Passive Treatment Options for the Removal of Elevated Iron and Arsenic from Circum-neutral Mine Affected Water

S. Hayton[1,3], D. Trumm[2], T. Horton[1], J. Pope[2], D. Ross[3], M. Williams[3]

[1]*Department of Geological Sciences, University of Canterbury, Christchurch, 8041*

[2]*Verum Group, 97 Nazareth Ave, Christchurch, 8024*

[3]*OceanaGold (Reefton Restoration Project), 4081 State Highway 7, Reefton, 7895*

Abstract

Field trials were established at OceanaGold's Globe Progress Mine, located in the West Coast of New Zealand, to determine the most appropriate passive treatment system for post-closure.

The trials consisted of four bioreactors, with the addition of biosolids or mussel shells, to treat combined underdrain seepage. A vertical flow reactor (VFR), which utilizes oxidation of iron-rich water to co-precipitate and adsorb metals onto a non-reactive gravel bed, was also trialled to treat a separate underdrain seepage.

Results indicate arsenic removal was greater in bioreactors with biosolids, with about 80% removal at 24h hydraulic retention time (HRT). Sulfate removal increased with HRT and more sulfate was removed in biosolid treatments. Results from the VFR trials indicate 90% iron removal and 80% arsenic removal at a 24h HRT.

Keywords: ???

Introduction

OceanaGold's Globe Progress Mine, located in the West Coast of New Zealand, is an open cast hard rock orogenic gold mine, which ceased operation in 2015 and is now in the closure phase of the mining life cycle. It operates through an Access Agreement (AA) with the Department of Conservation (DOC), a government agency and is situated on public conservation land. Water discharges from site are governed by resource consents granted by local and regional councils. Compliance limits are based on water use and ecological protection. OceanaGold Corporation (OGC) have met these compliance limits while in operation by using an active treatment process.

The mine site consists of two Waste Rock Stacks (WRS), four pits (three of which have been backfilled while the fourth (Globe Pit) has become a pit lake), a Tailings Storage Facility (TSF) and a process/water treatment plant. There are three key sources of water that will discharge from site indefinitely post closure: the TSF pond, Globe Pit Lake, and the WRS/TSF underdrain seepages. It was predicted that the TSF pond water would meet discharge criteria after the TSF closure is complete with no treatment required, which has now occurred. Globe Pit Lake water quality also currently meets discharge criteria. However, there is a risk that arsenic levels within the lake may become elevated in future. This risk is being addressed by adaptive management (Hayton et al., 2020) with potential to incorporate pit lake flows into the passive treatment system if required. The WRS/TSF underdrains were predicted to need treatment indefinitely due to elevated iron, and arsenic, while sulfate reductions, though not required for compliance, were seen as being advantageous to downstream water quality.

The Water Treatment Plant (WTP) treated the TSF and the WRS/TSF underdrains during operations and care and maintenance. However, it was not practicable to continue actively treating underdrain discharges (or incorporate Globe Pit Lake water treatment) post closure. Therefore, an alternative passive treatment systems were developed and trialled for long term water treatment at the site. This paper explores two trials that were undertaken to establish the most appropriate and efficient method of post closure water treatment. A review of the literature determined the two most appropriate systems for this site were either a bioreactor or a vertical flow reactor (VFR) (Sapsford et al., 2007., Trumm, 2010., Hayton, 2020).

Methods

Influent Water Chemistry Characterisation

The WRS/TSF underdrains have a variety of sources and chemistries but report to one area. The underdrains can be separated broadly into two categories:

- The relatively high metal concentration of both the Potentially Acid Generating (PAG) Cell within the WRS and the Fossickers TSF underdrains; and
- The relatively low metal concentration WRS underdrain (referred to as Rock Drain).

All discharges are circum-neutral to slightly alkaline due to the presence of abundant carbonate within the local mineralized rock (Milham & Craw, 2009). The outlets from the PAG and TSF underdrains are collected in a single point. The elevated concentration of arsenic (1.7 g/m^3) and iron (28.5 g/m^3) make it unacceptable for direct discharge, while sulfate (425 g/m^3) is also elevated. The average flow for the combined underdrains reporting to this sump is approximately 3.5 L/sec. The Rock Drain has moderate concentrations of iron (7.6 g/m^3) and arsenic (0.2 g/m^3), elevated concentrations of sulfate (570 g/m^3), and flow rates vary from approximately 5 L/sec to > 60 L/sec. The Rock Drain discharged during operations to Devils Creek (downstream of the mine site) through a silt pond (Devils Silt Pond), which was controlled by a manual valve. Precipitation of iron from the Rock Drain water as it passes through the silt pond is sufficient for direct discharge from the silt pond meeting compliance requirements.

