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Full-scale sulphate-reducing bioreactor at the Iron King/Copper Chief Mine, USA

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Abstract

A full-scale passive treatment system (PTS) including a sulphate-reducing bioreactor (SRBR) was constructed at the Iron King/Copper Chief Mine (IKCC) near Cottonwood, Arizona, as part of a voluntary remediation effort to implement this innovative technology for passively treating mining influenced water (MIW) from two former, historic, underground copper mines. Construction commenced in the first quarter of 2009 and was concluded by the end of the second quarter. The SRBR design was based on the positive results of an in-field pilot study conducted in 2006. The SRBR 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 SRBR itself is also situated subsurface, with a lightweight fill cover consisting of a pumice layer overlain by wood chips, a geo-membrane liner, and topped off with 46 cm of plant growth medium which was hydro-seeded. The SRBR output reports to a small, concrete-lined mixing pond which inputs to a multi-terraced, aerobic polishing cell (APC) that is populated with native vegetation. Passively treated MIW that sporadically reports to the bottom of the APC is used to irrigate native vegetation adjacent to the arid site. The system was commissioned in mid 2009, is now fully functional, and over one year of operational data has been collected, analysed and will be related via this paper.

1 Introduction

The Iron King/Copper Chief Mine (IKCC) site is located in central Yavapai County, Arizona, approximately 6.5 km west of Cottonwood and 140 km north of Phoenix, Arizona, USA (Figure 1). Production from historic mining operations in the area began in 1904 and ended in 1945 (CCA, 2001). There are two hydrologically distinct areas on the site: the Copper Chief/Upper Iron King (UIK), and the Lower Iron King (LIK) (Figure 2). Three concrete bulkheads impound mining influenced water (MIW) from the two areas, creating two separate underground pools that exhibit different chemical characteristics.

Subsequent to the concrete bulkheads' installation, the MIW that was collected down-gradient in the UIK and LIK was managed by pumping it back up to the Glory Hole (Figure 2). The continued MIW management constituted 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 Programme (VRP), property owners, prospective purchasers and other interested parties 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 programme participants who work with a single point of contact at ADEQ to address applicable cross-programme 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 programmes.

This paper documents the field and analytical data collected as of the end of December 2010, while following the sampling and analysis plan that was provided in an operation and maintenance (O&M).

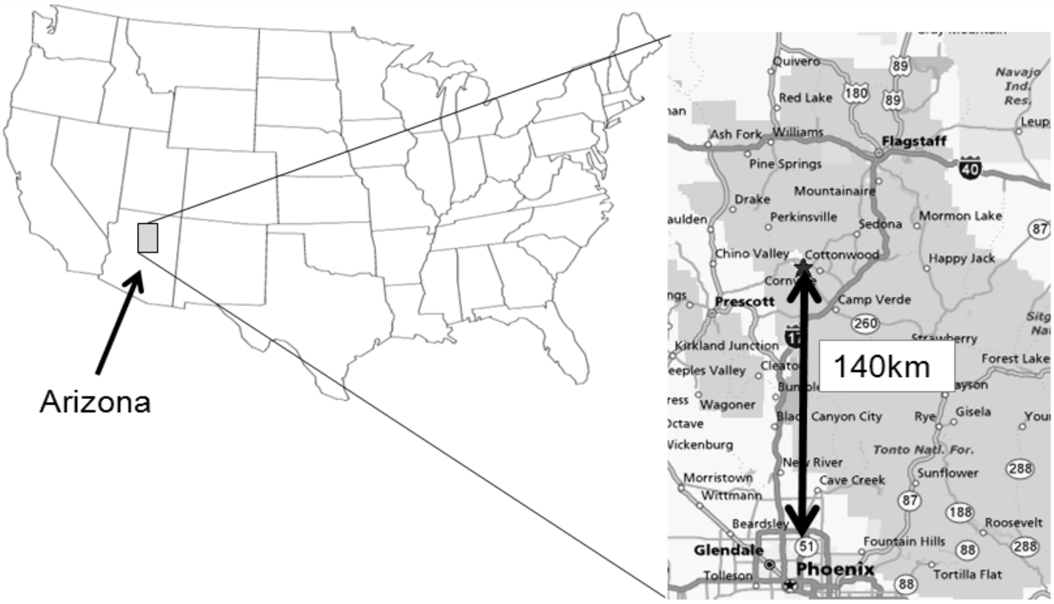


Figure 1 Site vicinity

The majority of the Iron King passive treatment system (PTS) was constructed during the months of March through June 2009. System commissioning, additional modifications, adjustments, and improvements were undertaken between July 2009 and March 2010. Since March 2010, the PTS has operated in a "steady state" condition.

