A PASSIVE MINE DRAINAGE TREATMENT SYSTEM AS A BIOREACTOR: TREATMENT EFFICIENCY, pH INCREASE, AND SULFATE REDUCTION IN TWO PARALLEL REACTORS[1]

by

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Abstract: Two pilot scale bioreactors designed to treat acid mine drainage primarily using sulfate reducing bacteria were constructed underground at the Eagle Mine Superfund site in Minturn, Colorado. The project was designed to test the applicability of microbiological treatment on water with high metals concentration and to test the process in an underground environment. Research objectives were: 1) to compare metal removal, sulfate reduction, pH increase, etc. of a pilot scale single stage system with a double stage system of equal volume at varying flow rates; 2) to determine where within a reactor treatment occurs; and 3) to determine whether a zone of lower treatment efficiency exists at the mine drainage-substrate interface and whether this zone migrates through the substrate at high flows. Preliminary results from experiments using 250 ml BOD bottles filled with cow manure, hay and mine water showed 99% removal of metals. Results from the pilot scale reactors yielded 95 to 100% removal of metals. 75% removal of metals occurred within the first 10 inches of substrate, and 98% occurred by 30 inches. A zone of lower treatment efficiency did exist at the mine drainage-substrate interface, but did not migrate through the substrate with time. A composted cow manure and hay substrate, in an upflow tower configuration, treated flows four times higher than other systems tested in the Rocky Mountain region.

Additional Key Words: acid mine drainage, sulfate reducing bacteria, mine reclamation, passive mine drainage treatment.

Introduction

Acid mine drainage is a major cause of surface and ground water contamination throughout mining districts of the United States. It is estimated that over 17,000 km of major streams have been contaminated by the draining of metal laden water from abandoned mines (Herlihy et al. 1987). With exposure to atmospheric oxygen and water, pyrite, a common ore bearing mineral, becomes unstable and is subject to autooxidation and microbial iron and sulfur oxidation. These processes produce high levels of acidity (Atlas and Bartha, 1987). The acid then solubilizes other common ore elements such as Mn, Pb, Ag, As, Cu, Cd, and Zn. Water containing these heavy metals flows from mine tunnels and tailings piles and discharges into surface and ground waters creating acid mine drainage pollution.

The Eagle Mine Superfund site located 100 miles west of Denver, Colorado is an abandoned Pb/Zn mine which ceased operations in 1984 (EM RIFS, 1985). Since that time, a constant flow of ground water has flooded the mine and subsequently leached into the Eagle River. The Eagle Mine water is highly contaminated with heavy metals (Fe:300 ppm, Mn:210 ppm, Cd:1.2 ppm, Cu:14 ppm, Zn:310 ppm, and Pb:0.6 ppm). The pH ranges from 2.6 to 3.0 and sulfate exists in concentrations of 4,500 ppm. Temperatures within the mine adit range from 2 to 9° Celsius.

At present, the water is collected and treated with an acid neutralization treatment process, which has proven to be costly and not entirely effective. Passive mine drainage treatment (PMDT) was chosen as a possible inexpensive alternative based on research performed at the Big Five Tunnel in Idaho Springs, CO, as well as the Quartz Hill tunnel near Blackhawk, Colorado (Wildman et al. 1990). The Quartz Hill tunnel produces similar levels of contamination to that of the Eagle Mine drainage and was successfully treated in bench scale bioreactors by Bolis et al. (1991).

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[1] Paper presented at the 1992 National Meeting of the American Society for Surface Mining Reclamation, Duluth, MN, June 14-16, 1992.
"Publication in this procedings does not preclude the authors from publishing their manuscripts, whole or in part, in other publication outlets."

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Proceedings America Society of Mining and Reclamation, 1992 pp 550-562
DOI: 10.21000/JASMR92010550

https://doi.org/10.21000/JASMR92010550

The drainage chosen for the experiment flows from the old milling area in the Eagle Mine called the Newhouse tunnel. This site was chosen primarily based on location and drainage characteristics.

