Containerized Water Treatment for Remote Mine Sites

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Abstract

Although lime treatment remains the most common treatment method for mine impacted waters, there are instances where it is neither a good fit from a technical performance perspective nor is it the most cost effective solution. Depending on site specific requirements, the shortcomings of lime treatment can be any one of the following: difficulty to achieve ultralow discharge limits for certain metals and metalloids, inability to be deployed in a modular/containerized fashion and high cost of managing waste sludge.

This paper describes the water treatment that was implemented at the Silvertip Mine located in a remote area of Northern British Columbia (BC). Although lime treatment was originally envisaged, the site water quality and discharge requirements combined with constraints in footprint and overall capital cost led to the adoption of sulphide precipitation as the treatment process of choice. Sulphide precipitation is known to be a highly effective tool for achieving ultralow discharge limits in mining effluents and offers the possibility of a containerized mine water treatment design which:

- Minimizes capital costs and the need for skilled labour trades at remote project sites
- Reduces water treatment plant footprint
- Reduces the quantity of residue produced during treatment and enables possible value recovery

The Silvertip project was able to take advantage of all these benefits. The treatment process underwent regulatory reviews and performance demonstration which was required because the application at Silvertip was the first sulphide precipitation treatment system to be applied in BC. The success of Silvertip removes the need for pilot demonstrations for future projects where sulphide treatment may be considered. To help reduce project risks and costs, BQE Water accepted full responsibility for water in the project, from the initial evaluation of treatment options and bench scale testing, through permitting, to the full scale implementation.

Introduction

The Silvertip project is an underground silver-lead-zinc mine located in a remote area of British Columbia, approximately 16 km south of the Yukon border and 90 km southwest of the small community of Watson Lake. Several companies have been involved in the exploration and development of the property since the late 1950's, resulting in the construction of significant site infrastructure, including 26 km of access roads and 2.7 km of underground workings. In June 2015, JDS Silver received a Mines Act permit to resume mine operation. The water treatment process forming the basis of the JDS Silver permit application was HDS lime neutralization. However, due to low discharge limits for zinc and cadmium, which represent the two metals of concern in this project, HDS lime would result in a large plant footprint and large quantities of waste sludge being produced. This led JDS Silver to investigate possible alternate treatment systems with BQE Water contracted to assist.

Figure 1: Silvertip Mine Site

Water Treatment Requirements at Silvertip

There were two distinct phases for the project:

1. Dewatering of existing underground workings; and
2. Treatment of excess mine impacted water during the mine and mill operation.

During the initial underground dewatering phase, the ponds that would form part of the overall site water management system, including the 20,000 m3 main collection pond (MCP) and 5,000 m3 main polishing pond (MPP), were still under construction. Consequently, underground water was pumped directly to the WTP for treatment prior to direct discharge into Silvertip Creek as shown in Figure 2.

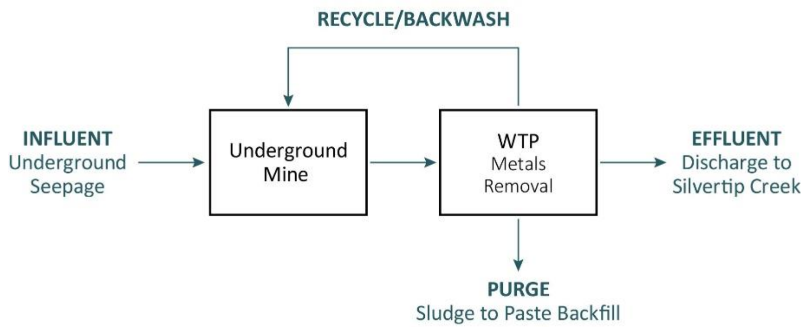

Figure 2: WTP Block Flow for Underground Dewatering Phase

During the mine and mill operation phase, site water including underground seepage, dry-stack tailings seepage, mill process water and run-off from various sources were collected in the MCP. As presented in Figure 3, the WTP is used to actively manage MCP levels by treating excess water to the applicable discharge limits prior to discharge into Silvertip Creek. The main function of the MPP located downstream of the WTP is to minimize the risk of non-compliance by introducing a delay between sampling of the WTP for discharge and release of treated water into the environment. This delay allows for sufficient time to carry out assays by an analytical laboratory located in the Lower Mainland near Vancouver to be reported.

