High Efficiency Modular Treatment of Acid Mine Drainage Field Applications at Western U.S. Sites with the Rotating Cylinder Treatment System (RCTS)

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The most common practice for treatment of acid mine drainage is lime precipitation. This process oxidizes the iron containing water in oxidation reactors and neutralizes the acid with the addition of lime. Hydroxide precipitation of most metals occurs as the pH is increased to near 8 s.u. Ferrous iron, however does not precipitate to an acceptable concentration at pH 8 and lower unless it is oxidized to ferric iron. The rate of ferrous to ferric iron conversion is slow at low to moderate pH and increases exponentially as the pH increases. Conventional systems typically utilize compressors to provide oxygen, and mixers in the reaction tanks to dissolve lime slurry and to aid in the oxidation process. The Rotating Cylinder Treatment System (RCTS) utilizes rotating perforated cylinders contained in troughs or cylinders to oxidize and mix the lime slurry with the acid mine drainage. The system has been tested on multiple sites in the Western U.S. to treat water containing dissolved iron concentrations at up to 7 grams/L (7,000 mg/L). The system is also effective at treating net alkaline drainage containing dissolved ferrous iron and supersaturated bicarbonate without the addition of neutralizing agents.

Key words: oxidation, aeration, lime treatment, acid mine drainage, acid rock drainage, water treatment, mine remediation, and gas exchange

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Introduction

Lime precipitation is the most common and proven treatment method for acid mine drainage. These systems utilize the basic properties of lime to precipitate metals as metal hydroxides and calcium to remove sulfate as gypsum. Lime slurry is often delivered at concentrations to increase the pH to near 8. At this pH most metals will precipitate efficiently from solution. However, ferrous iron will not precipitate to an acceptable concentration unless oxidized and converted to ferric iron (USEPA 1983).

The time required to oxidize ferrous to ferric iron is on the order of days at pH less than 6. However, as the pH is increased, the rate of oxidation increases exponentially (Singer and Stumm 1969). It is therefore, advantageous to raise the pH sufficiently to convert the ferrous iron to ferric (Wilmoth 1977). The oxidation rate is also dependant upon the ferrous iron activity and the activity of the oxidant (Singer and Stumm 1969). Using conventional methods the oxidation typically occurs in large reaction vessels in which air is bubbled into the water with diffusers. The bubbles are then broken up with mixing rotors which also provide the agitation for lime dissolution.

The RCTS replaces the reaction vessels, compressors, diffusers and agitators found in conventional systems. The oxidation and mixing is accomplished by passing the untreated acid mine drainage and lime slurry through a trough, in which a perforated cylinder rotates. As the cylinder rotates a film of water adheres to the inner and outer surfaces where gas exchange occurs. In addition, water bridges across the perforations for additional gas exchange.

The agitation is provided primarily by the impact of the perforations with the water flowing through the trough. Air is forced into the water where additional gas transfer can occur. The turbulence that is produced provides efficient lime mixing and dissolution.

The RCTS treatment system was implemented and tested on several sites in the Western U.S.. At the Rio Tinto site, acid mine drainage was treated with dissolved iron concentrations upwards of 7 grams/L. A system was also mobilized at the Leviathan Mine site where a batch system was implemented to treat ~ 800,000 gallons in approximately 90 hours. At the Nevada City site, net alkaline water containing ~4 mg/L iron was treated without the addition of any base.

RCTS Test Units

RCTS units are designed for specific applications. All of the units presented are mobile and modular and can be placed in series to provide the specific mixing and gas exchange required at each individual site.

RCTS-Four-Rotor Test Units

Four-rotor units are designed to provide oxygen and the residence time necessary to oxidize and precipitate iron from solution. These units are utilized when the metal precipitate must be captured and a separate reaction pond is either sized inadequately or non-existent. A 600-gallon capacity unit and a 1200-gallon capacity unit were utilized in the tests presented here (see figures 1 & 2).

