Acid-Generating Waste Rock Encapsulation in a Subalpine Environment

Larry Breckenridge, Fred Bickford and Amy Livingston

Global Resource Engineering, USA

ABSTRACT

The Amulsar site, owned by Lydian International, is located at high elevations (2,500 m) in south-central Armenia. The site will produce two types of mine waste from an open pit gold mining operation: silicified andesite that is fully oxidized, and argillized andesite that contains sulfides. As a result, there is a risk that the mine waste will produce Acid Rock Drainage (ARD).

Global Resource Engineering (GRE) designed a Barren Rock Storage Facility (BRSF) that encapsulates the argillized andesite within envelopes of silicified andesite to isolate it from groundwater and surface water. Cell design included a degree of compaction to reduce the conductivity of the argillized waste.

Groundwater models were created to predict the following: infiltration and runoff into the BRSF during operations, the optimal design parameters of an evapotranspiration (ET) soil cover, and the impact of heavy spring snowmelt on the BRSF water balance. Geochemical models were then created to predict the quality of leachate and runoff during operations and postclosure.

The results of the groundwater models determined that the waste had sufficient storage capacity to absorb most of the operations-phase water, resulting in low volumes of ARD production during operations. The BRSF closure design included a three-layer soil cover 1.7 m thick, which was shown to provide excellent store-and-release performance, and greatly limited infiltration into the closed BRSF.

60-year-old mine waste piles exist on sites that have not produced severe ARD. Calibrating geochemical models to this data, GRE demonstrated that the region's cold climate and the argillized waste's low conductivity slowed sulfide oxidation reactions. The predicted water quality of BRSF leachate is suitable for passive treatment methods, thus saving the project millions of US dollars in active water treatment costs, and providing a path to clean closure.

Keywords: Mine waste encapsulation, predictive modeling

INTRODUCTION

Amulsar is an open-pit gold mining project being developed by Lydian International in the Lesser Caucasus Mountains of south-central Armenia. The deposit contains 94.9 million tonnes (Mt) of proven and probable reserves at an average gold grade of 0.75 g/t and average silver grade of 3.27 g/t. The life of the project is expected to be approximately 10 years, including two years of pre-mining construction. Ore mined from a series of coalescing pits near the top of Amulsar Mountain, at an elevation of approximately 2,500 m, will be crushed and then transported via a conveyer system to a heap leach facility.

The project will generate 283.1 Mt of waste rock. Disposal of some of that waste rock will be handled by backfilling early-mined portions of the pits, but 190.6 Mt will be disposed to the Barren Rock Storage Facility (BRSF). A portion of the waste rock has sulfide concentrations high enough to make production of Acid Rock Drainage (ARD) likely. Global Resource Engineering (GRE) was assigned the task of designing the BRSF to minimize ARD. This paper describes the waste rock and the methods used to characterize its ARD behavior, and explains the process used to generate a BRSF design that would minimize long-term postclosure ARD water production requiring treatment and optimize the quality of that water.

WASTE ROCK

The Amulsar deposit is hosted by an Eocene-Oligocene sequence of andesitic volcanic rocks that has been intruded by a sill-like porphyritic andesite intrusive. Waste rock that will be produced by the mining project can be divided into two lithologies. The Upper Volcanics unit (UV) is a strongly silicified variant of the andesitic volcanics. This rock type, which hosts the ore, is thoroughly oxidized, has low sulfide content, and has no appreciable neutralization potential. The Lower Volcanics unit (LV) forms a layer underlying the UV. The LV consists of alternating layers of andesitic volcanics and andesite sills. The sulfide content of the LV is variable, with sulfide contents of up to about seven percent. The LV is often argillized; most of the material observed through core drilling contains approximately 10% to 50% clay minerals.

Waste characterization

The waste rock was characterized using standard methodology of static geochemical testing followed by humidity cell tests (HCT). Results of the Acid-Base Accounting (ABA) testing can be seen in Figure 1.

