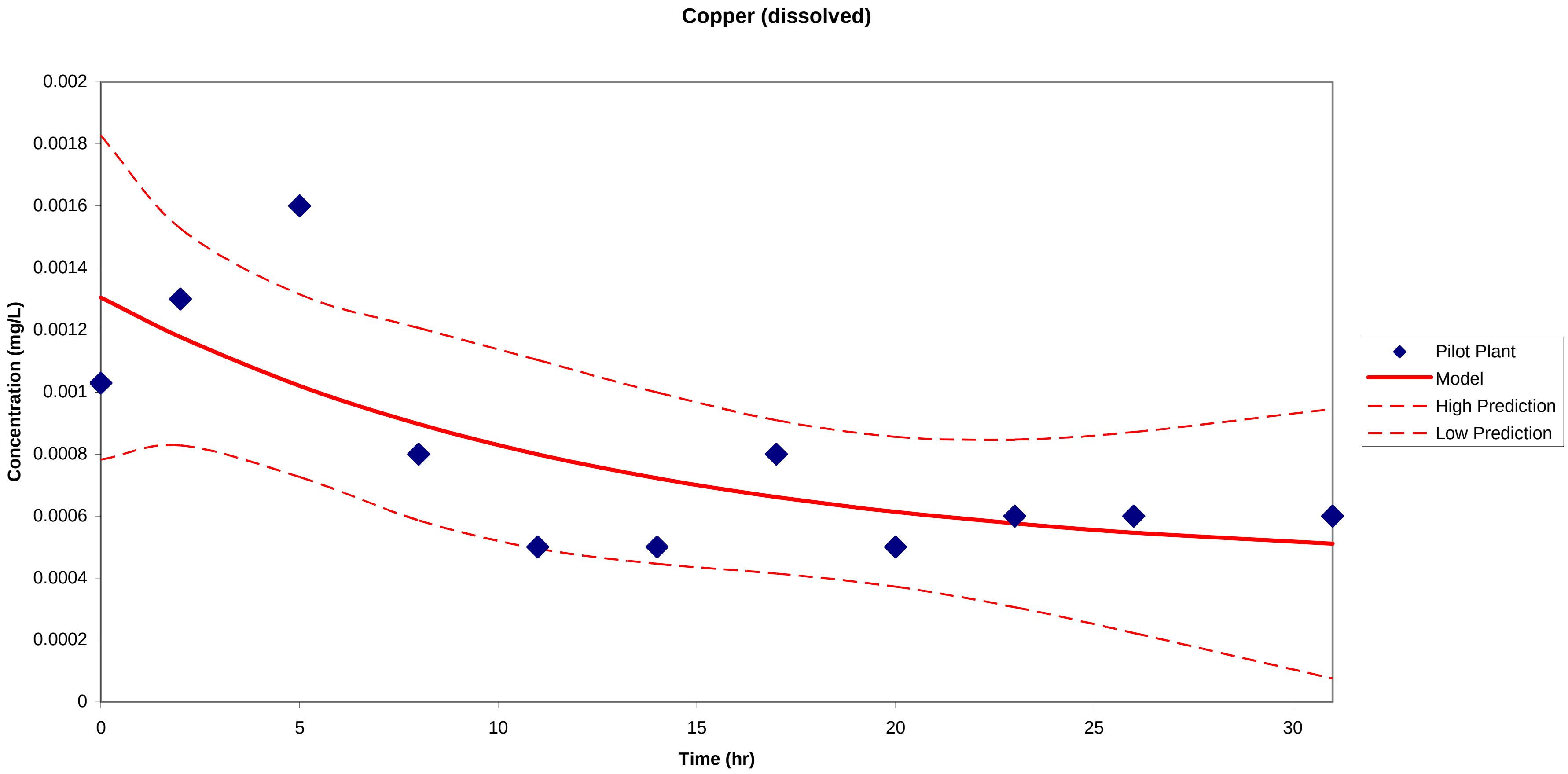


Figure H2 Regression Curve and Pilot Plant Data for Dissolved Copper Concentration in the Process Water (R^2 = 0.54 compared to average model, R^2 = 0.15 compared to linear regression model)

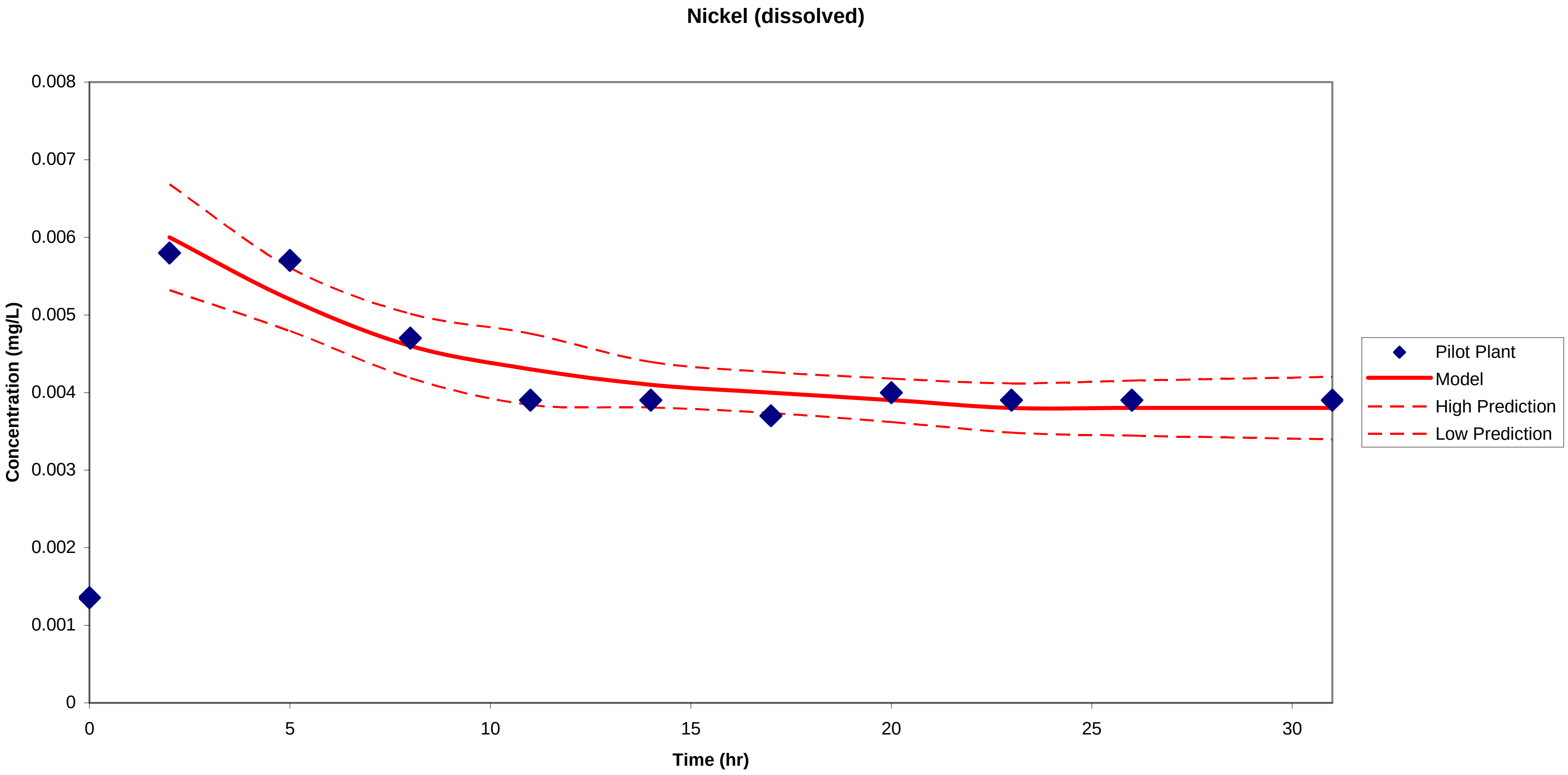


Figure H3 Regression Curve and Pilot Plant Data for Dissolved Nickel Concentration in the Process Water (R^2 = 0.90 compared to average model, R^2 = 0.89 compared to linear regression model)

