

Using novel technology for residue management and sustainable mine closure

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Abstract

An important aspect of mine closure is the management of waste residues such as waste rock, tailings, water treatment by-products and other metallurgical process waste. Issues with waste residues include their mass and volume, long-term stability and environmental impact, the methods required for safe disposal and the metal value that may be recovered through reprocessing or offtake. Well-planned management of residues is required not only at sites that are currently in production but also at legacy sites and for projects that are in the permitting and planning stages. In order to navigate the challenges presented by management of residues, many industrial players are employing novel technologies to achieve sustainability. This paper examines three case studies involving the use of new or unconventional technology to improve sustainability and reduce the cost of residue management at different stages of mine life. One case study involves recovery of copper value from low-grade stockpile decades after active mining ceased. The second details a new arsenic management plan at an operating copper smelter, which focuses on dramatically reducing the volume of arsenic waste. The third describes a novel approach to environmental control to reduce selenium discharge to ultralow limits.

1 Introduction

A wide variety of waste residues and by-products are generated during the operation of a mine. The properties of these materials change depending on the mining methods and mineral processing techniques used, environmental treatment requirements and the stage of the mine life. Residues that result from mining water treatment also require management. The character of water treatment by-products and the strategies used to manage them depend on the chemistry of the water treated, the treatment objective and the technology used to achieve that objective. As water treatment is often required for many years of a project's life and even into closure, residue management becomes an important long-term liability for mine owners. Accurately accounting for the cost of residue management thus becomes important for determining not just the up-front capital cost of water treatment but also the true life-cycle cost of different treatment methods. Viewed through this lens, cost-effective residue management involves reducing and, if possible, eliminating waste volume, improving long-term waste stability and minimising losses of value to waste. This paper describes three case studies where water treatment residue management is a key driver in the project. In these projects, novel technology is applied to manage waste sustainably.

2 Case study 1 – recovery of copper to help reduce closure costs

2.1 Project background

As much as 20% of total global copper production comes from active or passive heap leaching of copper from oxide and low-grade sulphide ores using solvent extraction (SX) combined with electrowinning (EW). The process economics of SX-EW at most mine sites dictates that the concentration of copper in the leach solution must be maintained at > 200 mg/L. During the active life of a mine, this is easily accomplished by stacking fresh ore on top of, or next to, the old ore. However, at the end of the mine life when no additional ore is

available, copper concentration drops below the SX-EW plant target. At this point, the plant shuts down and the mine operators face significant costs associated with decommissioning and closing the heap leach operation. Although the large majority of copper has been leached and recovered prior to closure, the value of residual recoverable copper remaining in heaps at the point of SX-EW plant closure is often very significant relative to the overall heap leaching closure cost.

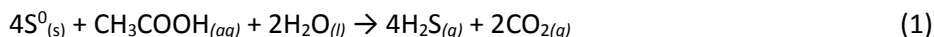
New copper recovery processes such as BioteQ's BioSulphide® process can enable mine operators to cost-effectively recover most of the residual copper value remaining in heaps that have reached the end of their life. This not only reduces the inventory of potentially mobile copper that may leach into the environment after closure, but also makes the proceeds from the sale of the recovered copper available to fund closure costs. The present case study represents an example of this approach.

This case involves a site that was one of America's largest copper producers for much of the twentieth century before operations were halted in the 1970s. After active operations concluded, a low-grade stockpile continued to leach copper, but the grade of the leach solution declined below the level required for SX-EW plants to operate economically. In 2004, BioteQ installed a copper recovery plant using the BioSulphide process, which allowed a cost-effective copper recovery to continue for an additional nine years.

The concept of metal recovery that is applied here to the closure of a heap leach operation may apply equally to sites with acid rock drainage, where the mass of valuable metals present in contaminated wastewater represents an opportunity to offset the long-term water treatment and/or site closure costs.

2.2 BioSulphide for metal recovery

The BioSulphide process involves two separate processes: generating hydrogen sulphide gas in a bioreactor and using biogenic hydrogen sulphide gas to precipitate metals from water. In the bioreactor, bacteria are fed elemental sulphur and acetic acid under controlled conditions to generate a rich stream of hydrogen sulphide gas, as per equation (1). The bioreactor where this chemistry takes place is completely isolated from the stream to be treated, simplifying process control and flexibility.



