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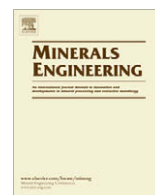
Geochemical evaluation of heap rinsing of the Gold Acres Heap, Cortez joint venture, Nevada

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ABSTRACT

This paper presents a summary of field and laboratory studies conducted to determine the need and extent of rinsing requirements for a spent oxide gold heap. The testwork utilized the Gold Acres Heap in Nevada. Monitoring data was reviewed to examine the geochemical processes occurring within the heap and predict the chemistry of future heap solutions for the Gold Acres Heap as well as the other heap facilities.

In conjunction with this field study, column rinsing tests involving freshwater and recycled process water were conducted using representative spent oxide ore from the Gold Acres Heap in order to simulate heap conditions observed during field rinsing.

A comparison between the column test results and the monitoring data collected during field scale recirculation indicates rinsing oxide ore recirculated barren solution does not decrease solute loadings. The column test indicates applying multiple freshwater rinses to the heap will only exacerbate the release of constituents by changing the pH-redox conditions of the heap.

Consequently, this study indicates rinsing heap material with recirculation barren solution will produce no significant change (i.e., improvement) in the heap solution chemistry with respect to environmental release. Rinsing with freshwater will result in a higher risk for potential environmental degradation than not rinsing at all.

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1. Introduction

The process of decommissioning and closure of a heap leach gold operation may involve rinsing with recirculated solution and/or freshwater to chemically stabilize the spent ore. The rationale for this practice is that the majority of soluble constituents in a spent oxide ore heap are present as interstitial water within the heap or present as easily exchangeable soluble complexes adsorbed to the oxide and clay minerals that constitute the majority of the heap material. Evidence from other heap rinsing projects in Nevada indicates that water quality standards for cyanide can often be met by rinsing. However, water quality standards for arsenic, nitrate and sulfate are often not achievable, regardless of the extent of rinsing (Parshley and Bowell, 2001). It is also true that the effectiveness of rinsing a heap varies depending upon the geochemical characteristics of the heap material, and is therefore site specific. Consequently, a site specific approach to heap rinsing is necessary in order to achieve long-term closure objectives (Collord et al., 1999; Parshley and Bowell, 2001).

As part of a series of case studies intended to provide information that benefits the operation and closure of this heap and other heaps, data has been gathered during the loading, leaching, and rinsing of this final lift, with the following principles in mind:

1. provide for instrumentation of the final lift and future soil cover in order to evaluate the factors which affect the hydraulics of the leaching or rinsing of the pad;
2. assess the effectiveness of rinsing, or solution application regimes;
3. assess the impacts of ore placement methods;
4. examine the geochemical processes occurring within the heap; and
5. determine the risk that long-term solutions may present to the local environment.

Cyanide application to the final lift of the Gold Acres Heap was initiated in August 1995 and essentially ceased in the spring of 1999 (additional material was placed on the western portion of the pad, and cyanide solution applied until September 2004). Following cessation of cyanide addition, the heap was allowed to drain during a short rest period until the fall of 2000, upon which the heap was rinsed with recycled heap solutions until early fall of

2003 when leaching operations at the heap were re-initiated. Active leaching of the Gold Acres Heap is currently underway.

The main objective of the Gold Acres Heap Leach Rinsing Research Project was to determine the effectiveness of rinsing spent oxide ore that is specific to Cortez heap leach facilities (i.e., heap leach material derived from the Pipeline deposit). Monitoring results from the Gold Acres pregnant pond were evaluated to determine the change in heap chemistry after active leaching operations ceased and before and during recirculation rinsing. The observed trends in heap chemistry are supported by laboratory column testing that provides additional insight into the factors that control the aqueous chemistry of the heap during rinsing. The similarity in rock type and chemical composition of the spent ore to typical heap leach oxide gold ore makes this study applicable in considering heap leach closure elsewhere.

2. Geology of site

The Pipeline deposit lies on the eastern flank of the Northern Shoshone Range, in Lander County, approximately 30 miles southeast of Battle Mountain. Gold mineralization in this area is spatially associated with base metal-skarn mineralization although it is considered younger (Hays and Foo, 1991).

Host rocks in the project area include upper and lower plates of the Paleozoic Roberts Mountain thrust, as well as younger sediments. A Cretaceous granitoid stock occurs under the Paleozoic sediments and Tertiary dyke swarms cut across the sediments. Gold ore is primarily hosted by the Silurian Roberts Mountain Formation associated with northwest trending thrust zones. Alteration of the deposit consists of silicification, carbonization and argillization. The deposit has also been oxidized post deposition; consequently sulfide content is low and is dominated by fine grained crystallized pyrite (<1% of all minerals in the heap ore). Heap ore mineralogy is dominated by (in descending order of abundance); quartz, calcite, illite, dolomite, nontronite, amorphous Fe oxide, hematite, chlorite, kaolinite, halyosite, epidote, tremolite and garnet. Sulfides identified by Hays and Foo (1991) include pyrite, arsenopyrite, chalcopyrite, sphalerite and galena.

From grab samples of the Gold Acres Heap, several secondary minerals (were identified by XRD and SEM analysis. These include, adamite, birnessite, brochantite, cerussite, chlorargyite, goethite, gypsum, secondary gold, jarosite, libethenite, linarite, malachite, scorodite, smithsonite and variscite (Bowell, 2004).

Geochemically, the deposit shows two distinct anomalous sequences. First; silver, gold, arsenic, boron, thallium and mercury are associated with the gold-bearing epithermal system and second; copper, lead, zinc, arsenic, bismuth, cadmium, iron, manganese, molybdenum, and silver are associated with the deep seated base metal mineralization.

3. Methodology and pre-characterization

A column rinsing test using spent ore from the Gold Acres Heap and barren solution from the site was conducted in order to assess the geochemical mechanisms that are active during rinsing of the Gold Acres Heap. The column rinsing test was conducted at McClelland Laboratories, Inc. (MLI), Sparks, Nevada and involved rinsing Gold Acres Heap material with barren solution from the site. The test column was monitored for seven rinse cycles of barren solution, one rinse cycle of freshwater, and two rinse cycles of recirculated freshwater. During the test program, influent and effluent chemistry was monitored and all chemical analyses were performed by WET Labs of Sparks, Nevada.

For the purpose of this paper, a summary of the procedures and findings of this rinsing test is provided in the following section.

3.1. Heap material collection

A total of 3.628 metric tons of heap material was collected with a track hoe at 1 m intervals from a trench excavated on the uppermost lift of the Gold Acres Heap for a total of seven samples at 1 m sample intervals, representing a total of 7 m of heap material, or the complete lift height. Material from each of the sample intervals was placed in a 300 L plastic-lined drum and shipped to MLI for the column testwork.

In addition to the 300 L drums of heap material, a separate smaller sample for each 1 m interval of the heap was collected for chemical analysis and physical measurements. Each of the seven samples weighed 15 kg. Duplicate drums were also filled from each of the intervals and stored on site in the event it is needed for baseline information or it was decided that additional testing was desired.

3.2. Initial heap material testing and preparation

The 15 kg samples of heap material were blended and split to obtain appropriate weights for moisture content determination, 4-mesh (4.76 mm) screening and analysis. During this initial sample preparation and analysis, each 1 m interval remained separate. Splits from each sample were analyzed by WET Lab for WAD CN, paste pH and Eh, and were also analyzed by ALS Chemex of Reno, Nevada for Au and Ag. MLI determined feed moisture contents and ±4 mesh particle size distributions.

Prior to being loaded into the test column, each sample interval of heap material in the 300 L drums were blended and split, while being kept moist, to obtain the following splits:

1. two 136 kg splits for loading into the two 0.38 m OD × 7 m test columns;
2. one 68 kg split for heap material master composite preparation; and
3. one 11 kg split for 10 cm screening and additional moisture content determinations.

The physical characterization data show that the largest percentage of heap material for each 1 m interval was minus 10 cm in size. As a result, it was not necessary to screen the heap material to remove the plus 10 cm fraction and the heap material was loaded into the test column "as received".

Feed moisture content was generally lower for the large samples of heap material (i.e., material contained in the 300 L drums) than the smaller samples of the same 1 m interval suggesting some drying occurred during preparation of the large heap samples.