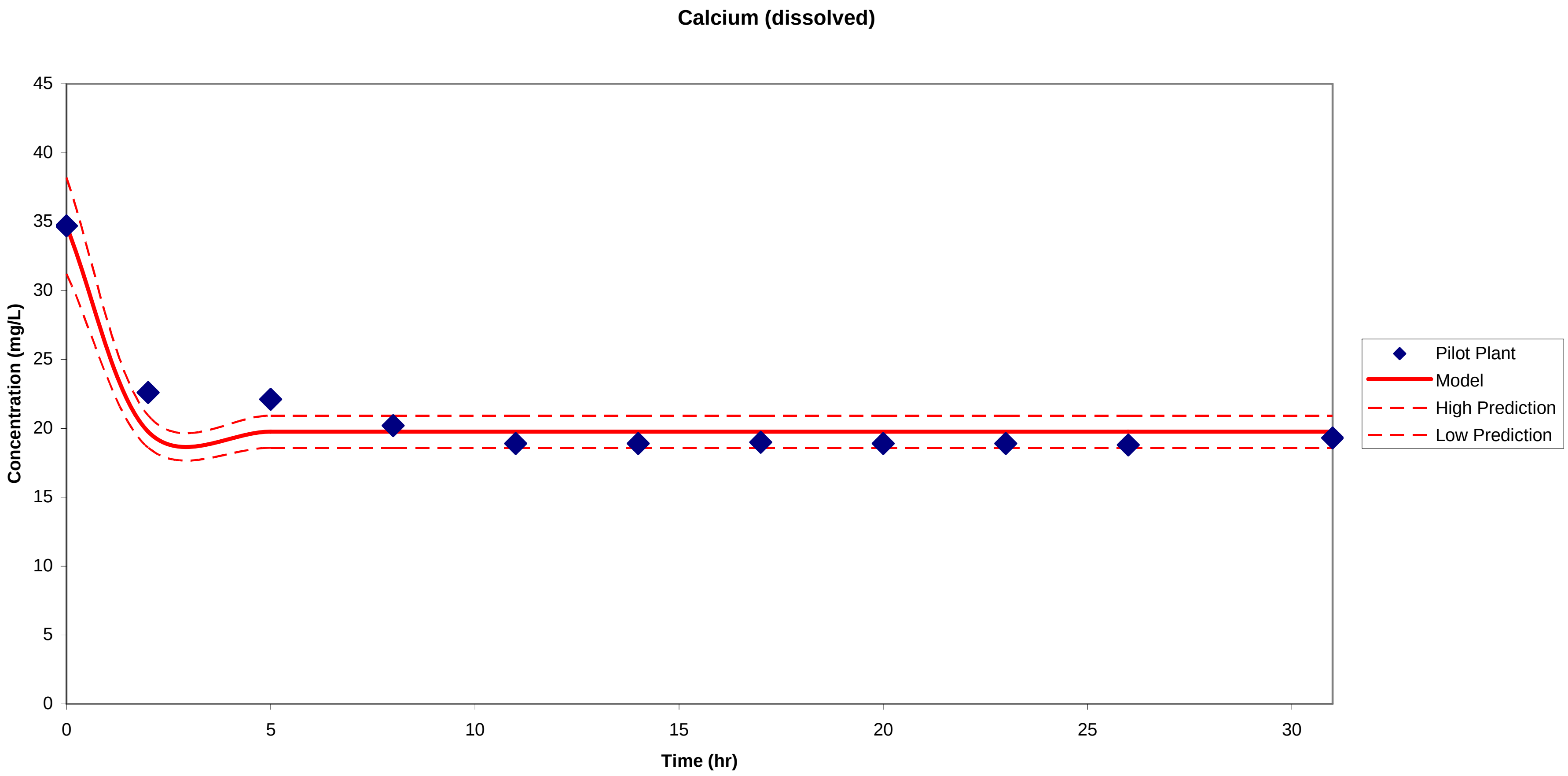


Figure H4 Regression Curve and Pilot Plant Data for Dissolved Calcium Concentration in the Process Water (R^2 = 0.97 compared to average model, R^2 = 0.94 compared to linear regression model)

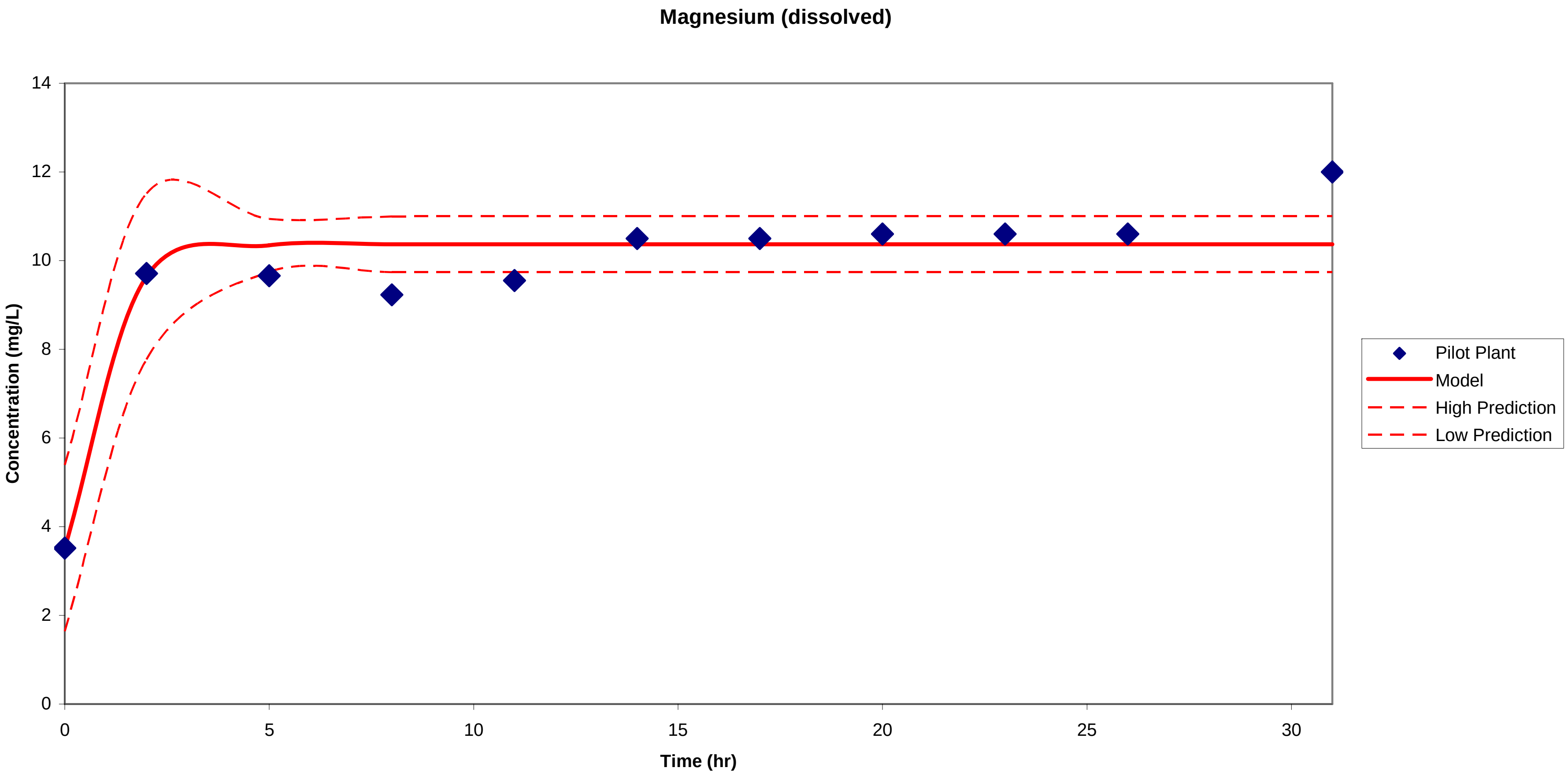


Figure H5 Regression Curve and Pilot Plant Data for Dissolved Magnesium Concentration in the Process Water (R^2 = 0.89 compared to average model, R^2 = 0.78 compared to linear regression model)

