

GEOCHEMICAL CHALLENGES ASSOCIATED WITH WATER TREATMENT AT ABANDONED OR NEGLECTED MINES IN SOUTHEAST YUKON

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ABSTRACT

At mine sites with geochemically reactive wastes the interim period between cessation of mining and implementation of a remediation plan may extend for years or decades, during which time chemical treatment of mine contact water is commonly required. Three non-producing mines in southeast Yukon (Ketz River, Wolverine and the Faro Mine Complex) are compared to illustrate how remediation implementation delays at abandoned and neglected mines are impacted by challenging pre-remediation water treatment requirements. The complexity, cost, and duration of water treatment activities differ greatly between the sites, depending on the chemical nature of the contaminants and volume of water to be treated. Remote, subarctic, mountainous conditions where most water management activities must be conducted during a short summer season contribute to water treatment challenges. Water treatment at Faro is anticipated to continue in perpetuity, whereas remediation at Ketz River and Wolverine could potentially eliminate the need for repeated and seasonal water treatment campaigns. A key lesson learned from these sites is that during implementation of water treatment for the interim period, it is commonly discovered that geochemical conditions have deteriorated so severely that remediation plans become obsolete. This leads to unanticipated water treatment costs while remediation plans are updated.

INTRODUCTION

This is a case study comparing treatment approaches for mine contact water containing dissolved contaminants of concerns at Ketz River Mine, Wolverine Mine, and the Faro Mine Complex (FMC) in southeast Yukon. All three sites require dewatering and treatment of tailings supernatant to prevent release of contaminated water to downstream receiving environments, and to ensure dam stability. The FMC has the added water treatment demands of maintaining three pit lakes as ground water sinks, which also serve as storage reservoirs for tailings supernatant, surface run-off and seepage captured from sulfidic wastes. By comparing and contrasting the treatment strategies, within this paper we illustrate how geochemically challenging conditions further complicate management of contaminated water after metal mines have stopped producing. This diverts limited capital and resources away from remediation activities, towards immediate water treatment needs. Reducing near-term water management risks to an acceptable level may take several years, during which time remediation planning and implementation may be further delayed, thus allowing annual care and maintenance costs to continue accruing.