WAD CN contents of all 1 m intervals was less than 0.2 mg/kg, paste pH's ranged from 7.90 to 9.92 s.u., paste Eh's ranged from +160 to +255 mV, gold content ranged from 0.12 to 3 g Au/t of heap material, and silver content was not detectable except for the 0–1 m interval (0.8 g Ag/t). The pH and Eh values were measured using laboratory probe meters made by Hanna and calibrated using external solutions.

Metal analysis, by ICPAES, indicates that sufficient concentrations of aluminum, antimony, arsenic, barium, calcium, chromium, copper, iron, potassium, magnesium, manganese, molybdenum, sodium, nickel, phosphorous, sulfur, strontium, titanium, vanadium and zinc were contained in the heap material master composite to be potentially mobilized by contact with solution (site barren or meteoric water).

3.3. Heap material master composite preparation

The master heap composite was prepared by combining splits from each 1 m interval that weighed 68 kg resulting in a composite

weighing 476 kg. The master heap composite was blended and split to obtain the following:

1. 453 kg split for particle size analysis;
2. 18 kg split for a two stage Meteoric Water Mobility Protocol (MWMP test); and
3. 4.5 kg split for analysis and mineralogical characterization tests. This split was re-blended and split to obtain approximately 1 kg for analysis. The remaining 3.5 kg of material was placed in a sealed container and saved. The 1 kg split was dried at low temp, crushed (−10 mm) and pulverized (−150 μm) prior to being submitted to ALS Chemex for ICP metals, CWR, and Au, Ag analyses. A sub sample was taken for XRD mineralogy and a sample from the 3.5 kg material taken for microscopy.

3.4. Loading testwork columns

A total of two 0.38 m OD × 7 m columns were prepared for the heap rinsing test, one for the rinsing test column and the other for the pore volume determination test column. Both columns were loaded using the same procedure with the exception of lime that was mixed with each 1 m interval for material loaded into the rinse cycle test column. Adding lime to the heap material raises the pH of the solution for a better approximation of actual heap conditions. The quantity that was added was determined using the paste pH data for each sample interval. The column loading procedure included the following steps:

1. place 6–7 m moist heap interval (130 kg) into the column in a manner to minimize segregation and compaction;
2. calculate apparent bulk density;
3. place 5–6 m moist heap material (71 kg) into the column on top of the previously loaded interval;
4. recalculate bulk density (5–7 m) and adjust interval weights for loading remaining five 1 m intervals;
5. place the remaining 1 m intervals (from 5 m to 0 m) into column as before using adjusted solids weight (112 kg moist, each interval); and
6. measure overall bulk density of the column charge (0.38 m × 7 m).

Interval weights in column charges were different for the layered 6–7 m and 5–6 m intervals than for the shallower intervals because an assumed bulk density (1682 kg/m³) was used until actual bulk densities could be calculated after loading the two deepest intervals.

The large diameter of the test columns was designed to overcome the problem with small diameter columns being more homogeneous than the flow paths they are trying to simulate. In reality, even large diameter columns will be more homogeneous than the actual heap and this consideration is important when interpreting heap column data.

3.5. Barren solution testing

Approximately 568 L of barren solution from the site was received in two 300 L drums for use in the testing program. Each drum of solution was mixed by agitation and a 2 L aliquot from each drum was collected by aspiration. The remaining site barren solution was transferred to smaller containers and stored in a freezer prior to being used in the column tests. The aliquots from the two drums were composited for a total volume of 4 L, filtered through a 0.45 μm filter, preserved and submitted to WET Lab for Profile II analysis including WAD cyanide. The results for the "as received" site barren solutions are provided in Table 1. Solu-

Table 1
Analytical results for site solution and rinsing test influent.

Parameter	Site barren solution	Steady state rinsing test influent
Alkalinity, T	40	36
CO₃, CaCO₃	<1.0	<1.0
HCO₃	49	44
Aluminum	<0.045	<0.045
Antimony	0.0047	0.030
Arsenic	0.61	3.1
Barium	0.033	0.044
Beryllium	<0.0010	<0.0010
Bismuth	<0.10	<0.10
Boron	0.12	0.41
Cadmium	0.0024	0.0051
Calcium	71	190
Chloride	130	230
Chromium	<0.0050	0.011
Cobalt	0.046	0.068
Copper	<0.050	<0.050
Cyanide, WAD	0.018	0.017
Fluoride	2.0	3.2
Gallium	<0.10	<0.10
Iron	<0.010	<0.010
Lead	<0.010	<0.010
Lithium	<0.10	<0.10
Magnesium	12	<0.50
Manganese	0.012	0.036
Mercury	0.00061	0.00024
Molybdenum	0.072	0.24
Nickel	<0.010	<0.010
Nitrate as N	180	350
Nitrite as N	0.082	0.22
pH, s.u.	7.53	7.62
Phosphorus	<0.50	<0.50
Potassium	9.7	14
Scandium	<0.10	<0.10
Selenium	<0.010	<0.020
Silver	<0.0050	<0.0050
Sodium	450	660
Strontium	1.2	2.0
Sulfate	210	410
Thallium	<0.0010	<0.0010
Tin	<0.10	<0.10
Titanium	<0.10	<0.10
Total dissolved solids	1900	3000
Vanadium	0.024	0.072
Zinc	<0.020	<0.050

All values in mg/L.
< Denotes less than the specified laboratory method detection limit.

tions were preserved prior to analysis for metal analysis by addition of 10 mL of concentrated nitric acid to a liter of sample.

3.6. Pore volume definition

For the purpose of the column rinsing test, the technical definition of "pore volume" is the volume of water (or gas) required to fill the void space within the particles of solid mass. Alternatively, it is common to define a "pore volume" as the volume of water (or gas) required to fill the void space within the particles of solid mass plus the volume of water (or gas) required to fill the void space between the particles of the solid mass (i.e., bedded charge). The technical term for the later definition is a bed volume, which is defined as the volume of water required to completely flood the solid mass within the bed.

As part of the column rinsing test, a pore volume determination test was conducted to determine the actual pore space (pore volume equivalent) of the heap material solid mass contained in a 0.38 m OD × 7 m bed. First, a special column was constructed for the pore volume determination test to ensure the heap material could be flooded in the column without solution loss. Then the entire bedded charge was flooded to the surface of the charge by pumping site barren solution (not recirculated solution) upwards

through the bedded heap material charge at a rate of 2 ml/min/m^2 of column cross-sectional area. The slow application rate was used to minimize bedded charge particle size disturbance. The flooded charge was allowed to sit idle to insure that all solid particles were completely saturated. Additional solution had to be applied after the 48-h soak cycle. The column was then drained completely. A detailed draindown rate and volume test was conducted while the flooded charge was allowed to drain. The total volume of solution required to saturate (flood) the bedded charge was 17.13 L/ton.

Draindown test results show that the draindown rate was rapid for the first 48 h during in which 2.6 L/ton drained from the bedded charge. In contrast, the long-term draindown rate was extremely slow, and an additional 139 days (3336 h) was required to completely drain the previously flooded heap material bedded charge. Draindown rate and volume (cumulative) curves are shown graphically in Fig. 1.

The results of the pore volume determination test indicate the pore volume equivalent of a 0.38 m OD × 7 m bed of heap material is 30.1 L. This pore volume equivalent was used for the recirculation/freshwater heap material rinsing test described below.

3.7. Steady state establishment cycle

Prior to the column rinsing test, the "as received" barren solution needed to be restored to barren solution/heap conditions comparable to those of the heap at the time the heap material samples were collected. Targeted NaCN and pH conditions were 0.03 kg NaCN/t solution and pH 9.2–9.7. In order to accomplish this, a steady state establishment cycle was conducted on the loaded test column by recirculation of site barren solution through the heap material for 5 months before the column test was initiated. The steady state establishment cycle was initiated at the same time as the pore volume determination test.

Consequentially, site barren was recirculated though the heap material column charge for about 155 days (12 day flood cycle, 2 day soak, 141 day drain cycle). A total of 100 L of site barren was recirculated through the bedded heap material during that period. At the end of the steady state establishment cycle, a sample of the steady state barren solution was collected and submitted to WET Lab for Profile II analysis including WAD cyanide. Cyanide and pH conditions for the steady state solution were 0.04 kg NaCN/t soluble and pH 9.7, respectively, which were acceptably close to targeted conditions.