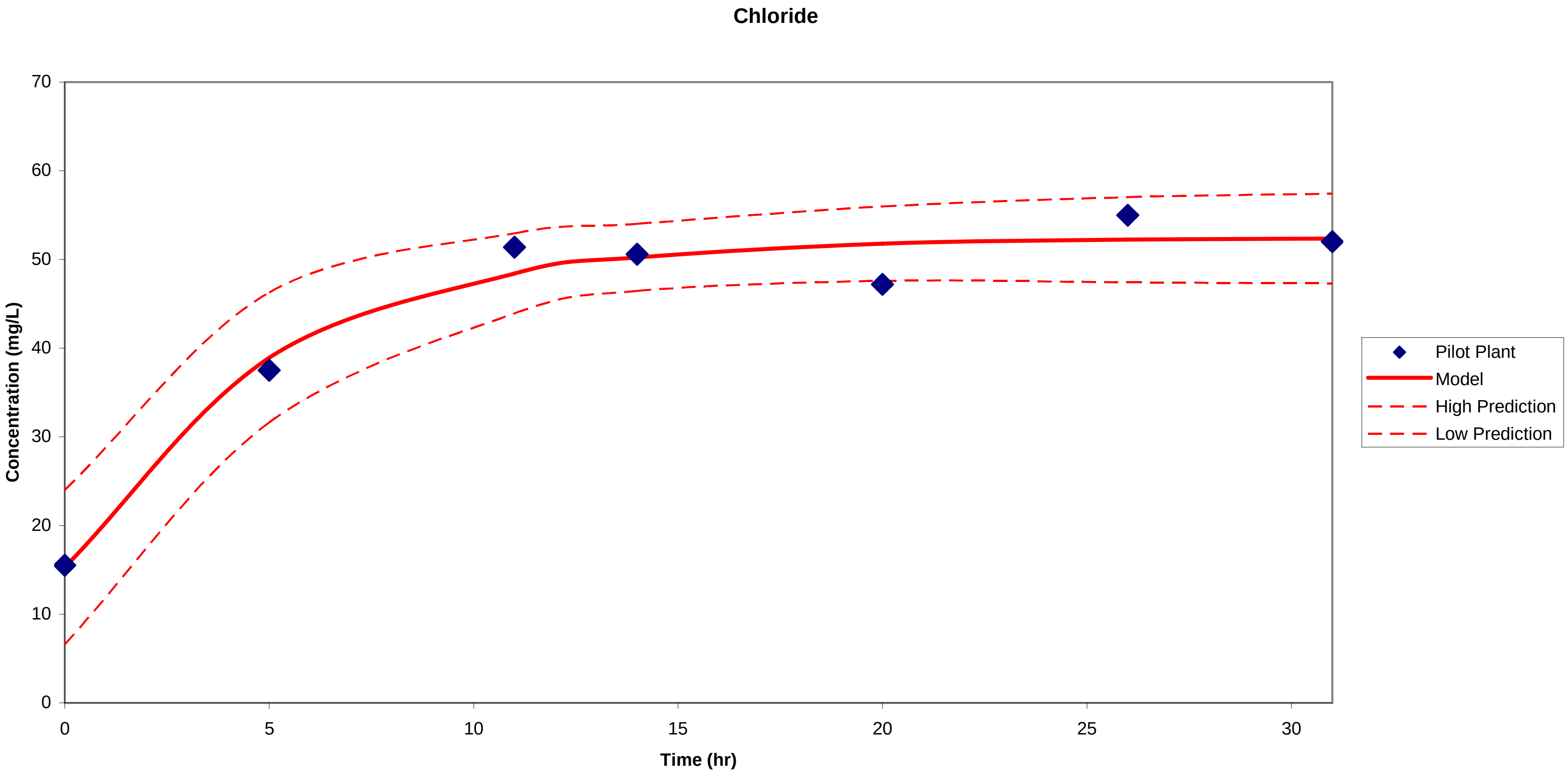


Figure H6 Regression Curve and Pilot Plant Data for Total Chloride Concentration in the Process Water (R^2 = 0.97 compared to average model, R^2 = 0.91 compared to linear regression model)

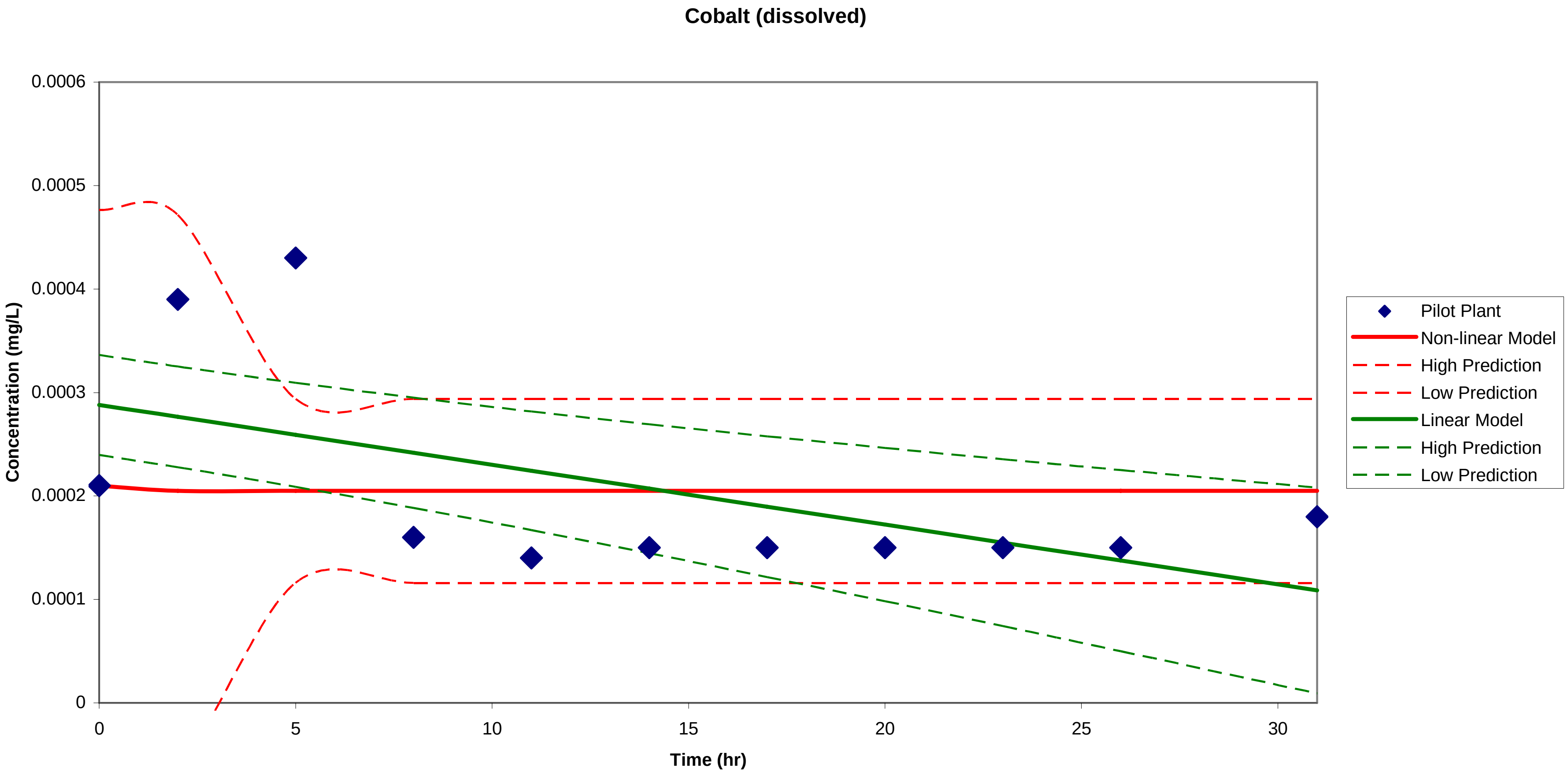


Figure H7 Regression Curves and Pilot Plant Data for Dissolved Cobalt Concentration in the Process Water (R^2 = 0.00 compared to average model, R^2 = -0.47 compared to linear regression model)