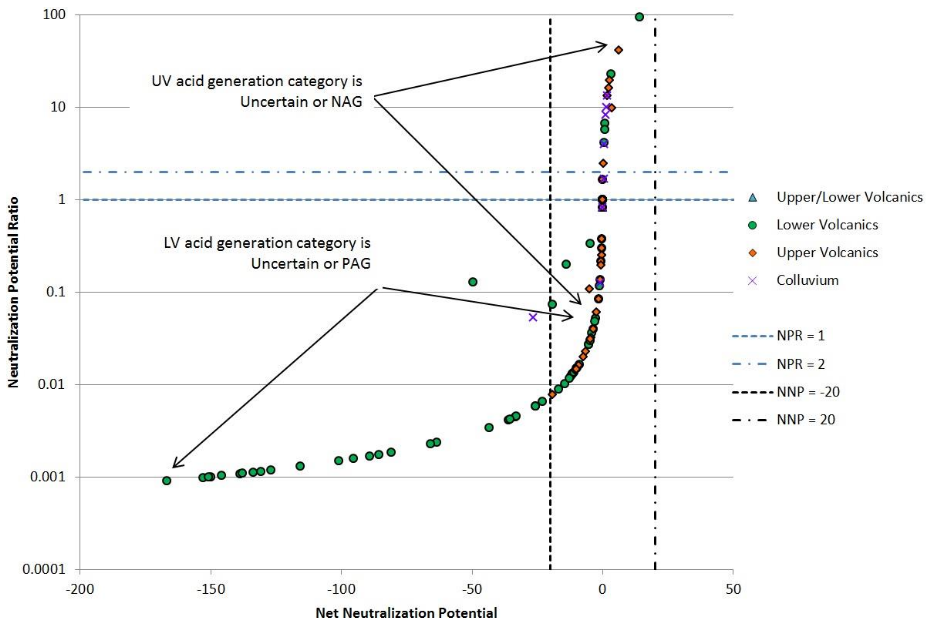

Figure 1 ABA test results

In Figure 1, samples that fall in the upper right-hand quadrant of the graph are non-acid-generating (NAG) based on accepted practice (INAP, 2009). No waste rock samples fall in this zone. Between the vertical dashed lines is a zone of uncertain ARD behavior. All samples of UV waste rock fall in this zone. In the quadrant to the lower left lie samples that are potentially acid-generating (PAG). Many LV samples and no UV samples lie in this zone, and no significant neutralization potential is present in either rock type.

Figures 2 and 3 show the graphs of pH over time and cumulative acidity over time for the HCTs.