The steady state recirculated site barren chemistry was compared to the "as received" barren solution and in general both solu-

tions were similar with respect to water quality (Table 1). The recirculated steady state site barren solution to be used as rinse solution for the heap material rinsing test, contained concentrations of antimony, arsenic, nitrate, sulfate and total dissolved solids at concentrations exceeding the Cortez nondischarge water permit levels. In comparison, concentrations of these constituents in the "as received" barren pond solution also exceed Cortez nondischarge water permit limitations, with the exception of antimony.

As expected, the constituent loading of the "as received" barren solution increased during the steady state establishment cycle. Antimony, arsenic, boron, barium, cadmium, calcium, chloride, chromium, cobalt, fluoride, manganese, molybdenum, nitrate, potassium, sodium, strontium, sulfate, total dissolved solids, and vanadium increased in concentration during the steady state establishment cycle. Magnesium and mercury concentrations decreased during the steady state establishment cycle. However, the concentration of these constituents in the steady state recirculated solution were within the observed range of barren solution chemistry obtained from recent monitoring data.

3.8. Rinse cycle

The column test was conducted by recirculating steady state site barren solution to obtain seven effluent pore volume equivalents, followed by a short term drain. The steady state solution was recirculated through the heap material and then a carbon circuit at a rate of 1.2 ml/min/m^2 of column cross-sectional area or 15 L per day. Fresh water was then applied until one effluent pore volume equivalent was obtained, followed by a short term drain. All of the effluents (i.e., pore volume equivalents and drains) were characterized by Profile II analysis. These analytical results from the first phase of recirculation rinsing show that constituent concentrations, which exceed Maximum Concentration Limit (MCL) remained fairly constant regardless of the heap rinsing method employed (i.e., recirculated barren solution or freshwater).

Based on these results, it was decided to expand the rinsing test to include additional freshwater rinsing. The expanded column test included a second freshwater rinse that was applied to obtain one pore volume equivalent of effluent. This effluent was then recirculated through the heap material for two additional pore volume equivalents. The same test procedures were used for the extension of the rinsing test as were used during the initial test rinse. The rinsing test was terminated after collecting the eleventh effluent pore volume. After the rinse cycle was terminated, the rinsed residue was allowed to draindown for 27 days. The final drain volume was stored frozen, but was not analyzed.
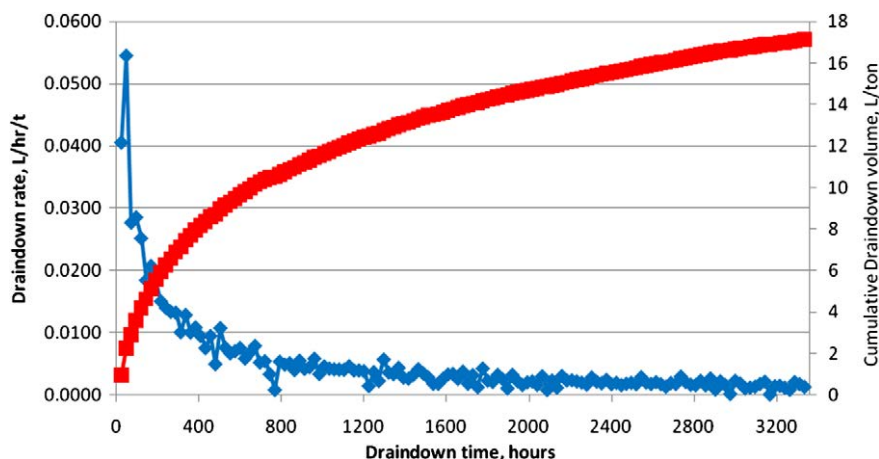

Fig. 1. Draindown curve, column test.

In addition to the Profile II characterization of effluent and drain solution, daily effluent volumes were analyzed for gold and silver prior to being pumped through a 5 stage carbon circuit. These loaded carbons were then assayed for gold and silver. Silver was not detected in daily effluents or recovered in the loaded carbons. However, cumulative recovered values from the effluent indicate 0.007 g Au/t of heap material was recovered during rinsing. Silver was not detected nor recovered because insufficient NaCN was present in the recirculated solution required to hold the precipitated silver $Ag(CN)_2$ complex in dissolved form.

3.9. Post draindown material testing

After the draindown was complete, the column was carefully unloaded from the bottom. Moisture samples, representing each foot of the original 7 m of heap material, were obtained from the column and residual moisture contents were determined. Remaining heap residue was combined by blending and split to obtain a sample for a 2-stage MWMP test (17 kg, moist). After sampling, the remaining heap material rinsed residue was returned to the original drums and sealed for ultimate return to the Cortez mine site. No additional tests or analyses were conducted on the rinsed residue.

3.10. Mass balance of column performance

The results of mass balance calculations are presented in Table 2. From Table 2, a negative change indicates attenuation and a positive change indicates release in comparison to influent concentrations. As shown in Table 2, the results are highly variable with some constituents being released throughout the test-work (e.g., alkalinity) and other constituents are attenuated in the heap solids from the influent (e.g., antimony). For instance, arsenic is attenuated in the column during the recirculation rinse but with the addition of the freshwater rinse is re-mobilized. When the freshwater rinse is recirculated (pore volumes 10 and 11) the release of previously attenuated arsenic is accentuated. Freshwater rinsing also causes a substantial increase in chloride, chromium, fluoride, nitrate, sulfate, total dissolved solids and vanadium.

4. Results

4.1. Trends on heap leach hydrogeochemistry over time

The chemistry of the Gold Acres pregnant pond solution has been reviewed for the period from August 1995 to May 2003. During this review period, the heap was in operation until spring of 1999, after which operations were halted for about an 18-month rest period. Heap solution was allowed to draindown during this rest period and monitoring of both the barren and pregnant pond solution continued. Following this rest period, the heap was rinsed with recycled heap solutions until the fall of 2003 when leaching operations at the heap were re-initiated.

For the purpose of this report, monitoring data collected from the pregnant pond was used to evaluate the trends in heap chemistry during the rest period as well as during the recirculation rinse period. Trends in the concentration of select constituents are plotted versus time for the entire review period (i.e., 1995–2003) in Figs. 2–6 and discussed in greater detail in the following sections. It should be noted that average meteoric precipitation for this site in Nevada is typically 240 mm (M. Shelp, pers. comm.).

4.2. Heap chemistry trends

As shown in Fig. 2, the pH of the pregnant pond solution remained fairly constant during the entire review period at 10 ± 1.0 s.u. with a slight decrease after cessation of cyanide application. A slight decrease in pH is observed over the rest period with pH values decreasing from 10 to 8.37 s.u.

Cyanide, as Weak Acid Dissociable (WAD) cyanide comprised mainly of divalent metal cation cyanide complexes, occurs at relatively high concentrations in the pregnant pond during leaching operations (10–50 mg/L). Fig. 2 shows WAD cyanide concentrations decreasing during the rest period from 12.1 mg/L in March 1999 to less than laboratory detection limits (0.005 mg/L) in August 2000. During recirculation rinsing, WAD cyanide concentrations increase slightly from those observed at the end of the rest period but remain low with the exception of a few measurements just above 2 mg/L.

Following cessation of cyanide application, all of the major solute concentrations peak during the rest period then gradually decline

Table 2
Mass balance results.