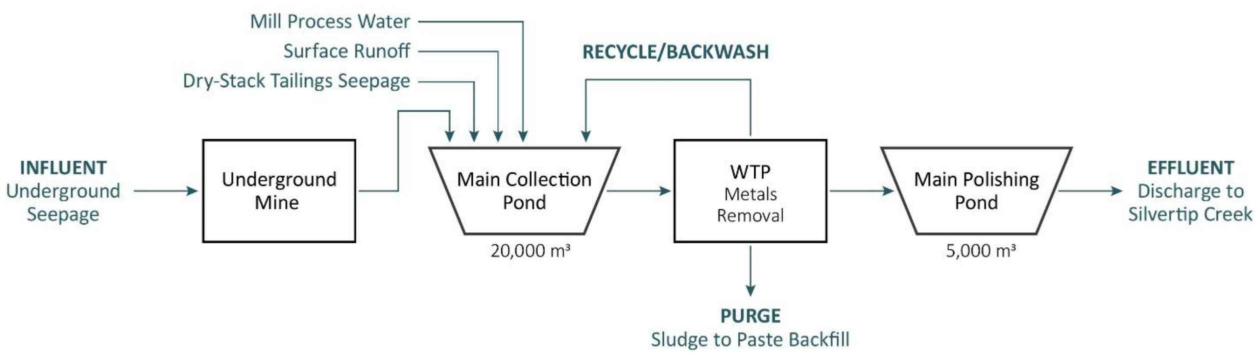

Figure 3: WTP Block Flow for the Mine and Mill Operation Phase

Table 1 summarizes the water quality data used to design the WTP for both phases of the project. Assay results were available to determine underground water quality. The water quality in the MCP during mine and mill operation was predicted by Lorax Environmental Services based on the water balance and geochemical modelling.

Table 1: WTP Feed Water Quality

WTP Parameter	Units	Underground Water Assay	Main Collection Pond (Mean)	Permit Discharge Requirement
Flow	m^3/day	720	2,640	1,752 Yearly Avg 3,000 Daily Max
pH	-	7.0	7.6	6.5-9.0
TSS	mg/L	27.8	-	30.0
As	mg/L	0.008	0.016	0.024
Cd	mg/L	0.020	0.041	0.0018
Co	mg/L	0.002	0.061	0.02
Cu	mg/L	0.001	0.033	0.03
Pb	mg/L	0.004	0.031	0.046
Hg	mg/L	-	0.002	0.000067
Zn	mg/L	3.700	4.170	0.500

The two main constituents of concern at Silvertip are zinc and cadmium but other constituents including copper, cobalt and arsenic were also flagged as potential concerns once the mine and mill are in production. Also noteworthy is that the sulphate concentration in both the underground and MCP water are either below or at gypsum saturation which is typically between 1,500 and 2,000 mg/L depending on the water composition and temperature. This is significant as the sulphate concentration has a bearing on the operation of the HDS lime neutralization process and the production of waste sludge.

Evaluation of Treatment Methods

Although there are many treatment processes that could theoretically be considered for the water flow and quality shown in Table 1, there are principally only two processes that are practical and that have been applied on a large scale to treat similar mining wastewater streams. These are HDS lime neutralization and sulphide precipitation. Originally, HDS lime neutralization was proposed as the treatment method of choice and included in the project permit application. However, the large cost of implementing HDS lime at a remote site such as Silvertip combined with the uncertainty of achieving the target end-of-pipe limits for some of the metals led JDS Silver to engage BQE Water to help re-evaluate the treatment approach for the project. The key process features and advantages and disadvantages of HDS lime and sulphide precipitation are discussed below with specific focus on the process implementation at Silvertip.