Bioreactor Design

Four different bioreactor substrate mixes were trialled with selection based on:

- Availability and longevity of the carbon source; and
- Material permeability.

It has been suggested that a mixture of substrates, especially those which decompose at different rates, provide the best metal removal (Cocos, Zagury, Clément, & Samson, 2002; McCauley, O'Sullivan, Weber, & Trumm, 2008; Zagury, Kulnieks, & Neculita, 2006). A base media mixture of spent mushroom compost, sawdust and bark was selected for all trials. This selection was based on findings from the literature, the local availability of the materials, and the pH of influent water. Limestone was not required from a treatment perspective as influent water was circum-neutral. Other additives incorporated in some of the trials include:

- Mussel shells, which were found to be effective at adding an organic component while maintaining porosity and were readily accessible as a waste product; and
- Biosolids, have been used in mine site reclamation work, while animal manure has been proven to be an effective additive to several bioreactor trials (Cocos et al., 2002; Skousen et al., 2017).

The substrate mixture percentages for different trials are shown in Table 1. Substrates were sampled, prior to being mixed, from the bulk stockpile and sent to Hill Laboratories for analysis. The analysis suite included metals (extensive suite at screen level), total sulfur, total nitrogen, and total organic carbon. The porosity was measured by placing substrates in a 10 L bucket and measuring how much water it took to fill the pore space. Mixed substrates were also sampled and sent for an extensive suite analysis at screen level of total recoverable metals.

The bioreactors are all designed as up-flow systems to prevent the addition of oxygen to maintain a reducing environment. Water is driven through the systems by gravity flow from a seepage collection sump (containing TSF and PAG underdrain water) into a mixing tank which fed into the base of the bioreactors. The water then passed through the mixed media layer and collected in a free water layer which was evenly drained by a pipe tree drain (Figure 1). An initial residence time of 24 hrs was targeted, but as the trial progressed this was increased to 48 hrs to test the effect of a longer HRT on the metal

Table 1 Bioreactor treatment mixtures (%).

Treatment	Compost	Saw dust	Bark	Boisolids	Mussel Shells
1/B-LC	20	30	30	20	–
2/M-LC	20	30	30	–	20
3/B-MC	40	20	20	20	–
4/M-MC	40	20	20	–	20

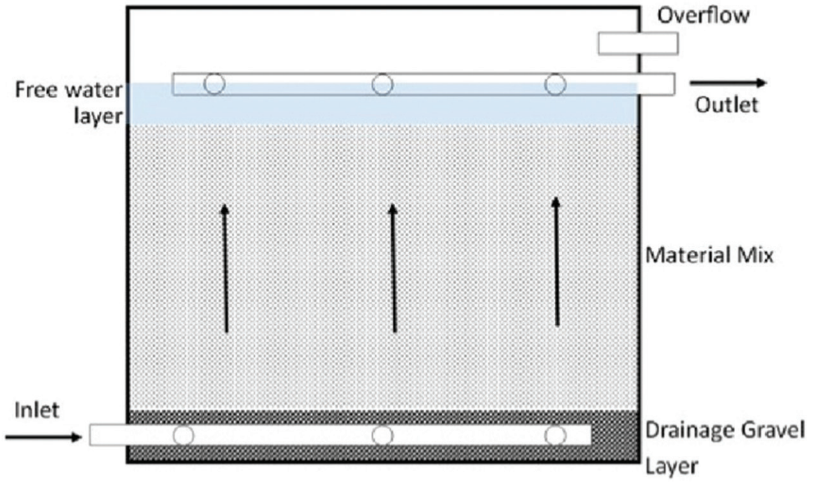


Figure 1 *Schematic of bioreactor design.*

removal. Exact HRT times were difficult to achieve. Microbial communities within the substrates provided a colonizing community of Sulfate Reducing Bacteria (SRB) and therefore they were not inoculated.

Bioreactor sampling

Bioreactor sampling was undertaken every fortnight for the 2-year duration of this trial. Influent samples were collected from the mixing tank, prior to gravity feeding into the bioreactors.