In the following stage of the process, the biogenic hydrogen sulphide gas is brought into contact with metal-bearing streams in a gas-liquid contactor. The design of the contactor vessel and the tight automatic control process conditions inside the contactor allow a selective precipitation of targeted metals of value or toxic metals that require removal from the metal-bearing stream. In the present case, copper is the metal of interest. It precipitates according to the reaction chemistry shown in equation (2).



The resultant copper sulphide slurry is clarified to produce treated water that is discharged from the plant and a copper sulphide solid that is dewatered in a filter press. A schematic of the BioSulphide process is shown in Figure 1.

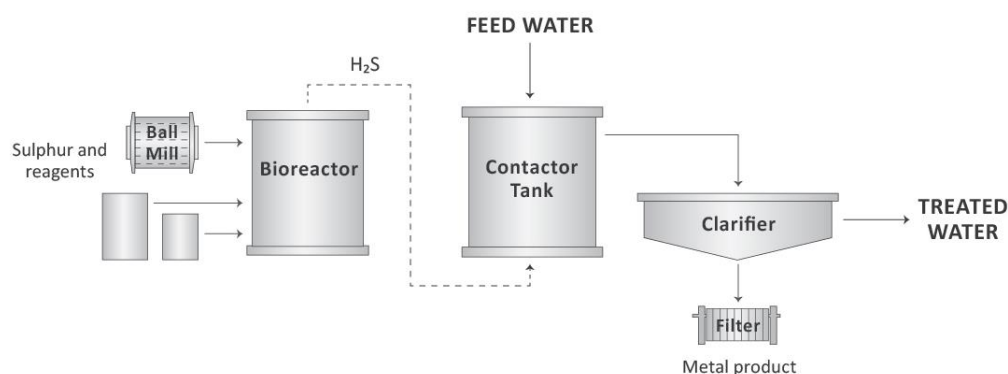


Figure 1 Simplified flow sheet of the BioSulphide process

The BioSulphide facility was commissioned in 2004. The plant was designed to produce up to 3.8 tonnes per day of sulphide (as hydrogen sulphide gas) with a treatment rate of up to 12,000 m³/day of leach solution. The design rate of copper recovery from the leach solution was 99%, and the treated solution was recycled to the top of the stockpile.

2.3 Operational results

The following figures show results from the plant over a decade of treatment. During this time, the volume of water treated and the concentration of copper in the water varied depending on seasonal rainfall and mine remediation activities. However, as Figure 3 shows, the process proved to be robust and highly adaptable to the variations in feed concentration and flow rate. This is partly due to the flexible design of the plant, but the inherent rapid reaction of copper with sulphide also contributes to the high process reliability. Throughout its operational history, the plant consistently removed more than 99% of the feed copper and recovered the metal as 40%–45% metal-grade concentrate appropriate for sale.