HDS Lime Neutralization

HDS lime neutralization removes metals in the form of metal hydroxides while relying on the generation of crystalline gypsum to improve both the settling properties of the waste sludge solids and the water quality of the final effluent (Aubé et al, 2015). The function of crystalline gypsum is three fold: 1) promote particle growth and faster settling which reduces the size of the solid-liquid separation equipment, 2) entrain fine amorphous metal hydroxides in the crystalline gypsum solids to produce lower residual total metals in the final effluent, and 3) minimize equipment scaling. In terms of operational flexibility, the HDS process has only one degree of freedom which is the pH set point in the metal precipitation reactors. The following reaction summarizes the chemistry for precipitating metal hydroxides and gypsum, where Me represents divalent metals such as cadmium or zinc but the reaction can easily be modified to include trivalent metals such as aluminum and ferric iron:

$$2H_2O_{(l)} + MeSO_{4(aq)} + Ca(OH)_{2(s)} \rightarrow Me(OH)_{2(s)} + CaSO_4.2H_2O_{(s)}$$

The extent of metal removal achievable by HDS lime neutralization is driven by the metal hydroxides solubility which is a strong function of solution pH. While some metals can be removed to very low levels at pH < 9, others require a much higher pH (Aubé et al, 2003). Most metals exhibit a minimum solubility at a particular pH that is unique to each metal, resulting in increases in the residual metal concentration in solution when the pH is either lower or higher than optimum. At Silvertip, the original design contemplated operating the HDS lime plant at pH > 9.5 and possibly as high as 11 to achieve all applicable target discharge limits. Since the operating pH was to be higher than the maximum allowable pH for discharge, the original design included an effluent acidification stage using carbon dioxide (CO_2) injected into the HDS effluent to bring the final pH to below 9.

Side effects of the operation at high pH and subsequent CO_2 addition to re-acidify the final effluent are an increase in waste sludge production and a risk of increased TSS in the effluent due to partial removal of calcium through calcium carbonate precipitation. The original HDS design used several large reactors in series with the option to aerate to ensure high lime utilization and conversion of ferrous iron to ferric iron. Most importantly, the fact that sulphate concentrations in the plant feed were either below or at gypsum saturation meant that a very small amount of gypsum would form in the plant. Since the HDS process relies on the production of crystalline gypsum to operate properly, there would likely be a very significant risk of poor HDS process performance at Silvertip unless the solid-liquid separation equipment was oversized to counter low solids production compared to conventional HDS. Clearly, this would have a negative impact on both capital cost and plant footprint.

From this analysis, we can summarize the key advantages and disadvantages of HDS lime for the application at Silvertip as follows:

Advantages:

- Process is well known and accepted by the industry and regulatory agencies in BC

Disadvantages:

- Process not likely to operate as conventional HDS due to low sulphate and metal loading in plant feed
- Need to operate at high pH and then acidify the effluent
- Due to large plant footprint (and cost), cannot be designed as a containerized system

Sulphide Precipitation

Sulphide precipitation removes metals from water in the form of metal sulphide solids. Unlike lime precipitation, sulphide precipitation systems offer two degrees of freedom in the process including pH and Eh set points in the metal precipitation reactor (Kratochvil et al, 2015). Sulphide is a much stronger ligand than hydroxide for most metals and this means the majority of metal sulphides exhibit solubilities that are many orders of magnitude lower than those of the corresponding metal hydroxides. Consequently, sulphide precipitation can achieve much lower concentrations of dissolved metals in treated effluent and often without the need for pH adjustment, as is the case for the Silvertip water.

Different forms and sources of sulphide are available including NaHS, Na_2S and TMT. Regardless of the type and source, the kinetic reaction between sulphide and metals in solution is fast. This eliminates the need for long retention times, unlike HDS systems, to ensure high reagent utilization.

With sulphide precipitation, no gypsum is produced which reduces the amount of waste sludge. In contrast to HDS sludge solids, metal sulphides can be blended with metal concentrates produced at the site; recovering value from metals contained in the wastewater, assuming it is of interest to mines with highly polluted streams containing significant mass load of metals (Ashe et al, 2008). At Silvertip, this is not the case as the sludge solids would be blended into the underground paste backfill material. The following reaction shows the example of the removal of divalent metals using sodium sulphide (Na_2S).

$$\mathrm{MeSO_4}_{(aq)} + \mathrm{Na2S}_{(aq)} \rightarrow \mathrm{MeS}_{(s)} + \mathrm{Na_2SO_4}_{(aq)}$$

The three aspects of sulphide precipitation that are sometimes cited as disadvantages are (1) the formation of very small, almost colloidal, particulates of metal sulphide that are difficult to separate from solution, (2) the lack of familiarity of the mining industry and regulators with these systems and, (3) the health and safety risks related to potential hydrogen sulphide formation.

