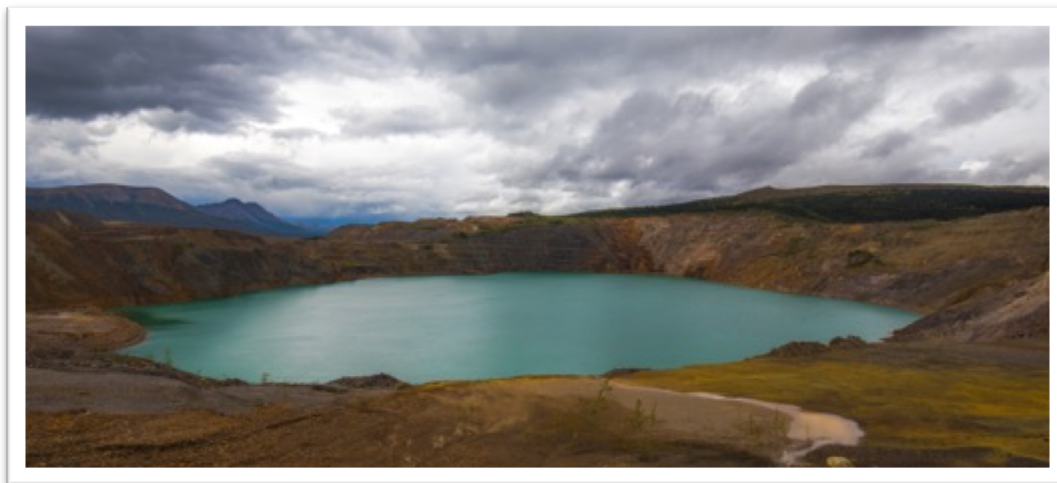# FARO WATER TREATMENT
ONSITE HDS PILOT PLANT TESTING REPORT

Prepared for:

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EXECUTIVE SUMMARY

A pilot plant study examining the application of the High Density Sludge (HDS) process at the Faro Mine, near Faro, Yukon, Canada, was completed in August 2017. The purpose of the test work was to treat a contact water representative of long term water quality and obtain optimum operating conditions for subsequent full scale water treatment plant design. The primary objective of the pilot plant program was to obtain an effluent that meets regulatory requirements. Other objectives were to produce high density sludge and obtain the necessary design parameters such as recycle ratios, operating pH, retention time and aeration requirements for subsequent water treatment plant design.

Based on the bench-scale test results conducted in July 2017 by Applied Water Treatment Inc. (AWT), a standard HDS pilot plant was developed for the onsite testing. Source water was collected by AWT and SRK Consulting (SRK) personnel and transferred to feed tanks placed adjacent to the HDS pilot plant. Feed water was prepared at a blend ratio (Blend-1) of 85% Faro Pit and 15% X23 water, provided by SRK, to achieve influent concentrations resembling the long-term predicted water quality.

To expedite pilot plant commissioning, water from X23 was treated for the first two days. The high dissolved metal concentrations in X23 generated sufficient sludge inventory needed for adequate recycle. After day two, the feed source was switched to the Blend-1. The pilot plant commissioning was completed by day four once the clarifier underflow density reached 1.15 (19% solids by weight). The sludge density continued to increase and reached an average of 1.21 (24.7% solids) throughout the pilot test. Based on past experience, the density in the full scale plant is expected to be in the range of 30 to 35% solids and would require engineering controls due to high manganese content in order to prevent line plugging and optimize clarifier operations.

Once the pilot plant commissioning was completed and baseline conditions were established, several key operating parameters were evaluated including:

- Operating pH
- Retention time
- Sludge recycle ratio

The sludge recycle ratio was varied from 18:1 to 80:1 (dry basis). Recycle rates below 18:1 provide insufficient sludge to maintain HDS conditions. A recycle ratio of 25:1 was determined to be optimum for the Faro Mine water treatment study as no benefit in lime consumption or effluent quality was observed at higher recycle ratios.

Four tests were carried out to determine the optimum operating pH. Resulting effluent water quality and lime consumption were used as performance metrics. Operating pH ranging from 8.9 to 9.9 were tested with 60 minute retention time. Lime consumption increased with pH from 0.40 to 1.20 kg/m^3 at pH 8.9 to 9.9, respectively. The water quality indicated that most

metals of concern were sufficiently removed for all pH tested, with a slight improvement at higher pH. Based on the effluent analysis, an operating pH of 9.6 is recommended for the water treatment plant design to achieve high removal efficiencies for dissolved metals, specifically cadmium and manganese.

A low anionic flocculant, Zetag4100, was used for the pilot plant and the consumption was on average 0.45 mg/L. Typically, flocculant consumption is higher in the pilot plant than compared to a full scale industrial clarifier and the treatment plant can expect a dosage rate of 0.2 to 0.5 mg/L.

Three retention time tests ranging from 40 to 70 minutes were tested during the pilot plant. The tests were conducted at the optimized pH of 9.6. Lime consumption ranged from 0.58 to 0.80 kg/m^3 at 40 to 70 minutes retention time, respectively. Typically, lime consumption decreases as retention time increases due to a higher utilization rate; however, for Faro HDS pilot study the lime consumption was slightly higher at longer retention time indicating that most of the lime is utilized within 60 minutes. High metal removal was observed in 60 minutes; however, slightly lower concentrations of cadmium and manganese were observed in the 90 minute test. The treatment plant design should consider a retention time of 45 to 60 minutes.

A second feed blend (Blend-2) consisting of slighter lower metal concentration was tested mainly due to a high storm event during the pilot campaign which prevented collection of X23 water. The effluent analysis met discharge targets and showed that the HDS process was robust. All metals of concern were removed when treating X23 only (during commissioning), Blend-1 and Blend-2 water.

A full analytical scan was completed for Test T9 operated at pH 9.6, 60 minute retention time and 25:1 recycle ratio. As expected, the total metal concentration was slightly higher than the dissolved metals. Total metal concentrations were below the discharge limits. Full scale plants often outperform pilot scale trials due to better settling and mixing dynamics in the full scale equipment. A sample from this test was also submitted for LC50 bioassay using daphnia magna and rainbow trout. The sample passed with 0% mortality at 100% concentration.

Based on the pilot plant results, a full scale HDS water treatment plant should provide effluent with low metal concentrations and produce a sludge density of 30 to 35% solids or higher. For the plant design, operating pH of 9.6, 45 to 60 minute retention time and 25:1 recycle ratio is recommended.

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1.0   INTRODUCTION

1.1   Project Understanding

Faro Mine Complex (FMC), Yukon, Canada, located approximately 14 km northwest of the town of Faro and 200 km north-northeast of Whitehorse. The property is accessible year-round via a paved road from Whitehorse to Faro and an all-weather gravel road from Faro to the site. The site is currently under Care and Maintenance which includes maintaining site access as well as treatment of wastewater emanating from several sources. Indigenous and Northern Affairs Canada (INAC) is currently preparing a remediation plan for the Faro Mine and one aspect of this remediation plan includes an active water treatment plant to treat wastewater from various sources containing heavy metals prior to discharge into the environment.

Based on our past experience at numerous other sites with similar water quality and previous studies completed at the site, it was decided that chemical precipitation is the most feasible and cost effective water treatment option. Applied Water Treatment Inc. (AWT) conducted a bench-scale testing study in July 2017 evaluating chemical precipitation treatment options primarily treatment with hydrated lime in a batch High Density Sludge (HDS) configuration. The results from the bench-scale tests indicated that treatment to pH 9.8 using lime is the preferred option due to reasons summarized below:

- Superior effluent quality
- Lower operating costs
- Enhanced settling and sludge density due to lime's coagulant properties

Following the bench-scale batch treatment study, an onsite pilot plant campaign was planned to evaluate and optimize various process conditions and gather reagent consumption data on a continuous basis to support preliminary design. Data collected during the pilot plant testing will be used to develop the process design criteria and process flowsheet.

1.2   HDS Process

The effective removal of base metals in a chemical treatment process is primarily the result of precipitation of metal as hydroxide or sulphide. Precipitation by hydroxide formation is the most common heavy metal precipitation method. The precipitation is achieved by raising the pH using an alkaline reagent such as hydrated lime [$Ca(OH)_2$]. The near-complete precipitation of the metals as hydroxides in the neutralization process proceeds according to the following reactions:

$$M^{++} + SO_4^{=} + Ca^{++} + 2(OH)^- + 2H_2O \rightarrow M(OH)_2 + CaSO_4 \bullet 2H_2O$$
$$2M^{+++} + 3(SO_4)^{=} + 3Ca^{++} + 6(OH)^- + 6H_2O \rightarrow 2M(OH)_3 + 3CaSO_4 \bullet 2H_2O$$
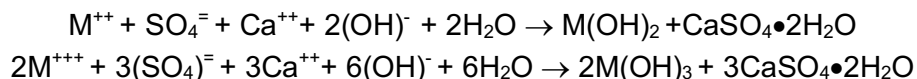
The products of these reactions are metal hydroxide precipitates and, in the case of hydrated lime, calcium sulphate (gypsum). If the sulphate concentration of the wastewater is high

enough, there will be sufficient gypsum produced to exceed its solubility and it will precipitate with the sludge and may result in gypsum scale formation.