Two parallel pilot scale reactors were designed to examine the following objectives: 1) the performance of metal removal, pH increase, and sulfate reduction at differing flow rates.; 2) performance of the SS reactor verses the DS reactor; 3) whether any spatial variation in treatment efficiency occurs with substrate depth; and 4) whether a zone of lower treatment efficiency exists at the mine drainage-substrate interface and whether this zone expands through the substrate with time.

Methodology

The system used for this experiment was designed as two parallel reactors, 1) a single stage (SS) reactor constructed from a 500 gallon cylindrical tank, and 2) a double stage (DS) reactor constructed from two 200 gallon cylindrical tanks. The tanks were fabricated from high density polyethylene plastic. Each was plumbed with 1.5 inch bulkhead fittings in an upflow configuration. 1.5 inch diameter PVC pipe was then attached to the bulkhead fittings. Figures 1 and 2 show a cross sectional view of the configuration of the SS and DS reactors respectively.

Mine drainage was collected at the source by a dam constructed of mine timbers and hypalon liner. PVC pipe (1.5 inch diameter) carried the mine drainage from the milling area, down an incline, and into a 500 gallon reservoir tank. This tank was fitted with a constant head drain pipe which maintained a constant hydraulic head adequate to drive the system. The reservoir tank was also plumbed with 1.5 inch PVC pipe which fed the two reactors. A globe valve placed upflow of the reactors controlled influent water. Two ball valves placed at the effluent pipes of each reactor controlled flow more precisely. Two PVC "Y" joints were placed downstream of the effluent valves to allow measurement of flow rates.

Sampling spigots were placed at the effluent of the reservoir tank, the effluent of each reactor, and between reactors 1 and 2 of the DS system. Finally, three sampling wells constructed of 2-inch PVC pipe were placed within the SS reactor. The wells were five feet long and each were perforated at different sampling levels. The wells were labeled A, B, and C, and had sampling levels of 10, 20 and 30 inches respectively.

Each reactor was identically plumbed and filled with equal volumes of identical substrates. The lower four inches of the reactors was filled with pea gravel to

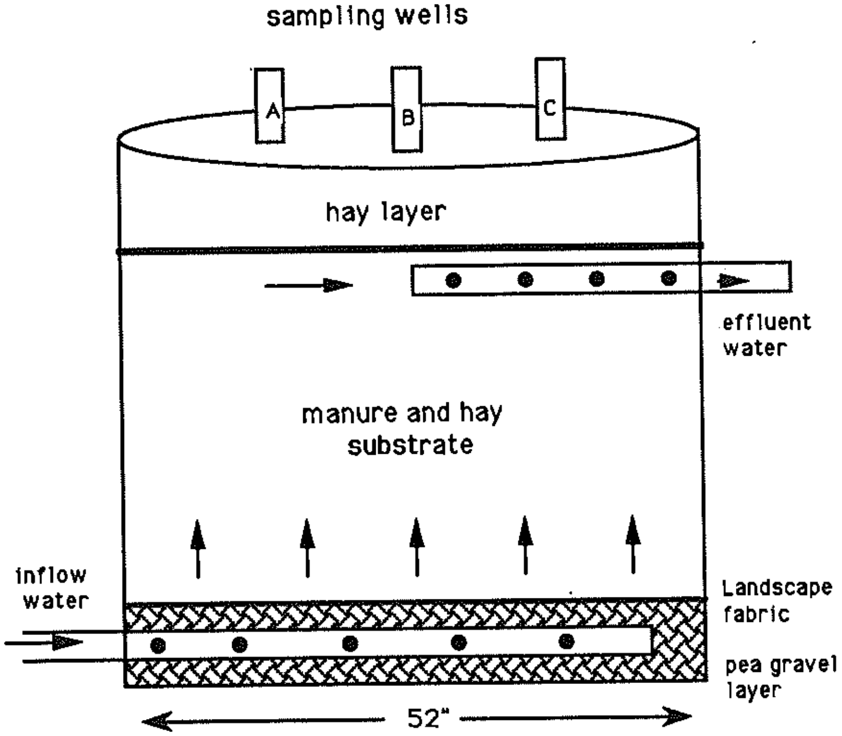

Figure 1: Single Stage recator constructed of 500 gallon HDP tank and filled with composted cow manure and hay substrate. Wells A, B, and C have sampling levles of 10", 20", and 30" from the base of the substrate.

