Electrochemical Treatment of Maurliden Mine AMD using Clean&Recover ECR™ Technology

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Abstract

Acid mine drainage (AMD) from the Maurliden mine presents substantial environmental challenges due to low pH and elevated sulfate and metal concentrations. This study evaluates the ElectroClear Reactor™ (ECR), a modified electrodialysis-based electrochemical process, for AMD treatment at mini-pilot scale. ECR achieved >98% removal of Zn, Ni, Cu, Al, As, Cd, Co, Mn, and Fe, together with 76% sulfate removal, producing discharge-compliant water and a sulfuric acid by-product. Optimal operation was achieved at 17 A and 0.5 $m^3 h^{-1}$, with an energy demand of 8.7–15.6 kWh m^{-3}. Compared to lime treatment, ECR provided equivalent neutralisation (pH 9.8), substantially reduced sludge generation, produced Zn-enriched sludge, and improved settling behaviour, demonstrating a pathway toward electrified, lower-carbon AMD treatment.

Keywords: Acid mine drainage, electrodialysis, resource utilisation, neutralisation, electrochemical treatment

Introduction

Acid mine drainage (AMD) remains a major challenge for mine remediation due to the acidity and elevated sulfate and metal concentrations, as exemplified at Boliden's closed Maurliden mine in northern Sweden Fig. 1. Current lime-based neutralisation effectively reduces acidity and metals but generates large sludge volumes, incurs high operational costs, and carries a substantial CO_2 footprint, highlighting the need for alternative treatment technologies.

Non-chemical active water treatment technologies have gained increasing attention, with electro- and membrane-based processes such as reverse osmosis, nanofiltration, ion exchange, electrocoagulation, and electro-oxidation widely investigated for AMD treatment (Arana Juve *et al.* 2022). However, these technologies typically require extensive pretreatment – and/or post-treatment - steps, including pH adjustment and removal of metals such as Fe and Mn, leading to increased process complexity and high CAPEX/OPEX. Electrodialysis (ED), combining electrical driving forces with ion-selective membranes, has been proposed as a cleaner alternative (Arahman *et al.* 2017; Aydin *et al.* 2019; Liu *et al.* 2022; Hopsort *et al.* 2024). ED has demonstrated high metal removal efficiencies (>97–99%) for ions such as Fe^{3+}, Zn^{2+}, Ni^{2+}, Mg^{2+}, and Mn^{2+} (Buzzi *et al.* 2013; Liu *et al.* 2022); however, it generates concentrated ion streams that require further treatment. Proposed solutions, including electrowinning or chemical precipitation, often overlook the economic implications of downstream recovery, complicating water treatment and mine closure strategies (Arana Juve *et al.* 2022; Cerrillo-Gonzalez *et al.* 2023).

To address limitations, Clean&Recover developed the ElectroClear Reactor (ECR™), a modified electrodialysis system employing a single sulfate-selective anion-exchange membrane rather than paired anion and cation membranes. Unlike conventional ED, which generates a concentrated brine that requires secondary treatment, ECR™ selectively isolates sulfate ions without producing a reject stream. In this study, a mini-pilot ECR was evaluated for treatment of Maurliden AMD, assessing the effects of current (11–20 A) and flow rate (0.1–0.5 $m^3 h^{-1}$) on water recovery and energy

consumption, alongside sludge production and characterisation benchmarked against conventional lime treatment.

Methods

AMD was collected from the Boliden's Maurliden mine in Fig.1. The ECR comprised 10 paired chambers, each containing an anionic membrane positioned between a titanium-based cathode and a mixed-metal-oxide-coated anode (iridium and ruthenium), with an effective total membrane area of 10000 cm^2. The water treatment tests were carried out on a mini-pilot ECR plant installed at the Boliden pilot plant facilities in Boliden, Sweden, Fig. 2. For all experiments, pH and Eh were measured and corrected using an Ag/AgCl reference electrode. All the water and sludge samples analysed using ICP-OES and ion chromatography, as presented in Table 1.