Effluent samples were collected from the discharge pipe of each reactor and analyzed for a range of parameters, including dissolved arsenic, dissolved iron, sulfate, nutrients and alkalinity. Field measurements of percent dissolved oxygen, pH, conductivity and temperature, were taken from the free water layer before discharge. Periodic iron speciation and sulfide measurements were made in the field using a portable spectrometer. Sludge samples were collected and analyzed twice, via XRF and XRD during the operation of these trials determine metal and mineral compositions.

Vertical Flow Reactor Design

The VFR is designed to aerate the neutral metalliferous drainage causing precipitation of iron and the co-precipitation or adsorption of other metals (e.g., As), the metal laden precipitate then settles onto a non-reactive gravel filter bed. The VFR is operated as a downflow system, with the Rock Drain water being pumped from a v-notch weir where it first daylights and enters the system from a spray nozzle at the top of an open 25,000 L tank. Water is stored in a 1.65 m free water layer where oxygenation of Fe2+ to Fe3+ occurs. The water passes through a series of gravel layers including a 100 mm thick fine chip layer (clean, angular chip ranging from approximately 2.3-6.7 mm), a 100mm thick coarse chip layer (ranging 7.5 – 10 mm), and finally into the 100 mm thick drainage gravel layer (rounded, ranging approximately 25-50 mm). Water is collected in an outlet coil within the drainage gravel layer that connects to the tank outlet. The water level in the VFR is controlled by the outflow gooseneck (Figure 2).

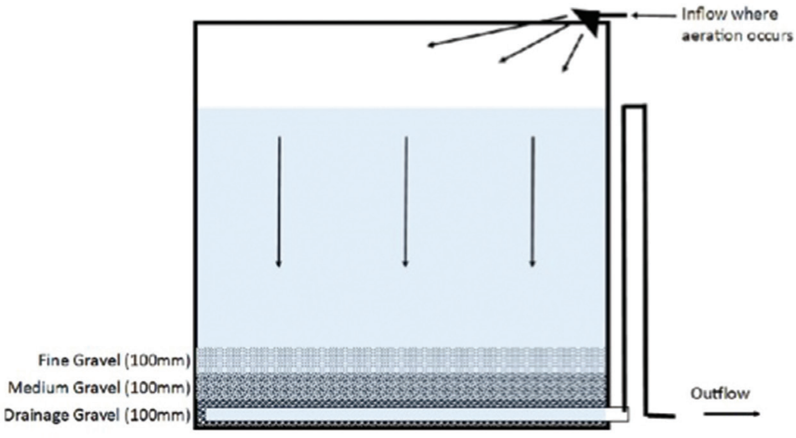


Figure 2 *Schematic of VFR design.*

Vertical Flow Reactor sampling

VFR sampling was undertaken every fortnight for the 2-year duration of this trial. Influent samples were collected from the Rock Drain weir.

Effluent samples were collected from the discharge pipe, and analyzed for a range of parameters, including dissolved arsenic, dissolved iron, total iron and sulfate. Field measurements of percent dissolved oxygen, pH, conductivity and temperature, were taken from the free water layer. Periodic iron speciation and sulfide measurements were made using a portable spectrometer. Sludge samples were collected and analyzed twice during the operation of these trials to understand the ratio of Fe to other metals accumulating on the gravel bed and to measure solids content and sludge drying rates.

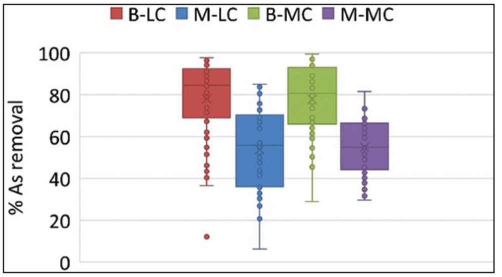
Results and discussion

Bioreactor

All bioreactor treatments removed dissolved iron, dissolved arsenic and sulfate to varying degrees. Treatments with biosolids removed more dissolved iron, arsenic, and sulfate than mussel shell treatments (Figures 3, 4, and 5). Treatments with higher percentage of compost showed no difference in removal of the dissolved metals or sulfate compared to lower percentages of compost. Removal rates for all treatments were generally higher with longer HRT, especially for sulfate, with removal in the biosolid treatments increasing from 20% at 50 hrs to 40% at 100 hrs.