While the risk of colloids formation is real, BQE Water has developed engineering designs minimizing this risk and has constructed 16 large scale metal precipitation plants treating mine wastewater at projects around the world. The tools used to prevent the formation of colloids focus on controlling the levels of solution supersaturation with respect to metal sulphides which are highly insoluble and form rapidly and irreversibly. Additionally, the process is proven at mine sites in extreme wet and cold environments in Northern Canada (Consigny et al, 2015). That said, none of the company's sulphide precipitation plants have been built in British Columbia which meant extra scrutiny would be applied to the water treatment at Silvertip if the ChemSulphide® process was to be applied there. Given the high solubility of hydrogen sulphide gas, the health and safety risk is quite low for applications like Silvertip where low sulphide doses are required to remove trace metals.

The key advantages and disadvantages of sulphide precipitation application at Silvertip can be summarized as follows:

Advantages:

- Well proven process
- Operate at neutral pH
- Eliminate the need for effluent acidification using CO_2
- Reduce the production of waste sludge
- Instant reaction, eliminate the need for large precipitation reactors
- Process can be designed to fit in standard sea containers
- Small plant footprint

Disadvantages:

- Lack of familiarity with the process amongst British Columbia regulators
- Introduction of new reagent at the mine site

Treatment Process Selection and Permitting Implications

Table 2 provides a summary of the comparison between HDS lime and sulphide precipitation salient to selecting the most appropriate water treatment for the Silvertip project.

Table 2: Comparison between HDS Lime and Sulphide Precipitation

HDS Lime Neutralization	Sulphide Precipitation
Lime reactor with aeration, long HRT	Use of in-line reactors
Large clarifier	Solid-liquid separation in a sea container
Need for effluent acidification via CO_2 addition to meet discharge pH limit	No need to change the pH (eliminate re-acidification stage)
Sludge production of up to 1.35 kg/m^3 of water treated	Sludge production $<$ 0.1 kg/m^3 (mostly TSS coming from underground)

Based on the comparison presented in the table above and preliminary assessment of cost, schedule and logistical benefits of the ChemSulphide® process, JDS selected sulphide precipitation as the treatment process of choice for the Silvertip project.

The position of the BC Ministry of Energy and Mines (BC MEM), the agency responsible for approving permits for mining projects in the province, is that a pilot demonstration is required for any water treatment process that has not yet been implemented at a BC mine site. This meant that despite the fact that BQE Water could provide operating data from multiple reference sites using ChemSulphide® for mine water treatment elsewhere in the world, JDS Silver would not receive a permit until ChemSulphide® was demonstrated on the Silvertip water.

Although bench scale testing was conducted as part of the initial treatment selection process, a pilot demonstration was required. Based on experience from previous projects, both BQE Water and JDS Silver had a high level of confidence in applying ChemSulphide® at Silvertip. This confidence coupled with the aggressive project schedule led JDS Silver to make the decision to proceed and build the ChemSulphide® treatment plant without a pilot demonstration. Instead, the plan was to commission the plant and use the first two weeks of plant operation as the demonstration on which Silvertip would receive their permit.

ChemSulphide® Plant Description

Each ChemSulphide® plant is unique, and this section aims to provide a closer look into the overall process that was implemented at Silvertip as well as highlight some of the readily available equipment that was used to meet the water treatment objectives on site.

Process Overview

The Silvertip WTP block flow diagram is presented in Figure 4.