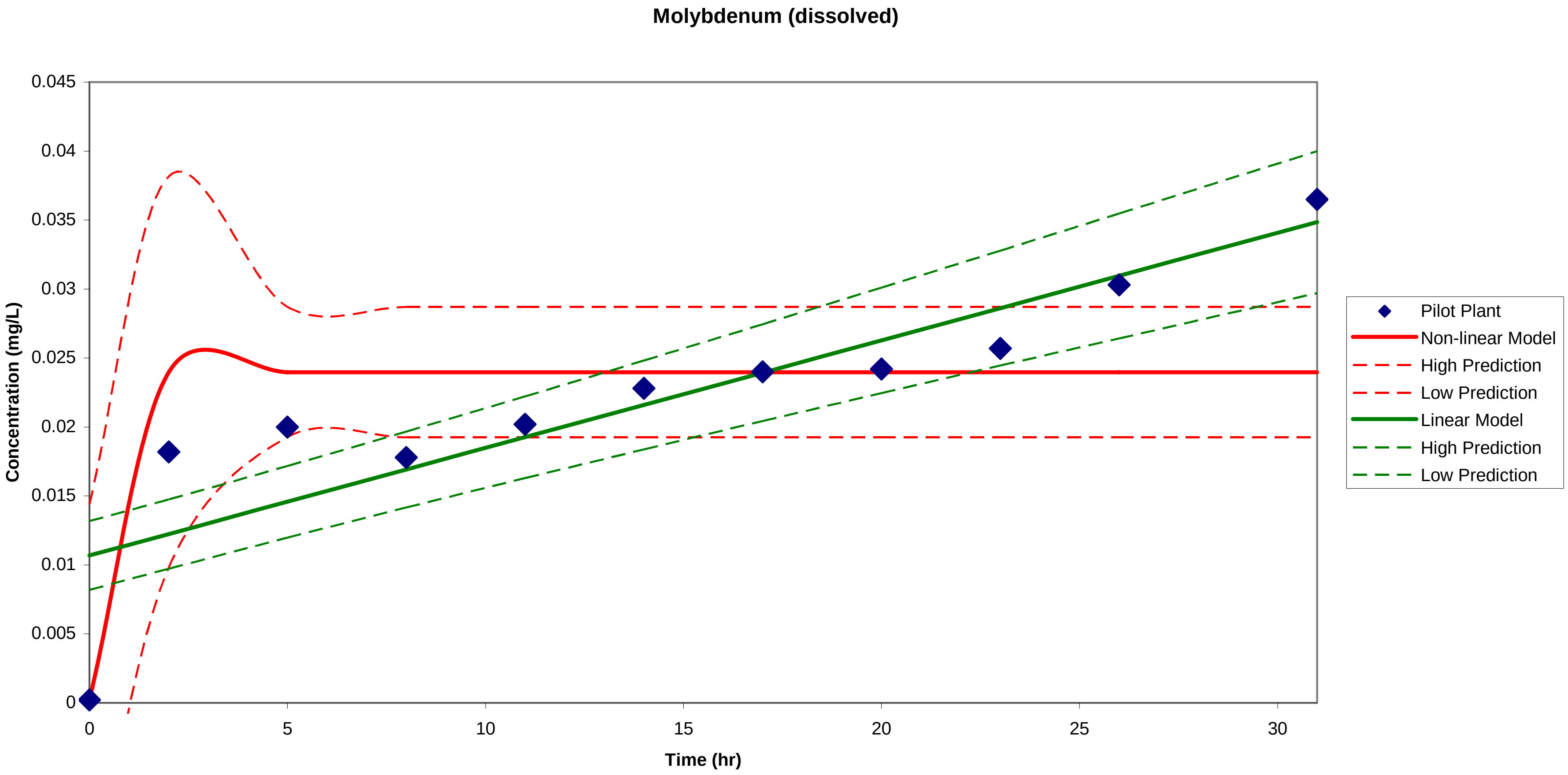


Figure H8 Regression Curves and Pilot Plant Data for Dissolved Molybdenum Concentration in the Process Water (R^2 = 0.63 compared to average model, R^2 = -0.57 compared to linear regression model)

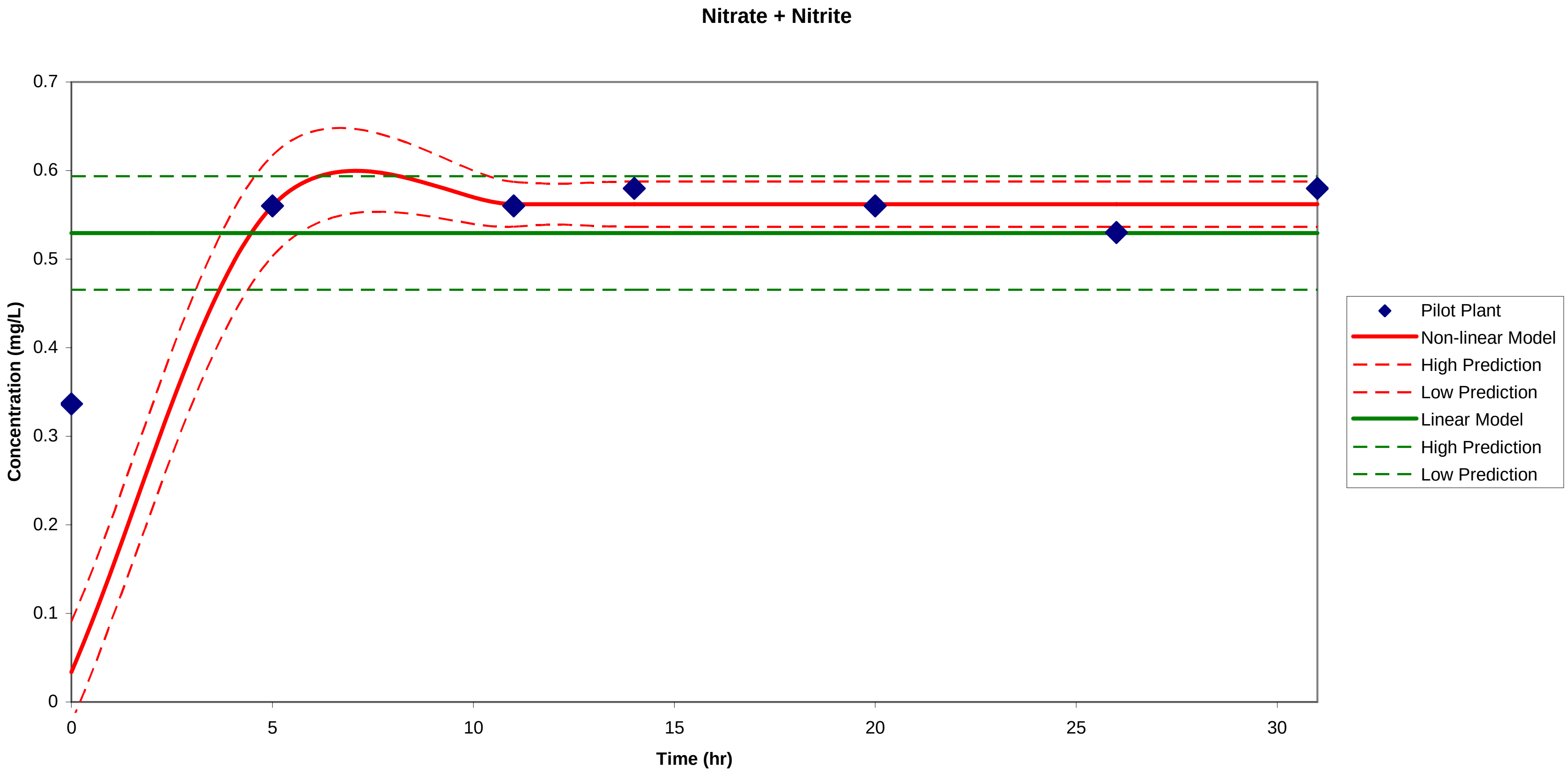


Figure H9 Regression Curves and Pilot Plant Data for Nitrate + Nitrite Concentration in the Process Water (R^2 = -1.07 compared to average model, R^2 = -0.30 compared to linear regression model)

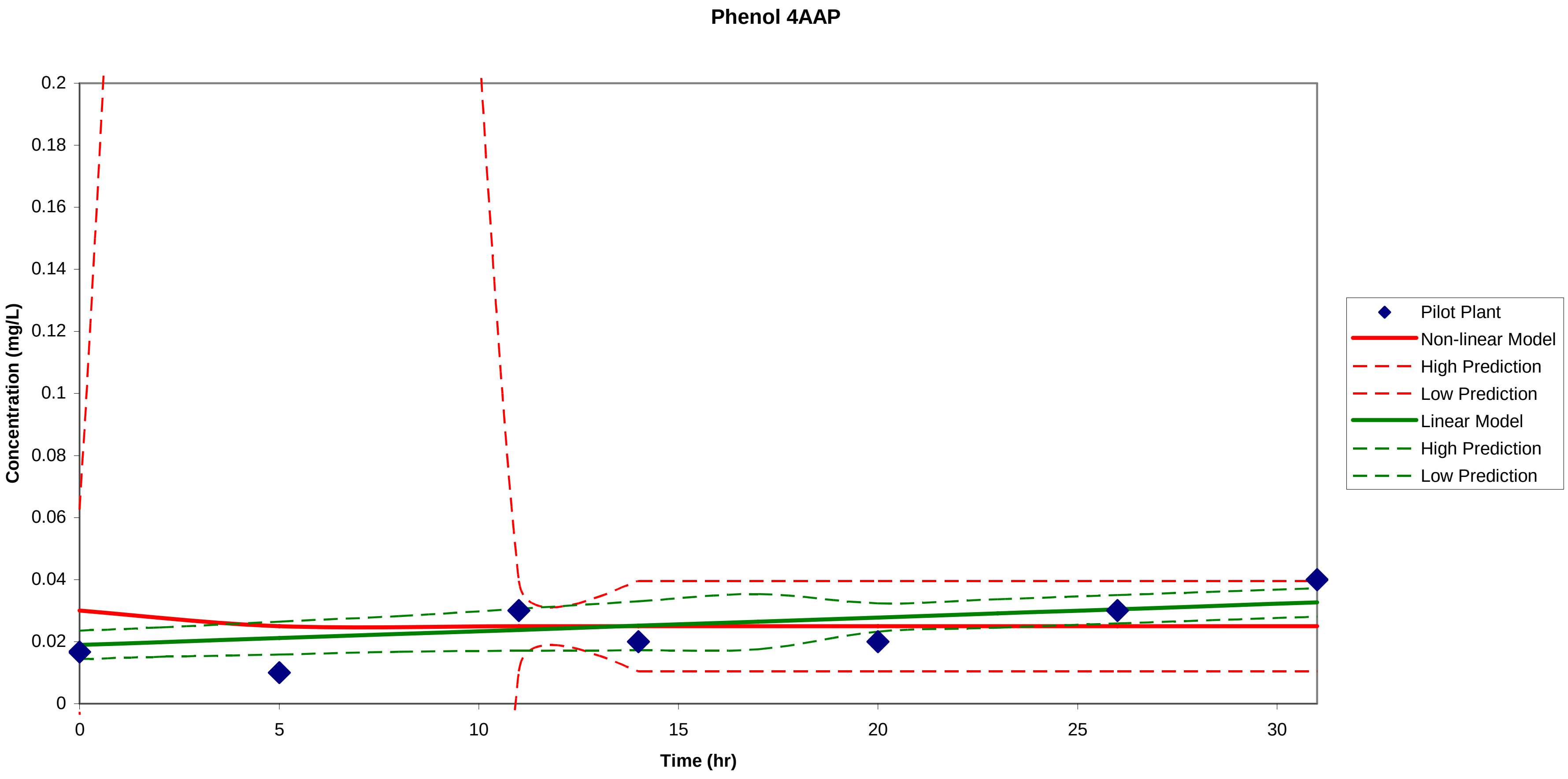


Figure H10 Regression Curves and Pilot Plant Data for Phenol 4AAP Concentration in the Process Water (R^2 = -0.19 compared to average model, R^2 = -1.35 compared to linear regression model)

Attachment A

A Pilot Plant Investigation into

BULK CONCENTRATE PRODUCTION FROM SAMPLES OF THE NORTHMET DEPOSIT

prepared for

POLYMET MINING INC.