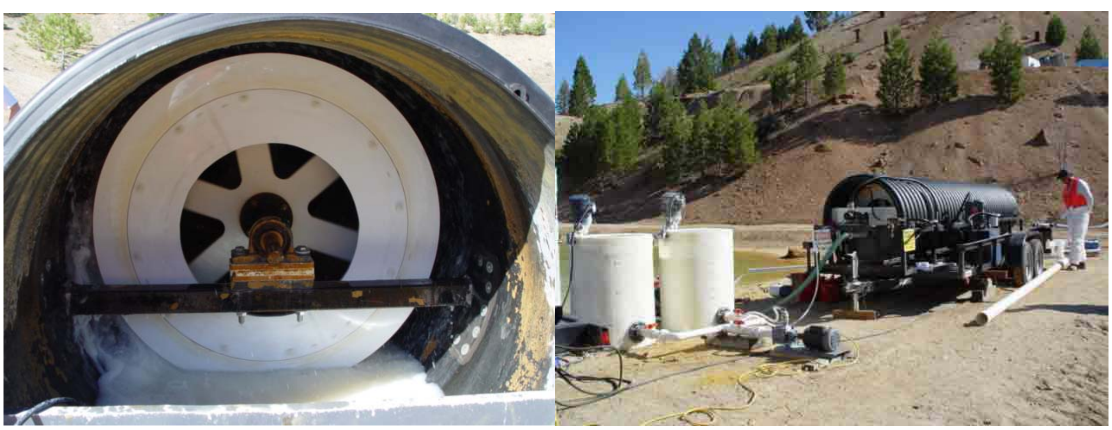
RCTS-HS High Speed Test Units

Single-cylinder RCTS-HS units spin at a higher rpm and are designed to provide more aggressive agitation and mixing for applications where a high rate of gas exchange is needed and/or a high rate of flow must be treated. Figures 3 shows the RCTS-HS unit used at the Leviathan Mine.

Figure1. The 600-gallon capacity and 1200-gallon capacity units at the Rio Tinto Mine Site

Figure 2. Iron oxidation from ferrous to ferric in the first two cylinders of the four-rotor unit.

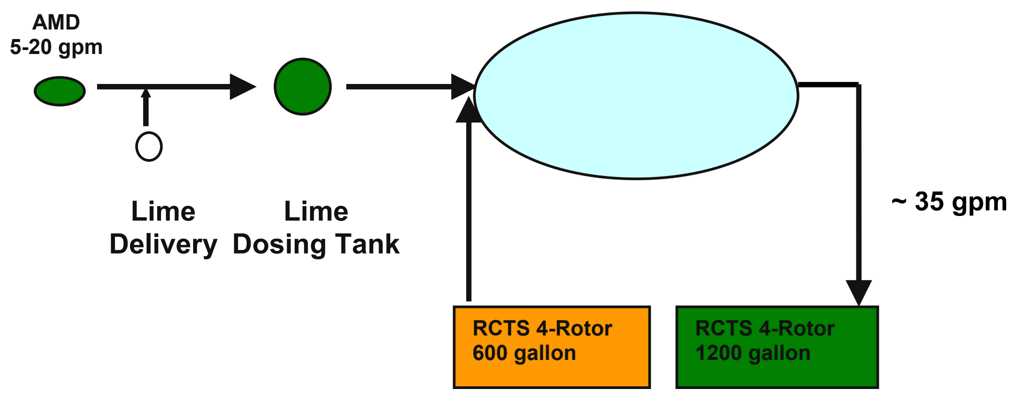
Figure 3. The RCTS-HS utilized at the Leviathan Mine.



The Rio Tinto Mine Site

During the summer of 2005, two four-rotor RCTS units were implemented in series to treat acid mine drainage containing more than 7 grams/L of dissolved metals and 24 grams/L of sulfate at the Rio Tinto Mine. Lime slurry was mixed with impacted water in a lime dosing tank to raise the pH from approximately 2.6 to approximately 8.5. The water from the flash reactor tank was then mixed with RCTS effluent prior to delivery to a settling pond. The pH-adjusted mixture from the settling pond was then fed into the RCTS system. The influent water flowed through each cell in series. Mixing resulted in an increase in pH and dissolved oxygen. Each unit consisted of four cells. Each cell contained perforated rotating cylinders which were coupled together in series. The treated effluent was discharged from the last cell and was mixed with pH-adjusted water from the flash reactor tank prior to flowing to the settling pond where the majority of metals precipitated and settled from solution. During the treatment process field water quality parameters were recorded and samples of untreated and treated water were submitted to a laboratory for analysis. The raw water flow rate to the system ranged from 5 to 20 gallons per minute (gpm) during two treatment events. The flow to the RCTS oxidizing units was approximately 35 gpm.

Figure 4. Schematic of the 2005 Rio Tinto water treatment utilizing two RCTS units, a lime dosing tank and a settling pond.



Rio Tinto Results

The RCTS treatment system was very effective at removing metals from the acid mine water. Table 1 displays results from the Rio Tinto Site. All applicable metals including manganese were typically reduced to less than 0.6 mg/L. The total system operated on less than 3500 watts of electricity.