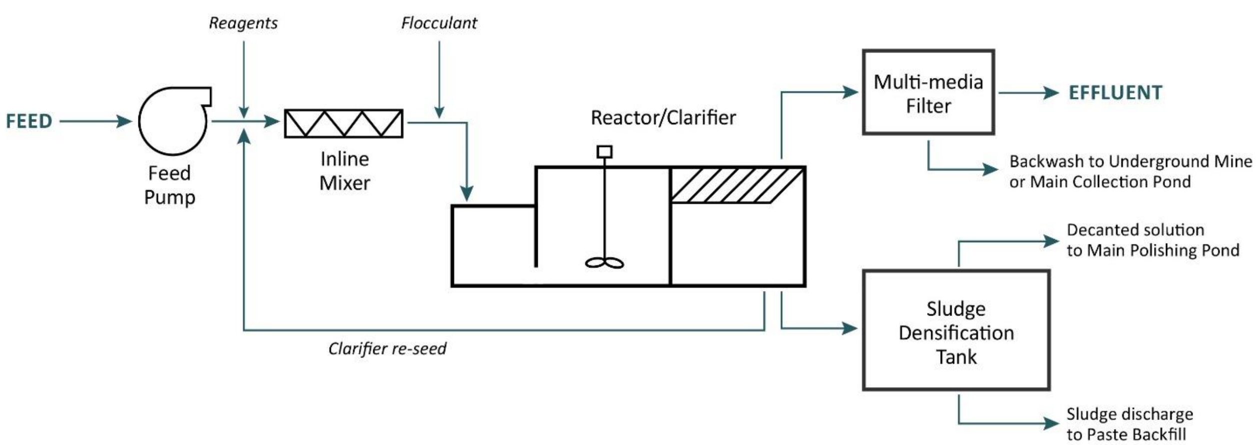

Figure 4: WTP Block Flow Diagram

The overall process contains six discrete steps that are described in Table 3.

Table 3: Water Treatment Stages at Silvertip

Step	Name	Description
1	pH Adjustment	Sulphide precipitation reaction produces acid. Sodium hydroxide is injected upstream in inline mixers to ensure the final effluent pH is within permitted limits.
2	Reaction	Sulphide reagents are injected upstream in inline mixers to react with dissolved metals in the impacted waters to yield metal sulphide solids and acid.
3	Flocculation	Flocculant is injected in a modified frac-tank clarifier. Gentle agitation in the mix chamber facilitates particle agglomeration and increases particle size to improve settling.
4	Clarification	Flocculated solution flows through a lamella plate, which reduces the superficial velocity of the flocs to separate them from the treated water.
5	Filtration	Clarifier supernatant is polished in multimedia filters to remove fine particulates before it is discharged to Silvertip Creek via the MPP.
6	Densification	Sludge is periodically purged to a holding tank, where additional residence time allows for further compaction. Thickened sludge is sent to the paste backfill plant for disposal.

Plant Overview

The modular WTP was designed to house all equipment in three 40'L x 11.5'W x 9.5'H extra-wide shipping containers and one 53'L x 8.5'W x 10.5'H frac-tank. The high rise rate of solids and low solids generation rate allow for smaller equipment, making containerization feasible. The unmodified shipping containers and frac-tanks were readily available from local vendors. Most of the lead time required to deliver these units was a result of customization to ensure proper accessibility and compatibility with the process.

As pictured in Figure 5, the containerization of the plant allows for easy placement onsite with minimal civil work. Another benefit of containerization is the ability to double stack containers to reduce footprint and eliminate pumps by taking advantage of gravity flow; two of the containers depicted in Figure 5 were double-stacked for this very reason.

Figure 5: Silvertip WTP

Project Execution

Table 4 shows key milestones for the Silvertip project. The plant was operating and discharging to the environment within five months of the final design being issued, meeting the compressed project schedule laid out by the client.

Table 4: Key Milestones for the Silvertip Project

Milestone	Date
Contract Awarded to BQE Water for WTP Design	December 01, 2015
Process Engineering Design Issued for Construction	February 03, 2016
Equipment Delivered at Site	April 24, 2016
Water Treatment Plant Operating and Discharging to Silvertip Creek	May 14, 2016

Containerization

All components of the WTP, with exception of the motor control centre (MCC), were fabricated and installed in the Lower Mainland near Vancouver, British Columbia. Shipping containers pre-modified with doors, penetrations, insulation, lighting and HVAC were shipped to a local fabricator for process equipment, piping and electrical installation. BQE Water was able to oversee construction and make frequent site visits to the local fabrication shop to advise on design, which is a major advantage that is typically not available when a plant is constructed onsite in remote areas.