Project 11263-001 - Report No. 1
July 5, 2006

NOTE:
This report refers to the samples as received.

The practice of this Company in issuing reports of this nature is to require the recipient not to publish the report or any part thereof without the written consent of SGS Lakefield Research Limited.

Attachment B

Table 1
Analytical Data Summary
Tailings Thickener Overflow Samples
PolyMet Mining Corporation
(concentrations in ug/L, unless noted otherwise)

Location Date Time	Tailings Thickener Overflow 4/3/2006 1:20 PM	Tailings Thickener Overflow 4/3/2006 4:30 PM	Tailings Thickener Overflow 4/5/2006 10:00 AM	Tailings Thickener Overflow 4/5/2006 1:00 PM	Tailings Thickener Overflow 4/5/2006 4:00 PM	Tailings Thickener Overflow 4/5/2006 7:00 PM
General Parameters						
Alkalinity, (hydrox.) as @CaCO3, mg/L	--	<2	--	<2	--	<2
Alkalinity, bicarbonate as CaCO3, mg/L	--	122 b	--	145 b	--	154 b
Alkalinity, total, mg/L	--	124 b	--	145 b	--	154 b
Bromide, mg/L	--	<0.2	--	<0.2	--	<0.2
Carbonate, mg/L	--	2	--	<2	--	<2
Chemical Oxygen Demand, mg/L	--	31	--	466	--	463
Chloride, mg/L	--	33.3 b	--	37.5 b	--	51.4 b
Cyanide	--	<10	--	<10	--	<10
Fluoride, mg/L	--	<0.4	--	<0.4	--	<0.4
Nitrate + Nitrite	--	460 b	--	560 b	--	560 b
Nitrogen total kjeldahl	--	200 b	--	300 b	--	200 b
Nitrogen, ammonia as N	--	50	--	90	--	90
Phenol 4AAP, mg/L	--	<0.01	--	<0.01	--	0.03
Phosphorus total, mg/L	--	0.06	--	0.65 *	--	0.42
Solids, total suspended, mg/L	494	60	574	702	259	545
Sulfate, mg/L	62 b	61.5 b	69 b	75 b	80 b	90
Sulfate, dissolved, mg/L	49	48.2	57	67	64	69
Sulfide total, mg/L	<2	<2	<2	<2	<2	<2
Sulfide, dissolved, mg/L	<2	<2	<2	<2	<2	<2
Sulfite, mg/L	2	<2	<2	2	3	3
Sulfite, dissolved, mg/L	2	<2	<2	2	2	3
Surfactants MBAS, mg/L	--	0.11	--	0.6	--	0.7
Chlorine, mg/L	--	<0.1 *	--	<0.1	--	<0.1 *
pH, standard units	8.64	8.56	8.55	8.58	8.61	8.57
Sulfate, mg/L	53	48	60	67	73	96
Sulfate, dissolved, mg/L	55	49	60	68	73	76
Sulfur, mg/L	20.7	18.3	24.1	26.8	28.7	32.0
Sulfur, filtered, mg/L	31.8	25.3	32.1	36.7	39.7	53.4
Tetrathionate, mg/L	0.6	0.4	0.4	0.4	<0.2	0.3
Tetrathionate, filtered, mg/L	0.5	0.2	0.2	0.4	<0.2	<0.2
Thiosalt, mg/L	<10	<10	<10	<10	<10	<10
Thiosalt, filtered, mg/L	14	<10	<10	<10	<10	<10
Thiosulphate, mg/L	6.6	5.8	4.5	5.7	7.0	6.1
Thiosulphate, filtered, mg/L	6.6	6.0	5.5	6	7.0	8.3
Trithionate, mg/L	4	3	3	4	4	4
Trithionate, filtered, mg/L	3	3	3	4	4	5
Metals						
Aluminum	30400	3320	20200	26300	15600	64500
Antimony	0.84	2.05	0.83	0.57	1.19 *	0.34 *
Arsenic	9.3	11.2	6.9	7.7	6.4	5.5
Barium	45.2	9.17	57.6	64.8	25.5	72.9
Beryllium	0.20	0.03	0.27	0.28	0.09	0.28
Boron	98.6	104	104	121	105	158
Cadmium	0.23	0.11	0.17	0.25	0.13	0.18
Calcium	41200	23900	47300	51700	32400	57200
Chromium	20.1	2.45 b	19	28.9	12.2	26.4
Cobalt	20.9	2.53	17.8	28	12.2	26.6
Copper	429	26.7	87.1	307	174	543
Iron	23000	2650	24900	41400	16400	42000

Table 1
Analytical Data Summary
Tailings Thickener Overflow Samples
PolyMet Mining Corporation
(concentrations in ug/L, unless noted otherwise)

Location Date Time	Tailings Thickener Overflow 4/3/2006 1:20 PM	Tailings Thickener Overflow 4/3/2006 4:30 PM	Tailings Thickener Overflow 4/5/2006 10:00 AM	Tailings Thickener Overflow 4/5/2006 1:00 PM	Tailings Thickener Overflow 4/5/2006 4:00 PM	Tailings Thickener Overflow 4/5/2006 7:00 PM
Lead	3.85	0.59	2.07	2.49	2.94	4.09
Magnesium	21100	9690	22200	32100	17800	31200
Manganese	229	29.4	177	221	158	456
Mercury	0.0773	0.0136	0.0072	<0.005	0.006	0.0032
Molybdenum	14.1	14.1	16.3	16.2	16.7	17.6
Nickel	205	22.9	121	228	105	297
Potassium	14300	13800	17200	18800	17800	21000
Selenium	2.7	2.5	2.3	2.7	1.8	1.5
Silicon	70700	17700	95200	127000	55800	141000
Silver	0.26	<0.02	0.15	0.24	0.13	0.26
Sodium	70000	66700	79400	97200	98900	117000
Thallium	0.05	<0.02	0.06	0.08	0.03	0.08
Tin	<0.1	<0.1	<0.2	<0.2	<0.1 *	<0.1 *
Titanium	338	46.5	424	662	264	728
Zinc	477	7.1 b	21.4 b	30.6	15.7 b*	29.4 b*
Dissolved Metals						
Aluminum, dissolved	71.7	110	103	99.1	106	82.1
Antimony dissolved	2.03	2.45	2.8	2.62	2.65	2.70
Arsenic, dissolved	8.2	11.0	6.3	7.1	5.9	5.5
Barium, dissolved	4.14	3.99	4.06	4.97	3.73	3.90
Beryllium, dissolved	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Boron, dissolved	107	102	113	140	117	124
Cadmium, dissolved	0.14	0.09	0.11	0.11	0.09	0.09
Calcium, dissolved	23900	21700	22600	22100	20200	18900
Chromium, dissolved	0.2 b	0.25 b	0.47 b	0.40 b	0.3 b	0.3 b
Cobalt, dissolved	0.41	0.38	0.39	0.43	0.16	0.14
Copper, dissolved	0.3 b	1.0	1.3	1.6	0.8 b	0.5 b
Iron, dissolved	<20	<20	<20	<20	<20	<20
Lead, dissolved	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Magnesium, dissolved	8970	8410	9710	9660	9230	9550
Manganese, dissolved	6.11	4.79	5.98	5.85	6.11	5.24
Mercury, dissolved	0.002	0.0018	<0.001	0.0017	<0.001	<0.001
Molybdenum dissolved	15.4	14.4	18.2	20	17.8	20.2
Nickel, dissolved	6.0	5.0	5.8	5.7	4.7	3.9
Potassium, dissolved	13300	13600	15000	17400	17200	19000
Selenium, dissolved	2.1	2.4	2.9	3.5	1.4	1.5
Silicon, dissolved	6740	7080	6560	7460	7050	6890
Silver, dissolved	<0.02	<0.02	<0.02	<0.02	<0.02 *	<0.02 *
Sodium dissolved	59500	65600	70100	87500	90200	97700
Thallium dissolved	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tin dissolved	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Titanium dissolved	<10	<10	<10	<10	<10	<10
Zinc, dissolved	2.2 b	2.0 b	2.3 b	4.9 b	1.9 b	2.1 b
SVOCs						
1-Pentanol	--	<400	--	<400	--	<400
2-Pentanol	--	<100	--	<100	--	<100
3-Pentanol	--	<100	--	<100	--	<100
VOCs						
Benzene	--	<0.50	--	<0.50	--	<0.50
Carbon disulfide	--	390	--	110	--	600
Ethyl benzene	--	<0.50	--	<0.50	--	<0.50

