Design, Operation, and Preliminary Findings from a Field Acid Rock Drainage (ARD) Study at the Bagdad Copper Mine in Arizona

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Abstract

A field test pad study is ongoing at the Bagdad mine in Arizona to understand acid rock drainage (ARD) and metal leaching (ML) potential of development rock and leached ore stockpiles under field conditions. Seepage oxidation-reduction potential (ORP) and dissolved oxygen (DO) data indicate test pads conditions are not oxygen limited and hence, are likely to promote sulfide oxidation. Seepage pH has remained in the circumneutral range for development rock pads. Seepage flow response suggests development of preferential flow paths within the pads. Study results will be used to support on-going mine planning and permitting processes at the Bagdad mine.

Keywords: Acid Rock Drainage, Metal Leaching, Mine Water Quality, Field Study

Introduction

Characterization of ARD and ML potential through standard lab predictive tests is critical to assessing the future seepage water quality from mined/processed materials. These tests are typically required as part of environmental permitting document submittals. Wide variations in mineralogy and particle sizes of materials create a need for a multi-faceted approach when evaluating ARD and ML potential. Major differences exist between lab testing and field parameters, such as temperature, particle size distribution (PSD), microbial activity, air and water flow mechanisms, which influence the evolution and propagation of ARD and ML processes (Kempton 2012, Pearce et al. 2015). Due to the small sample number and weight tested in standard lab tests and inherent heterogeneities present under field conditions, there is limited representation and prediction of ARD/ML potential through lab testing. Therefore, field testing using constructed test pads provides a more representative demonstration of ARD and ML generation from mine stockpiles under field conditions.

Study Site

The Bagdad mine is an open-pit copper and by-product molybdenum mine operated by Freeport-McMoRan Bagdad Inc., a subsidiary of Freeport-McMoRan Inc. (FCX) located in Yavapai County approximately 130 miles northeast of Phoenix in Arizona, USA (Figure 1a). Average annual precipitation rate at the site is approximately 380 mm/year (WRRC 2016). Average summer high temperature approaches 36 degrees Celsius (°C) in July, and the average winter low is just above 0 °C in January. A field study to understand ARD and ML potential of development rock and leached ore stockpiles under field conditions is ongoing at the mine. A total of six test pads - five development rock (TP3-TP7) and one previously acid leached ore material (TP8), were constructed on the South Waste Rock Stockpile (SWRS) in August-November 2018. This study will provide predictions for the following development rock types - Porphyry Quartz Monzonite, Quartz Monzonite, and Precambrian Undifferentiated. These rock types were selected based on their substantial contribution to total material tonnage in the mine

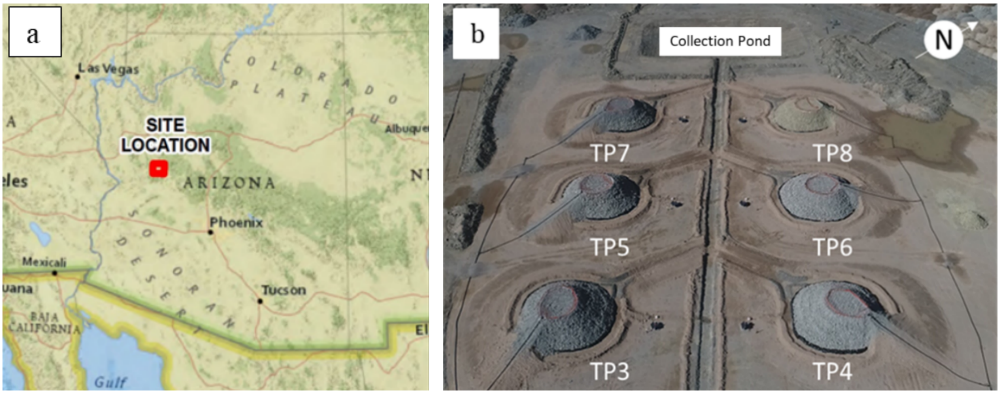

Figure 1 *(a) Bagdad mine location map and (b.) aerial drone image of the study site showing the constructed test pads, outlet/collection channels, and collection pond. Note: TP3 and TP4 - Quartz Monzonite; TP5 and TP6 - Porphyry Quartz Monzonite; TP7 - Precambrian Undifferentiated; TP8 - material from Mineral Creek leach pile.*