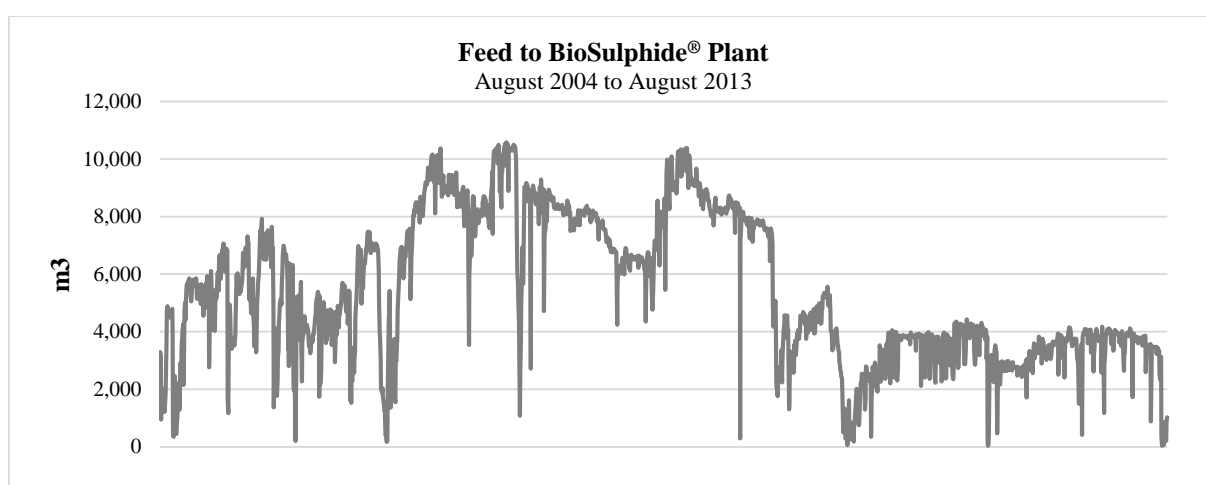


Figure 2 Daily feed flow to BioSulphide plant

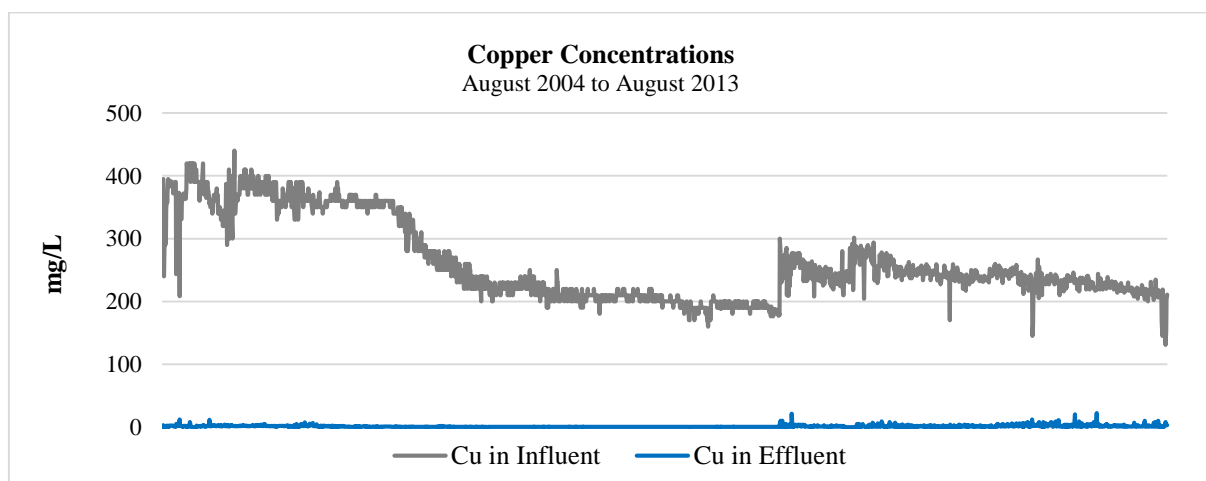


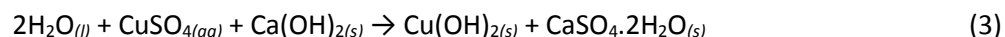
Figure 3 Daily influent and effluent copper concentrations

The operating costs of this process consist of both fixed costs for operator salaries and overhead and variable costs for reagents and power. These variable costs are proportional to the mass load of copper in the stream. The cost of power and reagents for this process is approximately US\$ 1.76/kg of produced copper. When the flow rate and metal concentration of the runoff were high, fixed costs represented a specific cost of US\$ 0.88/kg of copper. However, as Figures 2 and 3 show, both the flow rate and the metal concentration of the stream declined. As the metal load diminished, the fixed costs of the plant became a more significant

part of the overall operating cost. At the time of plant closure, the mass of copper recovered dropped to approximately 204,000 kg per year, driving the total cost of production to US\$ 5.07/kg. At this point, the incremental value of copper recovered was deemed too low compared to the operating cost of the plant.

2.4 Outcomes

The operation of the BioSulphide plant at this legacy site in the American Southwest allowed for the recovery of a significant amount of additional revenue from a closed heap leach pad. This represented not only a recovery of metal value but also the conversion of an environmental liability to a revenue stream. This approach contrasts sharply with conventional lime neutralisation. If lime had been used at this site, the following chemistry would apply:



However, this approach would have generated a significant volume of gypsum and copper hydroxide residue, which would require disposal. This residue material would not only represent a waste of contained metal value, it would also require long-term management to prevent the precipitated heavy metals from remobilising. Taking an average flow of 6,000 m³/d at 250 mg/L copper content, lime neutralisation at this site would have produced approximately 32 tonnes per day of 20 weight % slurry. This would have amounted to a total of 110,000 m³ of water treatment residue over the life of the plant. Instead, the copper sulphide produced by the site was sold to a local copper smelter, generating approximately US\$ 9 M in revenue over its decade of operation. This revenue was able to offset the cost of ongoing remediation and water treatment. Additionally, because the copper sulphide solid was sold to an off-site smelter, there was no additional cost or associated long-term liability for residue disposal.

