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Advanced acid mine remediation

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Abstract

Acid mine water remediation can be a significant challenge for active, closing, or abandoned mines. The usual objective is to sufficiently treat this water so that it can be safely released to the environment. Of the several technologies employed, passive treatment and lime precipitation are the most common. Passive treatment is usually the least costly but frequently not feasible. Lime precipitation effectively removes heavy metals but has the disadvantage of creating large amounts of sludge that is 95% lime and 5% metal for which disposal may be difficult. Additional steps of pH adjustment may also be necessary. Electrocoagulation as an alternative technology has proven effective since before 1900. However, high power cost, unreliable reactors and maintenance difficulties have severely limited its past application. Recent developments have solved its most significant problems of anode passivation, internal sludge buildup, and system maintenance. Sludge generation, which is only about 10% of lime treatment may provide the largest advantage. This sludge is over 50% metal, and its refinement may offset the cost of operation. This paper compares electrocoagulation and lime precipitation for effectiveness and cost.

Keywords: *acid mine drainage, water treatment, heavy metals, recovery, electrocoagulation, limestone-lime precipitation, sludge reduction, acid mine water remediation*

1 Introduction

Problems of acid mine drainage from abandoned mines are well known to the mining industry, the EPA, and many conservation groups. For example, the US Forest Service which administers over 78 million hectares, reports up to 39,000 abandoned mines in its jurisdiction of which 2,000 sites present significant risk (US Forest Service, n.d.). Water treatment for these mostly metal mine sites is estimated to cost USD 2.1 billion not including damage restoration. The Government Accountability Office estimates abandoned mines sites at 500,000 nationwide with 33,000 degrading the environment (Brown, 2019).

Acid mine water remediation is a significant challenge for active, closing, or abandoned mines. The usual objective is to sufficiently treat this water and remove the dissolved heavy metals so that it can be safely released to the environment. Simultaneously any sludge created must be inert and pass the toxicity characteristic leaching procedure (TCLP) requirement for landfill disposal. For point source treatment a commonly used technology is lime precipitation. This process has advantages that are well understood, it is usually effective and may very well be lower cost. It has the disadvantages of using toxic chemicals, requires several chemical adjustment steps, has a large footprint, and creates a large amount of sludge which makes potential metal recovery impractical. Electrocoagulation (EC) is an alternative technology that is highly effective for precipitating dissolved metals from acid water. Its advantages compared to lime treatment are fewer treatment steps, a small footprint, the use of few or no chemicals, and generates a low volume of sludge which reduces disposal costs. EC sludge has a high metal content which may permit metal recovery. Although EC technology has been studied since the late 1800s with hundreds of scientific papers supporting its efficiency, instances of effective implementation are very limited (Werner-Els, 2020). Limited design information, uncertain operational parameters, power costs, unreliable reactors and maintenance difficulties have discouraged its past application (Holt et al. 2005). The most significant problems are precipitation within the reactor (sludge buildup), anode passivation (fouling), and high maintenance cost. Power costs were important in the past but today this is usually a small proportion of the operating expenses. EC sludge generation, which is often only 10% of a lime treatment process, can be a large advantage. The EC sludge is normally about 50% metal and has the potential to be refined to offset the cost of operation. Due to the large number of still untreated abandoned mines and to assist in the safe closing of mines it is important to compare EC and lime precipitation for effectiveness and cost.

1.1 Solubility curves for dissolved metals in water

It is necessary to understand that both lime treatment and EC are based on the solubility curves for dissolved metal in water (Florence, 2014). The curves in Figure 1 indicate that most dissolved metals will precipitate when the solution pH moves up to 10. The aluminium and iron solubility are the lowest when the pH is closer to neutral with aluminium around 6.5 and iron around 8.