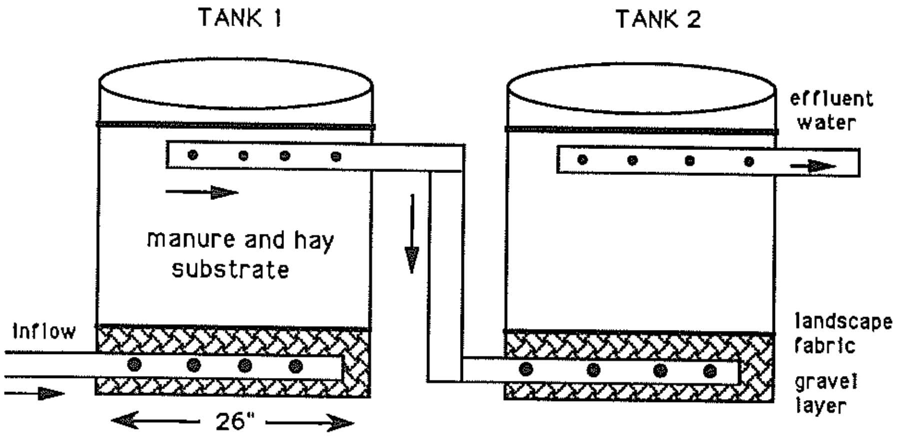

Figure 2: Double Stage reactor constructed of 2 200 gallon HDP tanks filled with composted cow manure and hay substrate. Effluent from TANK 1 discahrges directly into tank 2.

ensure even flow and deter short circuiting. A layer of landscape fabric covered the pea gravel to prevent substrate from mixing with the gravel and clogging the inflow pipe. The remaining space was filled with a composted cow manure and fresh hay substrate in a 4:1 volumetric ratio. Cow manure was chosen because of its high pH and proven effectiveness in previous experiments (Reynolds et al. 1991 and Bolis et al. 1991). Hay was added as an inexpensive nutrient to increase sulfate reduction reaction rates (Reynolds et al. 1991). Finally, each reactor was inoculated with 15 lbs. of substrate from the Big Five constructed wetland in Idaho Springs, Colorado (Bolis et al. 1991). The combined volume of substrate in both tanks of the DS reactor was equal to the volume of substrate in the SS reactor.

Upon completion of construction, the reactors were filled with mine drainage and allowed to soak for one week to initiate bacterial growth (Bolis et al. 1991). Operation commenced July 25, 1991 and terminated November 26, 1991 due to freezing. Initial flow rates were calculated at 50 ml/min based on a loading rate of 0.125 gal/min/100 ft^2 which effectively treated mine drainage at the Big Five constructed wetland in Idaho Springs, Colorado (Wildman et al. 1990). After five weeks of operation, flow rates were doubled to 100 ml/min and were doubled again to 200 ml/min at week eleven. Flow rates were increased to 400 ml/min by week sixteen, however freezing prevented the collection of adequate data.

Weekly sampling commenced July 31, 1991 and ended November 26, 1991. Eight samples were collected each week and measured for pH, Eh, conductivity, and temperature in the field. Eight additional samples were filtered through 0.45 µm Geotech filter and were analyzed for copper, cadmium, lead, iron, manganese, and zinc using both ICAP and AA. Eight unfiltered samples were collected for sulfate analysis using spectrophotometry. These samples were analyzed at Vista Laboratory in Broomfield, Colorado. Duplicate samples were taken each week and splits and blanks every other week for QA/QC purposes.

Hydraulic residence time (V/Q) was calculated for the water entering each reactor at the three flow rates. At 50, 100, and 200 ml/min, hydraulic residence for each reactor was 16.9, 8.45, and 4.22 days respectively. Velocity (Q/A) was also calculated for each reactor at the three flow rates. Velocity of the water traveling through the SS reactor at 50, 100, and 200 ml/min was 3.66×10^{-3}, 7.31×10^{-3}, and 1.46×10^{-2} cm/min respectively. Velocity of the water traveling through the DS reactor was 7.62×10^{-3}, 1.52×10^{-2}, and 3.05×10^{-2} cm/min at 50, 100, and 200 ml/min respectively.