As illustrated in Figure 1 below, metal hydroxide formation is highly pH dependant and different for each metal; however, based on past experience, an operating pH in the range of 8.5-10.0 is typical to meet the site discharge targets.
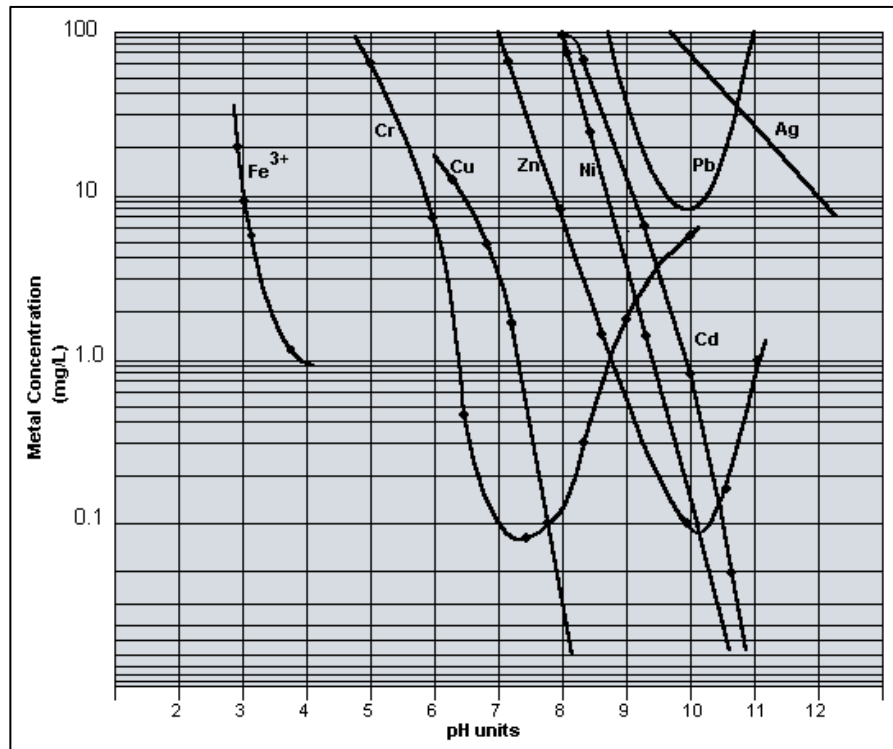
Figure 1 Metal hydroxide solubility curve

The chemical stability of the metal hydroxide 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 (HDS Process) and further enhance removal efficiency. However, a simple recycle is sometimes not sufficient to change metal ratios and, in extreme examples, iron is added to improve overall treatment efficiency. Otherwise, the sludge storage site must allow for the possibility of long-term instability. In addition to the high iron to total metals ratio, the chemical stability of the precipitate is also enhanced by alkalinity. The HDS process adds sufficient alkalinity to the sludge that it inhibits remobilization under slightly acidic conditions as tested in numerous toxicity leachability tests conducted at other operating HDS plants.

Oxidation of several metals specifically iron and manganese also play a critical role in producing a chemically stable sludge. Air is typically added to oxidize the metals of concern and oxidation of ferrous iron to ferric iron as well as manganese is the principal oxygen consuming reaction. Oxygen transfer into solution may well be controlling the reaction, which is why appropriately sizing the reactors is critical.

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 HDS process works on the same principle as the conventional lime treatment process but with a high degree of sludge recycle is added to the system. Sludge is recycled from the clarifier underflow to a small lime/sludge mix tank at the front end of the treatment process where lime is added. This mixture is used as a primary neutralization reagent. In this process, settled sludge densities from 20-40% solids can be achieved depending on the influent water chemistry.

1.2.1 Advantages of the HDS Process

Lime is the most economically favourable alkaline reagent that is used for water treatment and neutralization. It offers very significant advantages in terms of cost, sludge stability, and effluent quality.

The HDS process has many advantages over other conventional lime treatment systems. The most important is a substantial reduction in sludge volume resulting from an increase in sludge density. Conventional treatment systems can achieve 2 to 4% solids while the HDS process can achieve up to 40% solids depending on the influent water chemistry. The increased sludge density reduces the volume of sludge produced by over 90%. This reduces the sludge disposal costs, which in turn increases the cost effectiveness of the process.

In addition to reduced sludge volume and higher sludge density, there is an increase in sludge stability, both chemically and physically. Within a few days of deposition in a sludge storage cell, typical HDS sludges can drain to in excess of 50 to 65% solids and possesses enough physical stability to support heavy equipment. Chemically the sludge has shown excellent stability characteristics at mining sites in BC, Canada and at numerous other sites globally. Following thirty years of unlined sludge impoundment at one facility, there has been no contamination of the surrounding groundwater or any other evidence of metal reversion.

The efficiency of the overall treatment is significantly improved by recycling the precipitated solids. This in turn increases the sludge density, decreases the sludge volume, improves reagent utilization and most importantly improves effluent quality due to co-precipitation with iron.

Other advantages of the HDS process include:

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

2.0   PROJECT OBJECTIVES

A pilot plant study was undertaken to demonstrate the viability of the HDS process for neutralization of contaminated water at Faro Mine.

The specific objectives of the pilot tests were to:

- Determine ultimate underflow density;
- Produce an effluent low in suspended solids and dissolved metals (Water Quality)
  - Shock testing the system to simulate different flow ranges and evaluate its impact on plant operations specifically effluent quality;
- Determine reagent requirements on continuous basis
  - Lime dosing rate and utilization;
  - Optimal flocculent types and dosing rate;
  - Effluent pH adjustment (if needed)
- Confirm the optimum operating parameters for metals removal
  - Operating pH
  - Retention Time
  - Sludge recycle rate
- Establish process design parameters; and
- Evaluate sludge characteristics and disposal options
  - Settling rate for clarifier sizing
  - Sludge production
  - Toxicity Leaching
  - Filterability

3.0   PILOT PLANT DESIGN, PROCEDURES & TEST PLAN

3.1   General Approach

The purpose of the pilot plant test work was to assess the applicability of the HDS process in treating the contact water emanating from various sources. The contact water used for the pilot plant testing was comprised of 85% Faro Pit and 15% X23 water (Blend-1). Blend-1 was treated under HDS process conditions in a continuous pilot plant. Based on the bench-scale testing results and AWT's previous experience, the process was expected to achieve increased sludge density with successful removal of metals. Other objectives were to obtain the necessary design parameters such as flowrates, recycle ratios, tank sizes and aeration requirements in support of the design phase. Preliminary operating parameters were selected based on the bench-scale test results and previous pilot plants at other sites with similar water quality. The main indicators that were used during the pilot plant testing to evaluate treatment efficiency were the effluent water quality and the clarifier underflow sludge density. For the water quality, the primary focus was on treatment of cadmium, manganese and zinc in order to meet the current and expected permit limits.

3.2   Plant Configuration

The pilot plant was set up in a standard HDS configuration and consisted of:

- Influent feed stock tank where water from different sources was combined (day tank);
- One lime slurry stock tank with a marine impeller;
- Lime/sludge mix tank;
- Two lime reactor tanks, equipped with dual bladed hydrofoil impeller;
- One flocculant mix tank with a variable speed motor for gentle agitation;
- A conventional circular clarifier with rake arms and clarifier feedwell for solid/liquid separation.

As shown in Figure 2 below, the pilot plant was set up to run in the standard HDS configuration. The influent water was pumped using a variable speed pump from a 1,000 L tank into Reactor #1. The influent flowrate was manually controlled to achieve the desired residence time. Lime slurry and recycled sludge were mixed vigorously in the lime/sludge mix tank, and the mixture overflowed into Reactor #1. Lime addition was controlled to maintain the pH in Reactor #1 and the sludge recycle rate was set to provide sufficient recycle ratio in order to minimize scale formation, sufficient solids recycle to catalyze manganese precipitation, and provide activated surface area for new precipitate to form onto. Reactor #1 overflow was gravity fed to reactor #2 and to the clarifier from reactor #2 overflow. The reactor tanks were placed in series in order to minimize solution short-circuiting. Mechanical mixers, equipped with variable speed mixer motors and dual hydrofoil impellers were used to agitate the slurry in all reactors. Air was sparged into all reactors below the bottom impeller to oxidize manganese and iron. The flocculant (polymer) solution was added into the flocculant tank using a variable speed peristaltic pump. The flocculated slurry was gravity fed to the clarifier. The clarifier overflowed into an effluent collection weir and was pumped into holding tanks. Precipitated solids settled to the