Table 1
Analytical Data Summary
Tailings Thickener Overflow Samples
PolyMet Mining Corporation
(concentrations in ug/L, unless noted otherwise)

Location Date Time	**Tailings Thickener Overflow 4/3/2006 1:20 PM**	**Tailings Thickener Overflow 4/3/2006 4:30 PM**	**Tailings Thickener Overflow 4/5/2006 10:00 AM**	**Tailings Thickener Overflow 4/5/2006 1:00 PM**	**Tailings Thickener Overflow 4/5/2006 4:00 PM**	**Tailings Thickener Overflow 4/5/2006 7:00 PM**
Methyl isobutyl alcohol	--	**3600**	--	**4200**	--	**3900**
Toluene	--	<0.50	--	<0.50	--	<0.50
Xylene m & p	--	<0.50	--	<0.50	--	<0.50
Xylene o-	--	<0.50	--	<0.50	--	<0.50

-- Not analyzed.
b Potential false positive based on blank data validation procedure.
* Estimated value, QA/QC criteria not met.
Detections are presented in **bold.**

Table 1
Analytical Data Summary
Tailings Thickener Overflow Samples
PolyMet Mining Corporation
(concentrations in ug/L, unless noted otherwise)

Location	Tailings Thickener Overflow	Tailings Thickener Overflow	Tailings Thickener Overflow	Tailings Thickener Overflow	Tailings Thickener Overflow	Tailings Thickener Overflow
Date	4/5/2006	4/6/2006	4/6/2006	4/6/2006	4/6/2006	4/6/2006
Time	10:00 PM	1:00 AM	4:00 AM	7:00 AM	10:00 AM	3:00 PM
General Parameters						
Alkalinity, (hydrox.) as @CaCO3, mg/L	<2	--	<2	--	<2	<2
Alkalinity, bicarbonate as CaCO3, mg/L	155 b	--	150 b	--	159 b	166 b
Alkalinity, total, mg/L	155 b	--	150 b	--	159 b	166 b
Bromide, mg/L	<0.2	--	<0.2	--	<0.2	<0.2
Carbonate, mg/L	<2	--	<2	--	<2	<2
Chemical Oxygen Demand, mg/L	444	--	398	--	403	398
Chloride, mg/L	50.6	--	47.2 b	--	55.0 b	52 b
Cyanide	<10	--	<10	--	<10	<10
Fluoride, mg/L	<0.4	--	<0.4	--	0.4	0.5
Nitrate + Nitrite	580 b	--	560 b	--	530 b	580 b
Nitrogen total kjeldahl	300 b	--	300 b	--	400 b	300 b
Nitrogen, ammonia as N	100	--	80	--	90	90
Phenol 4AAP, mg/L	0.02	--	0.02	--	0.03	0.04
Phosphorus total, mg/L	0.47	--	0.44	--	0.24	0.51
Solids, total suspended, mg/L	559	694	626	368	582	862
Sulfate, mg/L	98	103	104	106	121	143
Sulfate, dissolved, mg/L	77	84	81	92	122	118
Sulfide total, mg/L	<2	2	<2	2	2	2
Sulfide, dissolved, mg/L	<2	<2	<2	2	2	2
Sulfite, mg/L	3	3	2	3	3	3
Sulfite, dissolved, mg/L	3	3	3	3	--	3
Surfactants MBAS, mg/L	1.0	--	1.2	--	0.7	1.2
Chlorine, mg/L	<0.1 *	--	<0.1 *	--	<0.1	<0.1 *
pH, standard units	8.47	8.50	8.05	8.60	8.40	8.50
Sulfate, mg/L	110	110	110	110	130	150
Sulfate, dissolved, mg/L	85	88	91	96	110	130
Sulfur, mg/L	36.3	37.4	38.5	38.2	41.3	48.6
Sulfur, filtered, mg/L	57.2	61.7	59.1	62.8	71.0	77.9
Tetrathionate, mg/L	0.4	0.5	0.6	0.4	0.6	0.5
Tetrathionate, filtered, mg/L	0.3	0.5	0.5	0.3	0.3	0.4
Thiosalt, mg/L	<10	<10	<10	<10	13	10
Thiosalt, filtered, mg/L	<10	10	<10	<10	<10	14
Thiosulphate, mg/L	5.5	8.2	7.3	8.8	9.1	9.7
Thiosulphate, filtered, mg/L	8.6	8.8	8.7	9.5	10	9.7
Trithionate, mg/L	3	4	7	6	6	7
Trithionate, filtered, mg/L	4	7	6	6	6	7
Metals						
Aluminum	60000	59000	51500	36400	27400	63600
Antimony	0.40 *	0.49 *	0.61 *	0.94 *	0.92 *	0.59 *
Arsenic	5.0	4.6	5.5	4.8	4.6	4.9
Barium	75.2	68.4	63.0	43.3	44.1	78.7
Beryllium	0.27	0.27	0.24	0.17	0.18	0.30
Boron	172	178	174	180	172	233
Cadmium	0.18	0.18	0.17	0.17	0.16	0.21
Calcium	55500	54900	50300	41900	42800	58000
Chromium	25.7	23.1	23.4	16.6	17.4 b	28.3
Cobalt	25.5	22.6	23.2	16.8	16.2	26.4
Copper	522	516	495	368	358	556
Iron	41400	37000	35900	24200	23500	42200

Table 1
Analytical Data Summary
Tailings Thickener Overflow Samples
PolyMet Mining Corporation
(concentrations in ug/L, unless noted otherwise)

Location	**Tailings Thickener Overflow**	**Tailings Thickener Overflow**	**Tailings Thickener Overflow**	**Tailings Thickener Overflow**	**Tailings Thickener Overflow**	**Tailings Thickener Overflow**
Date	**4/5/2006**	**4/6/2006**	**4/6/2006**	**4/6/2006**	**4/6/2006**	**4/6/2006**
Time	**10:00 PM**	**1:00 AM**	**4:00 AM**	**7:00 AM**	**10:00 AM**	**3:00 PM**
Lead	**3.80**	**3.35**	**3.15**	**2.29**	**2.25**	**3.91**
Magnesium	**31500**	**29000**	**28600**	**21900**	**22100**	**32400**
Manganese	**447**	**395**	**383**	**257**	**209**	**455**
Mercury	**0.0034**	**0.0014**	**0.0024**	**0.0023**	**0.0021**	**0.0028**
Molybdenum	**20.3**	**21.3**	**21.5**	**23.7**	**27.2**	**31.2**
Nickel	**283**	**291**	**264**	**203**	**174**	**321**
Potassium	**24100**	**24500**	**22700**	**23800**	**25200**	**29000**
Selenium	**1.6**	**1.6**	**1.8**	**1.7**	**1.8**	**2.0**
Silicon	**134000**	**140000**	**120000**	**96300**	**99100**	**135000**
Silver	**0.26**	**0.24**	**0.23**	**0.19**	**0.16**	**0.30**
Sodium	**117000**	**118000**	**116000**	**117000**	**132000**	**153000**
Thallium	**0.09**	**0.07**	**0.07**	**0.05**	**0.04**	**0.09**
Tin	<0.1 *	<0.1 *	<0.1 *	<0.1 *	<0.1 *	<0.1 *
Titanium	**755**	**718**	**643**	**475**	**478**	**774**
Zinc	**28.3 b***	**46.5 ***	**35.3 ***	**18.4 b**	**18.5 b***	**29.1 ***
Dissolved Metals						
Aluminum, dissolved	**143**	**139**	**134**	**149**	**125**	**155**
Antimony dissolved	**2.91**	**3.20**	**3.46**	**3.47**	**3.74**	**3.58**
Arsenic, dissolved	**5.0**	**4.4**	**5.4**	**4.5**	**4.3**	**4.7**
Barium, dissolved	**4.22**	**4.10**	**3.99**	**4.46**	**4.29**	**5.10**
Beryllium, dissolved	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Boron, dissolved	**138**	**148**	**144**	**150**	**181**	**195**
Cadmium, dissolved	**0.10**	**0.09**	**0.10**	**0.09**	**0.11**	**0.16**
Calcium, dissolved	**18900**	**19000**	**18900**	**18900**	**18800**	**19300**
Chromium, dissolved	**0.3 b**	**0.2 b**	**0.3 b**	**0.3 b**	**0.3**	**0.3 b**
Cobalt, dissolved	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.18**
Copper, dissolved	**0.5 b**	**0.8 b**	**0.5 b**	**0.6 b**	**0.6 b**	**0.6 b**
Iron, dissolved	<20	<20	<20	<20	<20	<20
Lead, dissolved	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Magnesium, dissolved	**10500**	**10500**	**10600**	**10600**	**10600**	**12000**
Manganese, dissolved	**5.34**	**5.37**	**5.62**	**5.77**	**6.13**	**6.33**
Mercury, dissolved	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Molybdenum dissolved	**22.8**	**24.0**	**24.2**	**25.7**	**30.3**	**36.5**
Nickel, dissolved	**3.9**	**3.7**	**4.0**	**3.9**	**3.9**	**3.9**
Potassium, dissolved	**21300**	**21600**	**21100**	**21400**	**23100**	**25500**
Selenium, dissolved	**1.7**	**1.6**	**1.6**	**1.2**	**1.4**	**1.8**
Silicon, dissolved	**6810**	**6590**	**6470**	**6240**	**6300**	**6840**
Silver, dissolved	<0.02 *	<0.02 *	<0.02 *	<0.02 *	<0.02 *	<0.02 *
Sodium dissolved	**100000**	**104000**	**101000**	**104000**	**115000**	**134000**
Thallium dissolved	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tin dissolved	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Titanium dissolved	<10	<10	<10	<10	<10	<10
Zinc, dissolved	**1.1 b**	**2.6 b**	**41.1**	**4.4 b**	**2.8 b***	**3.9**
SVOCs						
1-Pentanol	<400	--	<400	--	<400	<400
2-Pentanol	<100	--	<100	--	<100	<100
3-Pentanol	<100	--	<100	--	<100	<100
VOCs						
Benzene	<0.50	--	<0.50	--	<0.50	<0.50
Carbon disulfide	**520**	--	**630**	--	**730 d**	**580**
Ethyl benzene	<0.50	--	<0.50	--	<0.50	<0.50