Table 1. Treatment Results for the Rio Tinto Mine 2005 Concentrations (mg/L)

Date	Sample location	Al	As	Cd	Cu	Fe	Mn	Zn	Sulfate
7/19/2005	Influent	726	nd	0.340	320	6780	87.3	73.6	24,100
7/19/2005	Effluent	0.2	nd	nd	0.005	nd	1.01	nd	4110
7/26/2005	Influent	793	0.03	0.359	314	6890	96	79.4	24,180
7/26/2005	Effluent	0.1	nd	0.0005	0.005	nd	0.52	nd	2,410
8/5/2005	Influent	540	nd	0.338	228	4990	80.3	60	17,600
8/5/2005	Effluent	0.08	nd	0.0002	0.002	0.05	0.41	nd	1,800
8/11/2005	Influent	297	nd	0.210	130	2840	63.9	36.7	10,200
8/11/2005	Effluent	0.13	nd	nd	0.01	nd	0.2	nd	1,950
8/18/2005	Influent	305	nd	0.200	128	2950	58.1	35.2	10,900
8/18/2005	Effluent	0.114	nd	nd	0.014	0.06	0.2	nd	2,070
9/7/2005	Influent	572	nd	0.301	248	5110	67.4	57.5	17,600
9/7/2005	Effluent	0.26	nd	nd	0.018	0.40	0.23	nd	2,560
9/23/2005	Influent	325	nd	0.198	139	2940	58.2	36.5	9,710
9/23/2005	Effluent	0.07	0.001	0.0002	0.009	nd	0.58	nd	2,390
9/30/2005	Influent	279	nd	0.230	131	2570	51.9	32.3	9,910
9/30/2005	Effluent	0.04	0.001	0.0002	0.011	nd	0.581	nd	2350

The Leviathan Mine Site

The goal of this project was to quickly treat approximately 800,000 gallons of impacted water contained in a pond, to allow the water to be discharged, thus reducing the risk of pond overflow to Leviathan Creek during spring runoff. The treatment system consisted of an RCTS-HS (rotating cylinder treatment system- high speed) unit, two one-hundred-gallon lime slurry tanks, a lime delivery pump, and three two-inch water delivery pumps. Water was pumped to the RCTS-HS at a rate of 44-160 gpm, where lime was added to the water and the dissolved ferrous iron was oxidized. The high pH water and precipitated solids were then mixed back into the pond.

Initially, we assumed that the acidity of the water was low, due to the low iron concentrations in the water, and the lime addition rate was controlled to minimize the amount of unreacted lime that was added to the pond. During treatment the effluent was milky white in color due to particles in the water, which were assumed to consist of unreacted lime, calcium carbonate, gypsum and aluminum hydroxide. On the third day of treatment, we recognized that the acidity was higher than initially assumed (due to high concentrations of aluminum in the water). At that time the lime addition rate was increased and on day 5 an additional influent pump was added which allowed the lime to be delivered to the pond at a higher rate. During the treatment process field water quality parameters were recorded and samples of treated water were submitted to a laboratory for analysis.

