Infiltration-Diverting Cap and Full-Scale Biochemical Reactor Operation at the Iron King/Copper Chief Mine, Arizona

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Abstract A geomembrane and soil cap over a glory hole and a full-scale Passive Treatment System (PTS) including a biochemical reactor (BCR) were constructed at the Iron King/Copper Chief Mine near Cottonwood, Arizona, located on Mingus Mountain, as part of a voluntary remediation effort to mitigate mining influenced water (MIW) from two former, historic, underground copper mines. Construction of the glory hole area cap, designed to minimize or prevent rainfall and runoff infiltration into the underground mine workings, was completed in 2007. The borrow site that provided the earthen fill for cap construction created a bench for the subsequent construction of the PTS in the mountainous terrain.

Keywords ARD prevention, passive treatment, mining influenced water

Introduction

The Iron King/Copper Chief Mine (IK/CC) site is located in central Yavapai County, Arizona, approximately 6.5 km west of Cottonwood and 140 km north of Phoenix, Arizona, USA. Production from historic mining operations in the area began in 1904 and ended in 1945 (Clear Creek Associates 2001). There are two hydrologically distinct areas on the site: the Copper Chief/Upper Iron King (UIK), and the Lower Iron King (LIK; . Fig. 1). Three concrete bulkheads impound mining influenced water (MIW) from the two areas, creating two separate underground mine pools that exhibit different chemical characteristics.

Subsequent to the concrete bulkheads' installation, the MIW that was collected downgradient in the UIK and LIK was managed by pumping it back up to the glory hole (Fig. 1). The continued MIW management constituted

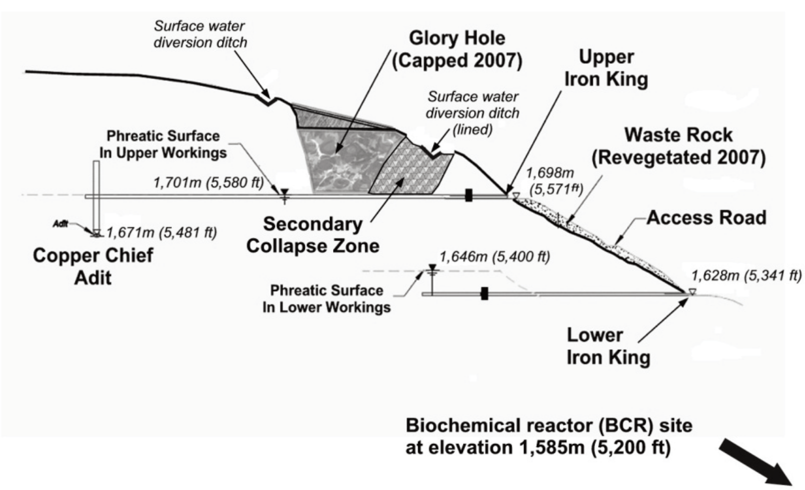

Fig. 1 *Underground mine schematic cross section*

a long-term maintenance issue and alternative remedies to pumping were considered. The passive treatment process was selected as the preferred alternative. Through the Voluntary Remediation Program (VRP), property owners investigate or clean up a contaminated site in cooperation with the Arizona Department of Environmental Quality (ADEQ). The VRP results in a streamlined process for program participants who work with a single point of contact at ADEQ to address applicable cross-program remediation efforts. The ADEQ reviews these voluntary remedial actions and provides a closure document for successful site remediation that is accepted by all relevant ADEQ programs.

PTS construction commenced in the first quarter of 2009 and was concluded about 60 days later. The BCR design was based on the positive results of an in-field pilot study conducted in 2006. The BCR cell was configured as a top-fed vertical flow reactor; the feed to the system is commingled MIW from the two mines that is conveyed via a 500 m long subsurface pipeline. The BCR itself is also situated subsurface, with a lightweight fill cover consisting of plastic chambers and wood chips, a geomembrane liner, and topped off with 46 cm of plant growth medium which was hydroseeded. The BCR output reports to a small, concrete-lined mixing pond which feeds a multi-terraced, aerobic polishing cell that is populated with native vegetation. The system was commissioned in mid-2009, is now fully functional and about three years of operational data has been collected, analyzed and will be related via this paper. Up to date operational data and the beneficial effects of the glory hole cover on mitigating MIW will be discussed.

Since March 2010, the PTS has operated in a "steady state" condition. This paper provides information on the glory hole cover and documents selected field and analytical data collected from the PTS as of the end of December 2012.