Table 1
Analytical Data Summary
Tailings Thickener Overflow Samples
PolyMet Mining Corporation
(concentrations in ug/L, unless noted otherwise)

Location **Date** **Time**	**Tailings Thickener Overflow** **4/5/2006** **10:00 PM**	**Tailings Thickener Overflow** **4/6/2006** **1:00 AM**	**Tailings Thickener Overflow** **4/6/2006** **4:00 AM**	**Tailings Thickener Overflow** **4/6/2006** **7:00 AM**	**Tailings Thickener Overflow** **4/6/2006** **10:00 AM**	**Tailings Thickener Overflow** **4/6/2006** **3:00 PM**
Methyl isobutyl alcohol	**3900**	--	**3400**	--	**3000 d**	**2800**
Toluene	<0.50 b	--	<0.50	--	<0.50	<0.50
Xylene m & p	<0.50 b	--	<0.50	--	<0.50	<0.50
Xylene o-	<0.50	--	<0.50	--	<0.50	<0.50

-- Not analyzed.

b Potential false positive based on blank data validation procedure.

* Estimated value, QA/QC criteria not met.

Detections are presented in **bold.**

Table 2
Analytical Data Summary
Make Up Water Samples
PolyMet Mining Corporation
(concentrations in ug/L, unless noted otherwise)

Location	**Initial**	**Makeup**	**Makeup**	**Makeup**	**Makeup**	**Makeup**	**Makeup**	**Makeup**	**Makeup**	**Makeup**
Date	**4/3/2006**	**4/3/2006**	**4/3/2006**	**4/5/2006**	**4/5/2006**	**4/5/2006**	**4/5/2006**	**4/6/2006**	**4/6/2006**	**4/6/2006**
Time	**7:20 AM**	**3:30 PM**	**11:30 AM**	**11:00 AM**	**3:00 PM**	**7:00 PM**	**10:00 PM**	**3:00 AM**	**7:00 AM**	**11:00 AM**
General Parameters										
Alkalinity, (hydrox.) as @CaCO3, mg/L	<2	<2	--	--	<2	--	<2	--	<2	--
Alkalinity, bicarbonate as CaCO3, mg/L	**91 b**	**88 b**	--	--	**92 b**	--	**84 b**	--	**84 b**	--
Alkalinity, total, mg/L	**91 b**	**88 b**	--	--	**92 b**	--	**84 b**	--	**84 b**	--
Bromide, mg/L	<0.2	<0.2	--	--	<0.2	--	<0.2	--	<0.2	--
Carbonate, mg/L	<2	<2	--	--	<2	--	<2	--	<2	--
Chemical Oxygen Demand, mg/L	**15**	**17**	--	--	**15**	--	**14**	--	**15**	--
Chloride, mg/L	**26.9 b**	**18.2 b**	--	--	**16.7 b**	--	**14.1 b**	--	**15.8 b**	--
Cyanide	<10	**20**	--	--	<10	--	<10	--	<10	--
Fluoride, mg/L	<0.4	<0.4	--	--	<0.4	--	<0.4	--	<0.4	--
Nitrate + Nitrite	**410 b**	**380 b**	--	--	**340 b**	--	**340 b**	--	**330 b**	--
Nitrogen total kjeldahl	**200 b**	**700**	--	--	**300 b**	--	**400 b**	--	**400 b**	--
Nitrogen, ammonia as N	<50	<50	--	--	<50	--	<50	--	<50	--
Phenol 4AAP, mg/L	<0.01	<0.01	--	--	**0.03**	--	<0.01	--	<0.01	--
Phosphorus total, mg/L	**0.01 ***	**0.01**	--	--	**0.01**	--	<0.01	--	**0.01**	--
Solids, total suspended, mg/L	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Sulfate, mg/L	**14.1 b**	**11.6 b**	**11.7 b**	**11.8 b**	**11.4 b**	**11.5 b**	**10.4 b**	**11.2 b**	**11.3 b**	**11.1 b**
Sulfate, dissolved, mg/L	**14.0**	**11.7**	**11.9**	**11.9**	**11.5**	**11.3**	**11.4**	**11.2**	**11.1**	**11.2**
Sulfide total, mg/L	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Sulfide, dissolved, mg/L	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Sulfite, mg/L	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Sulfite, dissolved, mg/L	<2	<2	<2	<2	<2	<2	<2	<2	<2	--
Surfactants MBAS, mg/L	**0.05**	<0.05	--	--	**0.07**	--	<0.05	--	**0.06**	--
Chlorine, mg/L	<0.1 b	<0.1	--	--	<0.1	--	<0.1	--	<0.1	--
pH, standard units	**7.90**	**7.86**	**7.94**	**7.80**	**7.88**	**7.85**	**7.87**	**7.85**	**7.82**	**7.80**
Sulfate, mg/L	**15**	**12**	**12**	**12**	**11**	**11**	**11**	**11**	**11**	**11**
Sulfate, dissolved, mg/L	**14**	**12**	**12**	**12**	**11**	**11**	**11**	**10**	**11**	**11**
Sulfur, mg/L	**4.82**	**4.02**	**4.11**	**4.10**	**4.00**	**3.94**	**3.84**	**4.30**	**3.86**	**4.19**
Sulfur, filtered, mg/L	**4.91**	**3.94**	**3.97**	**4.31**	**4.54**	**4.33**	**4.73**	**4.11**	**4.25**	**4.51**
Tetrathionate, mg/L	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Tetrathionate, filtered, mg/L	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Thiosalt, mg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Thiosalt, filtered, mg/L	<10	<10	**13**	<10	<10	<10	<10	<10	<10	<10
Thiosulphate, mg/L	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Thiosulphate, filtered, mg/L	**0.3**	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Trithionate, mg/L	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Trithionate, filtered, mg/L	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Metals										
Aluminum	**22.9**	**26.6**	**34.2**	**16.1 b**	**15.1 b**	**11.6 b**	**12.2 b**	**12.7 b**	**12.8 b**	**12.5 b**
Antimony	**0.11**	**0.07**	**0.08**	**0.08**	**0.06 ***	<0.05 *	**0.06 ***	**0.07 ***	<0.05 *	**0.06 ***
Arsenic	**0.5**	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Barium	**32.5**	**31.5**	**31.3**	**33**	**30.0**	**29.4**	**29.1**	**28.9**	**29.2**	**29.4**
Beryllium	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Boron	**12.4**	**11.5**	**11.0**	**11**	**8.5 b**	**8.1 b**	**8.2 b**	**7.7 b**	**7.8 b**	**8.1 b**
Cadmium	**0.05**	**0.03**	**0.04**	**0.03**	**0.02**	<0.02	<0.02	**0.02**	<0.02	<0.02
Calcium	**41600**	**38300**	**39400**	**36800**	**35500**	**36400**	**36900**	**37200**	**36400**	**38200**
Chromium	**0.4 b**	**0.23 b**	**0.3 b**	**0.24 b**	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Cobalt	**0.78**	**0.56**	**0.59**	**0.5**	**0.18**	**0.17**	**0.18**	**0.17**	**0.18**	**0.18**
Copper	**2.9**	**1.5**	**1.3**	**1.3**	**1.1**	**1.2**	**1.1**	**1.1**	**1.1**	**1.0**
Iron	**172**	**93**	**78.4**	**62.9**	**61.8**	**62.1**	**63.1**	**62.3**	**62.9**	**67.2**