bottom of the clarifier, forming a sludge bed. Settled sludge was recycled to the lime/sludge mix tank using a variable speed peristaltic pump or discharged from the system into 20 L pails. The sludge purge rate was manually controlled to maintain a constant sludge bed level height in the clarifier.
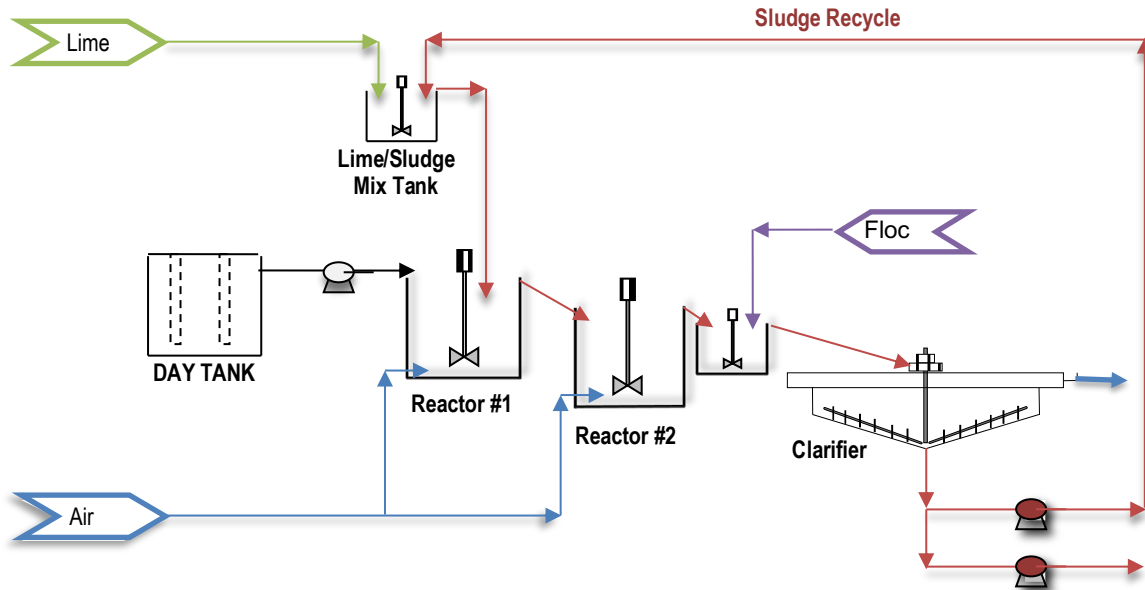
Figure 2 HDS pilot plant testing process flow diagram

3.3   Process Monitoring

In order to determine the process effectiveness, several operating parameters were measured regularly at two hour intervals and samples were collected for water quality analysis every 24 to 32 hours once the pilot plant was operating at steady-state conditions. All pilot plant observations were recorded in the project logbook. The plant operated 24 hours a day, with two 12 hour shifts. Shift operators held change over meetings at the start of every shift to pass along relevant operating notes.

Operating parameters that were measured every two hours included influent flowrate, sludge recycle flowrate, lime consumption, flocculant consumption, aeration, and pH in all tanks. In addition, sludge production and settling tests were conducted on regular basis to optimize the sludge recycle ratio, flocculant dosage, and plant operations in general. The following sections briefly describe the measurement procedures:

3.3.1   Flow Rate Measurements: Influent, Sludge Recycle and Flocculant

The influent and sludge recycle flowrates were selected to maintain the target retention time in both lime reactor tanks. All pumps were equipped with a variable frequency drive (VFD) and the pump speed was controlled to maintain the flows within +/- 10 mL/min of the target.

The influent flowrate was measured using a magnetic flow meter (magflow) which included a totalizer. The stopwatch and graduated cylinder was used to verify the magflow reading once a shift and no recalibration was required for the duration of the pilot plant.

The sludge recycle and flocculant flowrates were manually measured using a stopwatch and a graduated cylinder.

3.3.2 Water Quality Parameters

pH in all reactor tanks and the clarifier overflow was measured and recorded every two hours. The pH probes were calibrated with standardized pH buffers every 12 hours. A pH controller was used to control lime addition to maintain the target set-point in Reactor #1.

In addition, several parameters were monitored continuously (every 5 minutes) using a flow-through cell and a multi-parameter probe which monitored pH, temperature, oxygen reduction potential (ORP), and conductivity. The flow-through multi-parameter cells was installed to monitor clarifier overflow. Turbidity of the clarifier overflow was also measured once every six to eight hours using a portable turbidity meter.

3.3.3 Aeration

Air was added to the bottom of each lime reactor tank at a controlled flowrate. Due to the mixing dynamics and smaller reactor sizes compared to the industrial plant, the pilot plant air flowrate is typically much higher than needed. Based on previous experience, aeration requirements should be based on the theoretical equivalent to oxidize iron and manganese rather than pilot plant data.

3.3.4 Lime Consumption

Lime slurry was kept in an agitated stock tank and added to the process on demand using a peristaltic pump to maintain target pH in Reactor #1. The lime stock tank was placed on a load cell, the volume and weight were recorded every two hours. Lime consumption was calculated based on the lime used, lime slurry concentration and total volume treated.

3.3.5 Sludge Density

A clarifier underflow sample was taken every two hours for flowrate measurement as well as density determination. The density was determined per the equation below:

$$\rho = \frac{W\ (g)}{V\ (mL)}$$

Once per shift, the sample was filtered and solids dried at 90˚C to determine the percent solids and establish a correlation between density and percent solids for this sludge.

$$\% \, Solids = \frac{W_{Dry}\,(g)}{W_{Slurry}\,(g)}$$

3.3.6   Solid Generation Rate

Solids generation tests were performed to determine the amount of solids generated per litre of feed. A 1.0 L sample of feed water was subjected to the operating test conditions (pH and retention time) in order to precipitate the dissolved metals. Flocculent was added, and solids were allowed to settle. The clear overflow was decanted, and the settled sludge was filtered. The filter cake was dried for at least 24 hours at 90°C and weighed to determine sludge production in grams per litre.

3.3.7   Solid Settling Rate

Several settling tests were conducted for each water source tested. A 1.0 L sample was collected from Reactor #2 overflow. An appropriate amount of flocculant (mixed with distilled water to a concentration of 0.25 g/L) was added. The slurry was mixed by inverting a 1.0 L graduated cylinder end to end five times, then allowed to settle. The interfacial height between the slurry and the overflow was recorded every minute for the first 10 minutes, and after at regular intervals up to 240 minutes.

3.3.8   Solution Analysis

Samples were collected from both the clarifier overflow and the feed tank at the end of each test and submitted for analysis. The samples were filtered through 0.45 micron membrane filter, preserved with nitric acid and submitted for a dissolved metal ICP scan at ALS laboratory in Whitehorse, YK, Canada. The following test parameters were analyzed for each test condition:

- pH
- Conductivity
- Temperature
- ORP
- Turbidity
- Dissolved Metals

For T9 (conducted at optimum operating conditions), additional samples were collected for the following:

- Major anions
- Total Metals
- Toxicity (acute and chronic)

A 40 L sample was collected for the LC50 bioassay and the pH of this sample was adjusted to 7.5 using sulphuric acid prior to shipment. This was done to mimic the actual effluent

conditions. The toxicity testing was conducted at Nautilus Environmental of Burnaby, BC, Canada.

3.3.9   Solid Analysis

Clarifier underflow sludge samples were collected every two hours for sludge density and percent solids determination. In addition, a few sludge samples were sent to Global ARD Testing Services Inc. of Burnaby, BC, Canada, for an ICP scan and whole rock analysis.

3.4   Influent Collection & Preparation

Influent samples were collected from two sources and combined in a 1,000 L feed tank (day tank). Water from Faro Pit and X23 were collected by AWT and SRK personnel and transferred into feed tanks placed adjacent to the HDS pilot plant. X23 water was collected directly from the source, while Faro Pit water was collected from a line going from the Faro pit to the water treatment plant onsite. The feed tanks were prepared daily at a ratio provided by SRK.

Table 1 Blend ratios used for pilot plant feed

	Comm.	Blend-1	Blend-2
Duration (days)	3	14	1
Faro Pit	0%	85%	96%
X23	100%	15%	0%
VD04	0%	0%	4%
TOTAL	100%	100%	100%

As summarized in Table 1 above, during the commissioning phase, feed water into the pilot plant consisted of X23 only due to high dissolved metal concentration in X23 resulting in higher sludge production and thereby reducing the time required to build up the sludge inventory. The feed blend (Blend-1) used primarily for the pilot plant campaign was prepared by combining the Faro Pit and X23 sources at a selected ratio to provide water chemistry expected in the long term. While the second composite (Blend-2) was prepared due to a high storm event which caused very high TSS in X23. As a result, water from VD04 was blended with Faro Pit instead of X23 and the blend was treated in the pilot plant for a 24 hr period.

The day tank was agitated intermittently to ensure homogenous mixture and feed for the pilot plant was drawn from the day tank using a metering pump. The pumping rate was controlled to maintain constant flowrate within 10 mL/min of the target. Over time iron (primarily ferric) precipitated in the day tank due to high pH of the blend and high iron concentrations in X23.