| Parameter	Recirculation rinse effluent							Pore 8 (freshwater rinse) (%)	Pore 9 (2nd freshwater rinse) (%)	Recirculated Pore 9 effluent	
	Pore 1 (%)	Pore 2 (%)	Pore 3 (%)	Pore 4 (%)	Pore 5 (%)	Pore 6 (%)	Pore 7 (%)			Pore 10 (%)	Pore 11 (%)
Alkalinity, T	4160.44	497.44	407.00	339.17	293.94	248.72	248.72	203.50	859.22	203.50	474.83
Antimony	488.40	−515.53	−108.53	−488.40	−461.27	−488.40	−461.27	−461.27	−407.00	−352.73	−217.07
Arsenic	−26.26	0.00	105.03	−26.26	−26.26	−26.26	−26.26	26.26	0.00	105.03	420.13
Barium	370.00	−129.50	−37.00	−55.50	−37.00	222.00	−18.50	37.00	55.50	−166.50	−370.00
Boron	–	–	592.00	−42.84	−45.22	335.18	33.92	553.52	–	–	488.40
Cadmium	111.73	166.50	199.66	86.33	−44.60	11.80	23.26	−101.75	−64.60	14.03	234.54
Chloride	0.00	−35.39	70.78	0.00	0.00	106.17	35.39	106.17	106.17	−70.78	−389.30
Chromium	148.00	0.00	0.00	74.00	74.00	74.00	74.00	74.00	−133.20	−96.20	−155.40
Cyanide, WAD	143.65	290.71	−342.74	−74.00	81.40	–	–	1340.71	54.27	305.25	−172.67
Fluoride	152.63	−101.75	76.31	50.87	25.44	0.00	50.87	−76.31	559.63	712.25	101.75
Mercury	–	–	–	–	–	–	–	–	–	−440.92	−271.33
Molybdenum	−33.92	35.39	67.83	−62.62	0.00	0.00	0.00	0.00	−67.83	74.00	33.92
Nitrate as N	−93.03	−23.26	0.00	−23.26	−23.26	23.26	69.77	46.51	−23.26	−139.54	−418.63
Nitrite as N	5846	6216.00	1332.00	1480.00	1665.00	1221.00	−370.00	2331.00	5846.00	1406.00	−666.00
Sodium	−61.67	−98.67	−74.00	−49.33	−24.67	−24.67	−74.00	0.00	−12.33	−135.67	−296.00
Sulfate	−19.85	−19.85	−19.85	−19.85	0.00	−19.85	0.00	19.85	99.27	59.56	−119.12
TDS	27.13	0.00	0.00	27.13	0.00	−27.13	54.27	−27.13	54.27	−108.53	−27.13
Vanadium	101.75	−79.14	−22.61	−90.44	−67.83	−45.22	−56.53	−33.92	−226.11	−11.31	293.94
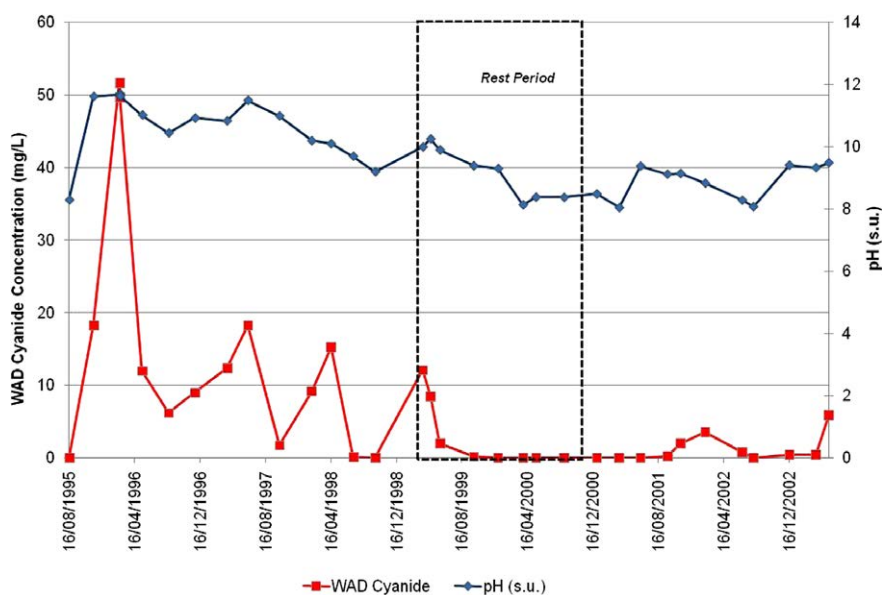
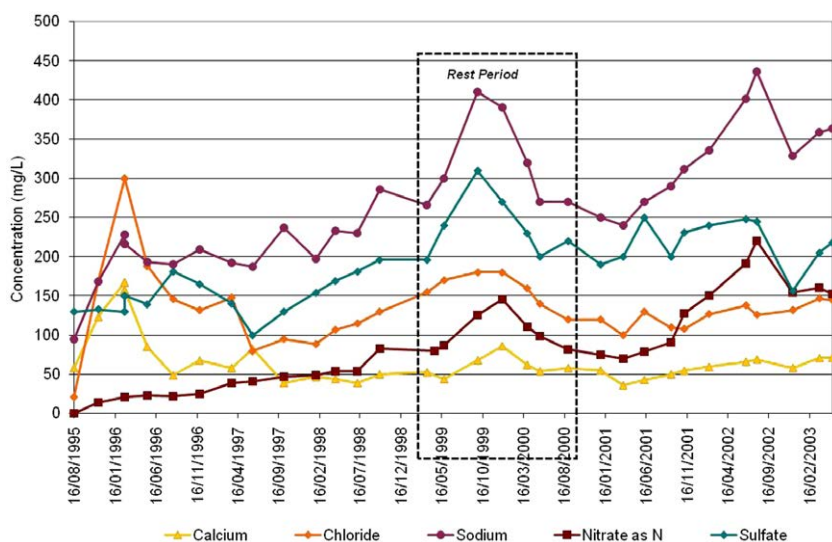**Fig. 2.** Monitoring data, heap pond. WAD cyanide and pH.

Fig. 3. Monitoring data, heap pond. Calcium, chloride, sodium, nitrate as N and sulfate.

toward the end of the rest period (Fig. 3). During the recirculation rinse phase, the majority of these constituents (i.e., calcium, chloride and sulfate) remain consistent and show very little change in response to rinsing. Conversely, sodium and nitrate concentrations gradually increase during rinsing. This trend suggests the concentration of sodium and nitrate will increase in response to saturation and evapoconcentration of the heap as precipitated salts are remobilized through the system during rinsing. However, these concentrations are still considered relatively dilute and appreciable salt formation in the future is unlikely. The observed peak in major solute concentration during the rest period most likely corresponds to meteoric rinsing of the rested pad.

The trends in metals and metalloid concentrations in the pregnant pond solution are shown in Figs. 4–6. As can be seen in Fig. 4, arsenic concentrations in the pregnant pond solution display a systematic increase to a maximum concentration of 2.19 mg/L during the initial leaching operation. During the rest period, arsenic concentrations decrease to 0.68 mg/L and then generally increase dur-

ing the recirculation rinse period at levels up to 1.57 mg/L. There were no significant changes in iron concentration in the pregnant pond solution, which remained less than 0.1 mg/L for the entire monitoring period (Fig. 4).

Fig. 5 shows mercury was mobilized during 1995–1999 at levels up to 0.494 mg/L. During the rest period the concentration of mercury in the pregnant pond solution decreased to 0.007 mg/L and during recirculation rinsing increased to about 0.08 mg/L. The observed spikes in mercury concentrations during the rest period most likely correspond to meteoric rinsing of the rested pad.

The trends in cadmium, copper, nickel and zinc concentrations in the pregnant pond solution are similar with higher concentrations in response to cyanide addition from 1995 to 1999 followed by a significant decrease during the rest period with many of the constituents occurring below detection limits (Fig. 6). A notable increase in these constituents occurs about a year after initiation of the recirculation rinse phase. This observation is also true for the metalloids, antimony and selenium. In general, all metals/metalloids occur at
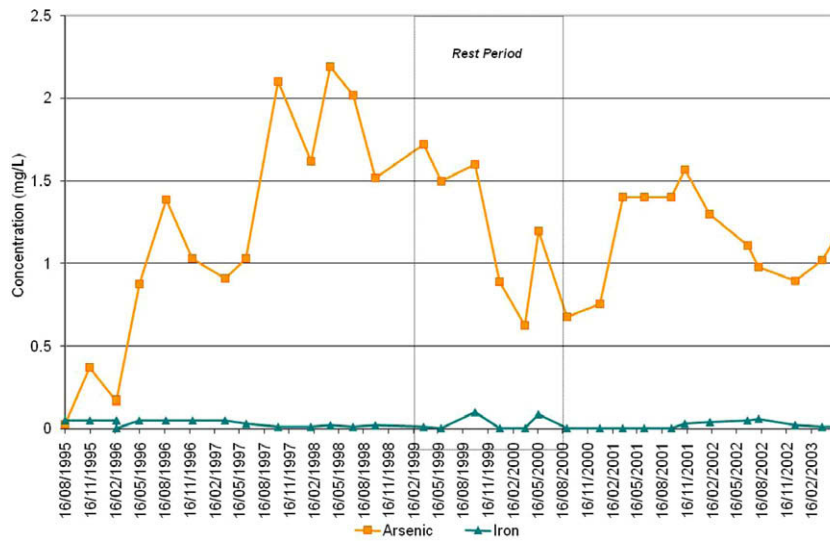
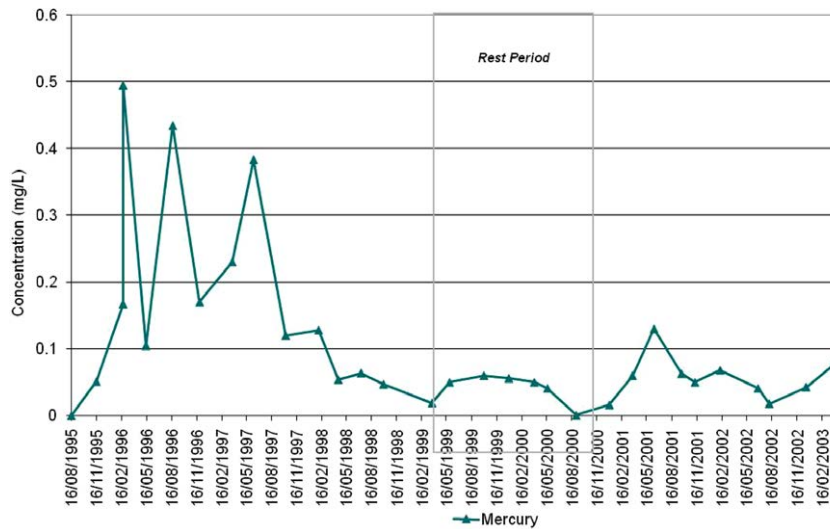**Fig. 4.** Monitoring data, heap pond. Arsenic and iron.