plan as well as uncertain classification of ARD potential based on lab testing. Due to semi-arid conditions on site, supplemental drip-line water application is used to augment water received by the pads via natural precipitation. Supplemental water application is expected to accelerate natural mineral-water interactions and facilitate a future water quality evaluation within the relatively short study duration of 2-3 years.

Methods

Construction Activities – Construction activities started in August 2018 on the upper level of the SWRS at the Bagdad mine. A collection pond was constructed to store stormwater run-off and seepage conveyed via test pad outlet channels and a main collection channel. For each pad, the subgrade was sloped at approximately 6 percent towards the center of the test pad to promote seepage collection into a perforated high-density polyethylene (HDPE) collection pipe installed along the center of the pad. The pipe was installed on top of an impermeable HDPE liner to prevent infiltration of seepage into the subgrade. Seepage from each test pad is gravity fed to a 300-L closed cylindrical polyethylene seepage collection tank buried in between the main collection channel and the front of the pad.

Optimum rock size for the test pad materials was selected as 0.3 m minus to eliminate coarse particles that are likely to have a negligible contribution to ARD generation from sulfide oxidation, while achieving a broad PSD within the pads. Test pad materials were placed in 0.5 m to 1.2 m lifts to allow for easy equipment maneuvering and to minimize compaction of materials. A total of nine EC-5 and GS3 sensors from METER Group, Inc. were installed within each test pad during lift construction to measure volumetric water content (VWC), temperature and bulk electrical conductivity (EC) data. The sensors were installed in custom-built boxes containing washed sand placed at 1.2 m and 2.1 m heights within the pads. A drip-line system from Netafim^{TM} was installed on the top surface and upper slopes of pads to augment water received via natural precipitation. Water is conveyed to the dripline system from a 33,000-L storage tank via a 0.1 m HDPE water supply pipeline installed along the perimeter and up the side-slopes of the test pads. A HOBO® weather station from Onset® was installed in the study site to record precipitation received by the pads. The final dimensions (plan view) for all pads are approximately 9 m × 9 m top, 21 m × 21 m bottom, 5 m height from center of the stockpile, and side slopes of 1.5H:1V. Figure 1b shows an aerial drone image of the pads, along with outlet and main collection channels, and collection pond. Figures 2a-d show the components of the seepage collection, water supply, and water application systems.

Material Collection and Analyses – Before construction, five to eight 210-L barrels of representative materials were collected and shipped to the FCX Technology Center in Sanchez, Arizona for PSD analysis and further material processing. For each test pad, materials in the barrels were blended and a representative sample was screened into finer size fractions for Acid-Base Accounting (ABA), Net Acid Generation (NAG), Synthetic Precipitation Leaching Procedure (SPLP), and total elemental analysis at SVL Analytical, Inc. (SVL), Idaho. Samples were also sent to the Mineralogy lab in the FCX Technology Center in Tucson, Arizona for X-ray Diffraction (XRD) analysis.

System Operation – System operation began in August 2019 and is planned to continue for 2 to 3 years. Potable water is filled in the storage tank and dechlorinated using a Rainfresh® Granular Activated Carbon (GAC) filter system before water application. Dechlorination treatment is expected to prevent any inadvertent effects of residual chlorine on microbial populations within the test pads. Microbial activity is known to accelerate ARD and ML generation from oxidation of sulfide minerals (Nordstrom et al. 2015, Percak-Dennett et al. 2017). A target water application rate of 3,800 L per week per test pad is used to accelerate natural mineral-water interactions as well as promote adequate seepage generation for water quality analyses. This target application volume is approximately three times the annual precipitation volume at Bagdad. Water is applied over a 3-to-4-hour period on the same day every week and actual volumes of water applied on each test pad are recorded by Netafim™ ultrasonic flow meters.