Table 2 below, summarize the average metal concentrations of the combined feed.

Table 2 Dissolved metal concentrations of both blended composites

	Units	X23	Blend-1	Blend-2
pH		5.81	6.4	6.6
Aluminum (Al)	ug/L	<150	314	3150
Antimony (Sb)	ug/L	<25	<5.0	<5.0
Arsenic (As)	ug/L	<5.0	<1.0	<1.0
Barium (Ba)	ug/L	<50	15	18
Beryllium (Be)	ug/L	<5.0	<1.0	1.1
Bismuth (Bi)	ug/L	<50	<10	<10
Boron (B)	ug/L	<2500	<500	<500
Cadmium (Cd)	ug/L	186	40.3	39.2
Chromium (Cr)	ug/L	<50	<10	<10
Cobalt (Co)	ug/L	1960	331.7	155
Copper (Cu)	ug/L	10	11.7	25.2
Iron (Fe)	ug/L	504000	59162	70100
Lead (Pb)	ug/L	<10	<2.0	16.9
Lithium (Li)	ug/L	250	83	69
Manganese (Mn)	ug/L	136000	23308	15350
Mercury (Hg)	ug/L	<2.5	<0.50	<0.50
Molybdenum (Mo)	ug/L	<50	<10	<10
Nickel (Ni)	ug/L	2380	437	205
Selenium (Se)	ug/L	<5.0	<1.0	<1.0
Silicon (Si)	ug/L	8480	4355	5395
Silver (Ag)	ug/L	1.4	0.25	<0.2
Strontium (Sr)	ug/L	4000	1140	758
Thallium (Tl)	ug/L	2.21	0.81	0.67
Tin (Sn)	ug/L	<250	<50	<50
Titanium (Ti)	ug/L	<250	<50	<50
Uranium (U)	ug/L	<5.0	<1.0	9.7
Vanadium (V)	ug/L	<250	<50	<50
Zinc (Zn)	ug/L	1220000	175592	68800
Zirconium (Zr)	ug/L	<5.0	<1.0	<1.0
Calcium (Ca)	mg/L	459	206	176
Magnesium (Mg)	mg/L	1500	278	119
Potassium (K)	mg/L	17.6	9.9	9
Sodium (Na)	mg/L	65.2	26.1	21
Sulphur (S)	mg/L	3550	737	383

As shown in the table, cadmium, cobalt, iron, manganese, nickel and zinc are key metals of concern.

3.5 Reagent Preparation

3.5.1 Hydrated Lime

Lime used for the pilot plant test program was industrial grade hydrated lime purchased by AWT from Univar Chemicals. The commercial designation of the purchased lime was "Classified Hydrated Lime" with specifications as shown in Table 3 below.

Table 3 Lime specification provided by Vendor (XRF Analysis)

	Units	June 2017
Available Lime as $Ca(OH)_2$	%	94.8
CaO	%	72.7
MgO	%	0.572
Al_2O_3	%	0.142
SiO_2	%	0.78
S	%	0.115
K_2O	%	0.037
TiO_2	%	0.0
MnO	%	0.0
Fe_2O_3	%	0.128
Free Moisture	%	0.57
CO_2	%	1.03
Loss on Ignition @ 600˚C	%	23.73

Hydrated Lime slurry was prepared by AWT personnel, at approximately 10% solids (1.070 density) and transferred into an agitated tank (primary lime stock tank). Lime slurry was prepared by adding 1.5 kg of hydrated lime into 13.5 kg of water. The slurry was screened through a #20 mesh screen and then transferred into the pilot plant lime stock tank. Once every few days, lime slurry sample was taken and analyzed for density and percent solids. Table 4 below summarizes the density and percent solids results for the hydrated lime slurry used in the pilot plant.

Table 4 Lime slurry concentration

	Density	% Solids
15-Aug	1.068	9.8
18-Aug	1.072	10.3
21-Aug	1.073	-
25-Aug	1.069	9.9
27-Aug	1.068	9.9
Average		**9.975**

Lime slurry was placed on a load cell, weight loss and volume consumed were recorded every two hours. Hydrated lime consumption was based on the lime used and percent solids determined during each test. The consumption rate was then converted to quicklime based on the lime specifications provided by the vendor.

3.5.2   Flocculant Preparation & Scoping

Flocculant comes in three basic types: cationic (positively charged), anionic (negatively charged) and non-ionic (no charge). Flocculation is a process where flocculants are added to promote colloids and other suspended particles to aggregate, forming a floc which is then settled. Typically, a flocculant has a different electrical charge than the suspended particles; thus, attracting the material to itself in clumps of particles to enhance solid/liquid separation. Flocculant solution was prepared by slowly adding dry flocculant to deionized water and mixed for 60 to 120 minutes until the flocculant was completely hydrated. The flocculant solution was prepared at 0.25 g/L.

For the flocculant selection test, 100 mL samples of the Reactor #2 overflow were transferred to beakers. A known quantity of different flocculants were added. The samples were stirred at the same rate and the results were compared qualitatively based on rate of floc formation, floc size, settling rate and most importantly supernatant clarity.

All three types of flocculants – anionic (Zetag4100, Hyperfloc AF302, and ZFloc912), cationic (Hyperfloc CP904), and non-ionic (IPAFloc16), were added at a high dose rate of 2.5 mg/L. The results are summarized in Table 5. Very little to no settling was observed with non-ionic flocculant; however, the anionic flocculant produced the best clarity. Since the results are mainly qualitative, it is difficult to analyze the data graphically. Instead, the results are ranked for each parameter relative to one another based on visual observations by a rating scale of 1 to 5, with 5 being excellent and 1 being poor with no settling. After 20 minutes of settling, overflow was also analyzed for turbidity.

Table 5 Flocculant scoping at 2.5 mg/L dose rate

	Low Anionic		High Anionic	Cationic	Non-Ionic
	Zetag4100	Hyperfloc AF302	ZFloc912	Hyperfloc CP904	IPAFloc16
Rate of Formation	2	2	2	3	1
Floc Size	3	2	4	2	1
Settling Rate	4	2	3	4	1
Clarity	4	3	3	2	1
Turbidity (NTU)	2.76	5.01	4.45	7.69	11.1

The low strength anionic flocculant, Zetag4100, yielded the best results with relatively fast settling rate and clear overflow. The Zetag4100 dosage was optimized in the pilot plant by adjusting the flocculant flowrate and observing clarifier overflow clarity

3.6   Test Plan

The pilot plant test plan, as summarized in Table 6 below, was prepared based on experience and results of the bench-scale testing study to determine the most effective operating condition. Key parameters that were evaluated included:

- Operating pH
  - Range: 8.9 – 10.0
- Retention Time
  - Range: 40 – 60 minutes
- Sludge recycle ratio
  - Range: 60:1 – 15:1 (dry basis)
- Impact of influent concentration on treatment efficiency

Table 6: Pilot plant test plan to evaluate operating conditions

	Test ID	Source Water	Optimization	Target pH	Target Retention Time (min)	Target Recycle Ratio
15-Aug-17	Comm.	Comm.	Commissioning	9.8	60	-
16-Aug-17						
17-Aug-17	T0	Blend-1	Commissioning	9.8	60	-
18-Aug-17						
19-Aug-17	T1	Blend-1	Recycle Rate	9.6	60	70:1
20-Aug-17	T2	Blend-1	Recycle Rate	9.6	60	40:1
21-Aug-17	T3	Blend-1	Recycle Rate	9.6	60	20:1
23-Aug-17	T4	Blend-1	pH	9.3	60	20:1
24-Aug-17	T5	Blend-2	Influent WQ	9.3	60	40:1
25-Aug-17	T6	Blend-1	pH	9.0	60	20:1
26-Aug-17	T7	Blend-1	Retention Time	9.6	40	20:1
27-Aug-17	T8	Blend-1	pH	9.9	60	20:1
28-Aug-17	T9	Blend-1	Optimum (Toxicity)	9.6	60	20:1
29-Aug-17						
29-Aug-17	T10	Blend-1	Retention Time	9.6	70	70:1

Test T1-T4, and T6-T10 were carried out using Blend-1 consisting of 85% Faro Pit, and 15% of X23. While Test T5 was carried out using Blend-2 consisting of 96% Faro Pit and 4% X23.

3.6.1 Commissioning

The first four days of testing consisted of assembling and commissioning the pilot and verifying the basic process. Four days of operation were necessary to build sufficient sludge inventory in the system to provide adequate sludge for recycle. Based on the bench-scale testing results, Blend-1 sludge production was 0.28 kg/m^3 or 0.67 kg/day, which meant that it would take 10 days of operation to generate a sufficient quantity of sludge. X23 water was used for the first two days without blending with Faro Pit. X23 sludge production was 1.87 kg/m^3 which allowed sufficient sludge inventory after only 2 days of operations. However, the sludge produced was of low density and required intermittent purge. After two days, the feed source was switched to Blend-1 before test parameters were changed.