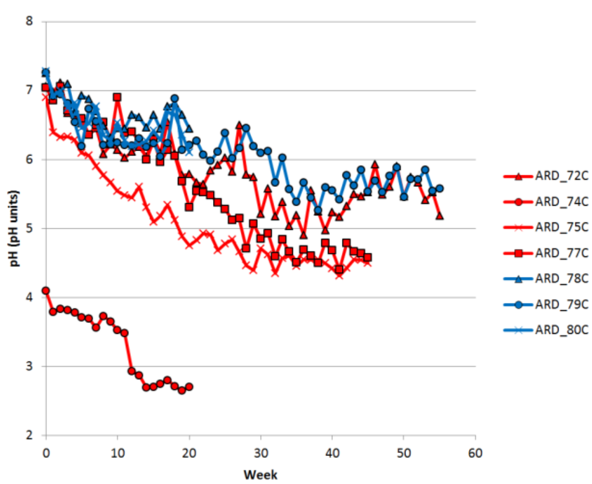

Figure 2 pH vs. time for HCTs

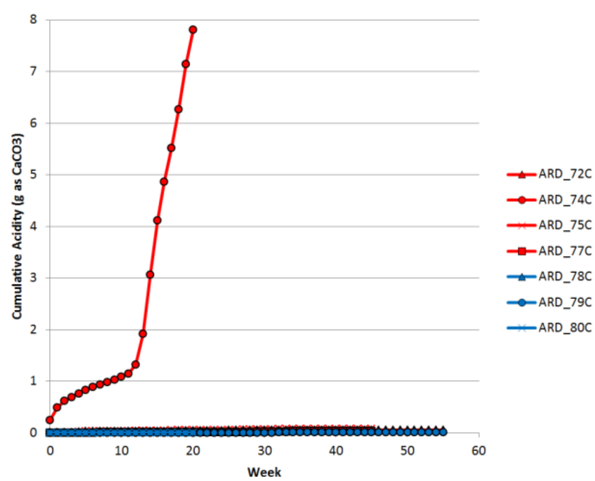

Figure 3 Cum. acidity vs. time for HCTs

No UV samples produced significant acidity, or produced elevated dissolved metals concentrations. LV samples showed variable behavior. Samples with high acid-generating potential (AP) produced acidic leachate, whereas many samples with lower AP did not produce significant acidity. One sample was oxidized prior to arrival to the lab. Two samples produced mild ARD for a full year, with the pH remaining above 4.5. One sample produced acidic leachate of significant quantity, and after 14 weeks exhibited the classic behavior of ferric iron oxidation catalysed by *Acidithiobacillus ferroxidan*s (biotic oxidation). However, in general, LV samples showed a remarkable resistance to biotic oxidation and strong ARD formation.

This behavior was reflected in LV waste piles left in the field by Soviet-era exploration activities on the Amulsar site. Two mine waste piles at the same elevation as the planned waste dump and from the same sulfidized LV formation have been in the field for sixty years. They generate ARD with ~100 mg/L total acidity, ~50 mg/L sulfate, and pH ranging between 4.0 and 3.3. Even after 60 years of exposure, these rocks have failed to undergo aggressive biotic oxidation despite the presence of abundant sulfides in the waste. Whether this behavior is primarily controlled by the cold climate (Sartz, 2011), the mineralogy of the rock, or the lack of microorganisms is uncertain at this stage in the investigation, but it is clear that the waste rock when exposed to the natural environment at this site displays some natural resistance to biotic oxidation. The ARD management plan will take advantage of this natural resistance to minimize the volume and intensity of ARD produced by mining activities.

BARREN ROCK STORAGE FACILITY

Waste rock that is not consumed in backfilling the pits will be disposed to the BRSF. The BRSF will occupy an upland topographic basin on the north flank of Amulsar Mountain, just north of the pit area (Figure 4).

BRSF basin characteristics

The southeast half of the upland basin that will host the BRSF is underlain by argillized LV and clayey alluvium and colluvium. The average hydraulic conductivity of surficial deposits in this area is low (~1x10^{-6} cm/s), which will limit the potential for seepage from the BRSF to impact groundwater beneath it. The remainder of the BRSF footprint is underlain by Cenozoic basalt flows with a higher average hydraulic conductivity. In places where the surface of the basalt is not already covered by an adequate thickness of low-permeability overburden, additional clay-rich material will be emplaced to minimize seepage from the BRSF into the foundation rock.

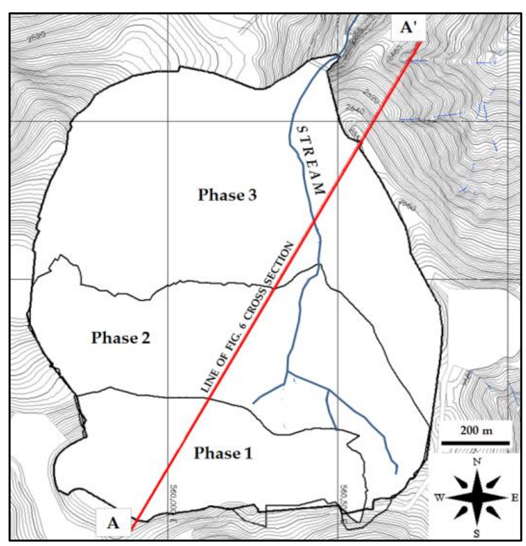

Figure 4 Map of BRSF basin

The north-facing southern slope of the basin hosts a set of springs. These mostly ephemeral springs largely drain perched water zones, whose recharge areas are on the mountain slopes upslope from the BRSF to the south. Springflows vary seasonally, with peak measured flows of about 20 L/s corresponding to peak snowmelt flows in April and May. The BRSF will be built with an underdrain consisting of a five-meter-thick layer of crushed UV. The underdrain will allow unrestricted flow of the emerging springwater to the toe of the BRSF without coming into contact with the encapsulated LV cells. The water from the springs will mix with seepage from the BRSF, and the mixed water will be captured at a detention pond just below the BRSF toe.