Sampling and Monitoring – A 19-L sampling container placed on a bracketed shelf installed in the seepage collection tank holds the most recent seepage for sample collection and analysis. Test pad seepage, water applied, field blank and duplicate samples are collected for analyses on a monthly/bimonthly basis. Aqueous chemistry analysis at SVL includes major cations and anions, selected trace elements, acidity/alkalinity, and total dissolved solids (TDS).

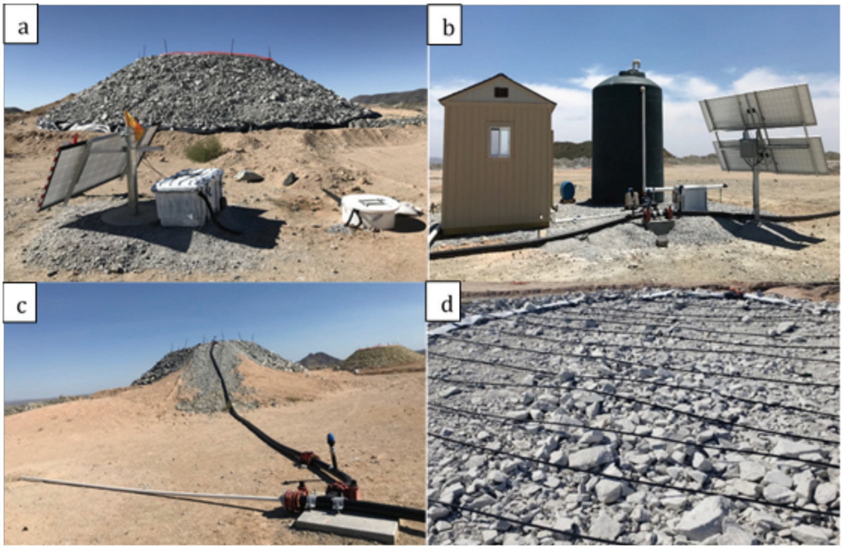

Figure 2 *Bagdad ARD test pad study components – (a) Test pad, seepage collection tank, sampling equipment box, and solar array; (b) water storage tank, solar array, pump, and Tuff Shed® housing Granular Activated Carbon (GAC) units; (c) water supply line installed along the perimeter and side slopes of test pads to supply water to the dripline system; and (d) drip-line system installed on top surface of the test pads.*

Additionally, field parameters - pH, EC, ORP, DO, and temperature are measured during and in between sampling events. A tipping bucket (Hydrological Services America, Model TB6/40) was placed on the shelf for continuous measurement of the seepage flow rate. A Mini Log Model ML1A data logger used to log the tip frequency data was housed in an insulated box next to the tank. Within a few weeks of installation, all ML1A data loggers stopped logging data possibly due to corrosion of reed switch contacts noted during visual inspection. These reed switches were replaced with custom silicone-potted ones prior to system start-up in August 2019. However, only the logger corresponding to TP6 logged data consistently before failing in January 2020. Starting mid-January 2020, two to three manual flow measurements are collected per week and distributed across the weekly water application cycle to include peak and low seepage flow periods. For each pad, a monthly average of manual flow measurements is likely to provide a reasonable estimation of seepage volumes for solute loading calculations. Moisture content data measured by the sensors are recorded by a ProCheck handheld meter during sampling events. In addition, sensors on the 1.2 m level are connected to an Em50 logger set to log data every 12 hours. The HOBO® U30 logger records weather data every hour.

Results and Discussion

This paper will focus on results from the development rock test pads (TP3-TP7). The objective of TP8 is to evaluate rinsing and drain-down of previously leached materials. Results from TP8 are being evaluated separate from the development rock pads and are not discussed in this paper.