The biosolids organic carbon content was lower than base mix substrates but higher than mussel shells. Biosolids also had the highest nitrogen and phosphorous concentrations, which are necessary for sulfate reducing bacteria (SRB) activity (Dev, Patra, Mukherjee, & Bhattacharya, 2015). Higher As, Fe, and sulfate removal in treatments with biosolids is most likely due to higher amounts of available nutrients in the biosolids, which enabled the SRB to more efficiently carry out their functions ultimately increasing the metal and sulfate removal (Dev et al., 2015; Patidar & Tare, 2006). Higher removal rates with longer HRT showed that the reduction of metals in solution and sulfate to metalloid sulfides was dependent on contact time with the SRB.

Analysis of precipitates from the systems was undertaken on two occasions. Material sampling proved extremely difficult to extract and analyze without the introduction of oxygen. XRF analysis showed that arsenic, iron, and sulfur were present, but in varying proportions in treatments and over sampling rounds. XRD analysis showed prominently amorphous materials, although on the second sampling round on treatment 2 (mussel shells, with less compost), Greigite, an iron sulfide mineral, made up 49% of the sample. This indicates that sulfate reduction is occurring in this system, and by inference, in the other treatments also.



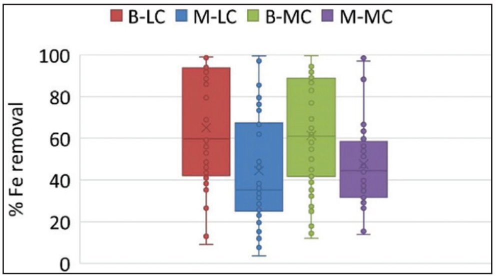


Figure 3 and 4 Percentage removal for iron/arsenic for each treatment. B = Biosolids, M = Mussel shells, LC = Less compost, and MC = More compost.

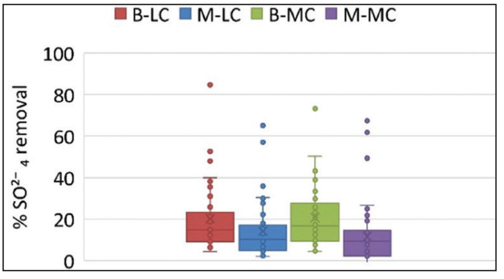


Figure 5 Percentage removal for sulfate for each treatment. B = Biosolids, M = Mussel shells, LC = Less compost, and MC = More compost.

Vertical Flow Reactor

The VFR trial showed high median removal rates for dissolved arsenic of 95% and dissolved iron of 99%. Removal rates were somewhat dependant on HRT, decreasing to approximately 75% and 84% for As and Fe, respectively, at the lowest hydraulic residence time of 10.5 hrs. Overall, results indicate that removal rates of over 95% for iron and over 90% for arsenic are consistently achievable over a 24 hour residence time.

The build-up of iron precipitates on the gravel bed creates a lower permeability layer requiring increased driving head to meet treatment design flow rates (Figure 6). If the VFR is operated under excessive driving head, sludge could be pulled through the gravel layer, resulting in sludge scour (Barnes, 2008) and system failure. A regular maintenance schedule on full scale system would be required to periodically remove the sludge layer to maintain flow rates and treatment performance (Trumm and Old. 2020., Trumm et al., 2022)

Sludge samples were taken on two separate occasions during the operation of this system and analyzed for metal concentrations and also for solids content (over time) to understand the drying times. This data showed that in dry weather conditions sludge could reach 63 wt% solids in 12 days, although during wet weather conditions it would remain around 20 wt% solids. Therefore, maintenance should be scheduled for summer to maximize sludge drying / density.

Conclusion

The VFR trial data showed that removal rates were consistently high at relatively low residence times. This suggests the VFR system can treat greater flows with the same footprint as a bioreactor (or the same flows in a reduced footprint). The VFR treatment system does not rely on biological activity and therefore is not affected by temperature nor is it reliant on nutrient and carbon availability. These two factors combined with a relatively simple design make the VFR system more suitable for long term post closure passive treatment at Globe Progress.