Glory hole cover objectives and description

Prior to construction of the glory hole cover, the IKCC site contained three principal MIW management-related features:

- Concrete bulkheads in the LIK adit, UIK adit, and the Copper Chief adit,
- Bulkhead seepage collection system located in the UIK adit with associated conveyance piping to the LIK adit pool, and
- LIK "primary" pump back system with associated piping to the glory hole.

The surface features of the glory hole area allowed rainfall and snowmelt to infiltrate into the UIK/Copper Chief mine workings. Subsidence cracks and surface depressions were also suspected of providing preferential pathways for rain water to percolate into the mine workings and recharge the UIK/Copper Chief mine pool, especially during the Arizona summer 'monsoon' season.

Fig.2 *Glory hole construction photo (2007)*

Fig. 3 *Post-construction photo (2009)*

Capping the glory hole area, sealing the mine subsidence features, and diverting runoff into natural drainages adjacent to the IK/CC site were obvious remedies to minimize the amount of MIW that the PTS would ultimately receive. While unable to prove in advance with any certainty, the glory hole area cover coupled with the cessation of pumping back bulkhead seepage might also result in improved MIW quality, especially in the UIK/Copper Chief mine pool.

A photo showing the geomembrane feature of the glory hole area cap under construction is provided in Fig. 2; a post-construction photo (2009) is provided in Fig. 3.

The key activities of the glory hole area cap and run-on diversion effort include:

- Placing native soil backfill to design subgrade (the borrow site for this material became the site for the subsequent construction of the PTS in 2009),
- Constructing diversion ditches above the highwall to divert run-on away from the 0.8 ha capped zone,
- Placing 60 mm thick Linear Low Density Polyethylene (LLDPE) geomembrane (7,500 m^2) sandwiched between protective geotextile,
- Rebuilding the glory hole for more easily receiving MIW pump-back from the LIK adit until the PTS was commissioned,
- Sealing the LLDPE to the power-washed rock face of the highwall with polyurethane foam (PUF),
- Covering the geomembrane with: 12 in (25.2 cm) of native soil plant growth medium atop an identical thickness of borrow material fill (both harvested from the PTS/borrow site),
- PUF sealing of subsidence cracks,
- Re-grading surface depressions that could capture rainwater and enhance infiltration,
- Constructing geomembrane-lined diversion ditches across a secondary subsidence zone, and
- Implementing ancillary surface water drainage improvements (road culvert, riprap).

Passive treatment system objectives and description

The specific objectives of the PTS were to: remove target metals (*e.g.* iron, copper, zinc, cadmium, etc.) as sulfide precipitates, remove aluminum as a hydroxy-sulphate, remove sulfate by reduction to dissolved sulfide ion, add alkalinity to the MIW in the form of bicarbonate, precipitate manganese as an oxide (the common mineral pyrolusite [MnO_2]), and maintain the pH at a value of 6 or above.

The design of the PTS was based on the results from the bench-scale study, available site topography, and previous experience from other PTS design and construction projects. The PTS is designed to treat up to 26.5 L/min (7 gpm) of commingled MIW collected from both the UIK and LIK adits.

Prior to and during the PTS construction, MIW collected in both the UIK and LIK adits was pumped through a 76 mm (3 in) diameter HDPE pipeline to the existing glory hole that was rebuilt in conjunction with the glory hole area capping project in 2007.

In summary, the PTS consists of the following key components as shown schematically in Fig. 4:

- An underground "mixing and settling zone" inside the LIK adit,
- Buried pipelines to convey water (both treated and untreated) throughout the system year-round,
- A covered BCR, with cleanouts and sampling wells,
- A mixing pond, including a piping by-pass channel to prevent the possibility of embankment overtopping during a large rain event,
- A six-terraced aerobic polishing cell (APC) with irrigation water distribution and collection system, and

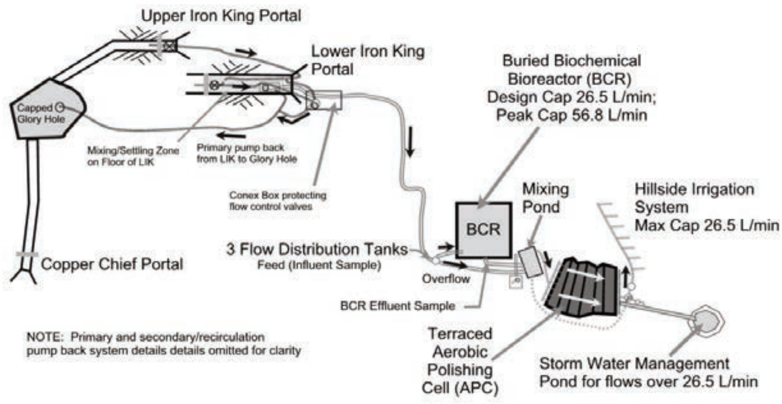

Fig. 4 *Passive treatment system (PTS) schematic*

- A storm water pond and associated storm water channel.

