

Demonstration of a Biological Sulfate Reduction Process at Scale, Treating Acidic, Sulfate-Laden Mining-Influenced Water

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Abstract

Mintek's cloSURE[®] technology treats acidic, sulfate-laden mine-influenced water through biological sulfate reduction followed by sulfide oxidation, producing treated water suitable for re-use. Demonstration-scale operation, treating mine influenced water at 25 m³ d⁻¹ achieved sulfate-reduction rates greater than 250 g m⁻³ d⁻¹, and the treated water met South Africa's Target Water Requirements for re-use in irrigated agriculture. However, the water had high concentrations of alkalinity and carbonate minerals, limiting its reuse opportunities. Operation of the plant provided insights into key engineering aspects relating to scale-up and recovery after feed disruptions. Results to date suggest that cloSURE[®] will be a technically feasible and economically sustainable biological treatment process for sulfate-laden mine waters at field-scale.

Keywords: cloSURE[®], mine-influenced water, biological sulfate reduction, sulfide oxidation, trace analysis, residence-time distribution, process scale-up, effluent quality

Introduction

South Africa's coal and goldfields are associated with high amounts of pyrite, resulting in mining influenced water (MIW) that ranges from acidic with high concentrations of sulfate to circum-neutral water. Sulfate concentrations can range from 1 000 mg L⁻¹ to above 10 000 mg L⁻¹. Metal concentrations are typically low, leaving almost no opportunity for value recovery. Mintek has been developing and scaling up a semi passive biological sulfate reduction treatment process, cloSURE[®], targeting MIW with elevated concentrations of sulfate between 3 000 mg L⁻¹ and 4 500 mg L⁻¹. Given the concentrations of sulfate, sulfide management has been an important part of the research and development, and a sulfide oxidation step follows biological sulfate reduction for the production of biosulfur. The aim of the treatment technology is reuse of the treated water in irrigated agriculture, or as an alternate resource to promote post mining activities.

There is only one operating passive biological sulfate reduction plant in South Africa, treating 50 m³ d⁻¹ mine-influenced water emanating from a closed colliery, with sulfate concentrations between 1 200 mg L⁻¹ and 1 600 mg L⁻¹ (Pulles & Heath, 2009; Pulles *et al.* 2016). The aim of the treatment process is sufficient sulfate reduction for bionutralisation and precipitation of key metals, in order to meet the discharge requirements to release the treated water to the environment. There have been two active demonstration plants operated in South Africa, which were ultimately terminated despite positive results being reported in the literature (Rode *et al.*, 2004). It is understood by the authors that these active sulfate reduction processes were not sustainable over the long term due to the high costs of the process and the provision of sufficient organic carbon for reduction of elevated sulfate concentrations.

Pulles and Heath (2009) demonstrated that reliance solely on a packed bed of organic



material to provide the electron donor for sulfate reduction did not provide consistently available organic carbon and once the readily hydrolysable carbon was consumed, the bed entered a crash phase, capable of sustaining only limited sulfate reduction. A key focus of the cloSURE® demonstration plant project is on a semi passive process with an inert packed bed (woodchips or waste plastic) coupled with a continuous liquid organic carbon feed, sourced from local waste materials. This is intended to increase the longevity and long-term hydraulic conductivity of the bed, minimising interventions such as churning the bed to release organic carbon which also risks solubilising metal precipitates trapped in the bed. Furthermore, co-treatment of difficult-to-treat organic wastes is realised, such as abattoir wash water or landfill leachate.

This paper evaluates the operational performance of the cloSURE® process at demonstration scale under real mine-water conditions and focuses on treatment efficiency, effluent quality, and process stability.

Process Overview and Operational Conditions

The cloSURE® process consists of two stages. The first step entails biological sulfate reduction, which employs sulfate reducing microbes that use sulfate as the terminal electron acceptor for respiration and organic carbon as an electron donor in energy metabolism. This results in the production of sulfide which binds to bivalent metals forming metal sulfide precipitates, and hydrogencarbonate which generates alkalinity and increases pH values. The sulfate reduction ponds are operated in a down-flow configuration which is intended to simulate a plug-flow reactor and prevent loss of sulfide to the atmosphere. The reactions are as follows:



The second step of the process involves the development of a floating biofilm containing sulfur oxidising bacteria which partially oxidise sulfide to biosulfur under conditions

where the stoichiometric ratio of sulfide to oxygen is greater than 2:1 (Buisman *et al.* 1990; van Hille and Mooruth 2011). When well established, the floating biofilm minimises oxygen dissolution and maintains low oxygen conditions in the reactor to prevent oxidation of sulfide to sulfate, and it minimises losses of sulfide to the environment. The floating biofilm is harvested to provide a value product containing elemental sulfur which could be used as a fertiliser, and is continuously formed according to the following reaction:



The layout of the demonstration plant is shown in Figure 1, with two systems each incorporating a biological sulfate reduction pond with an operating volume of 250 m³ followed by six sulfide oxidation channels each with an operating volume of 45 m³. The plant was operated continuously, with each system flow rate set at 25 m³ d⁻¹. Each biological sulfate reduction pond consisted of a packed bed of waste woodchips and was inoculated with effluent collected from prior sulfate reduction piloting studies at the same site. Abattoir wash water was introduced as a carbon and nutrient source to start-up the ponds, and the carbon source was changed to ethanol for continuous operation, due to logistical practicality under demonstration conditions. The pond had a target residence time of 10 d and the ethanol was fed at a molar ratio of 0.67 g chemical oxygen demand to 1.00 g sulfate.

Treated water flowed by gravity to the sulfide oxidation channels, which had a volume of 24 m³ and a target hydraulic residence time of 7.5 d. Organic carbon and nutrients were introduced for development and maintenance of the sulfur biofilm. The resulting biofilm was harvested periodically. Treated water was routed to a sump and to a mine water storage dam, as well as to irrigation plots for testing of the suitability of the water for re-use in irrigation. The irrigation results are not included in this paper.

The feed water was acidic with an average pH value of 2.7 and variable concentrations of sulfate, between 2 300 mg L⁻¹ and 5 900 mg L⁻¹, averaging 2670 mg L⁻¹.

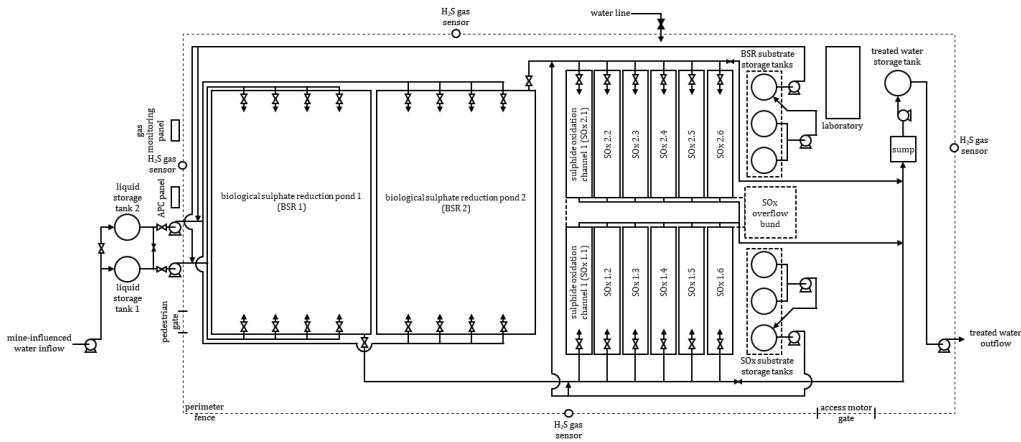


Figure 1 Schematic showing the cloSURE® demonstration plant layout.

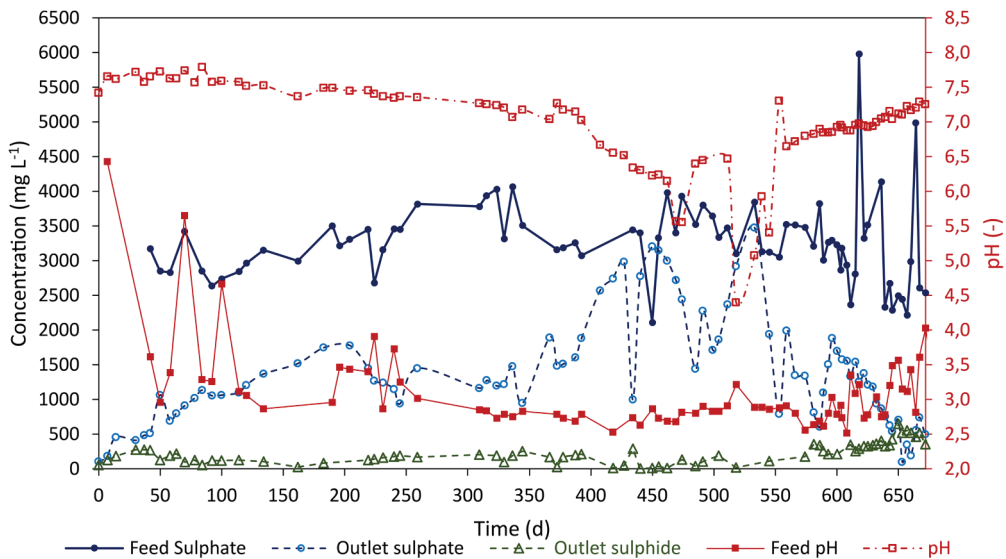


Figure 2 Time series data for operation of the biological sulfate reduction pond at the cloSURE® demonstration plant.