Another advantage of local fabrication was the ability to partially commission the WTP once the containers were fully packaged. Traditionally, inputs/outputs (IO) from process equipment and instrumentation are terminated to IO cards in a central control cabinet that houses the programmable automation controller (PAC). This method would require substantial inter-container wiring, which is contrary to the overall strategy of the project. Alternatively, the use of remote drops allows IO from process equipment and instrumentation to be terminated to IO cards in each container; onsite, each remote drop is connected via a single Ethernet cable to the central control cabinet housing the PAC. Partial commissioning of the WTP involved testing the PAC/HMI programs and confirming the input/output terminations to each remote drop. This commissioning step was conducted by BQE Water at the fabricators facility, allowing changes to be made easily in a controlled construction environment, which significantly reduced costs and disbursements.

The fully packaged containers were shipped to site after partial commissioning. Minimal site infrastructure was required to install the WTP at site, including:

1. Preparation of a level, crushed gravel pad for the WTP foundation
2. Placement of the shipping containers

3. Installation of the MCC into one of the fully packed shipping containers (a used MCC already at the mine was repurposed for the WTP)
4. Distribution of power from the MCC to the process equipment
5. Installation of inter-container and battery limit piping

The shipping container slated for housing the MCC was fast-tracked and shipped to site first to save time on the project schedule, allowing site construction activities to occur in parallel with local fabrication.

Operation

The underground dewatering phase began immediately after successful WTP commissioning and start up. Reagents were dosed into the system with effluent recycling back to the underground mine. Effluent was discharged into Silvertip Creek after three consecutive hourly assays met the discharge water quality targets. Figure 6 and Figure 7 summarize the zinc and cadmium assays during WTP start up and underground dewatering, respectively. In Figure 6, the influent zinc concentration decreased over the first few days as a result of effluent recycle to the underground mine; the plant was treating and retreating water in a loop. The influent zinc concentration increased shortly after the effluent was directed to Silvertip Creek.

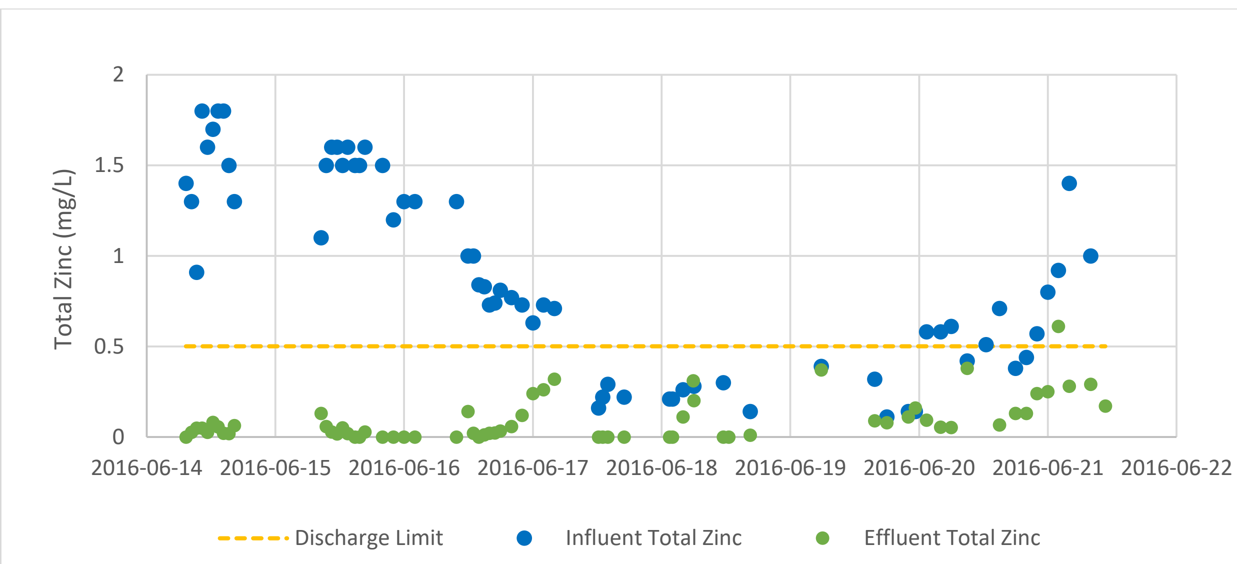

Figure 6: Hourly Zinc Assays Following Plant Start Up

Figure 7 shows the effluent concentration for cadmium and zinc were well below the permit limit. Effluent assays were below targets for discharge permit, and other non-permitted elements met BC WQG.