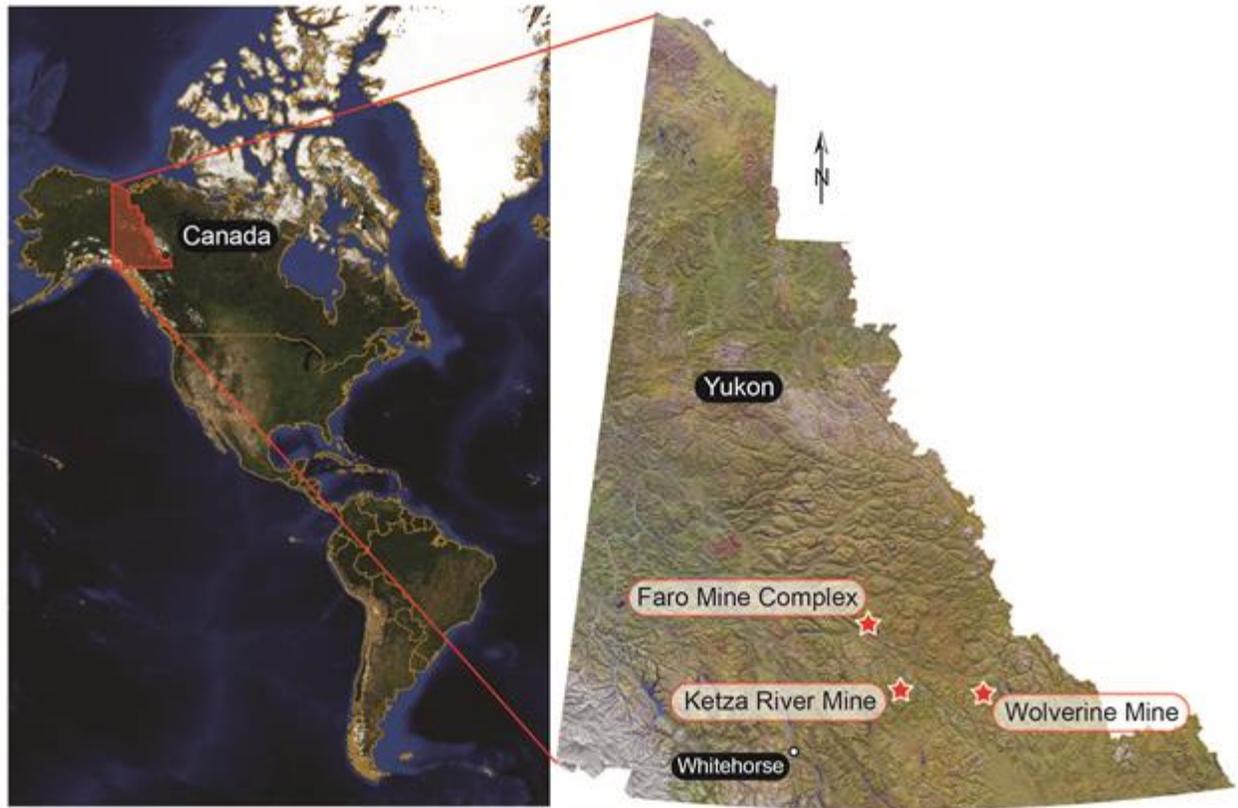


Figure 1 Location of sites in southeast Yukon.

BACKGROUND

The scale and scope of water treatment activities differ greatly between Ketzka River, Wolverine, and the Faro Mine Complex, due to the chemical nature of the contaminants and volumes of water requiring treatment. Ketzka River, where non-sulfidic gold-bearing ore was mined, represents an abandoned mine site with relatively simple water treatment requirements. A 16 L/s ferric chloride treatment process removes arsenic from tailings supernatant with circumneutral pH. This contrasts to lead-zinc sulfide ore mining at the abandoned Faro Mine Complex, where two conventional lime neutralization water treatment plants are used to remove zinc, iron, acidity and other metals at a combined rate of 500 L/s. Although not abandoned, Wolverine is another lead-zinc sulfide mine that has been neglected, requiring government intervention to install reverse osmosis water treatment to remove selenium, cyanide species, metals and acidity from tailings supernatant at a rate of up to 29 L/s.

WATER TREATMENT AT THE KETZKA RIVER MINE

The Ketzka River gold mine was abandoned by Ketzka River Holdings on April 10, 2015. Yukon Government is now responsible for managing the site, including all water treatment activities, and will be responsible for further developing and implementing a remediation plan that is currently at a conceptual stage. Of the three mines being compared, Ketzka River represents the simplest

water treatment requirements in terms of both water quality and quantity. Since 2015, total annual volumes of water treated ranged from 190,000 m³ to 308,000 m³. Summer 2019 will be the fifth year of the post-abandonment water treatment campaign. A total of 944,000 m³ were treated in the first four years, with the millionth cubic meter milestone to be passed in 2019. In comparison, the Faro Mine Complex releases 7 million m³ of treated effluent per year.

The Ketzka River gold mine sustained commercial production from March 1988 until November 1990. In that limited time, carbon-in-pulp cyanidation was used to extract gold from ~ 350,000 tonnes of oxide ore extracted from open pit and underground operations. Arsenic-rich tailings slurry was discharged into a TSF with a maximum storage capacity of ~ 600,000 m³. TSF containment is provided by a high risk dam with a crest length of ~ 400 m, a maximum height of 20 m, and an emergency spillway that is not sized to pass a large flood event. The site is in the sub-alpine at elevations above 1300 m, with the TSF located in a valley bottom where several small springs and creeks converge, thus groundwater continually discharges to the TSF pond. Treatment of tailings supernatant with arsenic concentrations up to 1 mg/L is required during the ice-free season in order to maintain safe water elevations behind the dam, and to reduce arsenic mobilization to the receiving environment.