3.6.2 Recycle Ratio Optimization

Once baseline plant operation was established and sufficient sludge buildup was obtained, the clarifier underflow recycle flowrate was varied to determine the optimum recycle rate. Test T1, T2 and T3 were carried out using Blend-1 at pH 9.6 and 60 minute retention time. The sludge recycle flowrate was varied to evaluate different recycle rates from 60:1 to 18:1. Recycle rates below 18:1 provide insufficient sludge to maintain HDS conditions.

3.6.3 pH Optimization

Test T4, T6, T8 and T9 were carried out using Blend-1 at 60 minute retention and at varying operating pH from 9.0 to 9.9.

3.6.4 Retention Time Optimization

Test T7, T9, and T10 were carried out using Blend-1 at retention times varying from 40 minutes to 70 minutes. The operating pH was maintained at 9.6 to evaluate impact of retention time on effluent water quality and lime consumption.

3.6.5 Full Analysis Scan

Test T9 was carried out to collect samples for full effluent analytical analysis, which included major anions, total and dissolved metal analysis, and a LC50 bioassay. The test was carried out at pH 9.6, 60 minute retention time and 22:1 sludge recycle ratio.

4.0   RESULTS & DISCUSSION

This section summarizes the test work performed and the analytical results. Metals of concern are bolded in the tables presented in this section. Raw data for individual tests are provided in Appendix A.

4.1   Water Quality

4.1.1   pH Optimization

Blend-1 composite sample was treated to pH 9.0, 9.3, 9.6, and 9.9 with 60 minute retention time in the two reactor tanks. pH was maintained by adding hydrated lime slurry prepared at 10% solids. Samples for dissolved metal analysis were taken at the end of each test (24 to 32 hours). Table 7 summarizes the effluent water quality for pH optimization tests using Blend-1 water.

Table 7 Clarifier overflow analysis summary for pH tests using Blend-1

Parameter*	Units	WQ Target	Avg. Feed	T8	T9	T4	T6
pH			6.4	9.92	9.60	9.32	8.99
Retention Time	min		-	56	57	57	61
Recycle Rate	Dry Basis		-	18:1	22:1	18:1	20:1
Aluminum (Al)	**ug/L**		**314**	**<15**	**37**	**<15**	**<15**
Antimony (Sb)	ug/L		<5.0	<2.5	<2.5	<2.5	<2.5
Arsenic (As)	ug/L		<5.0	<0.50	<0.50	<0.50	<0.50
Barium (Ba)	ug/L		15	12.3	12.0	12.6	12.5
Beryllium (Be)	ug/L		<1.0	<0.50	<0.50	<0.50	<0.50
Bismuth (Bi)	ug/L		<10	<5.0	<5.0	<5.0	<5.0
Boron (B)	ug/L		<500	<250	<250	<250	<250
Cadmium (Cd)	**ug/L**		**40.3**	**0.080**	**0.247**	**0.324**	**0.613**
Chromium (Cr)	ug/L		<10	<5.0	<5.0	<5.0	<5.0
Cobalt (Co)	ug/L		331.7	<1.0	<1.0	<1.0	<1.0
Copper (Cu)	**ug/L**		**11.7**	**<1.0**	**<1.0**	**<1.0**	**1.4**
Iron (Fe)	**ug/L**		**59162**	**<25**	**26**	**<25**	**25**
Lead (Pb)	ug/L		<2.0	<1.0	<1.0	<1.0	<1.0
Lithium (Li)	ug/L		83	82	86	83	84
Manganese (Mn)	**ug/L**		**23308**	**<5.0**	**104**	**324**	**700**
Mercury (Hg)	ug/L		<0.50	<0.25	<0.25	<0.25	<0.25
Molybdenum (Mo)	ug/L		<10	<5.0	<5.0	<5.0	<5.0
Nickel (Ni)	**ug/L**		**437**	**<5.0**	**<5.0**	**<5.0**	**<5.0**
Selenium (Se)	ug/L		<1.0	<0.50	<0.50	<0.50	<0.50
Silicon (Si)	ug/L		4355	<500	<500	<500	<500
Silver (Ag)	ug/L		0.25	<0.10	<0.10	<0.10	<0.10
Strontium (Sr)	ug/L		1140	1890	1850	1930	1760
Thallium (Tl)	ug/L		0.81	0.354	0.598	0.698	0.842
Tin (Sn)	ug/L		<50	<25	<25	<25	<25
Titanium (Ti)	ug/L		<50	<25	<25	<25	<25
Uranium (U)	ug/L		<1.0	<0.50	<0.50	<0.50	<0.50
Vanadium (V)	ug/L		<50	<25	<25	<25	<25
Zinc (Zn)	**ug/L**		**175592**	**41**	**72**	**62**	**100**
Zirconium (Zr)	ug/L		<1.0	<0.50	<0.50	<0.50	<0.50
Calcium (Ca)	mg/L		206	543	498	499	494
Magnesium (Mg)	mg/L		278	119	229	261	265
Potassium (K)	mg/L		9.9	10.0	10.6	10.6	10.1
Sodium (Na)	mg/L		26.1	25.2	26.2	27.7	25.7
Sulphur (S)	mg/L		737	702	831	852	857
Sulphate (SO$_4$)	mg/L		1876	1630	1860	1950	1940

* All metals shown are as dissolved metals

Most metals of concern were removed to low concentrations for all operating pH values tested. In general metal concentrations decreased with increasing pH. The influent sulphate concentration was close to the gypsum saturation limit; as a result, very little to no sulphate removal was expected in lime treatment process.

Based on the analysis, a target pH of 9.6 is recommended for the design to achieve high removal efficiency for cadmium and manganese. However, a lower operating pH might be sufficient as illustrated in table above.

4.1.2   Retention Time Optimization

Three retention time tests were carried out ranging from 30 to 70 minutes in order to simulate conditions that might be observed for the full scale plant where flow is expected to vary seasonally. As before, hydrated lime slurry was added to maintain the target pH of 9.6 in the clarifier overflow. Table 8 below summarizes the water quality data for the retention time optimization tests.

Table 8 Clarifier overflow analysis summary for retention time tests using Blend-1

Parameter*	Units	WQ Target	Avg. Feed	T10	T9	T7
pH			6.4	9.49	9.60	9.58
Retention Time	min		-	71	57	39
Recycle Rate	Dry Basis		-	75:1	22:1	24:1
Aluminum (Al)	**ug/L**		**314**	**<15**	**37**	**<15**
Antimony (Sb)	ug/L		<5.0	<2.5	<2.5	<2.5
Arsenic (As)	ug/L		<5.0	<0.50	<0.50	<0.50
Barium (Ba)	ug/L		15	11.4	12.0	11.7
Beryllium (Be)	ug/L		<1.0	<0.50	<0.50	<0.50
Bismuth (Bi)	ug/L		<10	<5.0	<5.0	<5.0
Boron (B)	ug/L		<500	<250	<250	<250
Cadmium (Cd)	**ug/L**		**40.3**	**0.148**	**0.247**	**0.201**
Chromium (Cr)	ug/L		<10	<5.0	<5.0	<5.0
Cobalt (Co)	ug/L		331.7	<1.0	<1.0	<1.0
Copper (Cu)	**ug/L**		**11.7**	**<1.0**	**<1.0**	**<1.0**
Iron (Fe)	**ug/L**		**59162**	**<25**	**26**	**<25**
Lead (Pb)	ug/L		<2.0	<1.0	<1.0	<1.0
Lithium (Li)	ug/L		83	91	86	85
Manganese (Mn)	**ug/L**		**23308**	**7.3**	**104**	**135**
Mercury (Hg)	ug/L		<0.50	<0.25	<0.25	<0.25
Molybdenum (Mo)	ug/L		<10	<5.0	<5.0	<5.0
Nickel (Ni)	**ug/L**		**437**	<5.0	**<5.0**	<5.0
Selenium (Se)	ug/L		<1.0	<0.50	<0.50	<0.50
Silicon (Si)	ug/L		4355	<500	<500	<500
Silver (Ag)	ug/L		0.25	<0.10	<0.10	<0.10
Strontium (Sr)	ug/L		1140	2050	1850	1720
Thallium (Tl)	ug/L		0.81	0.922	0.598	0.545
Tin (Sn)	ug/L		<50	<25	<25	<25
Titanium (Ti)	ug/L		<50	<25	<25	<25
Uranium (U)	ug/L		<1.0	<0.50	<0.50	<0.50
Vanadium (V)	ug/L		<50	<25	<25	<25
Zinc (Zn)	**ug/L**		**175592**	**63**	**72**	**44**
Zirconium (Zr)	ug/L		<1.0	<0.50	<0.50	<0.50
Calcium (Ca)	mg/L		206	512	498	486
Magnesium (Mg)	mg/L		278	203	229	202
Potassium (K)	mg/L		9.9	10.4	10.6	10.0
Sodium (Na)	mg/L		26.1	27.0	26.2	26.0
Sulphur (S)	mg/L		737	804	831	774
Sulphate (SO$_4$)	mg/L		1876	1780	1860	1820

* All metals shown are as dissolved metals

The dissolved metals concentration is still of acceptable quality even at 30 minute retention time. The treatment plant design should consider a minimum retention time of 45 to 60 minutes to manage any potential risk of lower discharge limits in the future and to manage peak flow events.