Construction sequence

The BRSF will be built in three phases, Phase 1 occupying roughly the southern third of the ultimate facility footprint, Phase 2 built to overlie the northern slope of Phase 1 and extending northward to occupy the medial portion of the footprint, and Phase 3 overlying the northern slope of Phase 2 and extending to the footprint's northern extremity.

The phasing is required to establish an early platform for a low-grade ore stockpile on the south slope of the BRSF as it is being built up. The stockpile will be built during the first few years of mining, and at the end of the project's life the stockpiled ore will be processed.

An engineered evapotranspiration cover (ET Cover) will be placed over the final slopes of the BRSF concurrently with their completion. This will occur first over the Phase 3 northern slope. It will occur later on the slopes covered by the low-grade stockpile, as those slopes are exposed during removal of the low-grade ore. The BRSF is designed to encapsulate the LV waste such that it cannot easily come in contact with water or oxygen. The plan will benefit from the clay content in the LV waste, and the silicification of the UV waste. Cells of LV waste will be created through waste sorting. The LV will be contained in cells that are isolated from seeps, springs, and groundwater from below, and isolated from meteoric water from above. Once a final surface is achieved, the encapsulation will be completed with the placement of the ET Cover. Figure 5 shows the configuration of the final encapsulation cells down the axis of the BRSF in the interim between the completion of the BRSF and the processing of the LGS.

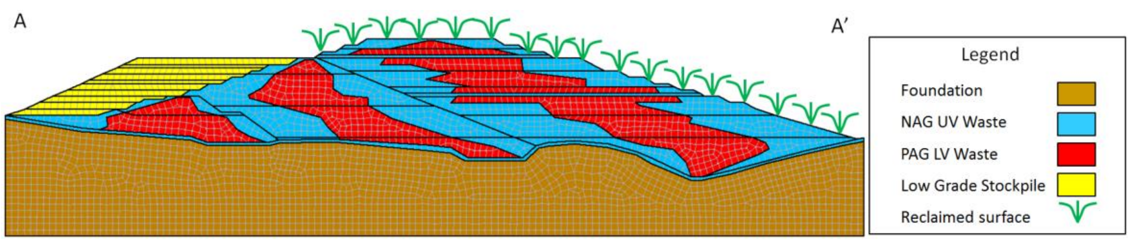

Figure 5 Cross section along axis of BRSF

PREDICTIVE MODELING OF BRSF LEACHATE AND RUNOFF

The BRSF encapsulation design is intended to minimize the quantity of mine waste leachate, and to isolate the LV formation from oxygen and water prior to the formation of biotic oxidation. Predictive modeling of moisture conditions within the BRSF was conducted to determine the quantity of leachate and surface runoff during operations and postclosure.

Numerical modeling of flow was done to generate a design that minimized seepage through the BRSF. The results of that modeling were then used as input to a geochemical model, which predicted the water quality of seepage. The flow modeling was done using Vadose/W (GeoStudio, 2014), a finite-element model that can comprehensively simulate the interaction of a range of meteorological variables with the ground surface, and then simulate the flow of infiltrating water through both saturated and partially saturated material volumes.

Flow modeling approach

The flow modeling used a two-stage process. The first stage involved creating a series of one-dimensional transient column models, with each model representing a unique combination of materials and slopes. These models used daily variations in precipitation, temperature, wind speed, and relative humidity for a typical year, with the "typical year" based on several years of data from a nearby meteorological station representative of site conditions, to predict the variation of infiltration and runoff over time for each combination of material and slope for a single year. The typical year precipitation is ~680 mm, with half of the water content falling as snow. Summers are dry with rainfall occurring primarily in the spring or in October. The surfaces involved included LV waste, UV waste, and low-grade ore, as well as the various tested closure covers.