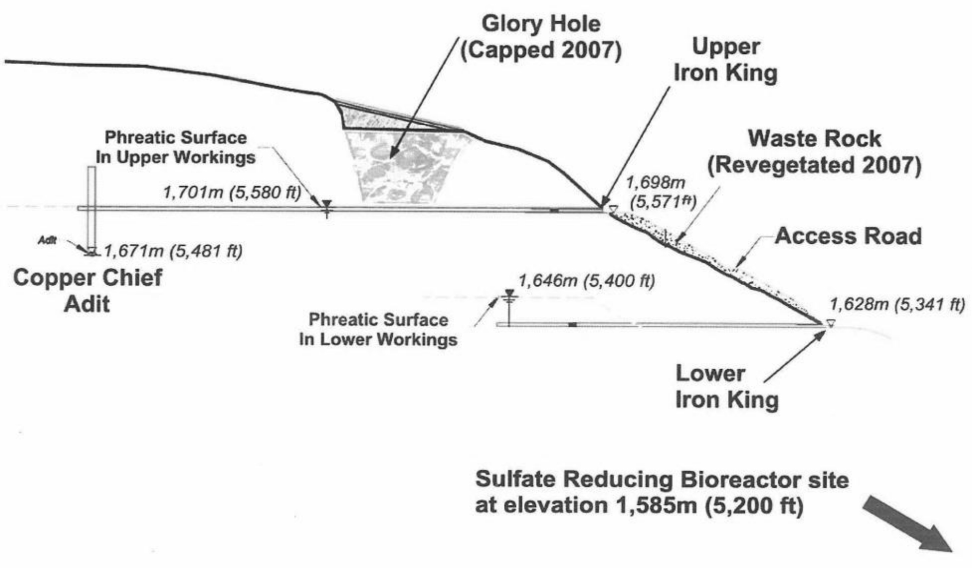


Figure 2 Underground mine schematic cross-section

2 System objectives and description

Specific objectives of the PTS are to: remove target heavy metals (e.g. iron, copper, zinc, cadmium, etc.) as sulphide precipitates, remove aluminium as a hydroxy-sulphate, remove sulphate by reduction to dissolved sulphide 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.

Design of the PTS was based on the results from the bench-scale study (GAI, 2006), available site topography, and previous experience from other PTS design and construction projects. The PTS is designed to treat up to 26.5 litres per minute of commingled MIW collected from both the UIK and LIK adits.

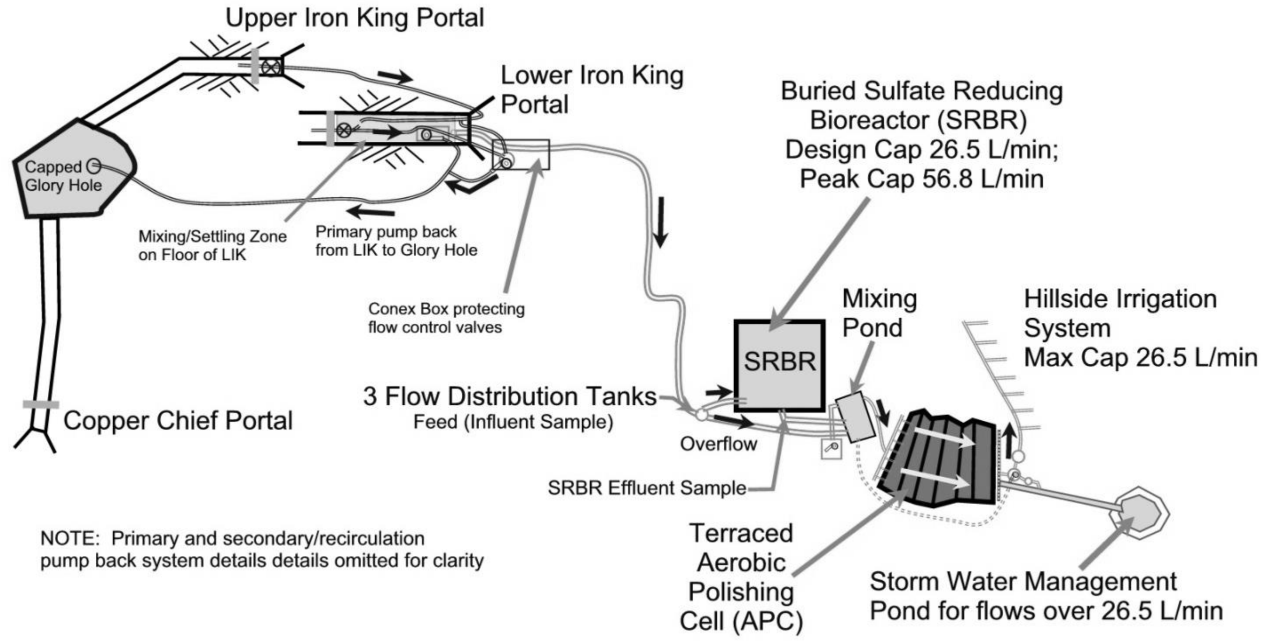
Prior to construction of the PTS, the Iron King site contained four principal MIW management-related features:

- Glory Hole cap.
- 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.
- LIK "primary" pump back system with associated piping to the Glory Hole.

Prior to and during the PTS construction, MIW collected in both the Upper and Lower Iron King adits was pumped through a 7.6 mm diameter HDPE pipeline to a sub-surface sump in the existing Glory Hole that was rebuilt in conjunction with the Glory Hole capping project in 2007.

In summary, the PTS consists of the following key components as shown schematically in Figure 3:

- 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 SRBR, 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.
- A stormwater pond and associated stormwater channel.



NOTE: Primary and secondary/recirculation pump back system details details omitted for clarity

Figure 3 PTS schematic

The following criteria were utilised for system design. This was based on historic design and installation experience for SRBRs that evolved over 20 years.

Table 1 Design criteria

Flow rate	Average: 26.5 L/min (7 USGPM) (7.6 to 56.8 L/min)
Sulphate reduction	0.3 moles/day/cubic metre
Acidity loading	35 grams acidity/day/square metre
Organic substrate	Wood chips and hay Manure inoculum Limestone intermix
Configuration	Trapezoidal
Length	13.5 m
Width	13.5 m
Side slopes	3H:1V
Estimated life cycle	15–20 yrs

3 Data collection

Sampling points relevant to the monitoring of the PTS are provided on Figure 3. All samples were submitted to ACZ Laboratories of Steamboat Springs, Colorado. While the APCs were routinely sampled, the SRBR performance is the focus of the paper.

The following field parameters were monitored in the Iron King PTS during 2010: pH, oxidation reduction potential (ORP), temperature, and conductivity. In addition, 21 analytical parameters were analysed in a typical sampling event suite, including total and dissolved metals fractions. For this paper, attention is focused on the following selected parameters: aluminium, iron, copper, cadmium, zinc, and sulphate. All flow rates were measured using bucket and stopwatch methods. A data logger with depth transponder was installed in the second quarter of 2011. The site is inspected at least quarterly or in response to an extraordinary rainfall event.

During 2010, the primary pump back system was engaged for approximately 11 weeks from early January to mid March. This action was required during repair efforts to install a series of influent distribution chambers in the southwest corner of the SRBR. The chambers consisted of a series of half-round, 40 cm perforated HDPE dispersion chambers, installed subsurface in the SRBR in tandem rows in an L-shaped layout (Figure 4).

Figure 4 Influent dispersion chambers during retrofit

As of the end of 2010, flow to the SRBR has been restored and the SRBR/PTS has treated about 4,500 cubic metres of IKCC MIW.

4 Mine pool chemistry changes

Since the PTS commissioning, efforts to drain down the IKCC MIW pools has 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 to note that the MIW influent data for some field parameters (pH and conductivity) improved in response to a decreasing contribution of UIK/Copper Chief MIW which has slowed to a virtual trickle. This situation was also reflected in some of the figures that exhibit metals data.

Improvements in MIW influent chemistry are also attributable to source control measures (e.g. Glory Hole 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. If the contribution of UIK/Copper Chief MIW to the PTS influent decreases as per the current trend, the operational load on the SRBR should further decrease in the future.

5 PTS results

The primary PTS performance parameters are those with typical elevated influent concentrations that contribute to mineral acidity; i.e. iron, aluminium, copper, zinc, cadmium, and manganese. Also included are sulphate and calcium as these parameters provide indicators relevant to the overall performance of the SRBR portion of the PTS.