Operational Performance

Figure 2 shows the time series data for the biological sulfate reduction pond for the duration of continuous operation. For the first 18 months, of operation, there were a number of challenges with feed availability and consistent flows, blockages of inlets and outlets, scaling of feed lines with iron precipitate, as well as challenges with supplementation of organic carbon. The results during that period show up to 77% removal of sulfate, increases the pH value

to 7.2, but inconsistent flows resulted in uncertainties about true sulfate reduction rates and performance. On Day 504 there was a change in the feed quality, likely due to an unknown contaminant from the mine upstream from the dam, resulting in a sudden increase in redox potential -373 mV to -20 mV, and a sudden decrease in pH value from 6.5 to 4.4 in the biological sulfate reduction pond. This indicated microbial activity had ceased. A cell count of an effluent sample showed there were 10^6 cells mL^{-1} ,



with the cells observed to be active under the microscope. The plant was stopped and the biological sulfate reduction pond allowed to recover in batch mode, while feeding additional organic carbon (abattoir wash water) each week. Over the next six weeks, key operational parameters (pH, sulfate, redox, alkalinity and sulfide) returned to normal in the pond and continuous operation resumed. This disruption indicated that the sulfate reduction step was robust and the microbial consortia were able to tolerate inhibitory conditions with appropriate maintenance measures.

In the remaining three months of operation, feed flows and organic carbon addition were more consistent, and the data suggest the pond was approaching steady state towards the end of the study period. The pH values in the effluent were between 7.0 and 7.5, redox potential decreased to -390 mV, and sulfate concentrations were between 100 mg L⁻¹ and 600 mg L⁻¹. The average sulfate reduction rate for the period was 229 g m⁻³ d⁻¹ with a maximum of 290 g m⁻³ d⁻¹. Typical values for passive treatment processes range between 28 mg m⁻³ d⁻¹ and 76 mg m⁻³ d⁻¹ (Pulles, 2009). cloSURE® is not strictly passive as it is intended for treatment of elevated sulfate concentrations and therefore requires addition of an organic carbon source on a regular basis, which enables the higher sulfate reduction rates. Sulfide concentra-

tions in the effluent increased to a maximum of 652 mg L⁻¹, with an average of 397 mg L⁻¹.

Two channels were used to demonstrate the sulfide oxidation step. The data (Figure 3) indicate that at least 274 mg L⁻¹ feed sulfide concentration is required before the biofilm and biosulfur product are formed. An average sulfide removal of 56% was achieved, up to a maximum of 80%, indicating there is room for further optimisation, particularly of the type of carbon source and amount of organic carbon and nutrients required. The pH remains stable in this step, and Figure 3 shows that the results are highly reproducible.

At the end of the operating period, the channels were approaching stable operation. A biosulfur product was formed on the surface of the channels, consisting of 59% total sulfur. Other major compounds in the biosulfur product included magnesium, calcium and carbonate compounds.

Final Treated Effluent Quality

Table 1 and 2 compare the average feed water quality with the average treated effluent quality, indicating removal of metals and sulfate and neutralisation of the water. The tables compare the treated water parameters with the most stringent Target Water Quality Requirements (TWQR) from South Africa's Irrigation Water Quality Guidelines, showing that all parameters except manganese meet the requirements for re-use of the treated water in irrigated agriculture.