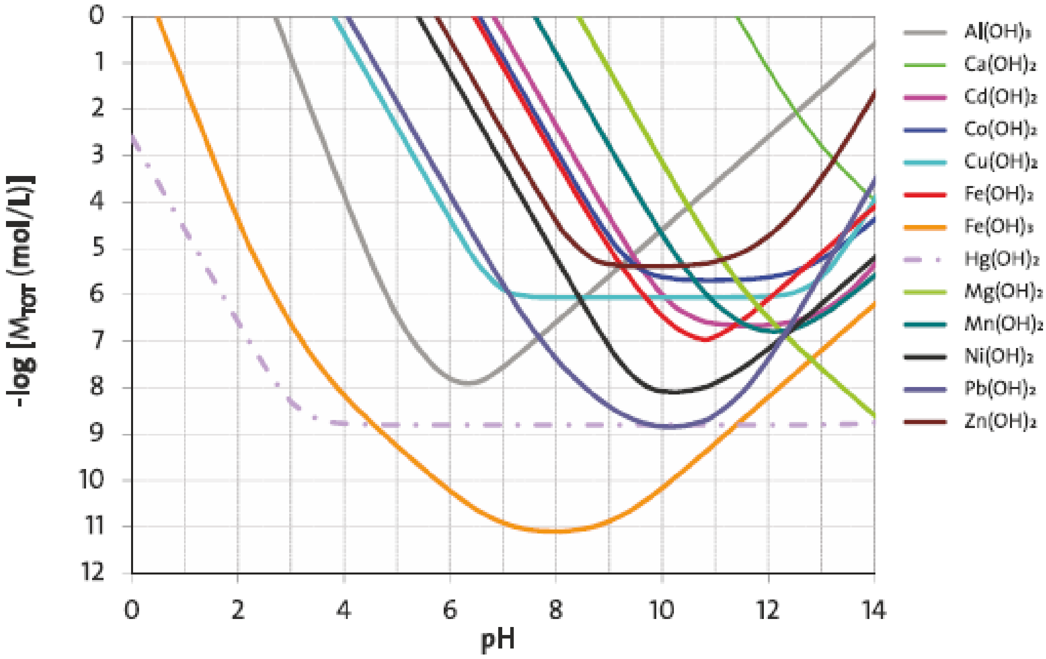

Figure 1 Metal solubility in water based on pH (Florence 2014)

The purpose of the lime treatment is simply to raise the pH to 10 and enable precipitation (caustic also works but is more expensive). Electrocoagulation, on the other hand, is the direct release of aluminium or iron ions into the water. If the pH is near neutral a strong floc forms, precipitates, and is easily removed along with the contaminants.

1.2 Lime precipitation for acid mine water treatment

Lime precipitation is a proven technology that can be highly effective. The standard today is the creation of high-density sludge (HDS). The various versions of lime treatment are discussed in the paper by Aube and Zinek (Aubé & Zinck, 2003). In this paper they discuss pond, pit, conventional, HDS, Heath Steele, Geco HDS, and the Staged-Neutralization Process, all of which are specifically tailored to the metal types and concentrations in the mine water. Although well known before that, early work was reported in 1981 by Peabody Coal (McDonald & Grandt, 1981) using conventional limestone-lime treatment. This treatment was reported to cost USD 19.35 per cubic meter (m^3) in 2023 dollars. Heviánková, et al. (2013) have published an important paper analysing the cost benefits of the lime-limestone combination over lime. The chemistry and dose levels are discussed in detail by Rochyani et al. (2015). A definitive work on lime treatment is the Global Acid Rock Drainage (GARD) Guide (The International Network for Acid Prevention (INAP), 2009). Chapter 7.10 discusses five case studies: The Argo Tunnel in Colorado, Bisbee No.7 Stockpile in Arizona, Equity Silver in British Columbia, Keystone Mine in Utah, and the Brukunga Pyrite Mine in South Australia.

Colorado has several examples of acid mine drainage where lime precipitation is used as the treatment process and are typical of lime treatment operations. Three excellent examples are the Argo Tunnel Water Treatment Plant in Idaho Springs Colorado, the North Clear Creek Water Treatment Plant in Black Hawk, Colorado, and the Interim Water Treatment Plant at Gladstone, Colorado.

1.3 Argo Tunnel water treatment plant at Idaho Springs, Colorado

The treatment plant at the Argo Tunnel began operation in 1998 and treats an average flow of 62 cubic meters per hour (m^3/h). The plant was initially conventional caustic treatment but was soon converted to conventional lime as a cost saving method. Before 2015 the plant was converted to HDS treatment where the treated water is recycled up to thirty times. A bulkhead was added in 2015 to maintain a more constant flow rate and mitigate possible blowouts. In 2023 the operating costs are expected to be about USD 1.9 million or USD 3.18/m^3 with about 40% of the cost for chemicals and sludge disposal. The plant operates 24 hours per day with five FTE employees on site for 10 hours per day. Capital costs for Argo are not presented here since the plant has undergone many modifications and upgrades since the initial installation.

About 390 kilograms (kg) of metal a day is removed from the water and roughly 9,500 kg per day of sludge is generated (Miller et al. 2007). This sludge is disposed of in the Erie Colorado landfill, a round trip of approximately 160 kilometres (km).

The influent and effluent data presented here for the Argo in 2007 (US Environmental Protection Agency, 2007) are shown in Table 1 and 2. While not identical for all mines this table is similar in each case.

Table 1 Influent into the Argo Tunnel Water Treatment Plant (US EPA 2007)

Parameter	Units	Argo Tunnel*	Big Five Tunnel*	Virginia Canyon*
Average Flow	m^3/hr	45-102	3-9**	1-41**
pH	SU	3	5.5	3
Iron	mg/L	120	65	3
Manganese	mg/L	90	30	90
Aluminium	mg/L	20	5	80
Zinc	mg/L	40	8	92

*All values are approximate based on historical data

**Flows to treatment plant can be controlled

Table 2 Permit Effluent Limitations - Argo Tunnel Colorado (US EPA 2007)

Constituent	Units	30-Day Average	Daily Limits
pH	–	–	6.5-9
TSS	PPM	20	30
Hardness	PPM	–	–
Iron	PPB	15,800	–
Arsenic	PPB	Report	400
Nickel	PPB	850	Report
Silver	PPB	0.02	0.62
Zinc	PPB	225	Report
Aluminium	PPB	–	–
Cadmium	PPB	3	5
Lead	PPB	4.75	219
Copper	PPB	17	35

Manganese	PPB	800	Report
Calcium	PPB	–	–
Magnesium	PPB	–	–
TDS	PPM	–	–

PPM = parts per million (mg/L). PPB = parts per billion (µ/L)

The Argo plant meets the permit release requirements, and the treated water is released to Clear Creek.