Leviathan Results

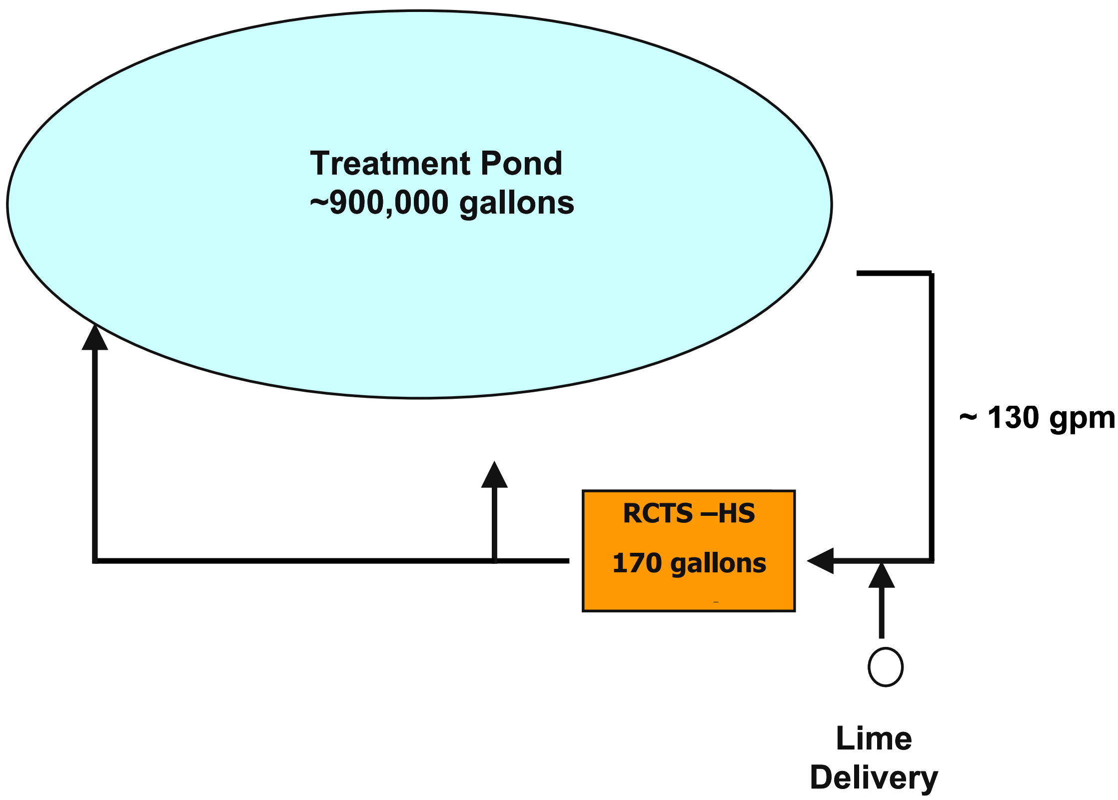
The RCTS treatment system was mobilized within 3 days of notification and effectively treated the contaminated acidic water in the holding pond. The acidity measured after 10% of the lime had been added, was 2,160 mg/L ($CaCO_3$), therefore the estimated acidity at the start of the treatment was ~2,376 mg/L ($CaCO_3$). Given this acidity, the total amount of lime needed to raise the pond to pH 8 assuming 100% efficiency is ~13,200 lbs. Overall, 14,375 lbs of lime were added over 15 days of treatment which represents a lime neutralization efficiency of greater than 89%.

Table 2 shows field measurements for the treatment period. The drop in pH from day to day is due to a complication that exists with the liner in this holding pond. The pond liner is covered with approximately 0.2 m of sand which holds considerable acidity. This acidity consumes alkalinity and over time the pond pH drops. This complicates neutralization because the pH drops significantly if lime is not added for extended periods of time. Therefore the discharge had to occur shortly after neutralization to minimize the mobilization of acidity. Approximately 800,000 gallons were treated in approximately 90 hours and approximately 500,000 gallons were subsequently discharged from the pond to provide additional storage for the site. Table 4 displays metal concentrations before and after treatment. It is important to note that the pond was not thoroughly mixed at the time the untreated sample was taken. The sample was taken near the edge of the pond toward the surface. Therefore the actual concentrations were likely higher overall in the pond.

Table 2. Field Measurements for Leviathan 2005 Pond 3 Emergency Treatment					
Date (Day)	Task Flow treated	Hours operated	Pound lime added (cumulative)	Beginning pH	Ending pH
5-23-05 test	Mobilization Initial test 47 gpm	1	50 (50)	2.87	3.01
5-24-05 (1)	Treatment 47 gpm	8	300 (350)	2.92	3.72
5-25-05 (2)	Treatment 47 gpm	7	400 (750)	3.25	4.90
5-26-05 (3)	Treatment 54 gpm	7.5	800 (1550)	3.62	4.30
5-27-05 (4)	Treatment 95 gpm	8	1500 (3050)	3.70	4.47
5-31-05 (5)	Treatment 130 gpm	8	1000 (4050)	3.66	4.86
6-1-05 (6)	Treatment 130 gpm	8	1900 (5950)	3.65	4.16
6-2-05 (7)	Treatment 160 gpm	8.5	2850 (8800)	4.13	4.43
6-3-05 (8)	Treatment 160 gpm	8	2250 (11050)	4.57	6.97
6-6-05 (9)	Treatment 160 gpm	8	800 (11850)	5.23	8.80
6-7-05 (10)	Treatment 160 gpm	4	150 (12000)	6.59	9.25
6-17-05 (11)	Treatment 160 gpm	8	850 (12850)	4.29	5.20
6-20-05 (12)	Treatment 160 gpm	7.5	1000 (13850)	4.78	8.14
6-21-05	Treatment and Discharge	10.5	400 (14250)	5.58	7.72
6-24-05	Treatment and Discharge	12	125 (14375)	6.18	6.99