The WTP was installed in 2012 with a design throughput of 250 usgpm (16 L/s), but is more commonly operated at 200 usgpm (12.5 L/s). Treatment consists of adding two reagents, ferric chloride and sodium hypochlorite, to influent pumped from the TSF. Arsenic is removed through co-precipitation with ferric oxyhydroxides. Precipitates are removed using granular media filtration. The filters are backwashed several times per day, with sludge deposited back into the TSF. Arsenic removal of 85 to 95% is regularly achieved from influent with arsenic concentrations from 0.5 to 1.0 mg/L. The greatest reductions in arsenic are achieved after a backwash cycle is completed, with arsenic reduction efficiency degrading as precipitates accumulate in the media filters. WTP operators target arsenic concentrations of 0.05 mg/L in effluent, well below the effluent discharge standard of 0.5 mg/L. Treated effluent is discharged to Cache Creek, which flows in a diversion adjacent to the TSF. Sludge deposition in the TSF is not considered problematic because sludge is only a minor contributor of arsenic compared to the overall arsenic load stored in the tailings. For instance, if influent with 1 mg/L arsenic was treated year round at the maximum design throughput of ~ 500,000 m³ per year (365 days at 16 L/s), with all arsenic being removed and returned to the TSF as sludge, no more than 500 kg of arsenic would be returned to the TSF. In some years, as little as 100,000 m³ of influent with 0.5 mg/L arsenic could be treated, which would contribute 50 kg of arsenic to the TSF. When compared to the ~ 14,000,000 kg of arsenic stored in the tailings, returning less than 500 kg of arsenic to the TSF per year is considered relatively insignificant.

The Ketzka ore deposits are hosted primarily within carbonate bedrock, which provides abundant neutralization potential for any localized acid rock drainage that may develop. Mining operations only exploited near-surface oxide zones, leaving underlying sulfide resources in place. Sulfides were therefore not deposited in the TSF, so TSF water quality is not predicted to degrade significantly over time. Most tailings stored in the TSF remain under a water cover however, by

the end of the summer treatment season when the TSF water elevations are at their lowest, some tailings are subaerially exposed along the TSF margins. TSF dams have been the subject of increased scrutiny over the past half-decade, and consultants have recommended that the Ketz River TSF dam either be significantly upgraded to align with Canadian Dam Association guidance, or operate the pond at a lower elevation to provide additional freeboard. The conceptual remediation plan includes dewatering the TSF, relocating the tailings and decommissioning the dam to reduce long-term geotechnical risk, therefore operating the pond at a lower elevation is the preferred approach until remediation is complete.

The key short-term geochemical challenge at Ketz River mine is determining if exposing additional tailings by consistently operating the pond at a lower elevation will increase arsenic leaching from the exposed tailings to the supernatant. The WTP is capable of treating influent with higher concentrations of arsenic than those currently being treated, however, the Government of Yukon wants to ensure that changing the TSF operating conditions will not cause exceedances of the influent parameters for which the WTP was designed. Despite not having severe geochemical conditions, managing water treatment at Ketz River requires consideration of the interplay between the risk associated with under-sized geotechnical infrastructure, the changing geochemistry of exposed non-sulfidic tailings, and operational constraints imposed by the installed water conveyance and treatment systems.

Remediation planning is in the early stages, and it will likely be a decade or more before remediation is complete. Until remediation of the TSF is complete, tailings supernatant will need to be treated to remove arsenic every year. Contaminated sites such as this require full-time presence by care and maintenance staff, who also conduct the water conveyance and treatment activities. Labour and fuel costs (for generator-supplied power) are the main expenses for ongoing site presence and water treatment operations, with base annual care and maintenance costs exceeding \$1.5 million. Regular water monitoring activities, geotechnical inspections, and occasional infrastructure upgrades add several hundred thousand dollars per year to care and maintenance costs. Site investigations (e.g. drilling, test pitting, and sampling), assessment, engineering design, construction of the remediation design, and project management are all additional costs not captured in the care and maintenance expenses.