The second stage involved applying the infiltration predictions of the one-dimensional models to a transient two-dimensional model representing a cross section through the center of the BRSF (Figure 5). For the two-dimensional model, infiltration values determined for each combination of slope and surface material were set as prescribed boundaries, making it unnecessary to employ the computationally demanding climate functions for the larger two-dimensional model domain. Like the one-dimensional model runs, the two-dimensional runs included discretization of time into one-day increments, but the simulation covered the multi-year operations period and extended well into postclosure. The two-dimensional model dynamically tracked the development of the facility year by year, showing each phase's growth, the succession of phases, and the building and removal of the low-grade ore stockpile. Seepage rates were determined, and then those results were extrapolated to the third dimension to calculate the seepage flows that would report to the BRSF underdrain, and ultimately to the downgradient detention pond.

In addition to collecting seepage from the toe of the BRSF, the downstream detention pond also collects surface runoff from the facility. Runoff rates per unit area predicted by the one-dimensional models were used in conjunction with the scheduled change over time of areas of specified material and slope characteristics to predict the volume of ARD-impacted runoff water that would be received by the pond.

Predicted seepage rates

The modeling showed that seepage flow rates were comparatively small, both during the operations period and later during closure. This is largely a function of the climate. Essentially no infiltration occurs during the frozen-ground conditions of winter, and much of the year's precipitation total is lost either to sublimation of snow or to the spring runoff. Evaporative loss is also significant. During the operations period, when raw waste surfaces are exposed, the relatively dry waste has considerable ability to absorb such moisture as is available. However, the rapid growth of the waste pile means that any exposed waste surface has only limited time to take up additional moisture.

The cover consists of 0.2 m of soil over one m of compacted clay, above a capillary break layer 0.5 m thick. Because the crushed UV that will constitute the upper part of the encapsulation envelope is expected to have the hydraulic properties required for the capillary break, no separate layer is required.

Although infiltration of precipitation water into the accumulating waste is modest during the operations period, installation of the ET Cover further limits the amount of water that ultimately passes through the waste pile and emerges as seepage collected in the underdrain. This is not because the cover is impermeable; it is not. Instead, the cover functions as an effective store-and-release mechanism, allowing temporary storage of shallow-infiltrating water in the cover volume above the capillary break, but then yielding that water back to the atmosphere via evaporation in response to the high evapotranspiration potential that the site displays during much of the year. In the spring, the cover absorbs into storage to a maximum bulk moisture content of 20% (by volume). This storage is depleted by summer evapotranspiration.

Figure 6 shows the predicted flow of seepage from the base of the BRSF over time, subdivided according to the phase-footprint source of the water. The graph shows the gradual increase in total seepage flow as each phase is built, and as building of each succeeding phase begins. Seepage falls rapidly during the so-called "hiatus" period, when the flow of waste rock still being generated by ongoing mining is being diverted to backfill the early-mined pit volumes. Installation of the ET Cover takes place on the facility's completed final slopes (generally, those not occupied by the low-grade stockpile) at the beginning of that hiatus or earlier where possible, reducing infiltration rates over that area. When mining has been completed at the pits, removal of the low-grade stockpile begins. Concurrent installation of the ET Cover is done as the footprint of the stockpile recedes. After installation of the ET Cover is complete, seepage rates show a gradual decline in the early years of closure. The final predicted infiltration rate is ~1% of total precipitation. Field lysimeters will be installed to verify this modelled result.