Results and Discussion

Results for treatment efficiency (percent removal) of Cd, Cu, Pb, Fe, Mn, and Zn for the effluent water from the single and double stage reactors at flow rates of 50, 100, and 200 ml/min are shown in table 1. Results for treatment efficiency of the sampling wells A, B, and C in the SS reactor are listed in table 2.

Table 1: Treatment efficiciency for the SS reactor and tanks 1 and 2 of the DS reactor. Values are expressed in percent removal. (NM = Not measured).

		CADMIUM			COPPER			LEAD		
flow	DATE	SS-1	DS-1	DS-2	SS-1	DS-1	DS-2	SS-1	DS-1	DS-2
50ml/min										
	31-Jul	NM	100	100	NM	98	97	NM	94	96
	8-Aug	100%	97	100	95	86	96	76	88	71
	16-Aug	96%	100	100	93	95	94	47	100	53
	19-Aug	100%	100	100	96	97	99	100	94	87
	28-Aug	97%	91	100	96	98	99	84	100	95
	3-Sep	98%	0	100	99	38	100	95	43	100
100ml/m										
	12-Sep	100%	50	100	100	76	100	100	100	100
	17-Sep	100%	27	100	100	78	100	93	85	93
	24-Sep	100%	89	100	100	95	100	100	100	100
	1-Oct	100%	77	96	100	83	100	100	100	100
	8-Oct	74%	85	97	94	96	97	97	95	96
200ml/m										
	15-Oct	100%	82	100	99	97	99	100	96	100
	29-Oct	71%	85	83	33	96	92	0	93	0
	5-Nov	NM	98	NM	NM	100	100	NM	100	100
	12-Nov	100	71	100	100	87	100	100	100	100
400ml/m										
	20-Nov	97%	63	100	94	85	100	100	100	100
	26-Nov	99%	85	100	99	97	99	100	100	100

		IRON			MANGANESE			ZINC		
	DATE	SS-1	DS-1	DS-2	SS-1	DS-1	DS-2	SS-1	DS-1	DS-2
50ml/min										
	31-Jul	NM	94	89	NM	95	99	NM	99	100
	8-Aug	97	93	86	100	93	99	99	99	99
	16-Aug	97	90	81	99	91	98	100	99	100
	19-Aug	95	94	83	98	88	98	99	99	100
	28-Aug	94	82	85	97	0	96	99	8	100
100ml/m										
	3-Sep	95	42	92	98	0	97	100	8	100
	12-Sep	98	39	97	98	0	97	100	0	100
	17-Sep	99	19	97	99	0	97	100	0	100
	24-Sep	100	75	91	99	0	93	100	0	100
	1-Oct	99	62	90	93	0	55	99	0	79
	8-Oct	92	45	93	32	0	63	45	0	81
200ml/m										
	15-Oct	99	33	97	96	0	87	100	0	99
	29-Oct	0	39	3	69	5	79	61	0	83
	5-Nov	NM	33	99	NM	20	93	NM	17	100
	12-Nov	98	53	99	95	11	84	100	17	100
400ml/m										
	20-Nov	92	58	99	95	10	86	99	29	100
	26-Nov	99	55	99	98	11	85	99	32	100

Table 2: Treatment efficiency of sampling wells from the single stage reactor. Well A = 10 " well B = 20", and well C = 30". Values presented in percent removal (NM = Not measured).