A Box–Behnken design (BBD) was applied for the parametric study. 15 experiments were conducted at varying voltage (27–63 V), current (11–20 A), and catholyte-to-anolyte (CA:AN) flow-rate ratio (0.6–1.4), while the final pH was fixed to ensure target removal. The responses were energy consumption (kWh m^{-3}) and runtime, allowing minimisation of energy demand and processing time. Operational parameters (flow rate, temperature, pH, redox potential, current, and voltage) were recorded at 10-min intervals, and selected streams were chemically analysed. In addition to the parametric study, the selected parameters were used for the next study, where the analyte was recycled for different AMD batches and summarised in Table 2.

Results and Discussion

Maurliden AMD was treated in the ECR, and samples were taken at different pH values. The starting pH for AMD was 2.8 with a redox potential of 546 mV and the pH increased to 11.5 while the redox change from oxidising to reducing conditions as the test progressed. The redox decreases sharply from 546 mV to 134 mV at pH 4 decreasing to -205 mV at pH 11.5. Most elements reach >95 % removal at pH 6 except for sulfate, Ba, Ca, and Cl. Beyond pH 10 as expected signs of Al resolubilising start, and the removal rate decreases to 92,8 % from >95 % level.

Based on the initial pH test presented in Fig. 3, pH 9.8 was selected as the optimum for metal removal. For the optimised case, the energy consumption for the 5 runs is

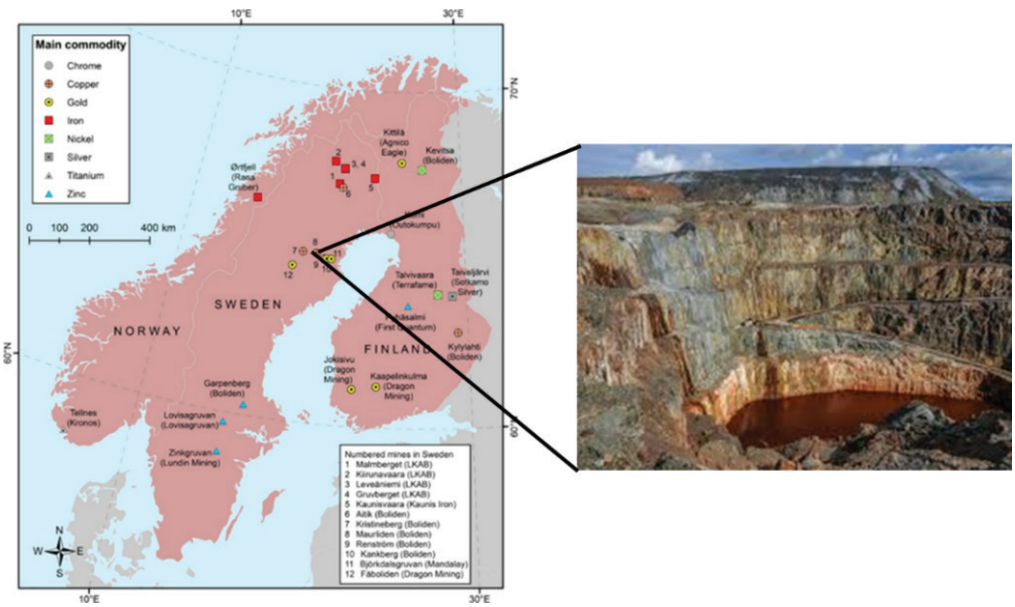

Figure 1 Maurliden mine located in northern Sweden (adapted from (Klein et al. *2022)).*