Table 3. RCTS Treatment Results for the Leviathan Mine 2005 Concentrations (mg/L)								
Date	Sample location	Al	As	Cd	Cu	Fe	Mn	Zn
5-24-05	Untreated	209	0.01	0.0399	1.89	17.3	10.4	0.881
6-20-05	Treated	0.25	0.005	0.01	0.01	0.1	0.23	0.02

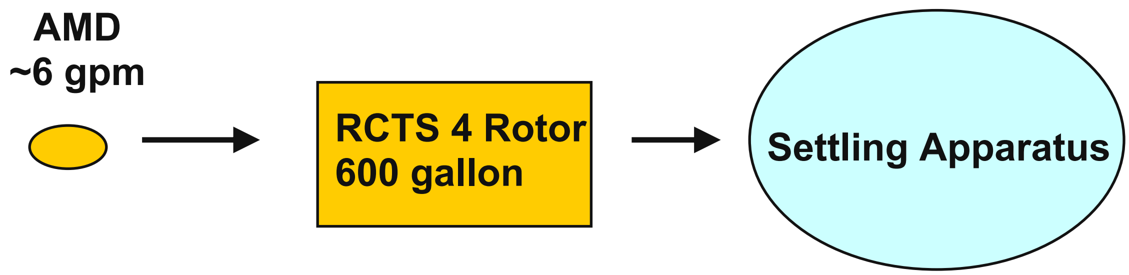
Figure 5. Schematic of the 2005 Leviathan Mine water treatment system



The Empire Mine Site

The goal of this test was to determine if the RCTS could be utilized to precipitate iron and co-precipitate arsenic from solution at the Empire Mine Site. An RCTS Four Rotor unit was utilized to treat a portion of this net alkaline mine drainage containing approximately 4.290 mg/L of iron and 0.047 mg/L of arsenic. The RCTS units that was used consisted of four cells with a total capacity of600 gallons. During the treatment process field water quality parameters were recorded and samples of untreated and treated water were submitted to a laboratory for analysis. The flow rate to the system was approximately 6 (gpm).

Figure 6. Schematic of the Empire Mine treatment system.



Empire Mine Results

The RCTS treatment system was effective at precipitating and reducing iron from 4.29 mg/L to 0.08 mg/L. It was proposed that sodium hydroxide be added to raise the pH from 6.6 s.u. to approximately 8 s.u.. However, sodium hydroxide addition was not necessary due to degassing of carbon dioxide from the water which resulted in consumption of acidity as follows.

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2 \Uparrow$$

Arsenic was also reduced from 0.047 mg/L to 0.025 mg/L. It is likely that additional arsenic can be removed with the addition of a small quantity of ferrous iron.

Conclusions

The RCTS treatment systems were effective at treating different types of mine drainage and different applications:

1. Treatment of highly concentrated acid mine drainage was achieved using minimal power, lime and space.
2. An RCTS-HS unit was rapidly mobilized to treat moderate strength acid mine drainage in a minimal amount of time.
3. A 600-gallon capacity unit was utilized to remove dissolved iron from net alkaline water by degassing carbon dioxide and consuming acidity without the addition of lime or caustic.

These systems are energy efficient and provide thorough mixing for efficient lime dissolution. Previous tests at the Rio Tinto mine showed lime efficiencies of 98%. Lime efficiencies at the Leviathan Mine were approximately 89% despite the fact that excess lime was added in the RCTS (RCTS effluent pH was greater than 12 s.u.) to provide additional alkalinity, allowing further neutralization within the pond.

The RCTS also provides greater oxygen addition per energy consumed than conventional systems. The EPA found that mechanical surface aeration systems provide 3.0-3.5 lbs of oxygen per horsepower hour, while submerged turbine aerators utilizing dual impeller turbines provide

2.5-3.0 pounds of oxygen per horsepower hour (USEPA 1983). For comparison, testing with the 600-gallon, four-rotor unit demonstrated approximately 9 pounds of oxygen consumed per horsepower hour, using the same oxygen demand equation (USEPA 1983).

$$O_2 = Qw \mathbf{\ x\ } Fe \mathbf{\ x\ } 7.14 \times 10^{-5}$$

Where O_2 = Theoretical O_2 demand (lb O_2/hr)
Qw = Acid mine drainage flow rate (gal/min)
Fe = Fe^{2+} initial concentration (mg/L)

The test unit operated on two cylinders powered by 0.375 hp and oxidized ~ 5,000 mg/L of iron at a flow rate of 10 gallons per minute.

References

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