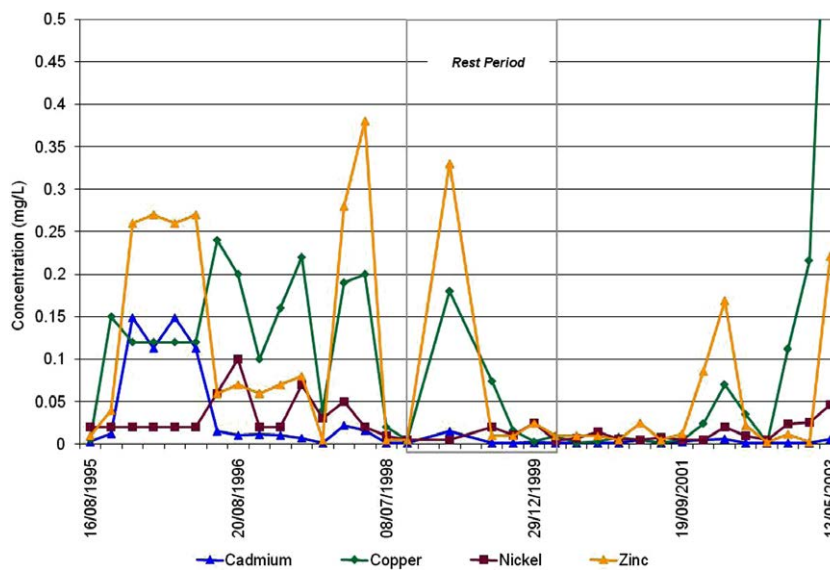**Fig. 5.** Monitoring data, heap pond. Mercury.

Fig. 6. Monitoring data, heap pond. Cadmium, copper, nickel and zinc.

concentrations at or near detection limits toward the end of the rest period and have increased since initiation of the recirculation rinse. However, this increase in metal/metalloid concentration after reactivation is much less than concentrations observed during the leaching operations from 1995 to 1999, with the exception of copper (Fig. 6). The leaching of secondary minerals dominated by copper and zinc correlating to a decrease in WAD cyanide and less so pH and an increase in arsenic and sulfate. This possibly reflects the dissolution of arsenate and sulfate minerals, possibly in response to meteoric rinsing. Although annually evaporation exceeds the ~240 mm of precipitation in spring and fall precipitation can exceed evaporation for short periods and hence the possibly flushing of soluble salts.

5. Column test results

A column rinsing test using spent ore from the Gold Acres Heap and barren solution from the site was conducted in order to assess

the geochemical mechanisms that are active during rinsing of the Gold Acres Heap.

The test column was monitored for seven rinse cycles of barren solution, one rinse cycle of freshwater, and two rinse cycles of recirculated freshwater. The change in effluent chemistry after each pore volume rinse indicates rinsing with recirculated barren solution has little to no effect on heap solution chemistry and rinsing with freshwater actually results in an increase in some of the priority constituents (i.e., constituents that commonly exceed the Nevada drinking water standard during routing heap solution monitoring). The trends in the test effluent chemistry are displayed graphically for key constituents in Figs. 7–12 and discussed in the following sections.

As can be seen in Fig. 7, the pH values remained fairly constant during the entire column test at about 9 s.u. Fig. 7 also shows initial WAD cyanide concentrations, of about 0.02 mg/L, generally decrease during the recycle rinse to less than the detection limit by pore volume 6. However, WAD cyanide concentrations significantly
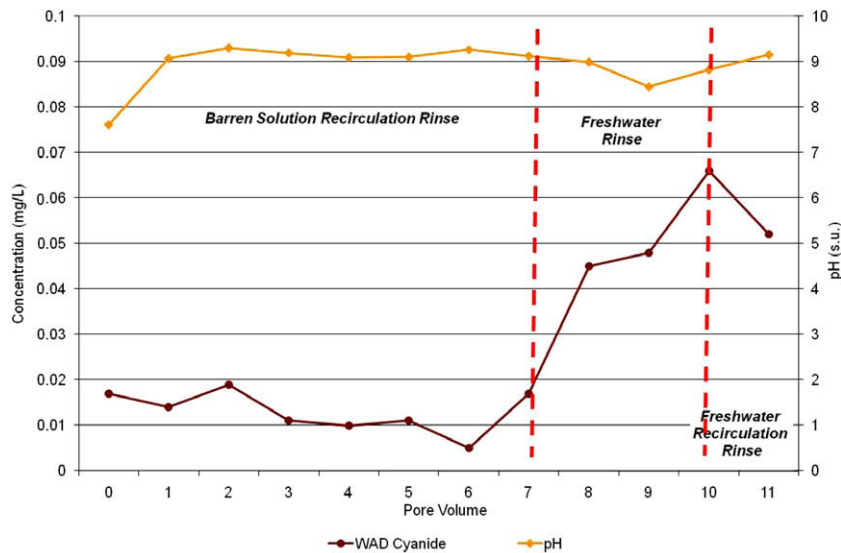

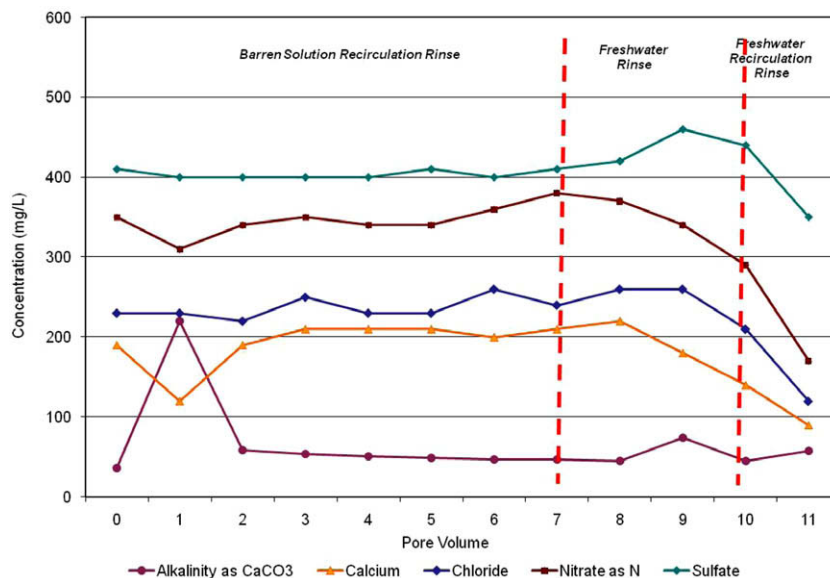**Fig. 7.** Results of pore volume column testwork, analysis for WAD cyanide and pH.