Details of the PTS design, construction, initial performance, and sampling point details are provided in Buchanan, *et al.* 2011.

Flow rate responses to rainfall

Estimating precise MIW flow data prior to the construction of the glory hole area cover was complicated by the pump back operations. However, site personnel recollections reflect a close and nearly instantaneous correlation of pumping effort in response to rainfall/snowmelt. After the cessation of pump back operations and the draining of the IK/CC mine pools, flow rates were relatively steady at about 7.6 L/min (2 gpm). Interestingly, a 74 day dry interval in mid-2012 appeared to suppress the flow rate to the PTS to nearly zero. When the drought broke in mid-July 2012, the PTS influent flow rate response lagged the 47 mm (1.86 in) storm event by a week. However, the peak flow rate measured, 23.8 L/min (6.3 gpm), quickly declined to about a third of that value. The glory hole area cover and associated diversions appear to be functioning as intended from a physical perspective by moderating the flow volume requiring treatment.

Mine pool chemistry changes

Since the PTS commissioning, efforts to drain down the IK/CC MIW pools had been a project priority to reach “steady state” operation. This condition was effectively achieved in the third and fourth quarters of 2010. It was interesting at the time to note that the MIW influent data for certain field parameters (pH and conductivity) improved in response to a decreasing contribution of Upper Iron King/Copper Chief MIW which had slowed to a relative trickle. This situation is also reflected in metals concentrations in PTS influent samples (collected every six months) as shown in Table 1.

Improvements in MIW influent chemistry are also attributable to source control measures (*e.g.* glory hole area cap, secondary subsidence zone sealing, and surface water diversion channels) that were implemented at the site in 2007 and the cessation of “primary” pump back activities to the glory hole as the PTS was commissioned. The metal contribution of UIK/Copper Chief MIW to the PTS influent did in fact decrease and the operational load on the BCR decreased as well. It is uncertain how the trend will continue as the iron and aluminum concentrations are negligible as of the end of 2012 and the PTS influent pH is 7.4.

Passive treatment system performance

The primary PTS performance parameters are those with typical elevated influent concentrations that contribute to mineral acidity; *i.e.* aluminum, iron, copper, zinc, cadmium, and manganese. Also included are sulfate and cal-

Parameter	Upper IK (Mar. '10)	Lower IK (Mar. '10)	Comb. UIK & LIK (Infl.) (Dec. '12)	BCR Effluent (Dec. '12)	APC (Terrace 1) (Dec. '12)
pH (—)	2.57	5.94	7.4	6.91	7.81
Aluminum	25.7	<0.03	0.10	0.13	0.05
Iron	342	16.3	<0.02	0.11	0.08
Copper	82.1	1.34	1.17	<0.01	0.08
Zinc	96.4	15.4	14.0	<0.01	0.58
Cadmium	0.22	0.077	0.047	<0.005	<0.005
Manganese	52.5	6.53	7.62	6.07	6.08
Calcium	465	253	287	326	287
Sulfate[1]	2600	890	1244	491	569

[1] Sulfate values are from March 2009 analyses (prior to PTS startup); units for ions in mg/L

Table 1 *Typical chemistry for primary parameters*

cium as these parameters provide indicators relevant to the overall performance of the BCR portion of the PTS. Data listed in Table 1 reflect the MIW chemistries from the two mines in early 2010 (several months after start-up), the commingled PTS influent, and BCR effluent in December 2012.

pH improvements and metals removal in the PTS

Field pH values measured at the PTS influent, BCR effluent, and Irrigation Water observed on the APC terraces are shown on Fig. 5.

Data provided in Fig. 5 indicate that the PTS clearly improved the pH of the commingled UIK and LIK MIWs during the observation period. Also, the influent MIW chemistry appears to be improving. This improvement is visually evident at the PTS site in a v-notch weir that measures influent flow rate immediately up-gradient of the BCR. Staining on the weir has changed in appearance from a red, iron-oxide dominated coloration to a turquoise color that is consistent with a lack of iron and/or aluminum and the continued presence of copper (Table 1).