Selected pre-study material characterization results – Based on XRD results, chalcopyrite and pyrite were identified as the two sulphide minerals present that, upon oxidation, are most likely to release acidity, sulphate and metals into seepage. No sulphate minerals were detected in the development rock materials. Calcite, biotite, and chlorite are the minerals most likely to provide short- to medium-term neutralization capacity. Based on Net Neutralization Potential (NNP) and Neutralization Potential Ratio (NPR) criteria (ADEQ 2004), most development rock samples are classified as having an uncertain ARD potential, with the rest classified as non-acid generating. Acid Neutralization Potential (ANP) from lab titration is higher than ANP estimated from total carbon content for all samples suggesting that silicate minerals such as biotite and chlorite provide acid neutralization capacity in addition to carbonate minerals. Samples from all the development rock test pads were determined to be non-acid forming based on NAG testing (NAG pH > 4.5).

Flow mechanisms and progression of wetting-fronts – The overall water balance in a rock pile, internal moisture content and flow regimes influence the evolution of long-term seepage chemistry (Lefebvre et al. 2001, Wels et al. 2003). Spatial variability in PSD, abundance of macropores, and high rainfall intensity are factors that promote the development of preferential flow in rock piles (Momeyer 2014, Fretz 2013). Due to different water retention characteristics of sand packed in the moisture sensor boxes (100% of material < 2 mm) and the coarser test pad materials (79-93% of materials > 13 mm), VWC values recorded by the sensors do not represent actual moisture content levels within the pads. However, VWC measured by the sensors are reasonably indicative of wetting front arrival times at different test pad depths. Following the high-intensity precipitation event in January 2019 which resulted in the initial 'wetting-up' of test pads, VWC recorded by one or more sensors on the 1.2 m level are observed to be higher than those recorded by the 2.1 m level sensors for all pads. This suggests that preferential flow paths may have developed following this precipitation event. Other studies have reported similar findings (Momeyer 2014). For this study, it is assumed that a high-intensity precipitation event occurs when precipitation comparable to twice the weekly water application volume (7,600 L) or greater is received in less than a week. Following high-intensity precipitation, seepage flow consistently reached peak levels within a few hours as opposed to 3-4 days observed after weekly water applications. Additionally, the magnitude of peak

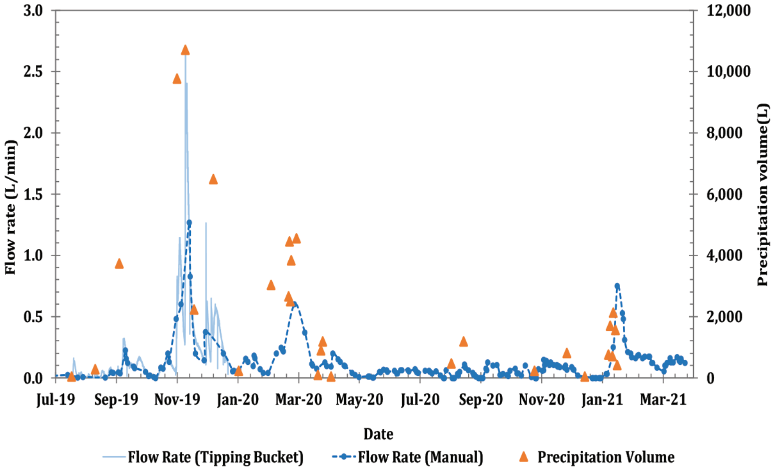

***Figure 3** Test pad TP6 tipping bucket and manual seepage flow rate measurements. Note: Precipitation volumes calculated from weather station data are plotted on the secondary y-axis.*