1.4 North Clear Creek treatment plant - Black Hawk, Colorado

The North Clear Creek treatment plant located in Black Hawk, Colorado provides a recent analysis. This plant had its grand opening on July 31, 2017. This is an HDS plant designed to treat 800 to 3,500 m^3 per day. The facility removes 163 kg of metal per day. The plant capital costs were USD 19 million.

Figure 2 shows a diagram of the North Clear Creek treatment plant, a typical High-Density Sludge (HDS) plant.

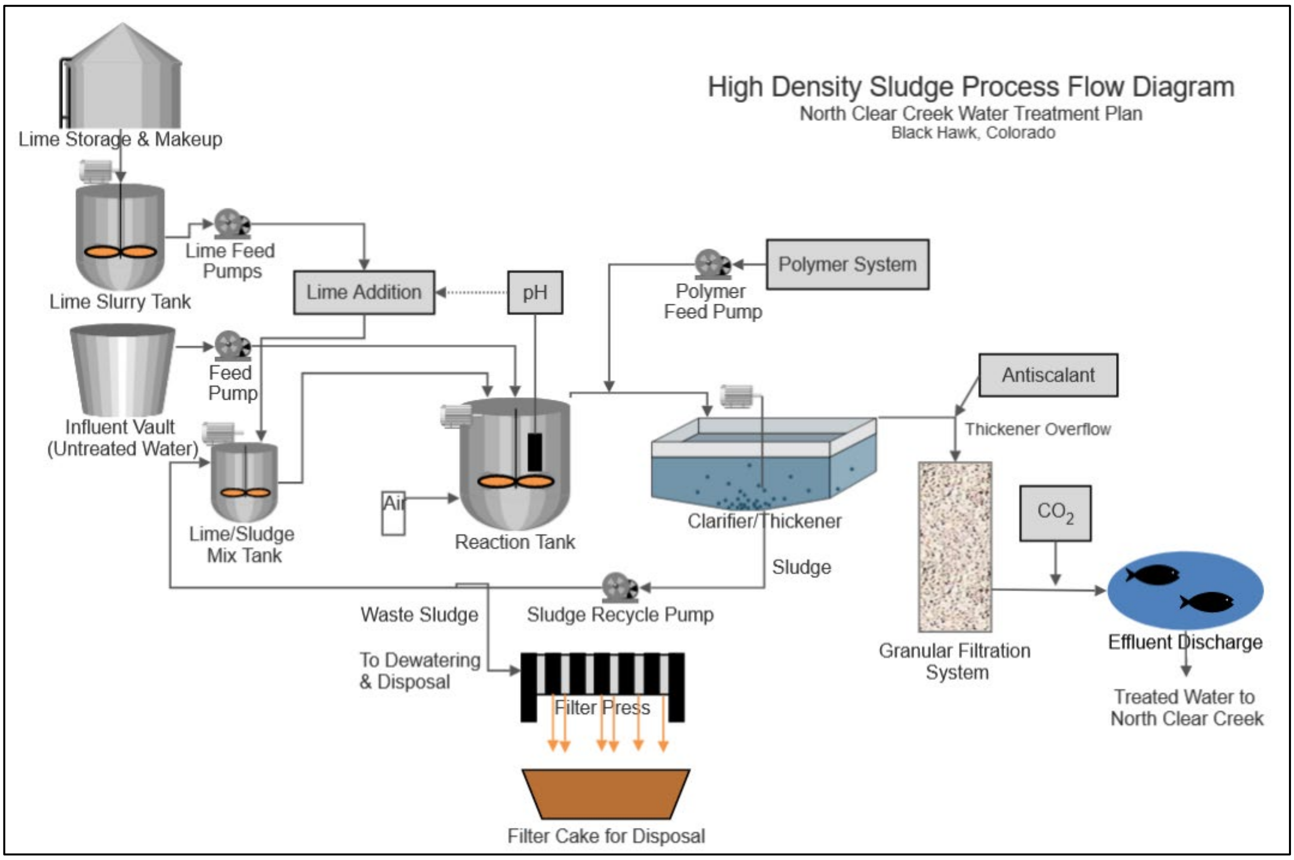

Figure 2 HDS process flow diagram for North Clear Creek water treatment plant (CDPHE 2017)

> *"In the reaction tank, air is added to oxidize the dissolved metals and the pH is raised to about 9.5. This forces the metals to drop out of solution. Hydrated lime (Ca(OH)2) is the reagent used to adjust the pH, and a small amount of polymer is added to build particle size and aid settling. The solution flows to the clarifier/thickener where the metals drop to the bottom of the tank creating a sludge, while relatively clear water flows off the top. The virtually clean water flows through the polishing filters prior to discharge while the sludge is dewatered in the filter presses." (CDPHE Fact Sheet, 2017, p.7)*

A comprehensive analysis of the performance of this plant is provided in the Evan Lloyd's Master Thesis for the Colorado School of Mines (Lloyd, 2020). He shows dramatic reductions in the metals of concern but with the caveats that at certain flows some metals were elevated, and that copper and zinc did not decrease to the same extent as iron and manganese. These measurements of metal contaminants were from water samples taken from the stream flowing below the treatment plant's location and may not be an exact representation of the water from the treatment plant.