3 Case study 2 – arsenic management and waste volume reduction

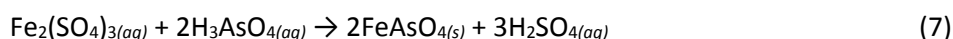
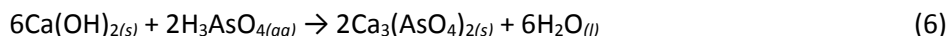
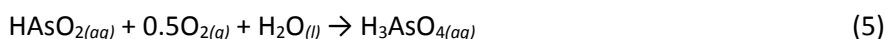
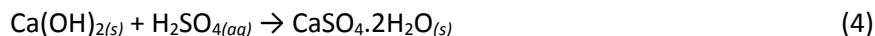
3.1 Project background

Historically, copper producers have avoided deposits with elevated levels of arsenic. However, as copper deposits with low arsenic content are depleted and the global demand for copper continues to increase, major copper producers have been forced to start extracting copper from arsenic-rich ore bodies. As a result of the close association of copper with arsenic in sulphide minerals separated from tailings by flotation, a significant portion of the arsenic present in these ore bodies ends up reporting to copper smelters. Consequently, arsenic management and the costs associated with arsenic disposal at copper smelters have become noteworthy challenges facing copper producers worldwide. When sulphide minerals containing arsenic are smelted, arsenic is volatilised with the SO_x-laden off-gas. This off-gas must be scrubbed prior to discharge. While some arsenic reports to dusts that are removed in high-temperature particulate scrubbers such as electrostatic precipitators, a significant portion of the total arsenic entering smelting operations reports to water-based scrubbers that produce liquid blow-down that is highly acidic and rich in dissolved arsenic. In South America, this blow-down is referred to as *Efluente Planta Acido Sulfurico* (EPAS). The life-cycle cost of the treatment of EPAS, which includes the cost of disposal of waste residue of treatment, represents a major environmental treatment challenge. An example composition of EPAS is shown in Table 1.

Table 1 EPAS solution composition

Parameter	Value
pH	0.3 to 0.8
Free acidity as H ₂ SO ₄ (mg/L)	> 70,000
Copper (mg/L)	300 to 1,500
Arsenic (mg/L)	4,000 to 9,000
Other metals of value present	Re, Mo

In the present case study, the project site is a copper smelter in Chile. The site has been in operation for decades and has seen a gradual upward trend of arsenic concentration in the copper concentrate it treats. This trend is expected to continue. Currently, arsenic in the EPAS solution is treated through lime neutralisation of the EPAS liquor with the addition of ferric iron in aerated tanks and a long retention time. Introducing lime into the stream neutralises the sulphuric acid to produce gypsum; air sparged into the lime reactor tanks oxidises As(III) to As(V), which readily precipitates with ferric iron, forming a mixture of ferric arsenate and ferric hydroxide with arsenic adsorbed onto the ferric hydroxide solids. Calcium arsenate is also produced in this process. The salient reactions are shown in equations (4) through (7).

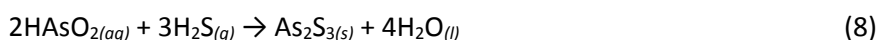


Major issues associated with the current method of treatment make it unsustainable in the long term:

- Very high mass and volume of arsenic laden waste: Depending on the stream composition, the waste solids production rate can vary from 100 to 250 kilograms of dry solids per cubic meter of EPAS treated. The waste residue contains less than 5% As on a dry-weight basis but is considered hazardous waste. At the site in question, this material is disposed of off-site, and the transport and disposal costs associated with this are prohibitive.
- High life-cycle costs: The reagents and power costs are high primarily because the oxidation of As(III) to As(V) is a kinetically slow process. The consumption of lime and ferric iron reagents is very high, and the solid residue disposal is expensive.
- The value of acid contained in EPAS and metals that can potentially be recovered is lost by lime neutralisation and precipitation of all metals into the waste solids residue.
- Low water recovery: Due to the poor dewatering properties of the waste solids, a large amount of water is lost, and the waste solids further increase the total tonnage and volume of the waste produced. Water recovery represents a major issue for smelting operations located in regions with water scarcity.