WATER TREATMENT AT THE WOLVERINE MINE

At present, there is no water treatment plant at the Wolverine mine to manage contact water that contains selenium, metals, acidity, cyanide, and sulfate. The volumes of water that will require treatment at Wolverine are more similar in scale to Ketz River than the Faro Mine Complex, but the nature of the dissolved contaminants at Wolverine make the water more difficult to treat than arsenic at Ketz River or acid rock drainage at the Faro Mine Complex. In particular, selenium concentrations up to 10 mg/L were sampled from the Wolverine TSF, including the rarely encountered selenium-cyanide compound, selenocyanate. Reverse osmosis is the preferred treatment approach for Wolverine, however, selenocyanate is highly toxic and neutrally charged, meaning that it can potentially pass through reverse osmosis membranes more readily than

charged selenium species. These types of treatment challenges can be overcome with the aid of treatment process assessments, such as computational modelling and pilot studies.

The Wolverine Mine was a 1700 tonnes per day underground operation that exploited a Volcanogenic Massive Sulfide (VMS) deposit from 2009 to 2015 to produce concentrates containing zinc, silver, copper, and lead using conventional milling and floatation (YZC 2017a). The mine plan provided for temporary storage of acid generating waste rock and tailings in surface facilities, and eventual backfill underground upon cessation of mining to prevent ARD/ML generation. The mine plan was not implemented as designed, allowing acid generating material to remain exposed to water and oxygen at surface. From 2016 to 2017, TSF supernatant pH unexpectedly dropped from circumneutral to ~ 4 (YZC 2017a; Figure 6-4).

The Wolverine mine is owned by Yukon Zinc Corporation, however, the company does not have the financial or human capital required to manage the site according to their mining and water licences. The underground mine was allowed to flood, and in 2017 water began daylighting at the portal. The company did not construct a water treatment plant, and instead conveyed the portal water to the TSF for storage. The Engineer of Record for the TSF recommended that in the absence of installed water treatment capacity, a minimum of 1.5 m of freeboard be maintained to safely store a 1:10,000 return period flood event without discharging TSF supernatant to the receiving environment (YZC 2017b). As of summer 2019, the TSF had less than the required 1.5 m of freeboard.

Due to the site's neglected state, the Government of Yukon is in the process of contracting a water treatment service provider to mobilize to site for implementation of a two-year water treatment campaign. The campaign will consist of using two containerized Reverse Osmosis (RO) water treatment trains to dewater the TSF in summer 2019 and summer 2020. Based on a Goldsim water balance model that accounts for variations in annual precipitation, the TSF is predicted to overtop in 2020 if water treatment capacity is not installed. Thus, the primary goal of the water treatment campaign is to prevent discharge of TSF water to the environment. The second goal is to establish suitable freeboard by the end of summer 2020 to allow for up to 2 years of additional inputs of water to the TSF before another water treatment campaign is required. The plan is to have discharged up to 300,000 m³ of treated water from the TSF by the end of the 2-year campaign, based on a 2500 m³ / day (29 L/s) treatment rate. Total annual inputs to the TSF are currently estimated at ~ 65,000 m³ and consist of the underground mine water, direct TSF precipitation, run-off from the small TSF catchment area, and site sumps. Due to the limited historical water balance data for the site, there is a large uncertainty in the total annual site water volumes that may require management.

The TSF consists of a 26.5 m high earth-fill dam lined with a single layer of 40 mil linear low density polyethylene (LLDPE), and is considered a high risk geotechnical structure (YZC 2017b). In spring 2019, water levels in the TSF rose above the maximum recommended elevation of 1310.0 m, which equates to an impounded volume of 1,315,000 m³, with 530,000 m³ being tailings, and the remaining 785,000 m³ being supernatant. At the spillway invert elevation of

1311.5 m, total impounded volume is ~ 1,513,900 m³ (YZC 2017b). Thus, available storage capacity falls below 200,000 m³ when there is less than 1.5 m of freeboard remaining.