1.5 Interim water treatment plant—Gladstone, Colorado

Consistent with other acid mine water in Colorado the major contaminants are arsenic, cadmium, lead, beryllium, zinc, iron, and copper.

In October 2015, the Interim Water Treatment Plant (ITWP), a conventional lime treatment facility, came online. In 2016 the EPA issued a report describing the performance of the treatment facility. Capital cost for the plant was about USD 2.7 million and annual operating costs are approximately USD 1.8 million or about USD 1.59 m^3. Tables 3-5 with the contaminants of potential ecological concern (COPECs) and flow rate are adapted from the 2016 evaluation and cost report on the Gladstone IWTP (CDM Smith, 2016)

Table 3 Gold King Mine influent to IWTP (CDM Smith 2016)

COPECs and Flow Rate	Units	Minimum	Maximum	Average
Flow Rate	m^3/day	1,600	5,200	2,900
Aluminium, Total	µg/L	13,000	75,000	26,957
Beryllium, Dissolved	µg/L	2.5	9.3	6
Cadmium, Dissolved	µg/L	35	170	66
Copper, Dissolved	µg/L	1,900	11,000	4,904
Iron, Total	µg/L	49,000	340,000	118,087
Lead, Dissolved	µg/L	0.3	35	12
Manganese, Dissolved	µg/L	1.2	30,000	23,391
pH	s.u.	3.3	3.4	3.3
Silver, Dissolved	µg/L	0.1	2	0.2
Zinc, Dissolved	µg/L	11,000	45,000	19,609

The maximums of the Gladstone IWTP effluent shown in Table 4 occurred during startup and the minimums are now more representative of system performance.

Table 4 Gold King Mine effluent from IWTP (CDM Smith 2016)

COPECs and Flow Rate	Units	Minimum	Maximum	Average
Flow Rate	m^3/day	1,600	5,200	2,900
Aluminium, Total	µg/L	170	12,000	3,094
Beryllium, Dissolved	µg/L	0.2	1.8	0.2
Cadmium, Dissolved	µg/L	0.2	44	5.7
Copper, Dissolved	µg/L	1.4	680	50
Iron, Total	µg/L	270	50,000	10,576
Lead, Dissolved	µg/L	0.1	1.5	0.2
Manganese, Dissolved	µg/L	18	25,000	12,545
pH	s.u.	6.8	9.4	8.4
Silver, Dissolved	µg/L	0.1	0.1	0.1
Zinc, Dissolved	µg/L	26	11,000	645

A final analysis of the Gladstone IWTP HDS plant performance is shown in Table 5.

Table 5 Gladstone IWTP percent load reduction between influent and effluent (CDM Smith 2016)

COPEC	Minimum	Maximum	Average
Aluminium, Total	42.90%	98.70%	86.50%
Beryllium, Dissolved	94.00%	98.40%	97.00%
Cadmium, Dissolved	84.80%	99.70%	93.10%
Copper, Dissolved	96.10%	99.98%	99.70%
Iron, Total	50.60%	99.80%	89.60%
Lead, Dissolved	77.50%	99.80%	95.70%
Manganese, Dissolved	26.30%	99.94%	52.10%
Silver, Dissolved	0.00%	23.10%	11.50%
Zinc, Dissolved	96.20%	99.92%	99.00%

The CDM Smith report also showed that the sludge met all toxicity characteristic leaching procedure (TCLP) standards as shown in Table 6.

Table 6 TCLP metals standards and Gladstone IWTP metals concentration (CDM Smith 2016).

Analyte	TCLP standard (mg/L)	Gladstone IWTP Sludge (mg/L)
Arsenic	5	0.03 U
Barium	100	0.05 U
Cadmium	1	0.31
Chromium	5	0.05 U
Lead	5	0.025 U
Mercury	0.2	0.02 U
Selenium	1	0.025 U
Silver	5	0.01 UJ

The Gladstone IWTP installation proves that conventional lime treatment is generally successful although studies show the HDS process to be more effective than the conventional lime treatment.

The relative advantages of standard lime treatment vs HDS are out lined in Chapter 7 of the Global Acid Rock Drainage (GARD) guide (INAP 2009). Details of advantages, of operational difficulties, and some disadvantages of lime treatment including sludge clogging are detailed in the EPA's 2006 Innovative Technology Evaluation Report (EPA 2006).

Table 7 summarises some of the advantages and disadvantages of lime treatment.