3.2 Arsenic treatment with BioSulphide

The approach BioteQ developed for the copper smelter in question involves using the BioSulphide process to treat the EPAS solution instead of lime neutralisation. This system involves contacting EPAS liquor with biogenically produced hydrogen sulphide gas. The overall process and flow sheet is the same as that described in section 2.1. However, the sulphidation of trivalent arsenic occurs via the reaction chemistry in equation (8):



Other heavy metals that have an affinity for sulphide, such as copper, zinc and lead, also report to this precipitate. After clarification in a thickener, the resultant sulphide precipitate is filtered and stored on-site in a secure landfill.

The benefits of the EPAS treatment using the BioSulphide process include the following:

- The volume of waste residue generated through treatment is significantly reduced. The metal sulphide residue solids contain over 50% w/w As on a dry-weight basis, offering an order of magnitude reduction in solids handling and disposal costs.
- Power and chemical costs are reduced based on the following:

- The reaction in equation (8) is fact, and equilibrium is very favourable for all arsenic to precipitate at the extremely low pH of typical EPAS without the need for neutralisation.
- The As(III) present in EPAS is precipitated as As(III) into As_2S_3 (synthetic orpiment), thus eliminating the need for oxidation prior to removal from EPAS.
- Water recovery is higher than in the current system.
- Acid contained in EPAS is recovered.
- The recovery of metals such as Cu, Re and Mo from EPAS becomes a possibility.

The current system involves trucking arsenic-bearing waste to a third-party site. As this material is hazardous, the mine owner bears both the cost and the liability for transport. Part of the proposed upgrade of the existing EPAS treatment using the BioSulphide process includes constructing a waste residue storage facility directly at the mine site; the greatly reduced mass and volume of waste means that local waste residue disposal is possible.

Currently this project is in the final stages of detailed process design. Construction of the facility is anticipated in 2016, and commissioning and operation are expected to take place in late 2016 to early 2017. The site owner selected the BioSulphide process over not only the current lime/ferric precipitation EPAS treatment method but also over the atmospheric scorodite precipitation method. Many in the scientific community consider scorodite to be probably the most stable arsenic solid. However, scorodite residue typically contains less than 25% As compared to the more than 50% achieved by the BioSulphide process. Based on life-cycle cost, the atmospheric scorodite process is so much more expensive than the BioSulphide process that the savings from using BioSulphide outweigh the incremental improvement in the stability of waste residue brought about by the scorodite process. Stability is a relative term linked directly to the conditions applied in the waste solids residue disposal facility; under certain storage conditions, sulphide residue stability is equal to or greater than the stability of scorodite.

4 Case study 3 – selenium management at a copper-gold mine in permitting

4.1 Selenium in mine water

Selenium has recently garnered significant attention as a contaminant of concern in a broad range of mining operations around North America. Since selenium is in the same group as sulphur on the periodic table, selenium can often substitute for sulphur in mineral structures such as coal or sulphide minerals. As such, it can be mobilised by acid mine drainage processes and be released to the environment. While small amounts of selenium are a necessary micronutrient for many organisms, concentrations even in the single digit parts per billion (ppb) range are deleterious to fish species, causing birth defects and warping skeletal structures. For this reason, regulatory guidelines for the maximum selenium concentration in industrial discharges in North America range from 5 to 20 ppb, with some site-specific requirements as low as 1 ppb.

Historically, the issue of selenium contamination has been understood to relate primarily to coal-fired power plants. As coal containing selenium is burned, selenium is volatilised. When the combustion off-gas (flue gas) passes through a wet scrubber, selenium reports to the scrubber wastewater. Selenium treatment must be used in order for this wastewater to be discharged to the environment safely. Selenium-bearing streams are typically warm and laden with organic chemicals; they have steady flow rates and metal loads due to the relative consistency and stability of power plant operations. As such, these flue gas wastewater streams are ideal feed for the various types of biological treatment systems that make up the majority of existing selenium treatment plants.