Table 2
Analytical Data Summary
Make Up Water Samples
PolyMet Mining Corporation
(concentrations in ug/L, unless noted otherwise)

Location	**Initial**	**Makeup**	**Makeup**	**Makeup**	**Makeup**	**Makeup**	**Makeup**	**Makeup**	**Makeup**	**Makeup**
Date	**4/3/2006**	**4/3/2006**	**4/3/2006**	**4/5/2006**	**4/5/2006**	**4/5/2006**	**4/5/2006**	**4/6/2006**	**4/6/2006**	**4/6/2006**
Time	**7:20 AM**	**3:30 PM**	**11:30 AM**	**11:00 AM**	**3:00 PM**	**7:00 PM**	**10:00 PM**	**3:00 AM**	**7:00 AM**	**11:00 AM**
Lead	**0.34**	**0.27 b**	**0.38**	**0.18**	**0.16**	**0.11 b**	**0.11 b**	**0.13 b**	**0.13 b**	**0.12 b**
Magnesium	**4200**	**3870**	**3960**	**3730**	**3540**	**3620**	**3660**	**3690**	**3610**	**3780**
Manganese	**10.9**	**6.62**	**8.04**	**5.4**	**6.79**	**6.58**	**7.20**	**6.79**	**9.21**	**8.28**
Mercury	**0.003**	**0.0012**	**0.0018**	**0.0011**	**0.0016**	**0.0011**	**0.0016**	**0.0026**	**0.0016**	**0.001**
Molybdenum	**0.34 b**	**0.27 b**	**0.25 b**	**0.28 b**	**0.21 b**	**0.21 b**	**0.20 b**	**0.21 b**	**0.20 b**	**0.19 b**
Nickel	**6.6**	**0.7 b**	**0.9 b**	**0.9 b**	**1.6**	**1.6**	**1.6**	**1.7**	**1.6**	**1.7**
Potassium	<2000	<2000	<2000	<2000	<2000	**2320**	<2000	<2000	<2000	<2000
Selenium	<1.0	<1	<1.0	<1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Silicon	**4470**	**4330**	**4450**	**4230**	**4170**	**4290**	**4290**	**4380**	**4310**	**4500**
Silver	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Sodium	**15100**	**12100**	**10800**	**10900**	**10400**	**9940**	**9770**	**9550**	**9550**	**9490**
Thallium	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tin	<0.1	<0.1	<0.1	<0.1	<0.1 *	<0.1 *	<0.1 *	<0.1 *	<0.1 *	<0.1 *
Titanium	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Zinc	**14.7 b**	**8.2 b**	**10.3 b**	**6.2 b**	**6.0 b***	**6.2 b***	**5.7 b***	**6.0 b***	**6.7 b***	**5.9 b**
Dissolved Metals										
Aluminum, dissolved	**5.4**	**5.6**	**8.8**	**5.6**	**6.1**	**5.0**	**5.6**	**5.2**	**5.1**	**5.1**
Antimony dissolved	**0.13 b**	**0.08**	**0.09 b**	**0.06**	**0.06 b**	**0.06 b**	**0.05 b**	**0.06 b**	<0.05	<0.05
Arsenic, dissolved	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Barium, dissolved	**30.8**	**31.4**	**30.7**	**32.2**	**29.3**	**28.6**	**29.3**	**28.6**	**28.8**	**28.5**
Beryllium, dissolved	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Boron, dissolved	**13.2**	**13.2**	**11.4**	**12.1**	**8.7 b**	**9.3**	**9.9**	**11.3**	**9.4**	**8.8 b**
Cadmium, dissolved	**0.04**	**0.04**	**0.03**	**0.04**	**0.03**	<0.02	<0.02	<0.02	<0.02	<0.02
Calcium, dissolved	**42000**	**38400**	**39300**	**36600**	**34900**	**34600**	**34300**	**34000**	**34600**	**33900**
Chromium, dissolved	**0.2 b**	**0.23 b**	**0.2 b**	**0.22 b**	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Cobalt, dissolved	**0.64**	**0.53**	**0.57**	**0.52**	**0.17**	**0.15**	**0.17**	**0.15**	**0.16**	**0.15**
Copper, dissolved	**1.9**	**1.4**	**1.0**	**1.2**	**1.1**	**1.0**	**1.0**	**1.1**	**0.9 b**	**0.9 b**
Iron, dissolved	**72.1**	**34.8**	**36.3**	**36.1**	**37.0**	**37.1**	**38.2**	**39.5**	**38.2**	**37.2**
Lead, dissolved	**0.10**	**0.07**	**0.09**	**0.08**	**0.06**	**0.06**	**0.05**	**0.05**	**0.04**	**0.05**
Magnesium, dissolved	**4160**	**3880**	**3950**	**3690**	**3570**	**3560**	**3420**	**3480**	**3440**	**3450**
Manganese, dissolved	**4.66**	**2.44**	**2.65**	**2.14**	**2.26**	**2.14**	**2.17**	**2.24**	**2.22**	**2.17**
Mercury, dissolved	**0.0015**	<0.001	**0.0013**	<0.001	**0.001**	**0.0011**	**0.0012**	<0.001	**0.0011**	**0.001**
Molybdenum dissolved	**0.34**	**0.27 b**	**0.28 b**	**0.24 b**	**0.22 b**	**0.22 b**	**0.21 b**	**0.24 b**	**0.18 b**	**0.20 b**
Nickel, dissolved	**3.6**	**0.5**	**0.4**	**0.6**	**1.6**	**1.4**	**1.6**	**1.4**	**1.5**	**1.4**
Potassium, dissolved	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000
Selenium, dissolved	<1.0	<1	<1.0	<1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Silicon, dissolved	**4350**	**4130**	**4360**	**4100**	**4070**	**3980**	**3880**	**3970**	**4010**	**3940**
Silver, dissolved	<0.02	<0.02	<0.02	<0.02	<0.02 *	<0.02 *	<0.02 *	<0.02 *	<0.02 *	<0.02 *
Sodium dissolved	**15200**	**12400**	**10800**	**10800**	**9600**	**9280**	**9040**	**9000**	**8930**	**8700**
Thallium dissolved	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tin dissolved	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Titanium dissolved	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Zinc, dissolved	**12.1 b**	**7.1 b**	**9.1 b**	**6.0 b**	**5.7 b**	**5.2 b**	**6.4 b**	**10.7 b**	**6.1 b**	**4.6 b**
SVOCs										
1-Pentanol	<400	<400	--	--	<400	--	<400	--	<400	--
2-Pentanol	<100	<100	--	--	<100	--	<100	--	<100	--
3-Pentanol	<100	<100	--	--	<100	--	<100	--	<100	--
VOCs										
Benzene	<0.50	<0.50	--	--	<0.50	--	<0.50	--	<0.50	--
Carbon disulfide	<0.50	<0.50	--	--	<0.50	--	<0.50	--	<0.50	--

Table 2
Analytical Data Summary
Make Up Water Samples
PolyMet Mining Corporation
(concentrations in ug/L, unless noted otherwise)

Location Date Time	**Initial 4/3/2006 7:20 AM**	**Makeup 4/3/2006 3:30 PM**	**Makeup 4/3/2006 11:30 AM**	**Makeup 4/5/2006 11:00 AM**	**Makeup 4/5/2006 3:00 PM**	**Makeup 4/5/2006 7:00 PM**	**Makeup 4/5/2006 10:00 PM**	**Makeup 4/6/2006 3:00 AM**	**Makeup 4/6/2006 7:00 AM**	**Makeup 4/6/2006 11:00 AM**
Ethyl benzene	<0.50	<0.50	--	--	<0.50	--	<0.50	--	<0.50	--
Methyl isobutyl alcohol	<100	<100	--	--	<100	--	<100	--	<100	--
Toluene	<0.50	<0.50	--	--	<0.50	--	<0.50	--	<0.50	--
Xylene m & p	<0.50	<0.50	--	--	<0.50	--	<0.50	--	<0.50	--
Xylene o-	<0.50	<0.50	--	--	<0.50	--	<0.50	--	<0.50	--

-- Not analyzed.

b Potential false positive based on blank
data validation procedure.

* Estimated value, QA/QC criteria not met.

Detections are presented in **bold.**