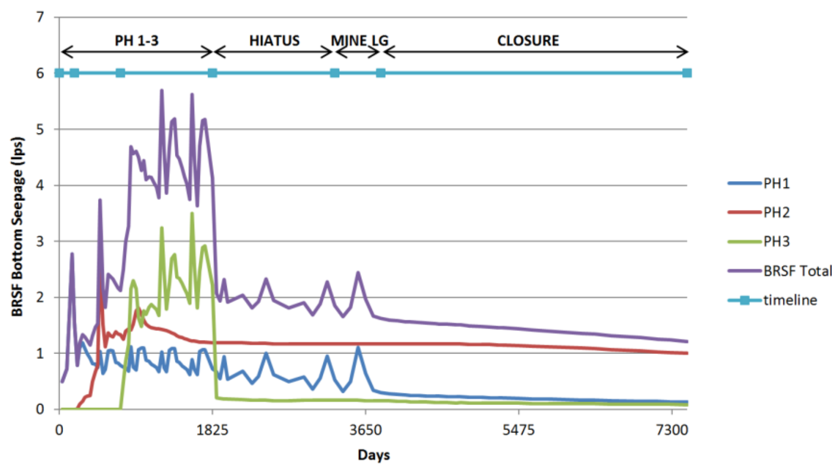

Figure 6 Predicted BRSF seepage flows vs. time

Maximum seepage rates of about five L/s are predicted during the three-year period that precedes the hiatus, with maximum rates around two L/s persisting through the end of removal of the low-grade stockpile. During operations all water is consumed, so that the cost of treatment is not an issue. From the beginning of the closure period onward, average seepage rates of less than two L/s are predicted, trending toward one L/s.

Moreover, the predicted seepage rates are small compared to the expected flow of water from the springs buried beneath the BRSF footprint. Although the spring-sourced flow rates will vary seasonally in a way that may not be synchronized with seepage from the BRSF, and the BRSF facility itself may cut off precipitation recharge to some of the source area of the springs, the water that ultimately reaches the toe of the facility will often be a mix of a small flow of ARD-impacted seepage with a larger flow of natural groundwater.

GEOCHEMICAL MODELING OF LEACHATE

In order to determine the effectiveness of encapsulation, the water quality in the BRSF was simulated using the PHREEQC geochemical model (Parkhurst & Appelo, 1999).

Oxygen penetration

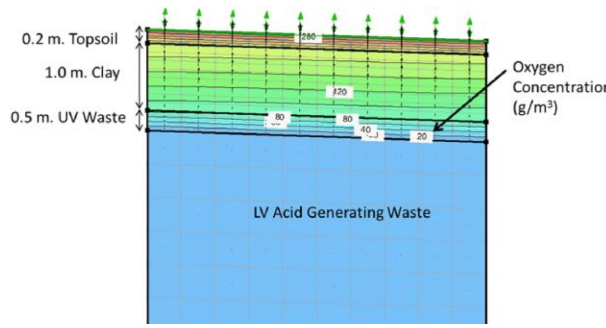

Figure 7 BRSF cover oxygen penetration

Prior to geochemical modeling, it is necessary to simulate the depth to which oxygen can penetrate into the waste. This was done with Vadose/W, which has the capacity to calculate oxygen diffusion into materials based on pressure gradients, temperature gradients, and the degree of soil saturation. The oxygen consumption (from the production of ARD within the LV) and oxygen diffusion modeling showed that oxygen does not penetrate the ET Cover. It is assumed that the BRSF will always produce ARD and some oxygen consumption will occur within the LV. Figure 7 shows oxygen diffusion at its maximum extent in late summer, when moisture contents in the cover are at the lowest levels they reach prior to winter ground frost. As a conservative measure, it was assumed that the total depth of oxygen penetration was approximately 1.5 meters.

Conceptual model

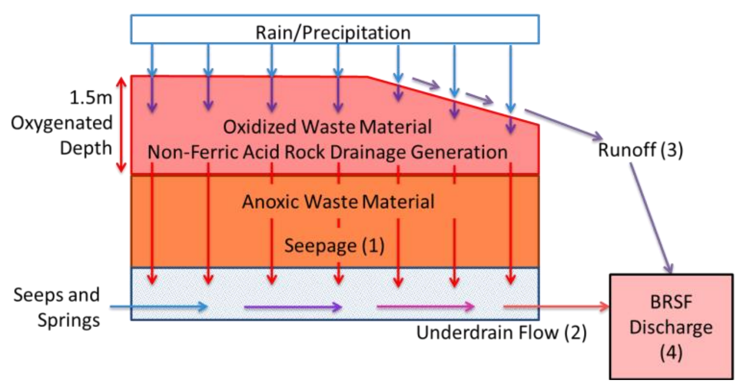

Figure 8 BRSF geochemical conceptual model

The BRSF geochemical model determines the water quality of the BRSF basin discharge by determining the water quality of each of the flows that come together at the toe of the BRSF and by mixing the flows together in PHREEQC to come up with a resultant water quality.