Table 7 Advantages and disadvantages of lime treatment

Advantages of lime treatment	Disadvantages of lime treatment
Well understood designs	Large amounts of sludge
Successfully removes most metals	Sludge may clog treatment systems
Sludge meets TCLP landfill standards	Lime or limestone may be inconsistent quality
Acceptable treatment cost	Multiple pH adjustment steps needed
–	Requires hazardous* chemicals

*Lime is considered hazardous and should be handled in accordance with OSHA Hazard Communication Standard 29 CFR 1910.1200 (Occupational Safety and Health Administration, 2020).

2 Electrocoagulation for acid mine water treatment

Kuokkanen et al. have authored an excellent review of electrocoagulation applications that this author recommends for further reading (Kuokkanen et al. 2013). Electrocoagulation (EC) is a process first invented in 1880 and first implemented commercially in London in 1889 (Moreno et al. 2007). It was first patented in the USA in 1906 and has been tested for treatment of many different industrial waters including acid mine drainage, landfill leachate, produced oil water, food processing, leather tanning, paper mills, aircraft washdown, bilge water, and many others. It has been shown to remove virtually all heavy metals, arsenic, fluoride, greases, organics, and PFOS/PFAS among a broad range of additional contaminants. In its simplest form an EC reactor consists of an anode (typically aluminium or iron) and an inert cathode inserted into the water to be treated. The anode it is dissolved into the water as Al^{+++} or Fe^{+++} ions when a DC current flows between the anode and the cathode. These ions are responsible for generating a strong precipitation of all contaminants leaving clean water and sludge. The ion dose level is proportional to the current thereby simplifying real time automation of the dosage levels. The chemistry of EC is now well understood (Vepsäläinen & Sillanpää, 2020) and several companies in the US and internationally are offering reactors.

Despite this high level of interest in EC and many articles on EC for different contaminated waters there are a very limited number of technical articles about applications of EC for treatment of acid mine water and its comparison to lime treatment. Most comparison studies are between EC and chemical treatments using metal salts such as aluminium sulphate (alum) or ferric chloride. One study that compares EC to chemical treatment concludes that the EC was effective at much lower cost than the chemical process (Oncel et al. 2013).

In November 1994, radioactive wastewater obtained from the U.S. Department of Energy's (DOE) Rocky Flats Environmental Technology Site near Golden, Colorado tested an electrocoagulation system at the Los Alamos National Laboratory (LANL) in Los Alamos, New Mexico. The primary objective of the tests was to evaluate the EC as an alternative treatment process for water contaminated with radionuclides or metals found at Superfund and other hazardous waste sites compared to conventional wastewater treatment using metal salt coagulants. The EC process was more efficient than the chemical treatment process in one of three test runs. In April 1995, a bench-scale study was conducted by testing the ability of the EC process to remove uranium, plutonium, and americium from water derived from the U.S. DOE's Rocky Flats Environmental Technology site solar evaporation ponds (SEPs). In these tests the EC process consistently removed more than 95% of the uranium, plutonium, and americium (US EPA, 1998).

Figure 3 shows the items that would normally be found in an EC acid mine water treatment process. Note that the number of components is significantly less than for HDS lime treatment. The total number of components is likely similar to that required for a conventional lime process.