4.1.3 Recycle Ratio Optimization

For the next set of tests, the recycle ratio was from 78:1, 33:1, 22:1 and 18:1 for tests T1, T2, T9 and T3, respectively. The tests were conducted at pH 9.6 with 60 minute retention time using hydrated lime. Results for clarifier overflow samples collected are summarized in Table 9.

Table 9 Clarifier overflow analysis summary for recycle ratio tests using Blend-1

Parameter*	Units	WQ Target	Avg. Feed	T1	T2	T9	T3
pH			**6.4**	9.58	9.50	9.60	9.51
Retention Time	min		**-**	59	57	57	56
Recycle Rate	Dry Basis		**-**	78:1	33:1	22:1	18:1
Aluminum (Al)	**ug/L**		**314**	**<15**	**<15**	**37**	**<15**
Antimony (Sb)	ug/L		<5.0	<2.5	<2.5	<2.5	<2.5
Arsenic (As)	ug/L		<5.0	<0.50	<0.50	<0.50	<0.50
Barium (Ba)	ug/L		15	10.9	11.7	12.0	12.0
Beryllium (Be)	ug/L		<1.0	<0.50	<0.50	<0.50	<0.50
Bismuth (Bi)	ug/L		<10	<5.0	<5.0	<5.0	<5.0
Boron (B)	ug/L		<500	<250	<250	<250	<250
Cadmium (Cd)	**ug/L**		**40.3**	**0.229**	**0.211**	**0.247**	**0.210**
Chromium (Cr)	ug/L		<10	<5.0	<5.0	<5.0	<5.0
Cobalt (Co)	ug/L		331.7	<1.0	<1.0	<1.0	<1.0
Copper (Cu)	**ug/L**		**11.7**	**1.9**	**<1.0**	**<1.0**	**<1.0**
Iron (Fe)	**ug/L**		**59162**	**29**	**<25**	**26**	**<25**
Lead (Pb)	ug/L		<2.0	1.8	<1.0	<1.0	<1.0
Lithium (Li)	ug/L		83	93	85	86	85
Manganese (Mn)	**ug/L**		**23308**	**90.5**	**128**	**104**	**139**
Mercury (Hg)	ug/L		<0.50	<0.25	<0.25	<0.25	<0.25
Molybdenum (Mo)	ug/L		<10	<5.0	<5.0	<5.0	<5.0
Nickel (Ni)	**ug/L**		**437**	**<5.0**	**<5.0**	**<5.0**	**<5.0**
Selenium (Se)	ug/L		<1.0	<0.50	<0.50	<0.50	<0.50
Silicon (Si)	ug/L		4355	<500	<500	<500	<500
Silver (Ag)	ug/L		0.25	<0.10	<0.10	<0.10	<0.10
Strontium (Sr)	ug/L		1140	1930	1870	1850	1950
Thallium (Tl)	ug/L		0.81	0.478	0.512	0.598	0.587
Tin (Sn)	ug/L		<50	<25	<25	<25	<25
Titanium (Ti)	ug/L		<50	<25	<25	<25	<25
Uranium (U)	ug/L		<1.0	<0.50	<0.50	<0.50	<0.50
Vanadium (V)	ug/L		<50	<25	<25	<25	<25
Zinc (Zn)	**ug/L**		**175592**	**59**	**44**	**72**	**57**
Zirconium (Zr)	ug/L		<1.0	<0.50	<0.50	<0.50	<0.50
Calcium (Ca)	mg/L		206	481	491	498	530
Magnesium (Mg)	mg/L		278	255	228	229	231
Potassium (K)	mg/L		9.9	9.90	9.90	10.6	11.5
Sodium (Na)	mg/L		26.1	27.1	27.1	26.2	28.0
Sulphur (S)	mg/L		737	796	789	831	845
Sulphate (SO$_4$)	mg/L		1876	2400	2700	1860	1940

* All metals shown are as dissolved metals

In general, the sludge recycle rate did have an impact on water quality. However, a higher sludge recycle rate resulted in a lower manganese concentration. A sludge recycle rate of 25:1 was recommended to provide sufficient sludge for recycle to maximize lime utilization and produce effluent with low manganese concentration while maintain high density in the clarifier underflow.

4.1.4   Full Analysis

Test T9 was carried out to collect samples for a full analytical analysis, which included major anions, total and dissolved metal analysis, and toxicity. The test was run at pH 9.6, 60 minute retention time and 22:1 sludge recycle ratio. Table 10 and Table 11 below summarize the analytical results.

Table 10 Expected nutrient and anion concentration after HDS treatment (Test T9)

	Units	Feed	T9
pH			9.6
Retention	min		57
Recycle Rate			22:1
Conductivity	uS/cm	-	3230
TDS	mg/L	-	3190
Acidity (pH 4.5)	mg/L	-	<1.0
Acidity (pH 8.3)	mg/L	-	<1.0
Alkalinity (as CaCO$_3$)	mg/L	-	15.2
BOD	mg/L	-	<6.0
DOC	mg/L	-	1.3
TOC	mg/L	-	1.4
Bicarbonate (HCO$_3$)	mg/L	-	18.6
Carbonate (CO$_3$)	mg/L	-	<1.0
Hydroxide (OH)	mg/L	-	<1.0
Chloride (Cl)	mg/L	-	3.3
Fluoride (F)	mg/L	-	0.39
Nitrate (as N)	mg/L	-	0.574
Nitrite (as N)	mg/L	-	0.0065
TSS	mg/L	-	5.5

Table 11 Expected nutrient and anion concentrations after HDS treatment (Test T9)

	Units	WQ Target	Avg. Feed	TOTAL T9	DISSOLVED T9
pH				9.60	9.60
Aluminum (Al)	**ug/L**		**314**	<15	**37**
Antimony (Sb)	ug/L		<5.0	<2.5	<2.5
Arsenic (As)	ug/L		<5.0	<0.50	<0.50
Barium (Ba)	ug/L		15	11.4	12.0
Beryllium (Be)	ug/L		<1.0	<0.50	<0.50
Bismuth (Bi)	ug/L		<10	<5.0	<5.0
Boron (B)	ug/L		<500	<250	<250
Cadmium (Cd)	**ug/L**		**40.3**	**0.369**	**0.247**
Chromium (Cr)	ug/L		<10	<5.0	<5.0
Cobalt (Co)	ug/L		331.7	1.8	<1.0
Copper (Cu)	**ug/L**		**11.7**	**<2.5**	**<1.0**
Iron (Fe)	**ug/L**		**59162**	**399**	**26**
Lead (Pb)	ug/L		<2.0	<1.0	<1.0
Lithium (Li)	ug/L		83	86	86
Manganese (Mn)	**ug/L**		**23308**	**199**	**104**
Mercury (Hg)	ug/L		<0.50	<0.25	<0.25
Molybdenum (Mo)	ug/L		<10	<5.0	<5.0
Nickel (Ni)	**ug/L**		**437**	**<5.0**	**<5.0**
Selenium (Se)	ug/L		<1.0	<0.50	<0.50
Silicon (Si)	ug/L		4355	<500	<500
Silver (Ag)	ug/L		0.25	<0.10	<0.10
Strontium (Sr)	ug/L		1140	1860	1850
Thallium (Tl)	ug/L		0.81	0.616	0.598
Tin (Sn)	ug/L		<50	<25	<25
Titanium (Ti)	ug/L		<50	<25	<25
Uranium (U)	ug/L		<1.0	<0.50	<0.50
Vanadium (V)	ug/L		<50	<25	<25
Zinc (Zn)	**ug/L**		**175592**	**829**	**72**
Zirconium (Zr)	ug/L		<1.0	<0.50	<0.50
Calcium (Ca)	mg/L		206	593	498
Magnesium (Mg)	mg/L		278	261	229
Potassium (K)	mg/L		9.9	11.1	10.6
Sodium (Na)	mg/L		26.1	28.6	26.2
Sulphur (S)	mg/L		737	904	831
Sulphate (SO$_4$)	mg/L		1876	1860	1860

In addition to the dissolved and total metals, 40 L of the sample was also submitted for bioassay testing. As summarized in Table 12, the results indicated that the sample passed bioassay analysis with 0% mortality at 100% concentration.

Table 12 Bioassay analysis summary for Test T9

	Daphnia Magna	Rainbow Trout
Dissolved Oxygen (mg/L)	9.9	9.8
Temperature (˚C)	17.5	15.5
Conductivity (uS/cm)	1456	1457
Test Duration (hours)	48	96
LC_{50}	>100%	>100%
% Mortality at 100% concentration	0%	0%

4.1.5   Expected Effluent Water Quality

Based on the series of tests completed throughout the pilot plant trials, it is anticipated that the full scale treatment plant will produce an effluent with the quality shown in Table 13, provided the full scale treatment plant is designed to provide 60 minutes retention time at an operating pH of 9.6 and recycle rate of 25:1. While a better quality effluent can be achieved as shown in Table 13 when the treatment plant is operated at a higher pH of 9.9.