Fig. 8. Results of pore volume column testwork, analysis for alkalinity, calcium, chloride, nitrate and sulfate.
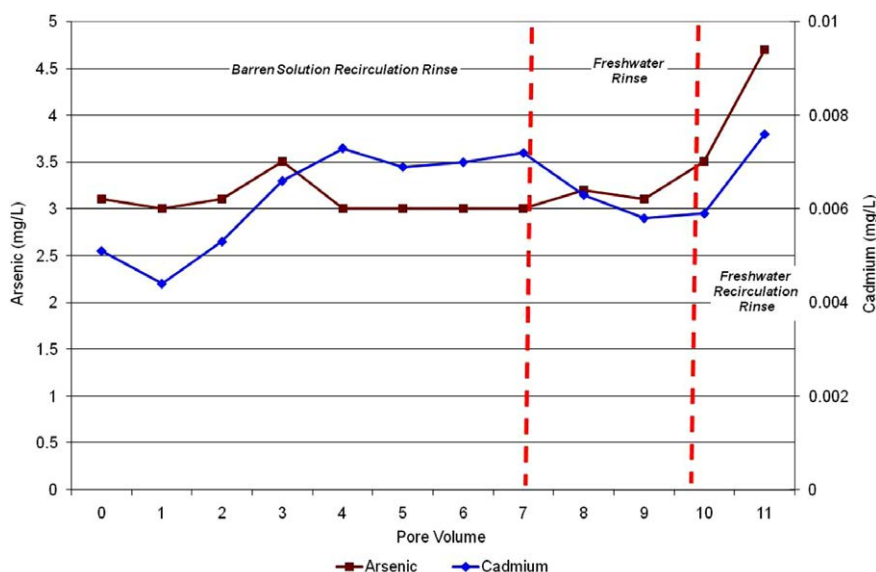
Fig. 9. Results of pore volume column testwork, analysis for arsenic and cadmium.
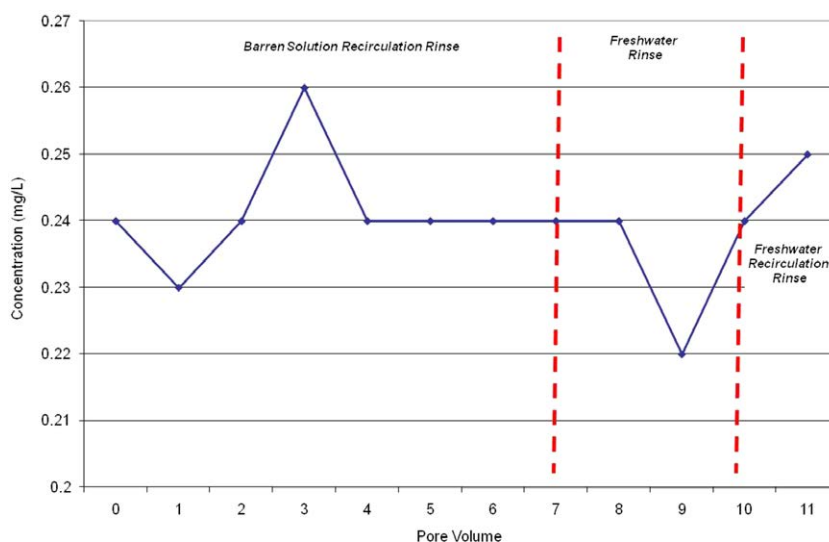

Fig. 10. Results of pore volume column testwork, analysis for molybdenum.

increase during the freshwater rinsing and freshwater recirculation to over 0.06 mg/L by pore volume 10. This increase indicates that rinsing with freshwater may influence speciation of otherwise stable and lower toxicity cyanide complexes (such as ferrocyanide). When these stable cyanide complexes breakdown they release cyanide that binds with transition metals, such as cadmium, to form more weak acid dissociable cyanide.

The concentration of major solutes including, calcium, chloride, nitrate and sulfate, showed little response during the barren solution recirculation portion of the column test (Fig. 8). During the final freshwater and freshwater recirculation rinses the major solute concentrations begin to decline, suggesting significant dilution is required to have any effect on these constituents. This explains why total dissolved solids (TDS) concentrations show little response during the barren solution recirculation rinse. Consequently, repeated flushing of meteoric water will continue to remove soluble components from the heap, negating any benefit of the rinsing process with respect to these constituents.

Alkalinity concentrations do not follow the same trend as the other major solutes shown in Fig. 8 due to the buffering capacity provided by the lime that was added to the column as well as buffering capacity provided by carbonate minerals that occur in the heap material. A significant release in alkalinity occurred after passing the first pore volume through the system. Following this initial flush, alkalinity concentrations remained stable during the remainder of the column test.

The change in metal and metalloid concentrations during the column rinsing test is shown in Figs. 9–12. Each of these constituents generally follow a similar trend and remain relatively constant during the barren solution recirculation rinse as well as the first freshwater rinse. During the second freshwater rinse and the subsequent recirculation rinses of freshwater, the majority of the metal and metalloid concentrations increase. Some exceptions to this trend include cobalt, which decreases upon further freshwater rinsing (Fig. 11) and chromium and manganese, which do not show any significant change during the entire column rinsing test (Fig. 11). Also, mercury concentrations were below analytical detection of 0.0001 mg/L during the most of column rinsing test (Fig. 12). However, mercury was detected in the rinsate following the final freshwater rinse, indicating
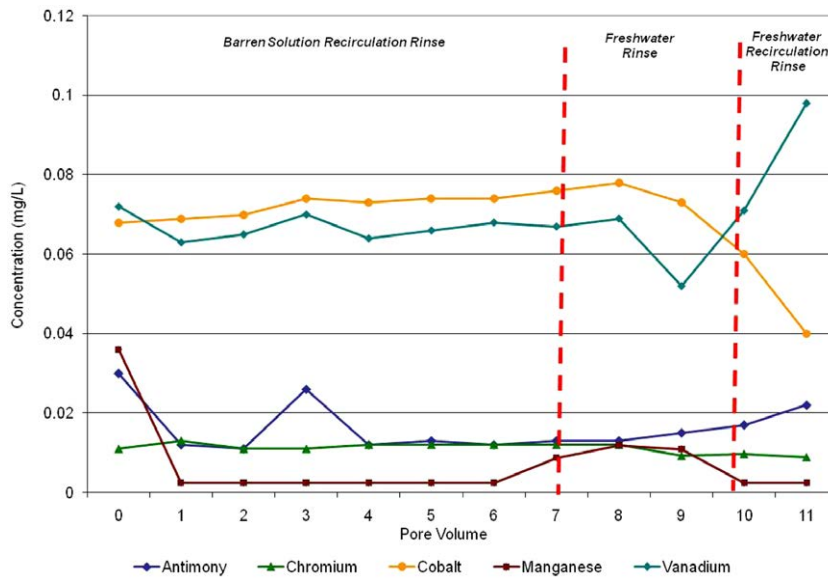
Fig. 11. Results of pore volume column testwork, analysis for antimony, chromium, cobalt, manganese and vanadium.
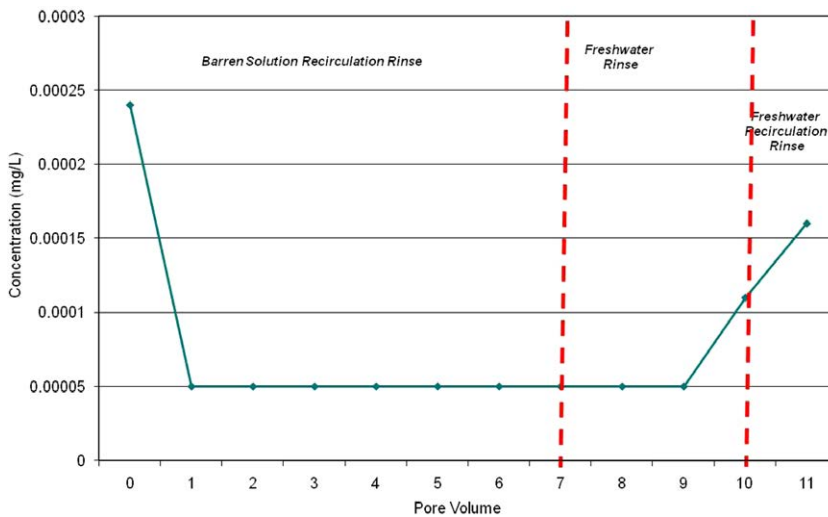

Fig. 12. Results of pore volume column testwork, analysis for mercury.

flushing of previously stable mercury species to concentrations of 0.00016 mg/L.