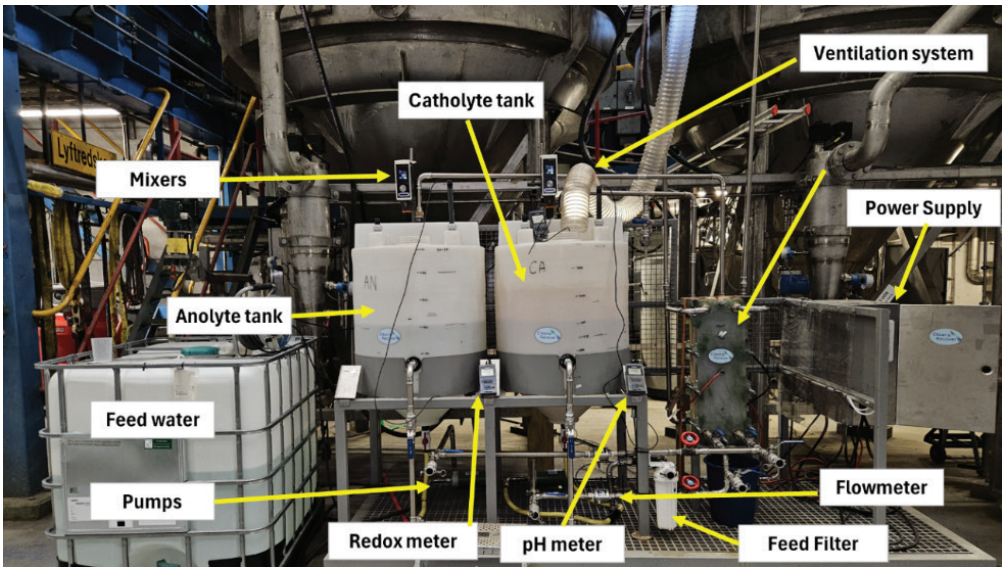

Figure 2 ECR™ setup at the pilot plant in Boliden.

Table 1 Chemical characterisation of the Maurliden AMD.

Parameter	Units	Maurliden AMD	Treated water	% Removal
Fe	mg/L	205	0.04	99.9
Mg	mg/L	157	21.6	86.2
Al	mg/L	79.3	0.79	99.0
Zn	µg/L	136000	2.0	99.9
Mn	µg/L	28000	61.1	99.8
Cu	µg/L	5040	1.0	99.9
As	µg/L	1010	5,2	99.5
Ni	µg/L	157	0,5	99.7
Pb	µg/L	28,8	0.2	99.3
U	µg/L	19.9	0.01	99.9
Cr	µg/L	13	0.5	96.2
SO4	mg/L	4020	968	75.9
Cl	mg/L	15.8	4.0	74.9
F	mg/L	8.69	2.05	76.4
pH	-	2,8	9.8	
Electrical conductivity	µS/cm	3478	121	
ORP	mV	546	52	

presented in Fig. 5. In these runs, the anolyte was recycled.

The trends in energy consumption (Fig. 4) reflect the increase in cycle times from 1.50 h (run #1-1) to 3.33 h (run #1-5). At constant current, the voltage decreased with anolyte recycling as a result of increased conductivity; however, energy use increased, likely from elevated sulfate levels altering membrane diffusion gradients. At pH 9.8, the removal of

Table 2 Experiments with anolyte recirculation.

Run	#1-1	#1-2	#1-3	#1-4	#1-5
Energy, kWh/m³	10.2	11.6	12.5	13.1	18.3
Voltage, V	50	45	42	39	40
Amps, A	17	17	17	17	17
CA flowrate, m³/h	0.5	0.4	0.3	0.3	0.3
AN flowrate, m³/h	0.3	0.4	0.4	0.4	0.4
CA:AN flowrate ratio	1.4	1,0	0,8	0,8	0,6
Final pH	9.8	9.8	9.8	9.8	9.88
Running time, h	1.50	1.92	2.17	2.50	3.33

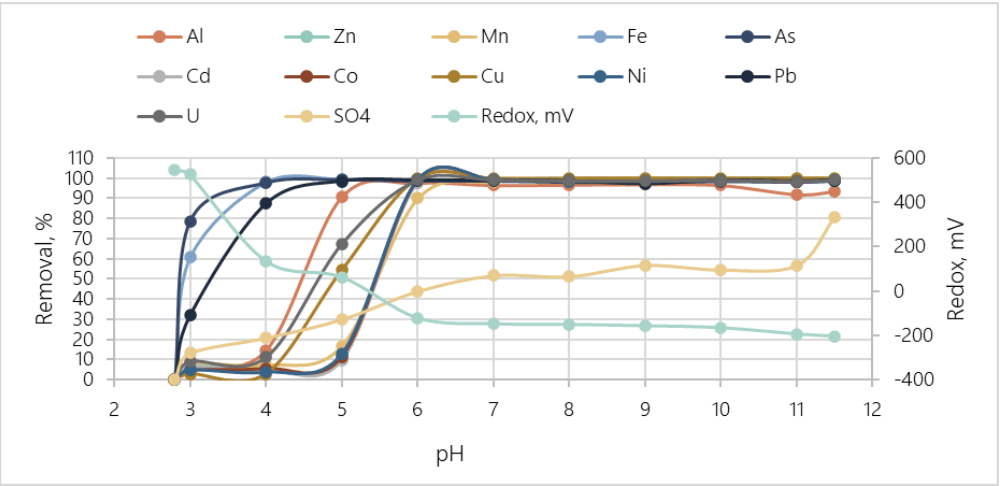

Figure 3 Variation of element removal as a function of pH.