		CADMIUM			COPPER			LEAD		
flow	DATE	W-A	W-B	W-C	W-A	W-B	W-C	W-A	W-B	W-C
50ml/min										
	31-Jul	100%	NM	NM	97	NM	NM	100	NM	NM
	8-Aug	96%	100	100	85	95	97	23	42	61
	16-Aug	93%	100	100	87	96	96	0	0	11
	19-Aug	96%	100	100	94	97	97	57	100	100
	28-Aug	97%	91	99	98	98	98	89	80	89
	3-Sep	98%	98	98	100	98	98	95	88	90
100ml/m										
	12-Sep	100%	100	99	100	98	97	100	88	88
	17-Sep	99%	100	99	100	100	98	91	100	100
	24-Sep	99%	100	100	100	100	99	100	95	100
	1-Oct	99%	100	100	98	100	100	100	100	100
	8-Oct	99%	100	100	99	100	98	100	100	91
200ml/m										
	15-Oct	99%	100	100	99	99	99	100	100	90
	29-Oct	99%	100	100	98	99	99	100	100	100
	5-Nov	99%	100	100	98	99	99	100	100	100
	12-Nov	97%	100	100	98	99	99	100	96	99
400ml/m										
	20-Nov	97%	100	100	97	99	98	100	100	100
	26-Nov	97%	100	100	99	99	99	100	100	100

		IRON			MANGANESE			ZINC		
	DATE	W-A	W-B	W-C	W-A	W-B	W-C	W-A	W-B	W-C
50ml/min										
	31-Jul	93	NM	NM	89	NM	NM	98	NM	NM
	8-Aug	76	83	92	88	99	99	98	99	100
	16-Aug	75	82	90	84	97	98	98	99	99
	19-Aug	81	82	87	83	95	92	997	99	99
	28-Aug	87	83	91	76	94	80	96	99	98
100ml/m										
	3-Sep	90	89	91	72	94	70	97	100	91
	12-Sep	89	87	88	66	94	72	98	100	91
	17-Sep	92	92	92	71	95	75	99	99	95
	24-Sep	98	94	95	94	95	86	99	99	99
	1-Oct	91	94	97	63	94	93	97	99	100
	8-Oct	91	94	98	59	95	95	97	100	99
200ml/m										
	15-Oct	91	95	98	51	94	98	96	100	99
	29-Oct	94	96	99	59	95	98	97	99	99
	5-Nov	94	96	99	59	96	98	96	99	99
	12-Nov	94	97	99	62	96	98	95	100	99
400ml/m										
	20-Nov	96	98	98	68	97	98	97	99	99
	26-Nov	95	97	99	65	96	99	96	99	99

Field Measurements

The effluent water from the SS reactor showed an increase in pH from 2.6 in the mine water to near neutral at 50ml/min and above neutral at 100 and 200 ml/min. In tank 1 of the DS reactor pH increased to 6.3 at 50 ml/min but dropped below 6 at 100 and 200 ml/min. Tank 2 of the DS reactor increased mine water pH above 6.5 for most of the experiment at all three flow rates. Figure 3 shows pH of the SS reactor effluent and tanks 1 and 2 of the DS reactor compared with mine drainage pH.

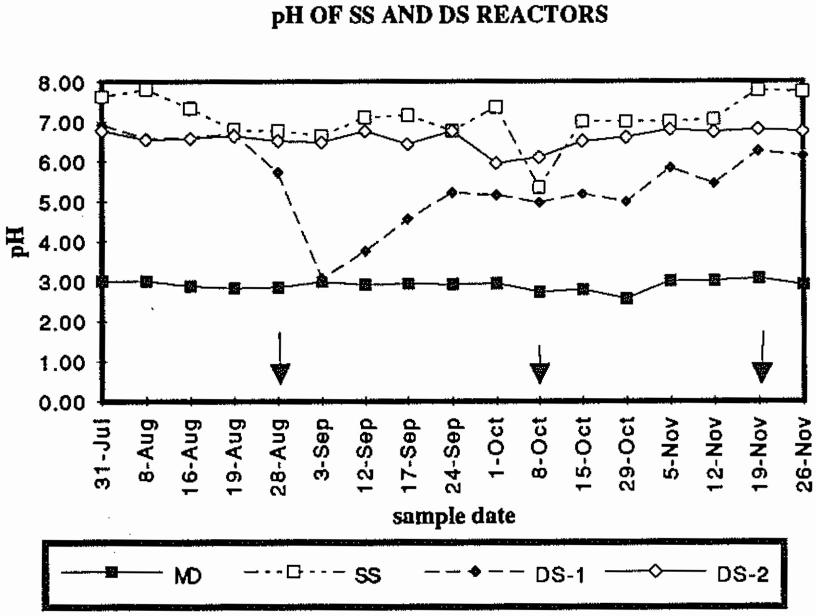

Figure 3: pH of the Single stagereactor and Tanks 1 and 2 of the double stage reactor with respect to mine drainage pH. Arrows represent flow rate increases of 100, 200, and 400 ml/min.