6. Environmental assessment of rinsed material

A two stage Meteoric Water Mobility Procedure (MWMP) extraction test has been conducted on both Gold Acres Heap material as received from the mine site as well as on heap material rinsed with eleven pore volumes during the column rinsing test. The Nevada MWMP test was developed to simulate the leaching of mine waste materials with meteoric water during high precipitation events that occur periodically under the generally more arid conditions that are normal for Nevada (NDEP, 1990). The results of the MWMP test can be used to identify the presence of leachable metals and readily soluble salts stored in the material as well as provide an indication of their availability for dissolution and transport in response to a precipitation event.

A two stage MWMP extraction is similar to standard Nevada MWMP procedures except that it consists of two applications of deionized water rather than one. The two phases of deionized water application were separated by an interim drain phase. The effluent collected at the end of each phase of the MWMP test was submitted to Wet Labs for Profile II analysis. The MWMP analytical results are provided in Table 3.

MWMP results generally show the majority of the constituents decrease in concentration between the first and second stage of the MWMP test for both pre-rinse and post-rinse samples. However, Phase 2 MWMP effluent from heap material rinsed with eleven pore volumes still contained concentrations of antimony, arsenic, cadmium and nitrate concentrations that exceed the respective Nevada drinking water standards (Table 3). Mercury (Phase 1 only) and pH values are also above Nevada drinking water standards in the rinsed heap MWMP extracts. However, nitrate concentrations in the MWMP effluent from the heap material rinsed with eleven pore volumes decrease to levels below the Nevada drinking water standard.

A comparison of MWMP results for the pre-rinse heap material to the post-rinse heap samples indicates constituents generally increase as a result of the multiple rinse phases. This data suggests the potential for constituent release increases with subsequent

Table 3
Current drinking water Nevada drinking water standard's versus MWMP extract data.

Parameter	Nevada drinking water standard	Heap master composite feed		Heap rinsed residue	
		Stage 1	Stage 2	Stage 1	Stage 2
Aluminum	0.05–0.2	–	–	–	–
Antimony	0.006	0.0098	–	–	0.0082
Arsenic	0.05	1.0	0.56	3.3	2.2
Barium	2.0	–	–	–	–
Beryllium	0.004	–	–	–	–
Cadmium	0.005	–	–	0.013	0.0088
Chloride	250–400	–	–	–	–
Chromium	0.1	–	–	–	–
Copper	1.3	–	–	–	–
Fluoride	2.0–4.0	–	–	–	–
Iron	0.3–0.6	–	–	–	–
Lead	0.015	–	–	–	–
Magnesium	125–150	–	–	–	–
Manganese	0.05–0.1	–	–	–	–
Mercury	0.002	–	–	0.0022	–
Nickel	0.1	–	–	–	–
Nitrate as N	10.0	11	–	–	–
pH (s.u.)	6.5–8.5	–	–	8.96	8.91
Selenium	0.05	–	–	–	–
Silver	0.1	–	–	–	–
Sulfate	250–500	–	–	–	–
Thallium	0.002	–	–	–	–
TDS	500–1000	–	–	–	–
WAD cyanide	0.2	–	–	–	–
Zinc	5.0	–	–	–	–

– Indicates constituent concentration is below the respective drinking water standard (Nevada drinking water standard).

rinsing episodes. The MWMP data indicates rinsing Gold Acres Heap material is not effective in reducing the potential for constituent mobilization from the unrinsed heap material. Additionally, constituents that currently exceed Nevada drinking water standards will remain above the respective standards regardless of rinsing activities.

7. Discussion

In order to predict the chemistry of future heap solution, a better understanding of the factors influencing the chemistry is necessary. In the case of the Gold Acres Heap, the rinsing test program suggests the following factors may influence the chemistry of the heap draindown:

- geochemistry of the ore material in the heap;
- chemistry of any amendments added to the ore such as lime, organic growth reagents, or suppressants;
- chemistry of the recycled water and meteoric recharge (the latter typically being low solute and neutral in Nevada); and
- residence time of the solution in the heap and the hydrology of the heap.

Each of these factors is significant to predicting future heap chemistry since they all influence the pH-redox conditions of the heap, which is the main control on heap solution chemistry. How each of these factors contribute to the overall chemistry of the Gold Acre Heap is discussed in greater detailed in the following sections.

7.1. Ore leachate geochemistry

The heap leach process is controlled by oxygen content since it is required for gold dissolution in cyanide solutions (Smith and Struhsacker, 1988; Miller et al., 1999). However, oxygenated water will also interact with other, more reactive mineralogical constituents of the gold-bearing ore (e.g., sulfide minerals).

Sulfide minerals exposed to oxygenated water will react when sufficient enthalpy has been introduced into the system to overcome the stability of the sulfide mineral. The finer the grain size of the mineral, the lower the order of crystallinity, or the greater contact between different sulfide minerals, the lower the enthalpy barrier and the quicker the oxidation reactions will occur. Results of the ICP analysis indicate the total sulfur content of the heap material is 0.04 wt% indicating the sulfide content is extremely low considering sulfates such as linarite, gypsum and brochantite that contribute to the total sulfur content are also present in the heap material.

Calcite and dolomite are important gangue mineral phases present in the Gold Acres ore and as such offer some buffering capacity of acid in solution. Significant net neutralizing potential is anticipated due to the presence of these minerals in the heap ore, at concentrations two orders of magnitude greater than the amount of sulfide present (i.e., sulfide minerals comprise approximately 0.1% of the ore used in the column rinsing testwork and calcite and dolomite content of the ore is approximately 12% and 8%, respectively).

Numerous other constituents occur in the heap ore and may interact with oxygenated water and become mobilized in solution. The accumulation of solutes in solution will eventually lead to the saturation with respect to some species. Consequently, these aqueous species will precipitate as secondary minerals such as arsenates, phosphates, carbonates, sulfates or hydroxides. Secondary minerals, that are relicts of geological in situ sulfide oxidation, are present in the Gold Acres Heap material. These minerals include adamite, birnessite, brochantite, cerussite, chlorargyite, goethite, gypsum, secondary gold, libethenite, linarite, malachite, metastibnite, scorodite, smithsonite and variscite. These minerals could potentially release metal constituents and metalloids upon dissolution by oxygenated water.

In addition, several oxyanions such as vanadante, arsenate, antimonite, chromate, molybdenate and selenite occur as surface adsorbed species to oxide minerals such as goethite and birnessite, or phyllosilicates such as chlorite, nontronite, kaolinite and illite. Some of the mobilized solutes can be attenuated through surface adsorption onto mineral surfaces, for example the adsorption of iron hydroxides by clays or the adsorption of arsenic species by

goethite. This is the process of element binding at the mineral solution interface and is pH dependent (Bowell, 1994). As a result, many oxide surfaces alternate from being positive at low pH (i.e., attracting anions) to negative at high pH (i.e., attracting cations; Dzomak and Morel, 1990).

Heap drainage chemistry, particularly the level of arsenic and heavy metals has been shown to be influenced by adsorption onto precipitated hydrous ferric oxide, or HFO (this may also include minerals like schwertmannite, goethite and jarosite amongst others; Fuge et al., 1994; Bigham, 1994; Bowell et al., 1996). It should be noted that in many acidic environments, flushing or dissolution of HFO can lead to high arsenic concentrations in solution as well as competition from complexing ions mobilizing arsenic–oxyanions.

An important control on the diversity of the precipitated mineral assemblage is pH. For example during the oxidation of sulfides at low pH, Fe oxyhydroxides, scorodite and sulfates are formed, while at higher pH other salts such as Ca-arsenates, smithsonite and malachite are precipitated. Clay minerals such as smectite $(Na_3(Al, Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O)$ may also be responsible for the concentration of base metals in these ores. Where they are intermixed with HFO they promote cation adsorption over a wider pH range than with pure Fe oxyhydroxides (Parfitt, 1978).

The chemical form of adsorbed species is highly dependent on the redox state of the heap. It follows that these adsorbed species are more stable under operating conditions (i.e., active leaching or recirculation of barren solution). Flushing the heap with either recirculation rinse solution or freshwater results in the removal of cyanide and gold from the system, which ultimately changes the pH-redox condition of the heap. Consequently, the mobilization of adsorbed constituent is more likely to occur under these conditions. In essence, this is what is being observed in the rinsing testwork results.