The TSF pond is up to 14 m deep and chemically stratified, with higher metal concentrations at depth, closer to the tailings interface. Acidity has an inverse relationship to metals concentrations, with lower pH (3.5) measured near the surface, increasing to pH 5 at depth, particularly below 9 m. Contaminants of concern showing elevated concentrations include selenium, sulfate, metals (e.g., antimony, arsenic, cadmium, copper, iron, lead, mercury, silver, zinc), cyanide, and some rare compound species such as selenocyanate. Mine contact water from the underground portal is commonly suitable for discharge, with the exception of iron. During operation of the RO water treatment plant for the tailings supernatant, water from the underground will be used to harden the treated RO effluent before discharge to Go Creek.

The proposed 2-year treatment campaign is an urgent measure required to mitigate against environmental effects that would result from near-term release of tailings supernatant that is toxic to aquatic organisms. The treatment strategy is driven mainly by selenium removal requirements due to high concentrations (0.2 to 0.3 mg/L at pond surface; an order of magnitude greater at pond depths below 6 m) and difficulty in removing from solution. Selecting the appropriate RO configuration, including membranes and pre- and post- treatment reagent addition, is best supported by pilot testing due to limited published data regarding removal of rare, neutrally-charged contaminants such as selenocyanate. The treatment process will involve drawing influent from the less contaminated upper pond layer, and passing it through two RO trains (configured in parallel) capable of producing up to 2500 m³ / day (29 L/s) of treated permeate. Permeate will require conditioning before discharge to the receiving environment because it will be so lacking in dissolved constituents that it would be corrosive to the receiving environment. The retentate, which contains dissolved contaminants of concerns that were rejected by the RO membranes, will be discharged back into the TSF pond as far away from the influent draw point as possible.

The two most likely geochemical challenges that could arise during the 2-year water treatment campaign include pond turn-over and gradual hardening of the TSF pond water. Pond turn-over would rapidly mix the pond to produce an influent with higher contaminant concentrations by an order of magnitude. Selenium concentrations of 0.2 to 0.3 mg/L at surface are targeted to be reduced by an order of magnitude by the RO water treatment plant. If pond mixing produces influent with selenium concentrations of 2 to 3 mg/L, the current treatment approach may not be able to reduce selenium concentrations by two orders of magnitude to achieve the target maximum effluent concentrations. Continual discharge of briny retentate back into the TSF pond without a desaturation step will likewise cause a progressive increase in contaminant concentrations in the pond. This is not predicted to be problematic in year 1 of the treatment campaign. For year 2, the RO treatment process may require an additional pre-treatment step to soften the influent, and reduce the likelihood of scale and membrane fouling.

Selenium also poses an additional operational challenge for confirming the discharge acceptability of treated effluent in timely manner. Before treated effluent can be discharged to the

receiving environment, laboratory analyses must confirm that contaminant concentrations are below the maximum allowable levels. With respect to selenium, Brooks Applied Labs and ALS are the only labs able to test for selenium and conduct selenium speciation analyses. Selenium analyses also take longer, and are more expensive than standard metals analyses. Once the RO WTP is started-up and the process achieves a steady state, effluent will need to be directed back to the TSF instead of the environment until all analyses are complete and deemed acceptable. Thus, several extra days of treatment will be lost due to the analytical complications associated with selenium, compared with analytical turnaround times for metal contaminants. The WTP start-up and sampling procedure will need to be repeated at the beginning of each treatment season, and whenever the treatment process experiences an upset. Real-time conductivity monitoring of the RO effluent will be used as proxy for water quality, with automatic shutoffs in the event of unacceptable conductivity excursions.

The original Wolverine mine plan envisioned all tailings and waste rock being returned to the underground. Due to temporary mine closure in 2015 and subsequent flooding of the underground, a revised plan envisioned closing the TSF as a dry facility by dewatering and treating TSF supernatant, placing PAG waste rock in the TSF, landforming the facility and then installing a composite cover consisting of geosynthetic liner and earthen growth medium. Long-term challenges with TSF water treatment are mostly related to ongoing discharge of permeate back to the TSF pond, and how to manage the final volume of highly concentrated contaminant brine. This variation of the remediation plan was submitted by Yukon Zinc Corporation to the Government of Yukon in 2017 (YZC 2017a), however, the plans are conceptual in nature and have not been validated against current site conditions, particularly the acidic TSF pond. Until such time as a final comprehensive remediation plan is developed, it will not be possible to design and implement a water treatment process that will be capable of eliminating the need for long-term active water treatment at the site. Given that the TSF pond was not predicted to turn acidic, there is also a lack of understanding of how poor the water quality could be in the future, and which water treatment technologies will be required.