All graphs provided in subsequent figures use week numbers on the X-axis. “Day zero” is 24 April 2009, the day that MIW was first delivered to the SRBR to commence the filling/incubation period. Week 88 is the week of 31 December 2010. For comparison, data in Table 2 reflect the MIW chemistries from the two mines in 2006.

Table 2 Typical 2006 influent chemistry for primary parameters

Parameter	Upper Iron King	Lower Iron King
pH (s.u.)	3.02	8.05
Aluminum (mg/L)	40.3	<0.1
Iron (mg/L)	495	4.4
Copper (mg/L)	113	<0.01
Zinc (mg/L)	152	10.5

Bulk sample collected in 2006 in front of bulkhead, used in lab jar tests (GAI, 2006).

5.1 pH

Field pH values measured at the SRBR influent, SRBR effluent, and Irrigation Water observed pooled on the APC terraces are shown on Figure 5. For comparison, pH data since the commissioning of the PTS in 2009 are provided.

The influent pH measured during most of 2010 was about 3.0 s.u. This is consistent with the MIW historically seen in the UIK. The final influent pH measurement in 2010 was observed on 2 December; the value was 5.98, which is consistent with the MIW typically seen in the LIK. The data indicate that the relative contribution of MIW from the UIK has decreased through the last quarter of 2010. This reduction was confirmed by qualitative observations by F-MC personnel in early 2011; the flow from the UIK has reportedly decreased to a trickle.

The SRBR effluent pH was measured at values of typically 6.2 or above during 2010. Samples of water pooled on various terraces of the APC typically exhibited a pH of 6.7 or above, even during periods when the PTS MIW influent pH was less than 3.0 s.u.

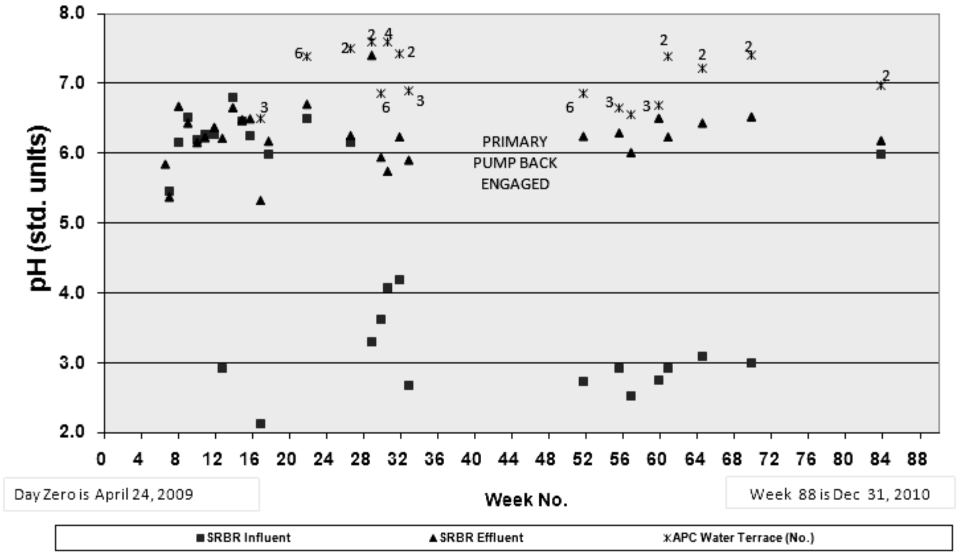


Figure 5 pH data

In summary, 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.

5.2 Metal removal

A detailed evaluation of removal efficiency trends is provided in Figure 6, which shows the individual removal efficiencies for dissolved iron, aluminium, zinc, copper, and cadmium, respectively. As shown in Figure 6, the nominal combined removal efficiency observed in week 60 is mostly attributable to iron and zinc; however, removal efficiency quickly rebounded thereafter. If the Figure 6 data were combined into a single graph, the net removal efficiency data would reflect a brief dip to about 75% removal efficiency in week 60, with values steadily increasing from 91 to 96.7% between weeks 51 and 84. Most metals in the MIW influent are in the dissolved form, so this trend reflects the overall performance of the SRBR unit of the PTS. As the PTS matures, this trend is expected to improve further.