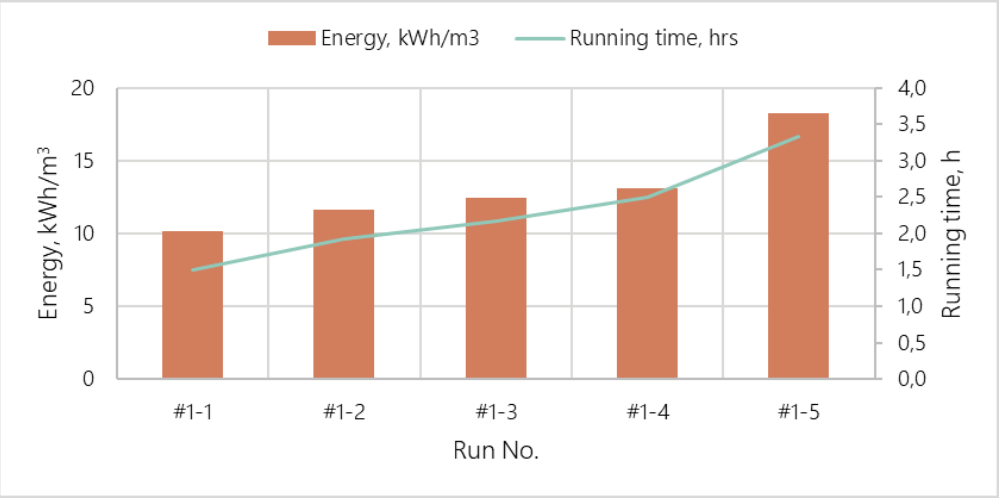

Figure 4 Energy use for the at pH 9.8 and 17 A.

cations exceeded 99 % at 80% water recovery, while Ca and Ba removal was minimal (0–15 %), attributed to low pH and short operation time, Fig. 5. Anion removal reached 70 % (Cl^-), 40 % (F^-), and 76 % (SO_4^{2-}). Low efficiency is attributed to reduced anolyte pH and sulfate loading, which limit sulfate ion transport due to a weakened diffusion gradient (Hopsort *et al.* 2024).

As expected from the design, the removal of the anions mainly sulfate is observed from the catholyte side. All sulfate ions migrated to the anolyte chamber to give a sulfuric acid by-product (1220 mg/L SO_4, pH 1.3) with some minor cations transported via the inevitable leakage (Hopsort *et al.* 2024). As the anolyte represents about 20 % of the total flow, feasibility is contingent on local utilisation, with nearby applications such as pH control in Fenton-based thiosalt treatment offering a practical integration option into existing operations.

Chemical characterisation and settling tests were conducted in the sludge. Sludge production was 1.4 kg m^{-3} of AMD treated for ECR, compared to 6.7 kg m^{-3} for lime treatment. The zinc content increased to 9.82% relative to 3.62 % in lime sludge (Table 3), indicating potential for sludge valorisation. This enrichment is attributed to reduced lime addition, reflected by lower calcium content in ECR sludge.

The stabilisation tests of the ECR™ catholyte sludges, benchmarked against the lime sludge of the Maurliden plant without flocculant, showed markedly faster settling for the ECR (Fig. 6), with clarification largely complete within 20 min and plateauing at 60 min versus 90 min for the lime sludge. This behaviour reflects the denser mineral-like nature of metal-enriched galvanic sludges compared to gelatinous flocs from lime precipitation (Yu Makoskaya *et al.* 2020). Consequently, ECR enables reduced retention times and smaller solid–liquid separation units, reducing the size of the equipment and the footprint of the process.