In the past, the industrial focus on selenium treatment in water has been on these flue gas wastewater streams. However, both regulators and mine operators have more recently recognised the importance of managing selenium and removing it from a wide range of streams impacted by resource industry activity. These streams include runoff and seepage from mining overburden, waste rock and tailings storage facilities.

In cases such as these, the character of the selenium-bearing stream differs significantly from that of flue gas wastewater. In contrast with flue gas wastewater, runoff streams typically have the following traits:

- large seasonal variability in flow and selenium content,
- cold water, often near freezing in northern climates,
- nutrient-starved receiving environment with no tolerance for added chemical oxygen demand (COD) or biochemical oxygen demand (BOD) nutrients,
- minimal organic content, and
- multiple remote outfalls requiring treatment.

Residue management must be considered in any long-term water treatment system. Biological selenium treatment systems produce a biological sludge by-product containing dead or inactive biomass and a large percentage of water. The selenium removed from the feed water is contained in this biological sludge by-product as tiny particles of elemental selenium. The amount of sludge generated depends on the type of biological reactor used and the operating strategy, but in modern biological systems, approximately 0.5 L of wet biological sludge is generated per cubic meter of water treated. As this material is biological in nature, it will necessarily change over time. Little is known about how this material behaves in the long term.

Managing this material represents a further point of contrast between the treatment of flue gas wastewater and mine runoff water. Coal-fired power plants typically generate large volumes of fly ash and metal-laden gypsum waste from flue gas desulphurisation. This material is typically stored in secure landfill facilities designed to minimise water contact and mobilisation of toxic contaminants. When biological selenium treatment is used, the amount of biological sludge generated is small relative to the amount of fly ash and metal-laden gypsum, and as such it can be blended with other waste material. In contrast, selenium water treatment for mines involves larger volumes of water and less access to secured landfill repositories. The long-term implications of residue management over the multidecade life of the mine is a key driver for the owner of the property described in this case study.

4.2 Project background

The project in this case study is a large copper-gold mine that is currently in the permitting process. As the ore body and project site are located in a sensitive watershed area, the requirements of water treatment on the site are being carefully evaluated. Of particular interest is selenium, which is present in certain fractions of the ore body and associated overburden and waste rock. The owner of the site is keenly aware of both the importance of selenium and the life-cycle costs of selenium treatment to ultralow discharge targets. In order to minimise the costs of active water treatment for selenium, the owner has taken two major actions.

First, the owner understands that the risk of selenium contamination in seepage is from a specific type of ore on the property. Therefore, the mine plan calls for sequestering this type of material in a predetermined waste rock holding facility. This means that the selenium released through weathering of the ore will be concentrated in a smaller volume of water. In this way, active water treatment for selenium will be required on a considerably smaller flow of water than if the selenium-bearing material was spread across the entire waste rock storage facility.

Second, the owner is investigating alternative treatment methods, with an emphasis on reaching ultralow discharge targets while minimising waste residue for management. To this end, the owner has investigated alternatives to conventional biological systems currently on the market.

4.3 Selen-IX to remove selenium from industrial water

Selen-IX™ is a selenium treatment system developed by BioteQ to selectively remove selenium from industrial water in order to reach environmental discharge targets. The first stage of the system uses a strong base anion-exchange resin in the sulphate form to selectively remove selenium from water to concentrations of less than 10 ppb. Once the resin is saturated with selenium, the ion-exchange resin is regenerated using a

concentrated sodium sulphate brine solution. During regeneration, selenium loaded on the resin is exchanged with sulphate from the sodium sulphate brine. This generates a low-volume brine stream that contains the selenium removed from the influent water.

The spent regenerant rich in selenium is then treated using an electrocell in which an iron anode is dissolved. This introduces iron into the selenium-rich regenerant. Iron and selenium then precipitate from the solution as an inorganic iron oxyhydroxide laden with selenium. Following this treatment, the iron-selenium solids are separated from solution in a clarifier with the aid of flocculant, and the now selenium-depleted solution is recycled for re-use in the ion-exchange system. The system is shown schematically in Figure 4.