7.2. Ore amendments

The Gold Acres Heap was agglomerated with lime at a rate of 0.8 kg/t of lime during processing in order to maintain a pH above 10.5 s.u. Sodium cyanide was applied to the heap at an equivalent application of 0.1 kg/t. The addition of these amendments results in a significant and immediate change in the pH-redox conditions of the heap.

The presence of free lime in the Gold Acres Heap has the potential effect of buffering pH to above pH 9 s.u. As expected, heap monitoring data collected for the pregnant pond had pH values within this range due to the presence of free lime. However pH values observed during the rinsing testwork were lower than excepted (i.e., pH values of 8 ± 1 were common) indicating carbonate minerals present in the heap material play a much more important role in the buffering capacity of the material than the free lime. This is because the lime in the residual heap material is partially to totally blinded by a rind of calcite and gypsum that has formed in response to the reaction of atmospheric CO_2 and process solutions (that has high HCO_3 and SO_4 concentrations) with the lime. The net effect of this blinding is that the consumption of lime during rinsing is likely to be slow and pH will remain buffered in the pH 8–9 s.u. range since an almost limitless supply of carbonate exists in the material (either as geological component of the precursor ore or an artifact of atmospheric reaction and lime consumption by process fluids). At this pH range, desorption of oxyanions would be favored as discussed above. As a result, additional rinsing would only promote continued desorption and release of oxyanions such as arsenic, antimony, chromium and selenium.

In terms of cyanide chemistry, the heap monitoring data demonstrates that once cyanide application is suspended, the WAD

cyanide concentration quickly decreases to within regulatory limits. The results of the column test work suggest a residual WAD CN concentration of 0.01–0.02 mg/L continues to be released over the long-term and concentration of WAD CN will eventually increase upon subsequent rinsing episodes as indicated by a spike in WAD CN concentrations during the column test procedure of 0.068 mg/L during the last phase of the test rinse. It is postulated that this spike in cyanide concentration is the product of de-stabilization of ferrocyanide and ferricyanide that would otherwise have degraded, in the absence of sunlight and significant oxygen, at an extremely low rate releasing negligible levels of cyanide due to extremely low solubility, (i.e., solubility on the order of 10^{-4} µg/L as opposed to "mg/L–µg/L range") of most components of WAD CN (Smith and Mudder, 1991).

Consequently, prolonged rinsing of the heap has the potential to increase the rate of cyanide release to concentrations above that observed in the base flow. An additional consideration is that mercury is present within the heap material and mercury concentrations are correlative with WAD cyanide concentrations. It is possible that mercury hydrolyzes and sorbs to mineral surfaces when WAD cyanide is initially removed from the system and if WAD cyanide is reintroduced to the system by the dissolution of ferro- and ferricyanides, the potential exists for mercury to be desorbed and released. This co-dependence of mercury concentrations on the presence of WAD cyanide may explain the observed trend in mercury concentrations during the column test. Similar observations have been made in other studies (Miller et al., 1999).

7.3. Rinse water chemistry

The chemistry of the recycled water has a direct impact on the pH-redox condition of the heap and thus, the final draindown chemistry. The prolonged rinsing of heap material, using either a recycle or fresh water rinse solution, will likely alter the pH-redox conditions within the heap and lead to release of constituents through desorption of adsorbed components, dissolution of secondary minerals, and buffering reactions resulting from sulfide oxidation. Consequently, it is the change in pH-redox chemistry that drives the geochemical system of the heap. The more often these changes occur as a result of repeated rinsing of the heap material, the less likely attenuation will occur and the more likely dissolution, desorption and physical flushing of solutes will continue to occur.

This relationship between rinse water chemistry and resulting heap draindown chemistry was demonstrated several times during the Gold Acres rinsing test program. First, the recirculation of barren solution through the test rinse column resulted in an increase in the concentration of numerous constituents including antimony, arsenic, boron, barium, cadmium, calcium, chloride, chromium, cobalt, fluoride, manganese, molybdenum, nitrate, potassium, sodium, strontium, sulfate, total dissolved solids and vanadium. Additionally, the prolonged rinsing of heap material with multiple pore volumes of freshwater resulted an increase in constituents. In both cases, the pH-redox conditions of the heap were altered due to a change in the rinse water chemistry being applied. This change in pH-redox conditions lead to the release of constituents through desorption of adsorbed components, dissolution of secondary minerals and buffering reactions (i.e., pH changes) as a result of sulfide oxidation.

7.4. Residence time

During operations, the pores in the leaching field are close to saturation. Leach solutions flush and react with both coarse and fine grained particles (less than 5 mm). However, draindown fluid flow is dominated by flow in the fine grained fraction and it is this

fraction that is important in terms of controlling long-term water quality. Residence time in this fraction is generally longer than in the coarser material and thus there is greater potential for equilibrium to be attained with relatively constant pH-redox conditions.

Fluid flow within the rinsing test columns is likely to be much more homogenous than what occurs under actual heap conditions. As a result, the data from the column test probably represents the upper limits of the effects of flushing on heap chemistry.

Under normal heap conditions, the change in solute concentrations as a result of flushing would be less significant as demonstrated by the results of the field scale rinsing test conducted at the Gold Acres Heap. During this test, no significant change in constituent loading was observed. This may be related to the relatively heterogeneous nature of the heap material and resulting increased residence time and stable pH-redox conditions of the entrained moisture in the heap. Flushing the heap with high volumes of freshwater could change this scenario by flushing both the coarse and fine grained fraction of the material. This would not only decrease the residence time of entrained water in both fractions but could also result in the physical removal of particles from the heap, some of which would contribute to the "total" fraction of water quality. In addition, the effect of these additional solutes and the changes in pH-redox conditions could potentially result in dissolution of some minerals, trace element leaching from others and desorption of species complexed on oxide and clay minerals. The net effect would be an increased need for water management strategies down gradient of the heap as a result of the degraded water that is produced during a high volume flush.

8. Conclusions

Results of the field rinsing test indicate rinsing the Gold Acres Heap with recirculated barren solution does not have any benefit in decreasing the solute load of the heap. In particular, arsenic, cadmium, chloride, nitrate and total dissolved solids concentrations do not decrease in response to multiple rinse cycles. This conclusion is supported by empirical data generated during the column rinsing test, which indicates rising with seven consecutive barren solution recirculation rinse cycles results in no significant change in heap solution chemistry. Furthermore, an increase in select constituents during the final freshwater recirculation rinses (pore volumes 10 and 11) of the column test indicates multiple freshwater rinse cycles will change the pH-redox conditions of the heap and adsorbed constituents that were previously stable may become re-mobilized. In support of this conclusion, MWMP data from both pre-rinse heap material and heap material that was rinsed with multiple pore volumes, suggests the potential for constituent release increases with increasing pore volume rinse cycles.

A comparison between the column test results and the monitoring data collected during field scale rinsing, indicates rinsing oxide ore from the Pipeline deposit with recirculated barren solution is not effective in decreasing solute loadings, in particular arsenic, cadmium, chloride, nitrate and total dissolved solids. Antimony concentrations decreased throughout both tests but remained relatively high when compared to Nevada drinking water standard. Additionally, the column test indicates applying multiple freshwater rinses to the heap will only exacerbate the release of constituents by changing the pH-redox conditions of the heap. Consequently, rinsing heap facilities at the Crescent Valley Operations is not considered a viable method for heap closure and long-term chemical stabilization of the spent oxide ore. Rather, the Gold Acres Heap case study indicates rinsing heap material with recirculation barren solution will produce no significant change (i.e., improvement) in the heap solution chemistry. In addition, rinsing

with freshwater will result in a higher risk for potential degradation than not rinsing at all.

Additionally, two stage MWMP tests were conducted on both pre-rinse heap material and heap material that was rinsed with multiple pore volumes in order to assess the change in the potential for mobilization of constituents as a result of rinsing. The MWMP test results confirm the high mobility of antimony and arsenic from heap material and indicate the potential for constituent release increases with multiple rinse cycles.

In summary, multiple rinsing of a heap does not result in improved water quality as indicated by Miller et al. (1999) but rather reduces long-term water quality due to changes in the pH-redox environment of the heap. It is postulated that rinsing after reduction of WAD cyanide from the heap material only disperses other constituents rather than removing them. Geological abundance in the heap ore coupled with the low release rates of many constituents will result in long-term leaching by rinsing.

Acknowledgements

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