Each flow is shown in Figure 8. Flows include: runoff from barren rock, runoff from unimpacted surfaces within the basin, seep and spring water, and seepage through the BRSF. The numerals shown in parentheses in Figure 8 represent the PHREEQC model solutions for the four designated water components discussed here.

Seepage through the BRSF discharges into the BRSF underdrain (Solution 1 in Figure 8). Initial contact water solutions were compiled from weekly loading rates determined by the HCTs, total rock volume, and total seepage. Raw HCT results were used in order to provide a conservative ARD condition that reflects the ARD behavior of the samples tested. The loading rates were determined by first averaging the weekly concentrations of all constituents in the HCT leachate, then averaging each constituent's weekly averages. The rates were then applied to the total weight of rock within the oxygenated zone and the total seepage flow in order to simulate the initial seepage water quality (Solution 1). Solution 1 is then subjected to an oxygenated equilibrium followed by an anoxic equilibrium. These steps simulate the conditions in the top layer of the BRSF (oxygenated) and deep within the BRSF (de-oxygenated), while allowing constituents to precipitate out in either condition.

Simulation of the underdrain water quality is derived by mixing the anoxic seepage mix (Solution 1) with the spring flow beneath the BRSF. The mix proportions are based on seep and spring surveys, and the seepage flows shown in Figure 6. BRSF seepage makes up from 16% to 37% of the mix. Spring water quality was based on samples taken during February, 2014. The mixture of spring water with the anoxic seepage greatly reduces the concentrations of metals and sulfate (Solution 2).

Runoff will also report to the BRSF pond, where it will mix with the toe discharge from the BRSF (Solution 2). Runoff water quality was determined by selecting a weighted average of the first eight weeks of the HCT results. Eight weeks is roughly the length of the Amulsar wet season (May and June), and therefore a reasonable contact time for runoff ARD reactions to occur. It is also important to note that rapid BRSF construction limits the potential contact time between runoff and LV mine waste. Runoff (Solution 3) mixes in the lined BRSF detention pond. During operations, this water is fully-consumed by the HLF. Upon closure, it must be treated prior to discharge. Figure 9 shows the predicted water quality. As a result of the LV waste encapsulation and the waste rock's natural resistance to biotic oxidation under site conditions, the modeling predicts that the Amulsar BRSF ARD seepage will be a moderate contamination source, with approximately 150 mg/L total acidity, 100 mg/L of sulfate, and pH of 3.8.