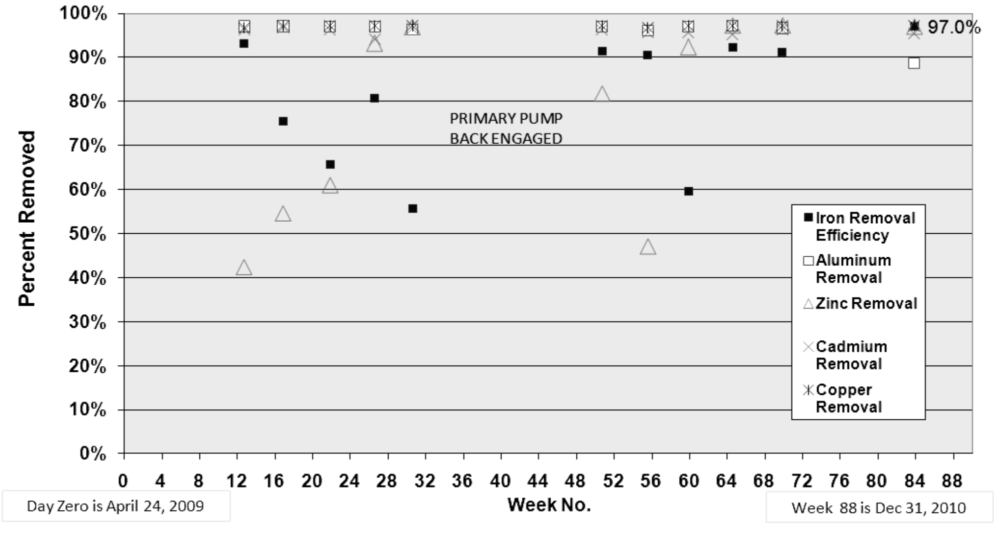


Figure 6 Primary metal removal efficiencies in the SRBR

5.3 Sulphate removal

Figure 7 shows raw sulphate removal performance in the SRBR; Figure 8 shows the volumetric molar metal/sulphate removal rates for the SRBR. The molar removal rate is measured in moles per day per cubic metre of organic substrate (moles/day/m^3). Cell design protocol typically attempts to match the volumetric removal rates for metals and sulphate at 0.3 moles/day/m^3. This is a benchmark value that has been established over dozens of SRBR situations ranging from bench-to pilot-to full-scale systems (Gusek and Figueroa, 2009).

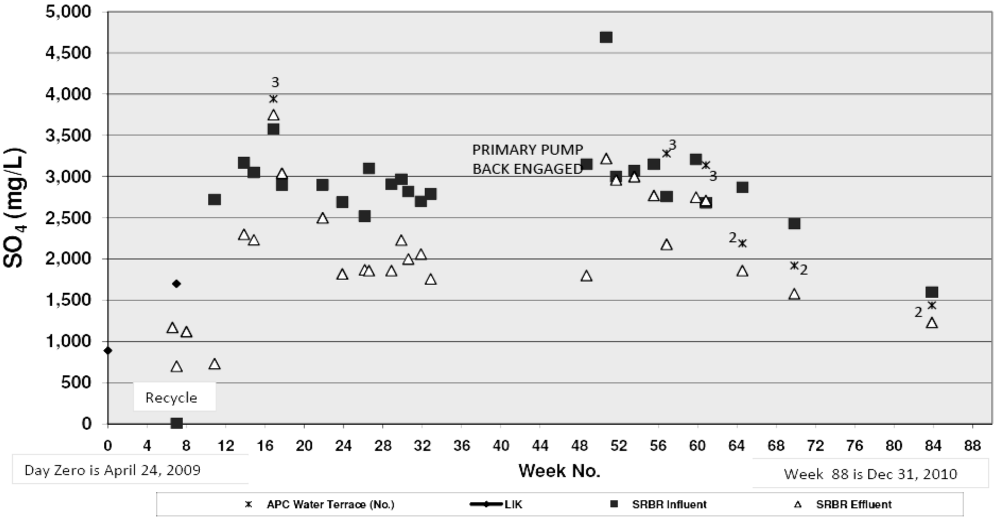


Figure 7 Raw sulphate data

Raw sulphate reduction in the SRBR is typically evident throughout 2010 (Figure 7). This data suggests that the sulphate reducing bacteria population has reached a measurable level of maturity, a condition indicative of steady-state operation. The influent sulphate concentration decreased through the year. This is consistent with the suspicion that the LIK MIW proportionally dominates the SRBR influent water.