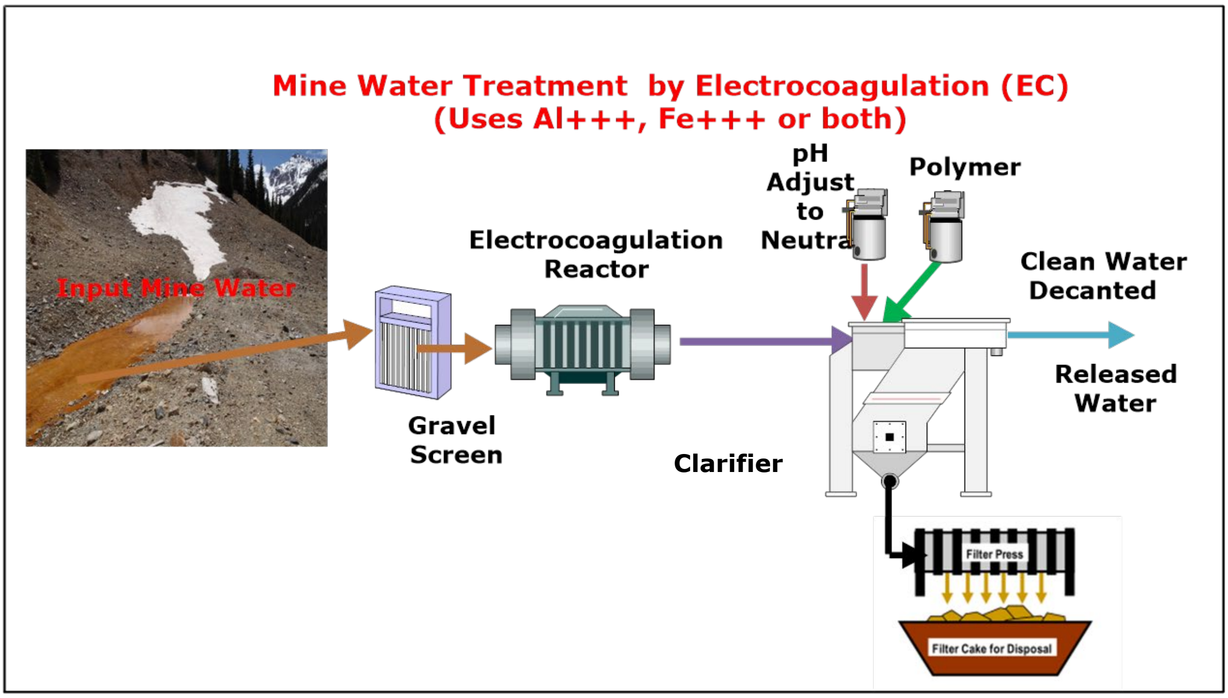

Figure 3 **EC process flow diagram for acid mine water treatment**

In 2016 the author collected 1.9 m^3 of Argo Mine water for the purpose of evaluating the effectiveness of EC in removing the contaminants. The samples were processed in a small bench top system processing in a batch mode of 3 litres per sample. Analyte analysis tests were performed by the University of Colorado LEGS Laboratory in Boulder, Colorado. Table 8 shows results for this water sample from the Argo Tunnel: untreated water, EC treated water, and the discharge limits for those contaminants of interest.

Table 8 EC treatment of Argo Mine drainage water

Element	Units	Discharge Limit	Untreated Water	EC Treated Water	Reduction
Cadmium	µ/L	3	71.17	0.11	99.85%
Copper	µ/L	17	2688	7.82	99.71%
Iron	µ/L	15,800	89,516	1343	98.44%
Lead	µ/L	4.8	298.6	BDL	100%
Manganese	µ/L	800	96,186	297.7	72.26%
Nickel	µ/L	850	179.3	8.5	95.24%
Silver	µ/L	0.02	BDL	BDL	-
Zinc	µ/L	225	138,771	37.4	99.97%

Note: BDL = below detection limit.

The results show that all contaminants of interest were removed to levels well below the discharge limits. This treatment was with aluminium anodes using a concentration of about 87.5 mg/L aluminium ions. Similar results have been obtained using iron anodes with dosage at the same molality. This table indicates that a lower dosage could still meet the discharge limits. It is important to optimize dosage as the operational cost of treatment is a function of the amount of aluminium or iron dissolved and the power required to dissolve the metal.

The logarithmic scale graph in Figure 4 presents the data of the above table visually. Note that in the sample tested there was no residual phosphorus or lead that could be detected in the treated water. Aluminium, magnesium, and phosphorous are included on the graph for illustrative purposes however, no discharge limits are posted for these elements.

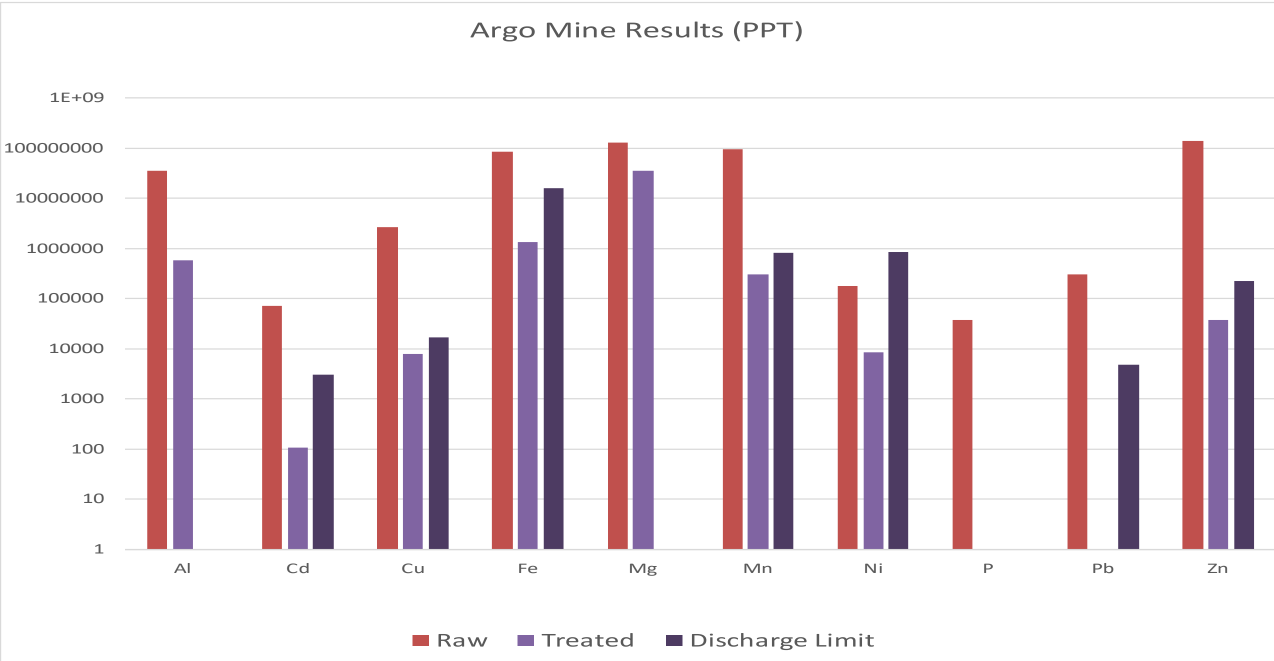

Figure 4 **Logarithmic scale graph of EC treatment removal levels for acid mine water treatment**

An analysis of 57 different water constituents was performed by the LEGS Laboratory at the University of Colorado, Boulder Colorado. Complete results are shown in Table 9.