Table 13 Expected effluent water quality for full scale treatment plant

Parameter*	Units	WQ Target	Avg. Feed	Expected	Best
pH				9.60	9.92
Aluminum (Al)	**ug/L**		**314**	**37**	**<15**
Antimony (Sb)	ug/L		<5.0	<2.5	<2.5
Arsenic (As)	ug/L		<5.0	<0.50	<0.50
Barium (Ba)	ug/L		15	12.0	12.3
Beryllium (Be)	ug/L		<1.0	<0.50	<0.50
Bismuth (Bi)	ug/L		<10	<5.0	<5.0
Boron (B)	ug/L		<500	<250	<250
Cadmium (Cd)	**ug/L**		**40.3**	**0.247**	**0.080**
Chromium (Cr)	ug/L		<10	<5.0	<5.0
Cobalt (Co)	ug/L		331.7	<1.0	<1.0
Copper (Cu)	**ug/L**		**11.7**	**<1.0**	**<1.0**
Iron (Fe)	**ug/L**		**59162**	**26**	**<25**
Lead (Pb)	ug/L		<2.0	<1.0	<1.0
Lithium (Li)	ug/L		83	86	82
Manganese (Mn)	**ug/L**		**23308**	**104**	**<5.0**
Mercury (Hg)	ug/L		<0.50	<0.25	<0.25
Molybdenum (Mo)	ug/L		<10	<5.0	<5.0
Nickel (Ni)	**ug/L**		**437**	**<5.0**	**<5.0**
Selenium (Se)	ug/L		<1.0	<0.50	<0.50
Silicon (Si)	ug/L		4355	<500	<500
Silver (Ag)	ug/L		0.25	<0.10	<0.10
Strontium (Sr)	ug/L		1140	1850	1890
Thallium (Tl)	ug/L		0.81	0.598	0.354
Tin (Sn)	ug/L		<50	<25	<25
Titanium (Ti)	ug/L		<50	<25	<25
Uranium (U)	ug/L		<1.0	<0.50	<0.50
Vanadium (V)	ug/L		<50	<25	<25
Zinc (Zn)	**ug/L**		**175592**	**72**	**41**
Zirconium (Zr)	ug/L		<1.0	<0.50	<0.50
Calcium (Ca)	mg/L		206	498	543
Magnesium (Mg)	mg/L		278	229	119
Potassium (K)	mg/L		9.9	10.6	10.0
Sodium (Na)	mg/L		26.1	26.2	25.2
Sulphur (S)	mg/L		737	831	702
Sulphate (SO$_4$)	mg/L		1876	1860	1630

* All metals shown are as dissolved metals

4.2 Clarifier Underflow

The initial commissioning of the pilot plant was carried out over a period of 96 hours and was terminated as the clarifier underflow density reached 1.15. Figure 3, below shows the underflow density for the whole duration of the pilot plant testing. The underflow sludge density continued to increase throughout the test and finally started to level off at an SG of 1.19 and reaching max of 1.205. During the operations, the sludge compacted very quickly within the clarifier which caused plugging and at times required sludge to be physically moved to the discharge cone to maintain plant operations. The slight decrease in the underflow density observed at 220 hrs during test T7 was mainly due to lower retention time in the clarifier.
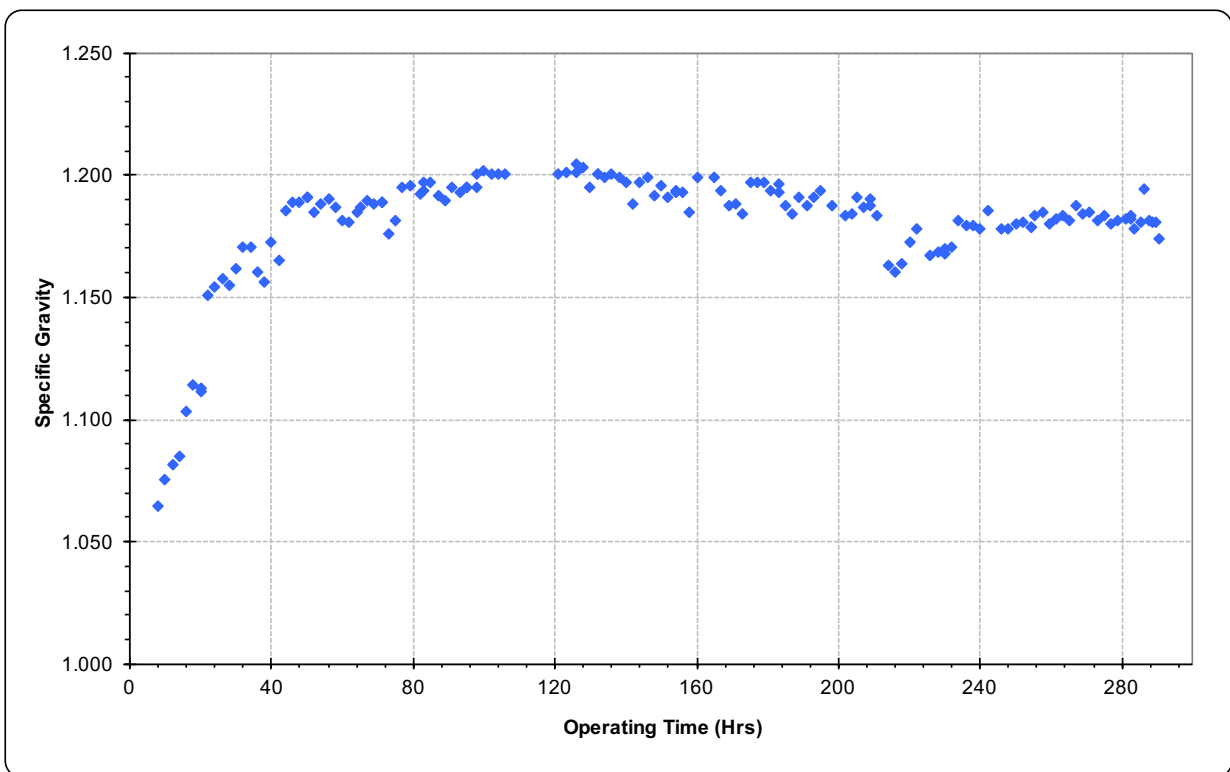
Figure 3 Clarifier underflow density as a function of operating time

Based on operational support experience, industrial clarifiers typically outperform pilot plant clarifiers due to a higher compression zone and settling dynamics. The full scale clarifier underflow density is expected to be approximately 30-35% solids. The design of the clarifier would require engineered controls to improve operations. There is the potential for sludge to compact within the clarifier due to high manganese content, which could result in plugged sludge lines or cementing at the bottom of the clarifier.

The clarifier underflow sludge density was proportionally related to the percent solids; Figure 4 below illustrates this relationship. As the specific gravity increased, the percent solids also increased linearly. Maximum percent solids achieved during the pilot test was 24.7% solids.

The equation shown on the chart:

$$y = 127.98x - 126.12$$
$$R^2 = 0.9646$$
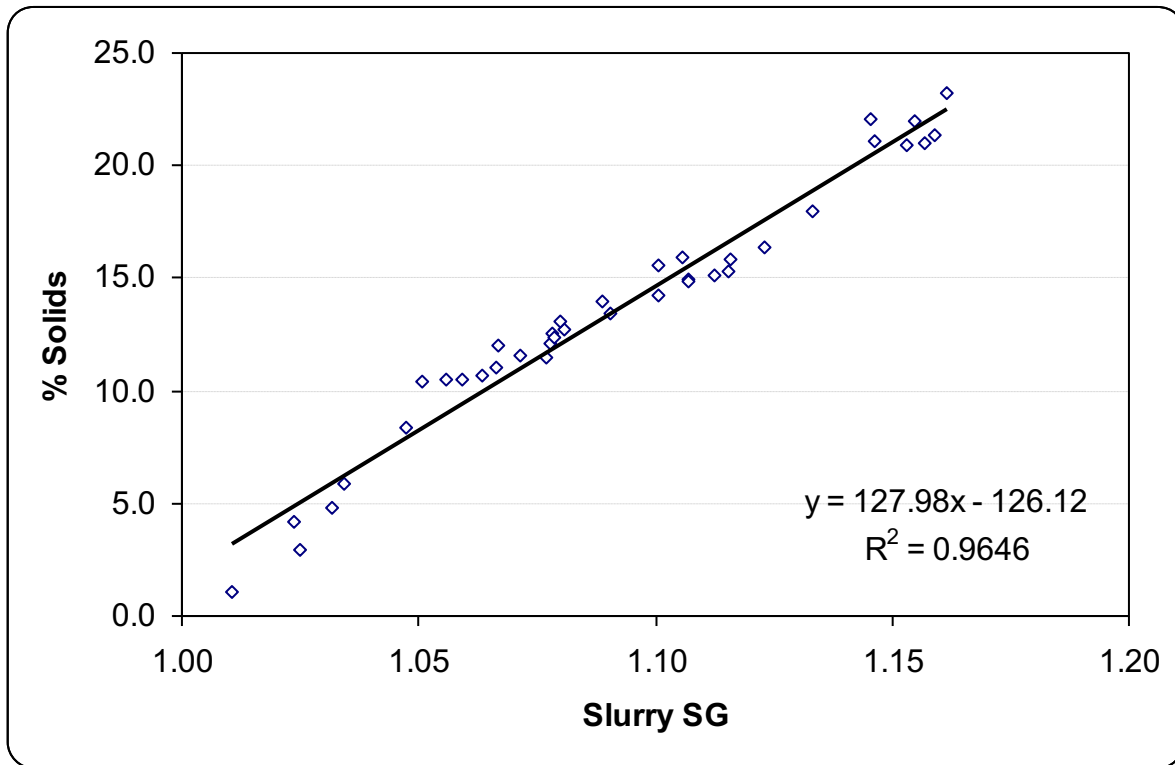
Figure 4 Percent Solids as a function of SG

4.3 Operating Parameters

4.3.1 Lime Consumption

Hydrated lime slurry was added to maintain the target pH. Table 15 and Table 16 below summarize lime consumption for each test.