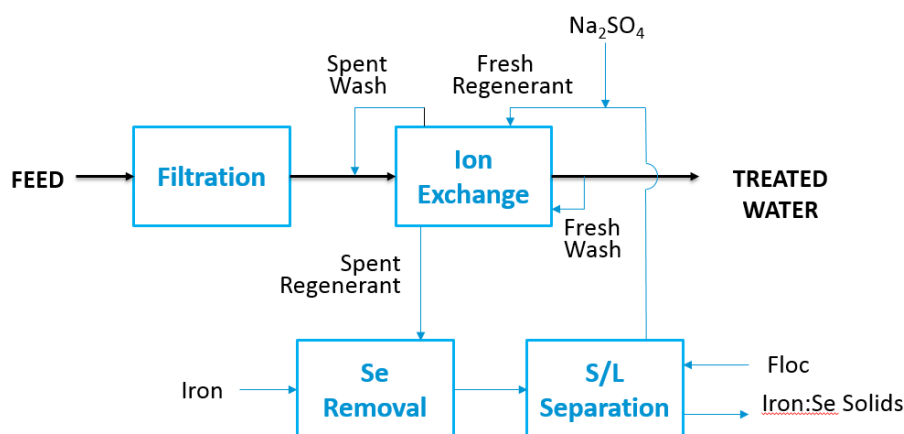


Figure 4 Simplified Selen-IX flow sheet

For this project, a containerised Selen-IX pilot unit capable of treating 2 L/min of influent feed water was mobilised to a pilot site in the British Columbia Lower Mainland. Surface water from the proposed mine site was shipped to the pilot site and spiked with metal species to match runoff quality predicted by geochemical modelling. At the time of writing, this pilot is ongoing and expected to be completed at the end of the first quarter of 2015.

4.4 Selen-IX pilot results

The composition of the feed water of the current project is shown in Table 2:

Table 2 Selen-IX pilot feed water composition

Parameter	Value
pH	4.1–4.5
Dissolved Se (mg/L)	0.103
Nitrate as N (mg/L)	32
Sulphate (mg/L)	1,950
Total dissolved solids (mg/L)	2,910

In the current pilot program, the target effluent selenium concentration is 1 ppb or less. This objective has been achieved, as shown in Figure 5. These results were generated over a week of locked-cycle pilot operation.

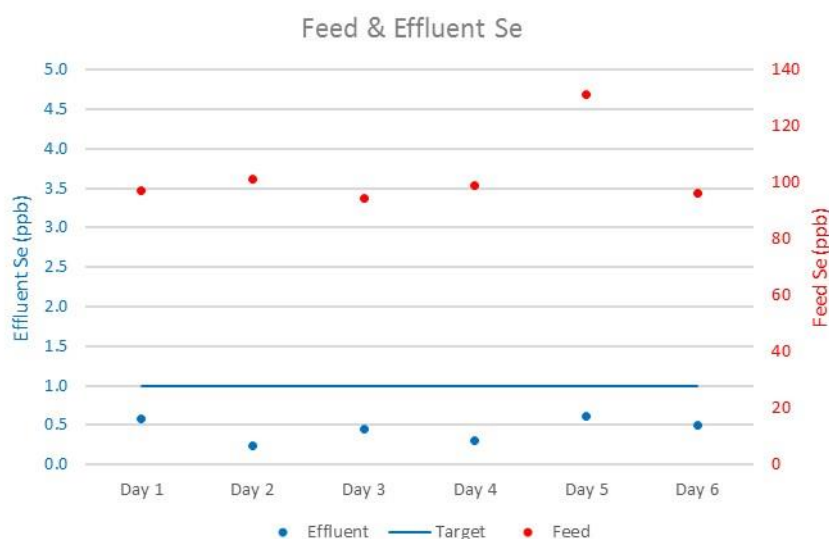


Figure 5 Selen-IX pilot results, selenium concentration influent and effluent

The character of the solid iron-selenium by-product from treatment is of great interest to the mine owner sponsoring this pilot program. While full solids characterisation results are not available at the time of writing due to the ongoing nature of the program, X-ray diffraction (XRD) analysis has been carried out on a sample of the material. The spectra of the material, shown in Figure 6, shows that the dominant species in the material are magnetite and elemental selenium. The relatively low base counts per second also show that the material is largely crystalline rather than amorphous. Toxicity characteristic leaching procedure (TCLP) testing of material generated during the pilot campaign has shown that the material is nonhazardous.