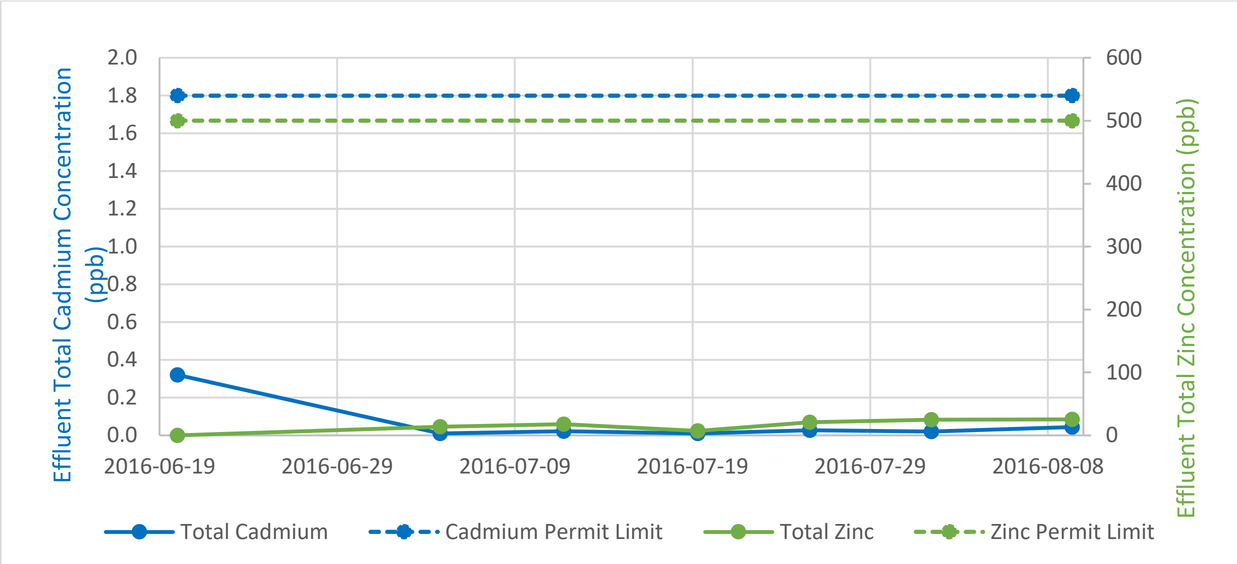

Figure 7: Weekly Environmental Discharge Zinc & Cadmium Assays

Figure 8 illustrates the dewatering rate of the underground mine following start up on June 14, 2016. Initially, the average design treatment rate for the underground dewatering phase was 30 m^3/hr (or 720 m^3/day, 22,320 m^3/month). The bottlenecks limiting the overall treatment rate of the WTP during the mine dewatering phase were:

1. Downtime associated with physically moving the dewatering pump deeper into the tunnels
2. Lost hydraulic capacity from moving the pump deeper into the tunnels