WATER TREATMENT AT THE FARO MINE COMPLEX

The purpose of having installed water treatment capacity at the Faro Mine Complex (FMC) is to prevent release to the environment of acid rock drainage and metal-bearing neutral drainage from multiple pits and ponds, with zinc being one of the key contaminants of concern. Treatment is required in order to maintain pits as net ground water sinks, and to provide storage capacity in pits and behind dams to reduce the likelihood of containment loss during high-flow events, or due to some other failure mechanism. At present, the FMC relies on two seasonally operated lime-neutralization, Low Density Sludge (LDS) water treatment facilities with combined capacity of 500 L/s to annually produce ~ 7 million m³ of treated effluent that complies with the discharge standards in the expired water licence. Annual water treatment volumes at the FMC are more than an order of magnitude larger than Ketz River and Wolverine however, treatment processes for ARD/ML are effective and well established.

Acid Rock Drainage at the FMC resulted from three decades of open pit mining and milling of pyritic lead-zinc sulfides that began in 1969, with final abandonment in 1998. The operations resulted in 390 million tonnes of combined acid generating waste rock and tailings, with another 40 to 45 million m³ of accumulated mine contact water. The FMC is geographically divided into the Faro side and the Vangorda Plateau, which are connected by a 14 km long haul road. Each half of the property resides in a separate sub-watershed that drains to the Pelly River, and each half has its own WTP. The Vangorda Plateau is in the Vangorda Creek watershed, and contains two open pits, Grum and Vangorda, with associated waste rock dumps. The Faro side of the property is in the Rose Creek watershed and contains Faro pit, associated waste rock dumps, the mill/processing area, and the TSF. The FMC was managed by the Government of Yukon from 2009 until spring 2018, when responsibility for the site was transferred to the Government of Canada. The site is currently in a state of care and maintenance while remediation planning advances. The Government of Canada submitted a remediation plan project proposal to the Yukon Environmental and Socio-economic Assessment Board (YESAB) in 2019.

Together, Faro and Grum pits contain 90-95% of the contact water stored at site. This water is characterized by circumneutral pH and elevated concentrations of dissolved zinc and sulfate. Grum pit has 6 mg/L dissolved zinc in surface water, whereas Faro pit surface water zinc concentrations range from 18 to 34 mg/L. The remaining 5-10% of contact water stored at site is of worse quality than the Faro and Grum pit waters, being variably impacted by acidity, iron, manganese, zinc, cadmium and sulfate. For example, Vangorda pit contains ~ 1.5 million m³ of water with up to 235 mg / L Zn at pH 3 to 5.

The first and only WTP on the Vangorda Plateau is a LDS system that was constructed in 1992 to treat acidic, metal-impacted water from Vangorda pit during mine operations. Only Vangorda pit water and waste rock dump seepage required treatment up until 2013, when continually rising water levels in Grum pit reached a trigger that indicated dewatering and treatment were to commence. Given the large difference in water chemistry between Grum and Vangorda pits, it was determined that configuring the WTP to receive two varied influent sources could lead to operational difficulties. To overcome this geochemical challenge, Grum pit dewatering was configured to transfer water to Vangorda pit prior to treatment. The comparatively alkaline Grum pit water being discharged into acidic Vangorda pit water provides some in-situ neutralization and treatment of Vangorda pit water, and provides for a single combined influent chemistry that the WTP can readily treat. The Vangorda WTP discharges approximately 1 million m³ of treated effluent per year.

Initiation of seasonal Grum pit dewatering doubled the annual volume of water processed by the Vangorda WTP, and the increased sludge production overwhelmed the sludge holding capacity of the settling pond used to polish the treated effluent. Previous to this when only Vangorda pit water was treated, the settling pond had enough capacity to store all sludge from the treatment season, which was removed from the pond in winter by truck and shovel. The increased sludge volumes produced by also treating Grum pit water were managed by installing a high-solids pump on a barge to dredge the sludge and pump it to Grum pit for disposal in the pit lake.