Table 9 Full results of EC treatment of Argo Mine drainage water

Element	Untreated (µ/L)	EC Treated (µ/L)	Reduced	Sludge (µg/kg)	Detection Limit
Al	34,825	581	98.3%	177,263,075	1.43
As	7.57	0.553	92.7%	25,689	0.17
Ba	10.9	8.59	21.4%	4,799	0.01
Ca	364,395	353,247	3.1%	36,405,078	346.44
Cd	71.2	0.105	99.9%	84,107	0.03
Ce	301	0.075	100%	196,443	0.00
Co	113	0.556	99.5%	110,955	0.01
Cr	28.0	3.95	85.9%	353,431	0.81
Cs	5.88	6.20	-5.49%	307	0.02
Cu	2,688	7.83	99.7%	3,565,461	0.04
Dy	23.1	BDL	100%	18,773	0.01
Er	11.8	BDL	100%	9,776	0.01
Eu	5.20	BDL	100%	4,253	0.01
Fe	85,916	1,344	98.4%	109,595,818	47.51
Gd	33.3	0.007	100%	27,643	0.00
Ge	0.630	0.071	88.7%	2,958	0.04
Hf	0.134	BDL	100%	464	0.02
Ho	4.28	0.023	99.5%	3,489	0.01
K	3,827	4,756	-24.3%	BDL	67.06
La	97.2	0.018	100%	83,086	0.01
Lu	1.28	BDL	100%	1,046	0.01
Mg	127,605	35,398	72.3%	34,112,816	3.38
Mn	96,187	298	99.7%	55,045,347	0.91
Mo	BDL	BDL	100%	BDL	2.61
Na	22,371	525,476	-2249%	5,901,791	20.13
Nb	0.583	0.938	-60.8%	1,383	0.51
Nd	97.5	0.031	100%	104,058	0.01
Ni	179	8.54	95.2%	212,709	0.20
P	37.6	BDL	100%	31,567	8.97
Pb	299	BDL	100%	16,113	0.03
Pd	0.966	BDL	100%	528	0.12
Pr	29.9	BDL	100%	25,302	0.01
Pt	BDL	BDL	100%	13,895	0.01

Rb	21.2	23.9	-12.7%	853	0.02
Rh	0.124	0.076	39.3%	67.6	0.02
Ru	BDL	0.117	-	BDL	0.00
Sc	8.43	BDL	100%	14,528	1.79
Sb	3.72	0.377	89.9%	430	0.05
Se	9.00	1.29	85.7%	BDL	0.25
Si	23,416	759	96.8%	19,725,437	121.93
Sm	25.52	0.008	100%	21,302	0.01
Sn	6.98	BDL	100%	2,007	0.53
Sr	1504	1436	4.50%	92,597	0.02
Ta	0.232	0.302	-30.0%	4,134	0.19
Tb	4.52	0.029	99.4%	3,666	0.01
Te	0.508	BDL	100%	BDL	0.36
Th	2.74	BDL	100%	2,647	0.00
Ti	6.68	BDL	100%	79,534	1.83
Tl	BDL	BDL	-	BDL	0.26
Tm	1.49	BDL	100%	1,225	0.01
U	35.6	0.478	98.7%	32,432	0.00
V	BDL	BDL	-	66,800	9.93
Y	118	0.036	100%	109,243	0.01
Yb	8.63	DL	100%	7,147	0.01
Zn	138,771	37.4	100%	36,368,126	0.87
Zr	1.06	0.105	90.1%	3,402	0.02

In addition to the content of the raw and treated water the content of the dried sludge was also tested, those results are shown in micrograms per kilogram. The total metal content of the sludge was 43%. An analysis of the sludges indicates the possibility of metal recovery from the sludge. Of particular interest was platinum: in the untreated and treated water it was below the detection limit of 10 ng/liter. Based on the sludge analysis the water contents were computed to be about 1.25 ng/liter. The sludge content was 14 mg/kg or about 13 grams per ton. In a mine, this would have been considered a fairly rich ore. At the typical Argo flow rate of 1600 cubic meters per day the platinum value was over USD 300,000 per year if it can be economically extracted. The EC anode used in these experiments was the aluminium alloy 6061. This alloy is readily available in plate form from which the anodes were cut. This alloy contains up to 5% non-aluminium metals which contribute small additions to the metals in the sludge. This alloy is unlikely to contain platinum or vanadium which were undetected in the water itself.

Table 10 shows a comparison of IWTP's lime treatment and EC treatment at the Argo Mine for percentage of contaminant removal. The daily results from the IWTP water were highly variable but the results from 7/22/2016 were chosen since they appeared close to optimum by inspection.