A team of specialist engineers and geochemists along with the assistance of OceanaGold staff have worked together to design a comprehensive full-scale VFR system (Trumm and Old. 2020., Trumm et al., 2022). This inter-disciplinary approach has accomplished a detailed and peer reviewed design, which takes into account various flow rates, clean outs, cut-off drains, and remote monitoring equipment powered by hydroelectric and solar power options. The Globe Progress passive treatment system is the first of its kind to be installed in New

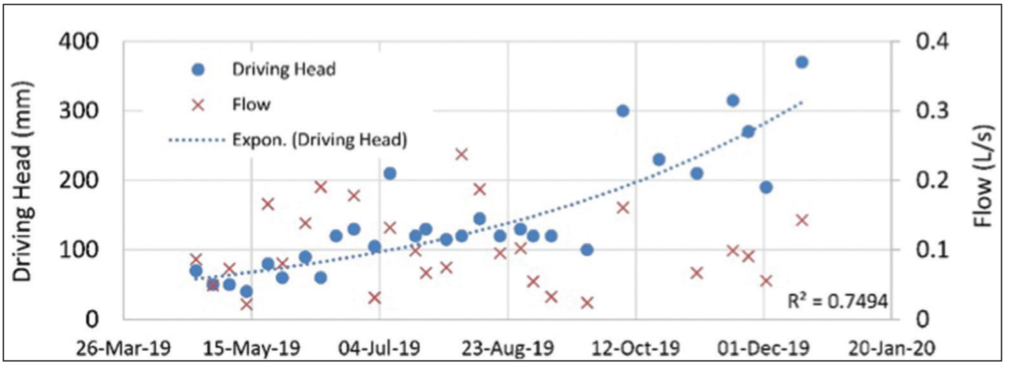


***Figure 6** Effect of sludge accumulation over time on VFR trial driving head and flow rate*

Zealand, with construction occurring in 2021–22.

References

Barnes, A. (2008). Rates and mechanisms of Fe(II) oxidation in a passive vertical flow reactor for the treatment of ferruginous mine water. Engineering, Cardiff University.

Cocos, I. A., Zagury, G. J., Clément, B., & Samson, R. (2002). Multiple factor design for reactive mixture selection for use in reactive walls in mine drainage treatment. Water Research, 36(1), 167-177.

Dev, S., Patra, A. K., Mukherjee, A., & Bhattacharya, J. (2015). Suitability of different growth substrates as source of nitrogen for sulfate reducing bacteria. Biodegradation, 26(6), 415-430.

Hayton, S. (2020). The use of Bioreactors and a Vertical Flow Reactor in the treatment of circum-neutral mine affected water. (Unpublished doctoral dissertation or master's thesis). University of Canterbury.

Hayton, S., Olds, W., Matheson, L., Wu, C., Ross, D., Nyenhuis, J., Williams, M., Weber, P. (2020). Globe Progress Pit Closure Planning. Paper presented at the Planning for Closure, Santiago, Chille (Online).

McCauley, C. A., O'Sullivan, A. D., Weber, P. A., & Trumm, D. A. (2008). Performance of mesocosm-scale sulfate-reducing bioreactors for treating acid mine drainage in New Zealand. Paper presented at the 25th Annual Meetings of the American Society of Mining and Reclamation and 10th Meeting of IALR 2008.

Milham, L., & Craw, D. (2009). Two-stage structural development of a Paleozoic auriferous shear zone at the Globe-Progress deposit, Reefton, New Zealand. New Zealand Journal of Geology and Geophysics, 52(3), 247-259.

Patidar, S. K., & Tare, V. (2006). Effect of nutrients on biomass activity in degradation of sulfate laden organics. Process Biochemistry, 41(2), 489-495.

Sapsford D, Barnes A, Dey M, Williams K, Jarvis A, Younger P. 2007. Low footprint passive mine water treatment: Field demonstration and application. Mine Water and the Environment. 26(4):243-250.

Skousen, J., Zipper, C. E., Rose, A., Ziemkiewicz, P. F., Nairn, R., McDonald, L. M., & Kleinmann, R. L. (2017). Review of Passive Systems for Acid Mine Drainage Treatment. Mine Water and the Environment, 36(1), 133-153.

Trumm, D. (2010). Selection of active and passive treatment systems for AMD - Flow charts for New Zealand conditions. New Zealand Journal of Geology and Geophysics, 53(2-3), 195-210.

Trumm D, Old W (2020) Passive Treatment Design – Devil's Creek. A report prepared for Oceana Gold. Verum Group ref: G37-19-41104 and Mine Waste Management ref: J-NZ0061-001-R-Rev2

Trumm D, Hayton S, Olds W, Wu C, Williams M, Nyenhuis J (2022) Selection and design of a full-scale vertical flow reactor for As and Fe Treatment, Globe Progress Mine, New Zealand. Presented at the IMWA 2022 Conference.

Zagury, G. J., Kulnieks, V. I., & Neculita, C. M. (2006). Characterization and reactivity assessment of organic substrates for sulphate-reducing bacteria in acid mine drainage treatment. Chemosphere, 64(6), 944-954.