Lime consumption increased with operating pH and was highest at pH 10.0. However, as discussed in the water quality discussion, very little to no additional benefit was observed for removal efficiency at higher operating pH.

Table 14 Hydrated lime consumption for pH optimization tests at 60 minute retention time

	T8	T9	T4	T6
pH	9.92	9.60	9.32	8.99
Hydrated Lime (kg/m^3)	1.20	0.78	0.69	0.40

Table 16 below summarizes the lime consumption for the retention time optimization tests. Lime consumption increased with retention time but remained the same for 60 and 90 minute retention time.

Table 15 Hydrated lime consumption for retention time optimization tests at pH 9.6

	T10	T9	T7
pH	9.49	9.60	9.58
Retention Time (min)	71	57	39
Quicklime (kg/m^3)	0.58	0.78	0.80

The actual consumption is usually higher than the theoretical requirement resulting from unreacted lime in the sludge.

4.3.2 Flocculant Consumption

Flocculant addition affects the clarifier overflow total suspended solids (TSS) and underflow density. High flocculent addition can interfere with clarifier underflow sludge density while insufficient flocculent addition can lead to high TSS in the effluent. Based on flocculant scoping test conducted during the water treatment pilot plant study, Zetag4100 was used for this pilot study.

The TSS in the clarifier overflow was as low as 6 mg/L; however, based on our experience, industrial plants typically outperform pilot plant clarifiers. The flocculant consumption ranged from 0.33 to 1.42 mg/L of feed. The flocculant consumption decreased as the sludge density increased to 24% solids. In a typical HDS plant with similar solids production, the polymer addition rate is usually between 0.2 to 0.5 mg/L of feed.

4.3.3 Settling Rate

Settling tests were carried out in a 1.0 L graduated cylinder by adding known amount of flocculant and allowing the solids to settle for a minimum of 240 minutes. The settled pulp density after four hours ranged from 20% to 24% solids. The pulp density achieved with settling tests is usually lower than the clarifier underflow sludge due to the differences in the mechanics of a clarifier compared to a 1.0 L graduated cylinder.

Figure 5 below shows the settling rate with varying flocculent dosage. These tests were carried out on Reactor #2 overflow, the clarifier feed. As expected, faster settling was observed with high flocculent dosage. The quantitative results indicated higher concentrations of fine suspended solids at higher dosage rates.
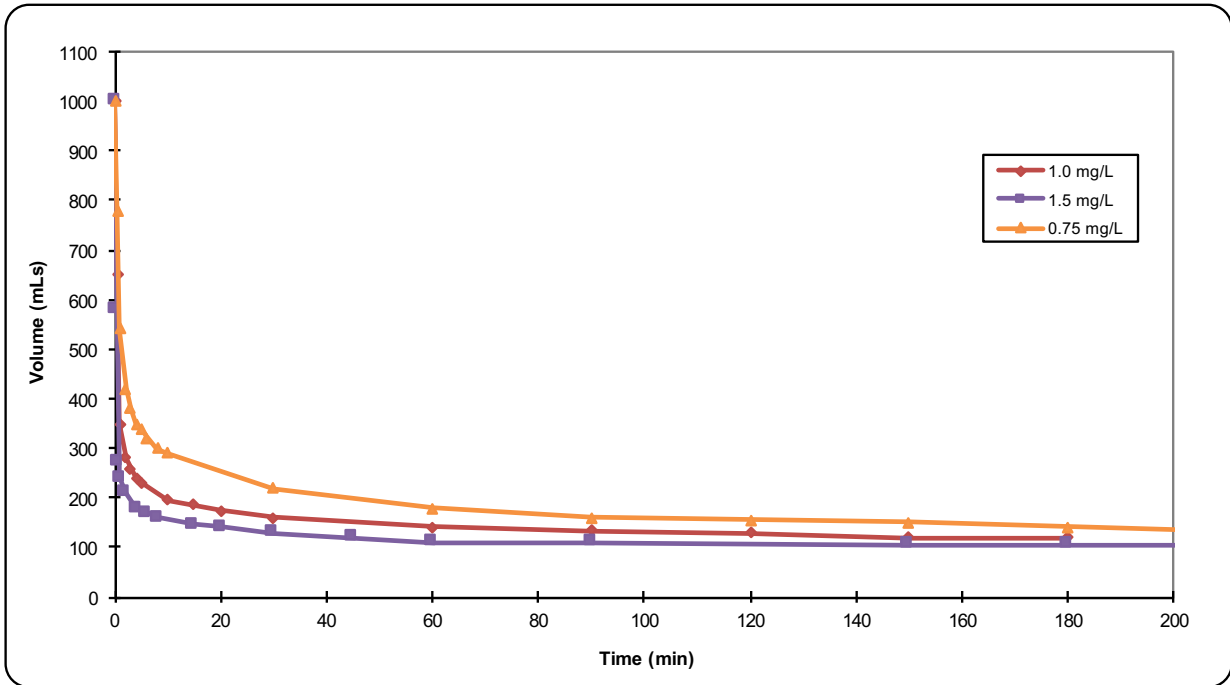
Figure 5 Clarifier Feed Settling Curve

4.3.4   Aeration

Air was sparged into each reactor at a rate of 7 L/min to oxidize iron and manganese present in the feed. In a pilot plant, the aeration rate is much higher than necessary, due to the low oxygen mass transfer in the pilot plant reactors. For the HDS plant design, air requirements should be calculated based on the theoretical amount of oxygen required for oxidation of manganese and ferrous iron.

5.0 CONCLUSION

The pilot test program has demonstrated the viability of the HDS process for removal of contaminants from contact water and determined the optimum parameters for the industrial plant. All project objectives as outlined in the test proposal and in Section 2.0 were met. The following were concluded:

- Treatment to pH 9.6 is recommended to produce a high quality effluent with low metal concentrations that passed the biotoxicity tests

- A retention time of 45 to 60 minutes is recommended to manage peak flow concentrations while maintaining effluent water quality.

- A recycle rate in the range of 25:1 is recommended to produce effluent quality low in dissolved manganese while optimizing reagent consumptions rates.

- For plant design (operating at the recommended conditions above), the key operating parameters are:

  - Sludge production of 0.70 kg/m^3

  - Lime consumption of 0.80 kg/m^3

  - Flocculant consumption of 0.2-0.5 mg/L

  - Aeration is needed to completely oxidize manganese and ferrous iron (calculated from theoretical requirements)

  - Recycle ratio of 25:1

5.1 Plant Performance

Based on the continuous pilot plant results, the proposed water treatment design using lime neutralization, specifically the HDS process with appropriate operation parameters, is a viable process to remove metals of concern in order to meet the existing water quality standards. The HDS treatment system is a very reliable process used at numerous mining sites around the world. In this treatment system, where excess of cadmium, manganese, zinc and other heavy metals are present, contaminated water can be treated successfully suitable for discharge as demonstrated in the pilot plant and experienced at a number of sites in British Columbia, the Yukon, Alaska and others around the world. The pilot plant results also demonstrated that the water treatment plant can manage fluctuation in influent chemistry (Blend-1 vs. Blend-2), flowrates ranging from 40 minutes to 90 minutes retention time, and operating pH as low as 9.0 ranging as high as 9.8.

The HDS treatment process is governed by a certain set of real-time operating parameters specifically operating pH, sludge recycle rate, retention time and reagent dosage. Therefore, effectively monitoring and controlling these parameters has shown reliable treatment performance. However, even with sufficient instrumentation the plant may experience upset conditions as a result of mechanical issues or power outage. The plant design includes

redundancy for critical equipment that is likely to fail including lime loop, sludge recycle pumps and sludge discharge pumps. In addition, the plant layout will be in a way that allows for one reactor to be offline for maintenance during low flow periods.