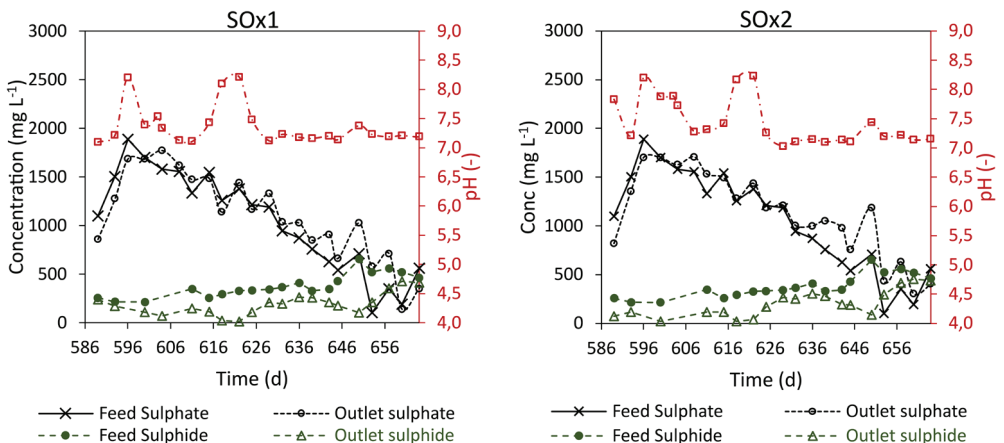


Figure 3 Time series data for the sulfide oxidation (SOx) channels, processing effluent from the biological sulfate reduction ponds.



Table 1 Average metals concentrations in the feed and effluent, compared to South Africa’s Water Quality Guidelines for Irrigation (red: exceeds TWQR, green: below TWQR).

	Al	Co	Cu	Fe	Mn	Ni	Zn
	mg L ⁻¹						
AMD Feed	44	0.2	0.05	240	20	0.2	1
Treated Water	<0.001	<0.001	<0.001	5	18	<0.001	<0.001
TWQR	5	0.05	0.2	5	0.02	0.2	1

Table 2 Average water quality parameters in the feed and effluent, compared to South Africa’s Water Quality Guidelines for Irrigation (red: exceeds TWQR, green: below TWQR).

	SO ₄	pH	EC	Alkalinity	Cl	F	Na	Ca	Mg	Total N
	mg L ⁻¹	-	mS m ⁻¹				mg L ⁻¹			
AMD Feed	2 670	2.7	29	0	22	3	113	613	277	9
Treated Water	657	7.6	386	1200	22	1	75	-	187	3
TWQR	-	6.5-8.5	-		100	2	-	-	-	-

Table 3 High level comparative costs of the cloSURE® process and reverse osmosis.

Financial Indicator	cloSURE® Plant*	Reverse Osmosis**
Total Fixed Capital Investment	USD 5,760,656	USD 16,304,765
Total operational expenditure	USD 1,177,010	USD 4,602,578
Treatment cost per m ³	USD 0.68	USD 2.67

Exchange rate: USD 1.0000 = ZAR 16.4995, based on the South African Reserve Bank Selected Historical Rates as of 5 March 2026.
 * Includes waste management costs ** Excludes waste management and brine treatment/disposal costs

The general assumption is that hydrogencarbonate and carbonate concentrations should be less than 120 mg L⁻¹ and 15 mg L⁻¹ respectively. As-yet unpublished irrigation trial data have shown poor plant development with the treated water from the cloSURE® process, likely due to the presence of elevated hydrogencarbonate alkalinity. A softening or hydrogencarbonate precipitation step would expand the opportunities for re-use of the treated water.

High-Level Costing

A high-level cost analysis was conducted based on the Guthrie method and the performance data of the demonstration plant, and compared to a reverse osmosis plant treating the same quality water and daily flows (Merckel & du Preez, 2026). A field scale-cloSURE® plant, treating 5 ML d⁻¹ with sulfate concentrations

between 5000 mg L⁻¹ and 7000 mg L⁻¹ is expected to have approximately a third of the capital expenditure of a reverse osmosis plant at USD 5.76 million, and operating costs of a quarter of that of reverse osmosis at USD 0.68 m⁻³, as indicated in Table 3. These costs are a best case scenario, assuming only transport costs for organic waste feedstocks and low cost inert materials for the packed bed. If sulphur sales are incorporated into the cost analysis there is potential for the process to breakeven or make a marginal profit.

Conclusions

The results of the cloSURE® demonstration plant excellent performance in the last three months of operation due to continuous feed and management of reactor in- and outflows. The data suggest that the biological sulfate reduction pond and the sulfide oxidation



channels were approaching steady state, with an average sulfate reduction rate of $229 \text{ g m}^{-3}\text{d}^{-1}$. Further, no neutralisation or pretreatment of the mine water feed was required, and due to the alkalinity generated in the process, the pH value remains stable post treatment. Metals were removed to within South African Target Water Quality Requirements, except for manganese, and the process is robust and quickly recovered after feed disruptions. A high-level cost analysis indicates the process will be economically feasible over the long term. Further optimization of the process is still required, specifically to reduce the residence time in the biological sulfate reduction ponds, to improve sulfur production in the sulfide oxidation step, and to soften the treated water for improved re-use opportunities. Operation of the demonstration plant provided insights into key engineering aspects relating to scale-up, and transfer and storage of large volumes of mine water for treatment, that are required to develop a technically feasible and economically sustainable biological mine water treatment process.

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