ECR™ offers an improved approach for AMD treatment, characterised by reduced sludge production and generation of a sulfuric acid by-product. In contrast, conventional electrochemical processes and membrane

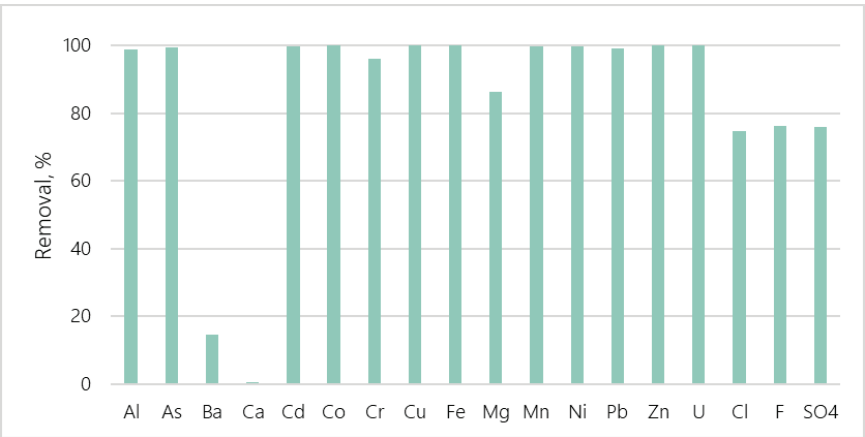

Figure 5 *Removal rates under optimised conditions.*

Table 3 *Sludge analysis.*

Process	Sludge (kg/m³)	Zn (%)	Cu (%)	Fe (%)	Ca (%)	Al_2O_3 (%)
Maurliden liming	6.7	3.62	0.18	9.16	21.3	4.64
ECR	1.4	9.82	0.31	14.75	2.91	10.07

– require extensive pretreatment, including pH adjustment and removal of organics and foulants. This work demonstrates a path toward electrified and decarbonised AMD treatment, reducing the reliance on bulk lime logistics and lowering overall water treatment costs.

Conclusions

This study demonstrates that mini-pilot-scale ECR effectively treats Maurliden AMD, producing effluent that meets discharge permit requirements. The process achieved >98 % removal of target metals (Zn, Ni, Cu, Al, As, Cd, Co, Mn) and up to 76% sulfate removal. Optimal operation was obtained at 17 A and 0.5 $m^3 h^{-1}$, with an average energy demand of 8.7–15.6 kWh m^{-3}. Compared to conventional lime treatment, ECR provided comparable neutralisation (pH 9.8) without lime addition, substantially reduced sludge production (1.4 vs 6.7 kg m^{-3}), generated a Zn-enriched sludge (9.8 wt.% Zn), and exhibited improved settling characteristics.

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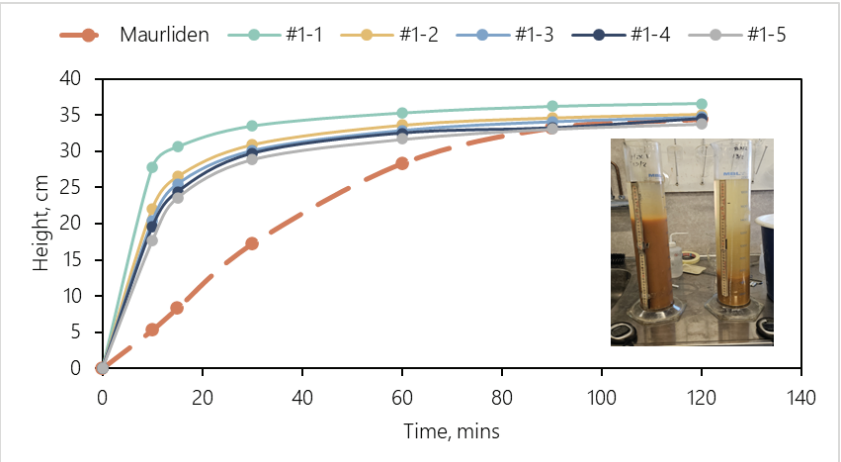

Figure 6 *Settling test showing liming sludge (left) and ECR sludge (right).*