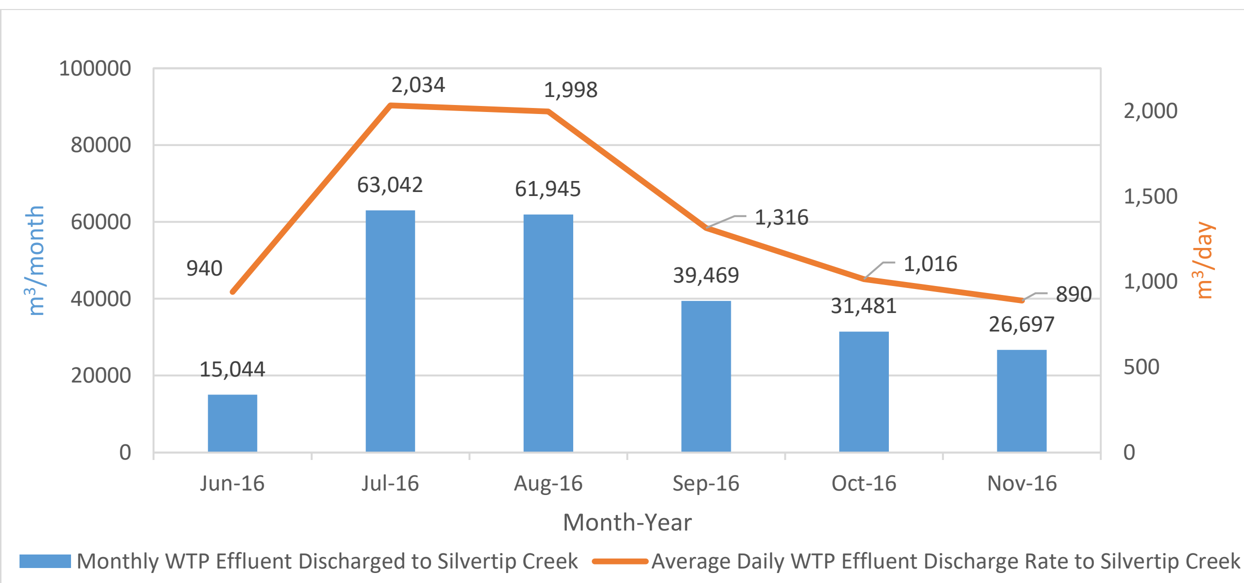

Figure 8: Dewatering Rate of the Underground Mine

The treatment rate was initially high and decreased over time as a result of moving the pump deeper into the tunnels. The WTP transitioned to treating MCP water in Q4 2016, following the completion of the underground dewatering phase.

Capital Costs

Traditional cost factor analysis, where multiplication factors of 4 or greater are applied to the base equipment cost, does not provide accurate estimates for containerized plants. The integration of highly packaged equipment reduces the total amount of labour required to deliver the plant. In this case, highly packaged refers to systems that are structurally mounted to a frame and have some degree of process piping and electrical/instrument wiring already in place. These units only require power and inlet/outlet piping connections to be made prior to being ready for operation. Loose shipped equipment, on the other hand, requires substantially more work to incorporate into the shipping containers. Table 5 categorizes loose shipped and highly packaged equipment installed in the Silvertip WTP.

Table 5: Loose & Highly Packaged Equipment in the Silvertip WTP

Equipment	Loose Shipped	Highly Packaged
Air Compressor	X	
Tanks/Pumps/Agitators	X	
Flocculant Makeup		X
Frac-Tank Clarifier		X
Lamella Plate Pack		X
Multimedia Filter		X

Table 6 summarizes the installed cost factor for the containerized Silvertip WTP. A key component to the lower installed cost factor is the element of offsite construction. With an overall effort to reduce costs, this approach offsets the high labour rates of remote sites with lower labour rates in urban areas. Further, this eliminates the high cost associated with transporting and housing skilled labour for plant construction. The end result is a project where over 95% of the costs are incurred offsite, with the remaining costs a result of integrating the containerized WTP on site.

Table 6: Silvertip WTP Cost Factor Analysis

Direct Costs	$ CDN
Final WTP Cost	1,700,000
Equipment Cost Subtotal	580,000
Installed Cost Factor	2.9

Conclusion

Sulphide precipitation is a very effective tool for achieving ultralow discharge limits in mining effluents and due to its specific qualities of fast reaction time and high solids settling rates offers the possibility of a containerized mine water treatment design which:

- Minimizes capital costs and the need for skilled trades labour at remote sites projects
- Reduces water treatment plant footprint
- Reduces the quantity of residue produced during treatment and enables possible value recovery

The Silvertip project was able to take advantage of all these benefits while paving the way for future ChemSulphide® process applications in British Columbia. The operational success at Silvertip removes the need for pilot demonstrations that would otherwise be required for treatment processes not yet implemented in the province. The reason that the Silvertip project was able to maximize the value generated by the ChemSulphide® process was because BQE Water was invited to participate in the project in early stages of planning and before any major decisions about water treatment were made. As an expert with a broad range of water treatment experience and technical capabilities, BQE Water helped reduce project risks and costs by accepting full responsibility for water in the project from the initial evaluation and bench scale testing, through permitting, to the full scale implementation.

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