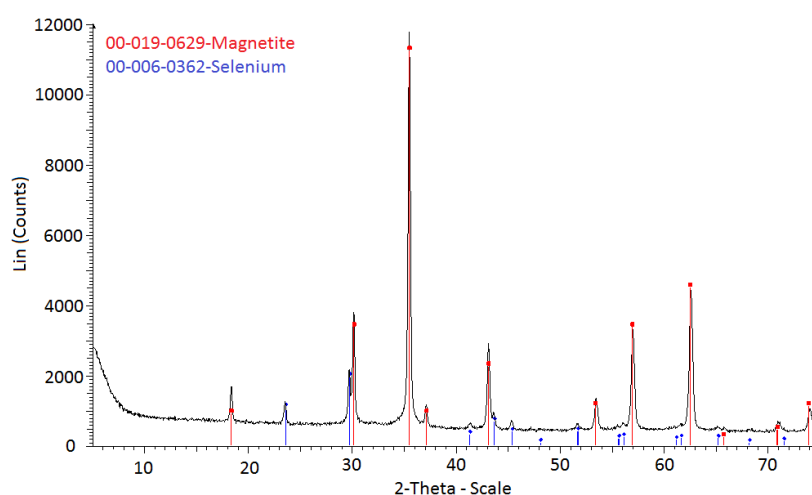


Figure 6 XRD spectra of iron-selenium by-product generated during Selen-IX piloting

The amount of solid residue generated through Selen-IX is proportional to the amount of selenium removed by the system and dependent on the effluent discharge criteria; the amount of iron required increases as discharge targets become more stringent. In this project, approximately 0.25 L of filtered material is expected to be generated per cubic meter of water treated, a reduction of half compared to modern biological systems.

4.5 Outcomes

Mine owners in North America are increasingly faced with the necessity of actively treating water from mine-impacted runoff for selenium. Biological treatment systems currently represent the best available technology for the removal of selenium from waste water. However, mine-impacted water has a number of

characteristics that make implementing biological treatment technically or logistically difficult: ultralow regulatory limits may not be practical to reach through biological treatment, and there are concerns about the long-term stability of residue management methods and the ability of treatment systems to respond to rapid variations in water flow rate and temperature. The receiving environments for treated water are often nutrient starved and thus intolerant of nutrient and BOD plumes that can result from biological treatment. All of these factors lead to high operating and capital costs for conventional systems, which leads to interest in novel systems such as Selen-IX.

Table 3 Challenges for selenium water treatment in the mining industry

Industry challenge	Selen-IX
< 1–5 ppb Se regulatory limits	Demonstrated Se < 1 ppb from streams with > 100 ppb feed
Quantity and long-term stability of residue	Compact inorganic Fe-Se solid of magnetite and elemental Se
Variable flow and mass loads	Easy to adapt IX cycles on the fly
Cold temperature of water	Insensitive to temperature
Intolerance of receiving environment for nutrients, BOD	No organics or phosphate added; no need for nutrient polishing
Multiple, remote points of discharge	IX modules lend can be decentralised
High life-cycle cost of ownership	Significant savings in life-cycle cost

Demonstrating effective water treatment for selenium is a key hurdle the proposed mine in question must get over in order to pass permitting. The owner recognises that effective water treatment goes beyond reaching ultralow discharge targets; the long-term life-cycle cost of residue management must be considered. The prospect of generating a stable, inorganic iron-selenium by-product is a significant driver for the owner's interest in Selen-IX. While the technology is still at the pilot scale, piloting results to date demonstrate its potential as a sustainable alternative to conventional selenium treatment methods.

5 Conclusions

When water treatment for mining is evaluated, there is a tendency to focus on the initial capital cost of treatment installation. While this analysis is important for acquiring financing and investment, when the life-cycle cost of treatment is considered, the ongoing operation and maintenance costs are often as significant as or more significant than the capital cost. This is particularly true when treatment involves generating waste residue or by-products. By-products take a variety of forms, ranging from nonhazardous tailings and metal-bearing waste with potential for remobilisation to biological sludge or liquid brine. Depending on the nature of the treatment in place, these residue streams can represent both environmental challenges and opportunities to recover value. In order to minimise the costs and maximise the benefits of environmental treatment, these residues and their management strategies must be well understood. The three case studies highlighted in this paper describe unique situations where novel technologies were used to manage waste in a cost-effective and sustainable way.