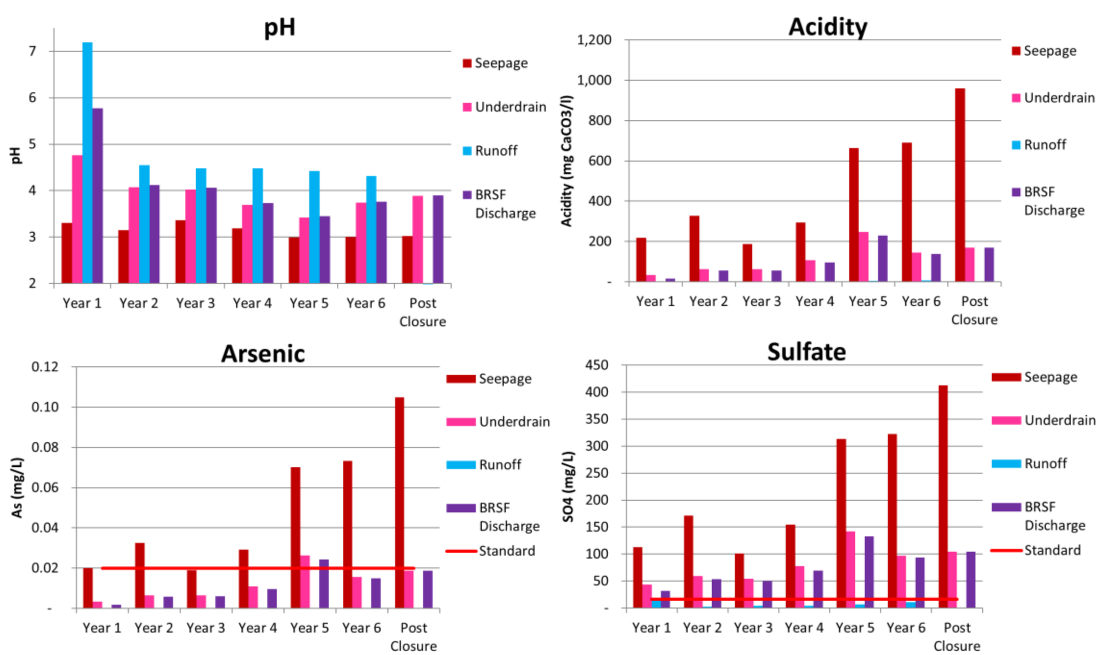

Figure 9 BRSF discharge water quality predictions

CONCLUSIONS

Characterization of Amulsar mine waste revealed that the LV formation has the potential to produce ARD. However, it is also apparent from mine waste exposed in the field that the waste has a resistance to the formation of the strongest level of ARD produced by sulfide-rich deposits. Biotic oxidation reactions catalyzed by *Acidithiobacillus ferroxidans* do not appear in the field, and only occurred in two of eleven HCTs. The Project plans to take advantage of this natural resistance by encapsulating the LV mine waste within the BRSF in cells that isolate it from oxygen and water. Flow modeling confirmed that the mine waste maintains a low moisture content during construction, and when the waste is rapidly covered, flow through the mine waste can be reduced to a nominal one to two L/s. Oxygen also cannot penetrate the waste. Oxygen diffusion modeling showed that oxygen cannot penetrate the 1.2-meter-thick ET cover. Encapsulation is therefore feasible.

Geochemical modeling confirms that the encapsulation successfully controls and minimizes ARD. Not only is flow decreased, but the kinetics of geochemical reactions is sufficiently slowed to produce only mild ARD. Mild ARD makes passive treatment methods possible for long-term ARD management.

Prior ARD management plans, which did not consider the encapsulation option, required an active treatment system to control ARD. This would have necessitated construction of an active treatment plant for use during operations and continuing into postclosure, along with an extra clay under-liner in the BRSF. These factors resulted in a total project cost of US$101M for ARD management (net present value (NPV) calculated based on a three-percent discount factor).

The current plan, with the encapsulation and ARD mitigation measures described above, makes it possible for the mine to consume all ARD-impacted water during operations. In addition, the improvements in predicted water quality allow for passive treatment upon mine closure. These changes save the mine US$40M in capital and operating cost (adjusted for NPV). The resultant savings have a large positive impact on the NPV and IRR of the entire project while still meeting strict regulatory guidelines.

ACKNOWLEDGEMENTS

GRE would like to thank Lydian International Inc., for permitting us to present our work on this project.

REFERENCES

GeoStudio (2014) *Vadose/W: A Vadose Zone Modeling Program,* GEO-SLOPE International Ltd.

INAP (2009) *Global Acid Rock Drainage Guide*, International Network for Acid Prevention.

Parkhurst, D. L., and C. A. J. Appelo (1999) *User's guide to PHREEQC (Version 2): a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations*, U. S. Geological Survey WRIR 99-4259.

Sartz, L. (2011) *Weathering of waste rock in different climatic conditions - a kinetic freeze/thaw and humidity cell experiment*, International Mine Water Association Congress.