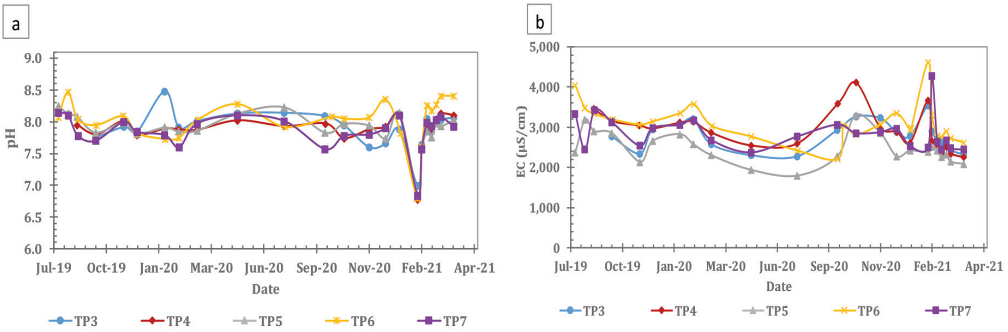

***Figure 4** Test pad seepage field parameters - (a) pH and (b) EC values.*

seepage flow rates following high-intensity precipitation events in November/December 2019, March 2020, and January 2021 were consistently higher than those measured after typical water applications. This is illustrated in Figure 3 using TP6 tipping bucket and manual seepage flow data plotted along with precipitation volumes calculated from weather station data. Manual seepage flow measured for TP6 and the other test pads are not as complete as continuous tipping bucket data. They do not always capture the actual value of peak flow following high-intensity precipitation, especially if safe site access is not available. Nevertheless, the overall findings are applicable for all test pads and consistent with development of preferential flow, which is likely to commence earlier and at greater intensities with increasing rainfall rates (Fretz 2013, Stewart 2019).

Test pad conditions and seepage chemistry – Test pad seepage pH and EC values have remained relatively constant throughout the study at 7.5-8.5 and 2,000-4,000 µS/cm, respectively (Figure 4a and b). Seepage pH values measured a few days after the high-intensity precipitation event in late January 2021 were substantially lower (pH = 6.7-7.0) but increased to the typical range within a week. These observations are consistent with fluctuations in carbon dioxide (CO_2) concentrations within the pads. Periods of higher water content are characterized by higher internal CO_2 levels resulting in decreased pore water pH. Drain down of the test pads promotes an increase in CO_2 degassing to the atmosphere and subsequently an increase in pore water pH (Peterson 2014).

Degree of water saturation and flushing frequency can influence sulphide oxidation rates and solute loading in seepage (Herasymuik et al. 2006, Hollings et al. 2001). Water application was paused during periods of high-intensity precipitation to prevent constant flooding of pore spaces with water, which could slow down sulphide oxidation by limiting oxygen supply. Conditions within the test pads are not oxygen limited based on consistently positive ORP data and moderate-high DO measurements (DO ≈ 5-10 mg/L; typical DO percent saturation of 50-80%). Additionally, seepage sulfate concentrations have typically remained in the 1,000-2,000 mg/L range. Hence, the volume and frequency of water application are generally appropriate to promote sulphide oxidation by flushing out built-up oxidation products and exposing fresh mineral surfaces for further oxidation.

Preliminary Conclusions

For all development rock test pads, seepage flow response and moisture content data are consistent with the development of preferential flow paths. Based on ORP, DO, and sulfate loading in seepage, conditions within the test pads are typically not oxygen limited. Hence, the volume and frequency of water application are appropriate to promote sulfide oxidation, other mineral-water interactions and meet the objectives of this study. For the development rock test pads, seepage pH values have remained relatively constant in the circumneutral range and EC values have remained in the 2,000-4,000 µS/ cm range. Mineral reaction rates (sulfide oxidation and dissolution of calcite, biotite and chlorite) and solute release rates will be calculated to estimate the future ARD potential and seepage water quality from these materials. The findings from this study will be utilized in support of on-going mine planning, permitting, and closure planning activities at Bagdad.

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