Table 10 Direct comparison of IWTP's lime treatment and EC treatment

	Reduction	
Analyte	**IWTP - Gladstone**	**EC – Argo Mine**
Aluminium	97.4%	98.3%
Arsenic	100.0%	92.7%
Cadmium	96.3%	99.9%
Calcium	-68.6%	3.1%
Cobalt	96.2%	99.5%
Copper	99.6%	99.7%
Iron	99.8%	98.4%
Lead	100.0%	100%
Manganese	71.2%	99.7%
Molybdenum	95.8%	100%
Nickel	90.9%	95.2%
Uranium	No report	98.7%
Zinc	99.3%	100.0%

Note: Gladstone IWTP did not test for the presence of uranium.

These results show that for all practical purposes the results of the two technologies are equivalent. Data for the rare earths was not available for IWTP but results from EC indicate complete removal from the water and their sequestration in the sludge.

A non-design analysis indicates that that an EC system capable of 1100 m^3/day at the Gladstone IWTP with a treatment level equivalent to the tests above would have a capital cost of approximately USD 4 million and an operation cost of USD 1.85/m^3 including power and polymer but without labour. Direct cost comparisons between the Argo facility and the Gladstone IWTP are difficult because of the numerous modifications to the plant over its years lifetime.

An EPA report for IWTP shows 450 kg per day of contaminants, 3,500 m^3 to 4,700 m^3 of waste sludge (equal to more than 700 truckloads) per year with the sludge consisting of 95% lime waste and 5% metals (US EPA, 2020). By comparison the EC process would remove approximately the same concentration of metals per day but only produce 70 truckloads of waste sludge per year. As in the Gladstone IWTP case, the TCLP tests on the EC sludge passed in all respects.

In 2013, the author treated and tested water from the American Tunnel before the Gold King Mine accident had occurred. The results, shown in Table 11, were determined in the author's laboratory but not confirmed by an independent lab. The dosage level was a combination of 43 ppm iron and 22 ppm aluminium. These results are consistent with results from the Bunker Hill Mine in Kellogg, ID and the Tip Top Mine near Minturn, CO. At this rather low dose, the operating cost with EC would be less than USD 1.32/m^3.

Table 11 EC treatment of American Tunnel acid mine water

Element	Units	Untreated	EC Treated	Removed
Al	µg/L	5,800	110	98.10%
Cu	µg/L	170	60	64.71%
Fe	µg/L	28,300	190	99.33%
Mn	µg/L	52,000	23,000	55.77%
Zn	µg/L	90	BDL	100%
pH	SU	3.15	5.8	–

Note: BDL = below detectable limits.

The historic high cost of power (around USD 1 per kWh) made early application of EC impractical purely for cost reasons. Although the scientific papers show the effectiveness of EC, the only information about implementation comes from commercial sources. In the past the main EC problems have been high maintenance costs resulting from two main issues.

- The first is the formation of a passive oxide film, an electrical insulator, on the anode that reduces the current flow and thus inhibits the dissolution of the anode. This greatly shortens operating life unless cleaned regularly. This passivation also increases power requirements.
- The second problem is the potential for precipitation to occur within the reactor. If this happens sludge will build up within the reactor and dramatically impede the flow of water through the system which can occur within 12 hours.

Advanced engineering of EC reactors has been proven to solve those problems as well as improved designs to reduce the maintenance cycle. Table 12 provides a summary of the advantages and disadvantages of EC treatment for acid mine water.

Table 12 Advantages and disadvantages of EC treatment

Advantages of EC treatment	Disadvantages of EC treatment
Lower sludge generation	Sludge may clog reactor
Successfully removes metals	Anodes may oxidize stopping dissolution
Successfully removes other contaminants	High maintenance costs with poor design
Sludge meets TCLP landfill standards	Industry understanding of EC is limited
No toxic chemicals required	Reactor designs proprietary to vendor
Easy to automate dosage titration	–
Often no pH adjustment required	–

3 Conclusion

Electrocoagulation, while widely studied, has few operational examples in the mining industry. The effectiveness of EC treatment may be superior to lime/lime-limestone treatment of acid mine water for removing the contaminants of concern. However, treatment with lime or lime-limestone is widely used and well understood. Lime treatment is usually effective and can be cost efficient. The capital costs for HDS systems are significantly higher than for conventional lime systems but operating costs are usually less. EC system capital costs are likely equivalent to or less than conventional lime treatment systems. EC generates about 70% less sludge than that generated by HDS systems and about 90% less than conventional lime sytems. EC treatment may be less expensive to operate due to the decreased cost of chemicals, sludge disposal fees, and transportation costs. When amortization costs are considered, EC may also be less expensive than HDS. EC may have important advantages with system simplicity, effectiveness, resource recovery or equipment cost. However, each EC reactor model is unique to its manufacturer. It requires careful validation of the choice of reactor to ensure that operational and maintenance problems are minimized. A comprehensive review of each mine site is required to determine the best and most appropriate process. To determine if EC is an acceptable solution, a short pilot with the selected reactor and an evaluation of the complete life cycle costs would make the comparison possible. With today’s advances in EC engineering, it should always be considered as a solution.

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