Despite its relative simplicity, lime-neutralization water treatment produces large volumes of sludge that require management. The volume of sludge produced is a result of the water chemistry, and increases proportionately with lime demand. At a site like the FMC where several pit lakes are available for sludge disposal, there is little concern about lack of the sludge storage space, despite the plan for perpetual water treatment. Sludge production and management remains a challenge, with one common mitigation being implementation of High Density Sludge (HDS) treatment, which more efficiently uses lime, and produces a sludge slurry with 20-30% solids, rather than the 2-3% solids commonly produced by LDS systems. On the Faro side, sludge is currently disposed of by discharging into cells excavated on the tailings surface. Long-term, the sludge will be discharged at depth in Faro pit.

Water management and treatment on the Faro side of the property is conducted with completely separate facilities than those on the Vangorda Plateau. The primary water management risk on the Faro side is tailings supernatant in the Intermediate Pond. The Intermediate Pond receives direct surface runoff from a 200 hectare TSF and shallow recharge that passed through oxidizing sulfidic tailings. The pond contains ~ 1 million m³ of water with zinc concentrations ranging from 5 to 100 mg/L, iron concentrations ranging from 18 to 135 mg/L, and pH as low as 4. The pond and the 55 million tonnes of tailings are retained by the 650 m long, 32 m high Intermediate Dam. It is the highest risk geotechnical structure on site, and seasonal (summer) dewatering of the Intermediate Pond at a rate of 126 L/s is required to prevent outflow of the acidic water down the emergency spillway into the Cross Valley Pond, and to maintain suitable freeboard for high-flow events such as freshet or summer rain events. Prior to installation of large-scale water treatment capacity in 2001, excess Intermediate Pond water was pumped to a rudimentary lime-neutralization system called the Down-Valley WTP that was established in the emergency spillway of the Intermediate Dam. Treated water was discharged into a polishing pond (the Cross Valley Pond) where sludge was settled and compliant effluent was syphoned to the receiving environment. Little information is available regarding the Down-Valley WTP because its use was discontinued after the year 2000.

The first large-scale WTP on the Faro side was constructed in the mill building in 2001 to manage contact water that was being stored on site after abandonment in 1998. Faro pit lake was, and continues to be, the primary storage reservoir for mine contact water prior to treatment. At its current elevation, the pit lake contains ~ 40 million m³ of impacted water. The Mill WTP was constructed using old ore-processing equipment. Flotation circuits that were used in the production of lead and zinc concentrates, and the thickener and clarifier for tailings management were modified to produce a 4,000 usgpm (~ 22,000 m³ / day) LDS water treatment plant capable of operating during the ice-free summer season. The Mill WTP received TSF supernatant from the Intermediate Pond, and zinc-impacted water from Faro pit. Sludge was discharged to cells excavated on the tailings, while treated effluent was discharged to the Cross Valley Pond for final settling prior to syphoned discharge to the receiving environment. Operation of the Mill WTP ceased at the end of 2012 treatment season when the mill building was condemned due to

unmanageable health and safety concerns related to worker exposure to degraded infrastructure and multiple contaminants such as lead and asbestos.

Full time LDS water treatment was re-established in time for the 2015 water treatment season. An Interim Water Treatment System (IWTS) with 6,000 usgpm capacity ($\sim 33,000 \text{ m}^3 / \text{day}$) was constructed in 2014 adjacent to the mill building. It discharges approximately 6 million m^3 of water per year directly to the environment, mainly due to geochemical upset of the polishing pond. The IWTS was deemed “interim” because it had a 10-year design life intended to bridge the period until remediation plan implementation begins. One of the first remediation plan projects to be built will be a single, High Density Sludge (HDS) WTP. Engineering studies completed in 2014 recommended a WTP with 8,100 usgpm ($\sim 44,000 \text{ m}^3 / \text{day}$) capacity that was capable of year-round treatment. Direct construction costs for the HDS WTP were estimated at approximately \$34M. The high costs were one factor that contributed to the decision to construct an interim WTP at total cost of \sim \$14M.