Combined metal removal efficiencies for dissolved iron, aluminium, zinc, copper, and cadmium exhibited in the BCR have varied from 73 % to 97 % since start up; the average removal rate during the last two years of steady-state operation (five sampling events) has been 95.7 %. Recently, the decreasing presence of iron and aluminum in the influent has

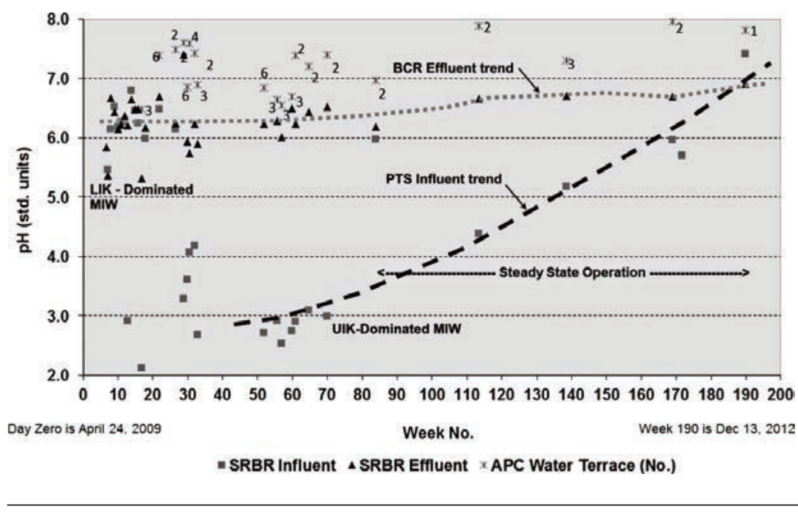

Fig. 5 *PTS pH data and trends*

resulted in a removal efficiency value of 93.1 % in the BCR which is representative of the combined removal of zinc, copper, and cadmium. Additional metal polishing also occurs in the APC feature of the PTS in the form of (oxidative) precipitated manganese (pyrolusite).

Sulfate removal in the BCR has been consistent since start-up. During the two years of steady- state operation, sulfate decreases of about 620 mg/L (ranging from 370 to 753 mg/L) have occurred in the BCR. Sulfate reduction rates were typically less than the benchmark 0.3 mol/d/m^3 of substrate as cited by Wildeman *et al.* (1993). Sulfate reduction ranged from 0.08 to 0.04 mol/d/m^3 during steady state operation. In comparison, metal loading during the same interval ranged from 0.05 to 0.0016 mol/d/m^3; the lower value was derived from analytical data associated with the December 2012 sampling event.

BCR substrate longevity estimates

Organic carbon in the form of wood chips, sawdust and hay, and alkalinity in the form of limestone sand are the main consumable components of the BCR substrate. The carbon "reservoir" is estimated to be about 128t; the accompanying limestone mass is about 158t. Sulfate reduction rates and limestone dissolution rates (inferred from calcium concentration increases in the BCR effluent compared to the influent – Table 1) were used to estimate the longevity of the substrate with respect to carbon and alkalinity, respectively. Conservative estimates revealed that about 30 years of substrate functionality remain. The analysis further suggested that the carbon reservoir in the substrate will be depleted well before the limestone reservoir.

Performance summary

Key observations relative to PTS operation follow. Since start up in 2009 to December 2012:

- about 18,500 m^3 (4.9 MUS.liq.gal) of MIW has been delivered to the PTS,
- dissolved removal efficiency of the BCR for the major MIW parameters (iron, aluminum, zinc, copper and cadmium, combined) ranged from about 73 % to 97 %,
- influent MIW pH improved from an initial value of about 2.5 to about 7.4, and
- during steady-state operation (Mar. '10 to Dec. '12), the PTS effluent chemistry exhibited only minor changes in response to improvements in the MIW influent chemistry, and
- during steady-state operation, APC samples exhibited a pH range of 7.0 to 8.0

Concluding remarks

The IK/CC PTS was completed under the ADEQ-VRP program in about six months at a cost of approximately $US1.6 million. Since its commissioning three years ago, it has met expectations. Average analytical results indicate greater than 95 % attenuation of target metals under steady-state conditions. The sulfate reduction is consistent with metals loading and the design. The current estimated life cycle is about 30 years, which is about a decade longer than initial expectations. Generally, only routine maintenance has been required. With the improvement in MIW influent quality, previous influent pipeline scaling issues are expected to be minimal.

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