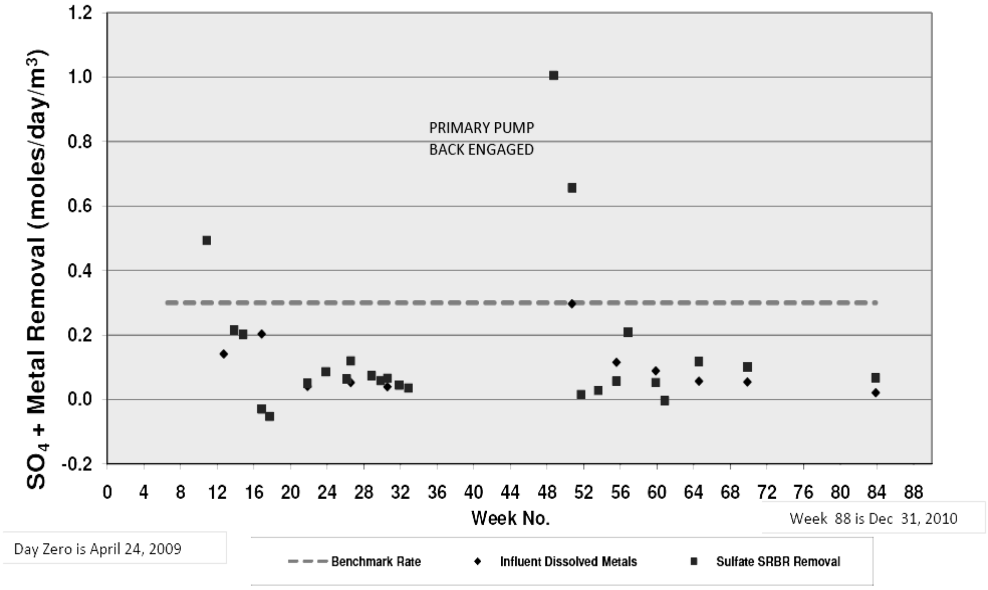


Figure 8 Sulphate and metals removal rates

Throughout 2010 (beyond week 56 in Figure 8), the typical volumetric sulphate and the dissolved metals volumetric removal rates are nearly matching, which is also a desirable operational condition. The elevated volumetric sulphate removal rates immediately after the primary pump back operation ceased are an expected result of the temporary SRBR cell incubation that occurred while the primary pump back was engaged.

Comparison of the volumetric sulphate and metal removal rates with the benchmark value suggests that the SRBR exhibits excess treatment capacity. This coincides with the steadily decreasing flow rates observed as the IKCC MIW pools were being lowered in 2010. The transition from UIK/Copper Chief MIW to LIK MIW results in additional excess treatment capacity.

6 Performance summary

Construction activities to retrofit the SRBR influent line in a way that mitigates the adverse effects of minor suspended solids (mostly iron precipitates) in the MIW influent were completed in early 2010. The PTS start-up process is complete as of the end of 2010 and the system is considered to exhibit the characteristics of steady-state operation. The second drain down of the UIK and LIK MIW pools is complete as well. Key observations relative to the 2010 PTS operation follow.

During 2010:

- About 4,500 cubic metres of IKCC MIW has been delivered to the PTS since the SRBR was filled in early April 2009.
- Dissolved removal efficiency of the SRBR for the major MIW parameters (iron, aluminium, zinc, copper and cadmium, combined) ranged from about 73 to 96.9%.
- Removal of trace MIW parameters was also documented.
- Influent MIW pH improved from an average of about 2.5 standard units to about 6.0 s.u.
- SRBR effluent exhibited a pH range of 6.0 to 6.5 standard units.
- APC water as measured in the APC terraces (when sufficient water for a sampling event was observed) exhibited a pH range of about 6.5 to 7.4 standard units.

These results are within the expectations of the design at this steady-state stage of the PTS’s operation.

7 Concluding remarks

The IKCC PTS was completed under the ADEQ-VRP programme in about six months for about US$ 1.6 million. Since its commissioning in mid 2009, it has met expectations. Analytical results indicate greater than 95% attenuation of target metals under steady-state conditions. The sulphate reduction is consistent with metals loading and the design. The current estimated life-cycle is from 15 to 20 years. To date, only routine maintenance has been required, and minor influent line retrofit to alleviate scaling issues.

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