Sulfate has become a geochemical challenge at the FMC because lime neutralization is incapable of removing substantial sulfate load from impacted water. Recent studies have indicated that year-round (winter) discharge will not be feasible because of low winter base flows in Rose Creek (the water body that receives treated effluent), and the low assimilative capacity of Rose Creek for sulfate in winter. Thus, the HDS WTP that eventually gets built will be sized to allow for all required treatment and discharge to be conducted in summer, when Rose Creek has greater sulfate assimilative capacity. The final design throughput of the HDS WTP may be around 10,000 usgpm ($\sim 55,000 \text{ m}^3 / \text{day}$). Additional benefits of an HDS WTP over an LDS WTP include more efficient use of lime (which is a high-cost, large volume consumable requiring long shipping distances), and a process that is less susceptible to chemical upset due to changing influent concentrations.

Unfortunately, geochemical conditions at the site have continued to degrade over the past 5 years to the point where an acid rock drainage ground water plume originating from the tailings has started to migrate down the Rose Creek valley in the alluvial aquifer beneath the TSF. The plume has contaminated the Cross Valley Pond (the former polishing pond) by upwelling into the base of the pond, and has started discharging as shallow ground water into the receiving environment downgradient of the TSF. A collection and pumping system was commissioned in early 2019 to capture iron and manganese-rich water discharging downgradient of the TSF. Luckily, zinc is being attenuated in the aquifer and is not being discharged to the receiving environment. The FMC is also in process of constructing an additional 2,000 usgpm ($\sim 11,000 \text{ m}^3 / \text{day}$) LDS WTP specifically to treat and discharge Cross Valley Pond water. The pH of the Cross Valley Pond water is still circum-neutral, but iron concentrations are around 400 mg/L, and zinc is up to 2 mg/L at depth. Combined, the contaminated Cross Valley Pond water and downgradient seepage being captured may contribute an additional 2 million m^3 of water per year to the Faro side contaminated water management system, which already discharges 6 million m^3 of treated effluent to the receiving environment.

Another potential geochemical challenge is also emerging at the FMC in the form of fluctuating and increasing concentrations of ammonia in seepage originating from sulfide wastes. This is most apparent on the Faro side, where WTP effluent sometimes exceeds the ammonia discharge standard. To mitigate this issue, the Interim Water Treatment System has been modified to allow effluent to pass through additional pH adjustment tanks. Lowering the effluent pH from ~ 9 to circumneutral reduces the concentration of unionized ammonia, which has greater toxicity than ionized ammonia.

Implementation of a remediation plan at the Faro Mine Complex will not eliminate the need to capture and treat ARD in perpetuity. As geochemical conditions continue to degrade and groundwater plumes advance, the volumes of water requiring treatment, and the contaminant loads of those sources, are likely to increase along with the costs to conduct this work. Prior to transition of FMC management from Government of Yukon to the Government of Canada, annual care and maintenance costs were \$12M to \$14M per year. This does not include recent costs to design and construct new water capture, conveyance and treatment infrastructure, or the ongoing costs to operate the new systems. The current challenges with capturing and treating the tailings ground water contaminant plume, and the emerging ammonia issues clearly illustrate the types of challenges encountered when attempting to contain long-term geochemical risk at an abandoned mine site where there was large-scale disturbance of acid generating sulfide wastes.

CONCLUSIONS AND RECOMMENDATIONS

Water treatment at the Faro Mine Complex is anticipated to continue in perpetuity, whereas remediation of the Ketzia River and Wolverine mines could potentially eliminate the need for repeated, seasonal water treatment campaigns. A key lesson learned from these sites is that during implementation of water treatment for the interim period before remediation implementation, it is commonly discovered that geochemical conditions have deteriorated to a point where assumptions upon which the remediation plans are based, become obsolete. Development of an updated remediation plan involves field investigations, design, community consultation, environmental assessment, water licencing, project management, and associated procurements. This results in a longer-than-anticipated, and therefore more expensive, interim period of water treatment.

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