At 10 inches of substrate, well A, mine water pH was raised to above 6.0. At 20 inches of substrate, pH increased to 6.5 and by 30 inches of substrate, ph reached above 7.0 most sample weeks. Figure 4 shows pH values in the SS sampling wells.

Eh of the mine water ranged from 650 mv to 750 mv during the seventeen week experiment. Effluent of the SS reactor showed a drop in Eh below zero at 50 and 100 ml/min, but increased above zero at 200 ml/min. Eh values for tank 1 of the DS reactor ranged from -18 mv to +600 mv during the experiment. Finally, Tank 2 of the DS reactor maintained a redox potential slightly negative at 50 and 100 ml/min and slightly positive at 200 ml/min. Eh measurements are often inaccurate and subject to interference (Langmuir 1971). Therefore, for this research redox potential was used only as a method to determine whether the reactors sustained reducing or oxidizing conditions.

Conductivity of the mine drainage ranged from 2,400 mmohs to 5,070 mmohs. Conductivity of the reactor effluents increased substantially over the mine drainage. This suggests a decrease in water quality.
However, field results and treatment efficiencies suggest otherwise. The increase in conductivity was explained by leaching of organ ionic groups from the manure substrate. therefore, it was determined that conductivity was not a valid measurement for this research and will not be discussed further.

Metal Removal

Flow of 50 ml/min. 96 to 100% of cadmium was removed in the single stage reactor. This decreased Cd concentration from 0.91 ppm in the mine drainage to 0.0 to 0.03 ppm. In tank 1 of the double stage reactor, treatment efficiency of Cd ranged from 0 to 100% and in tank 2 of the DS reactor Cd was removed 100% at

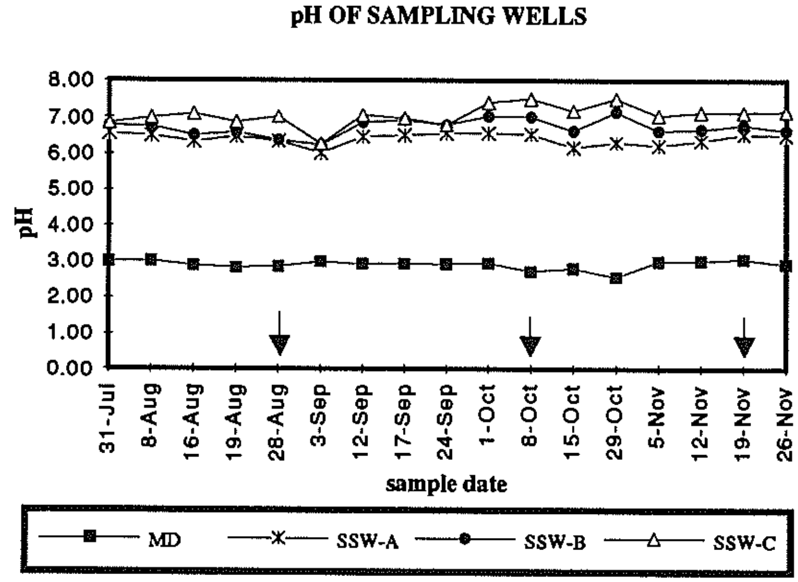

Figure 4: pH of the sampling wells in the SS reactr. Well A = 10", well B = 20", and well C = 30" of substrate. Arrows represent flow increases to 100, 200, and 400 ml/min.

50 ml/min. Figure 5 shows treatment efficiency of Cd for the SS and tank 1 and 2 of the DS reactor. The low treatment efficiency in tank 1 of the DS reactor was explained by several contamination incidents in which clogging of a pipe forced mine drainage to flow backwards through the system and contaminate the effluent sample.

At 10 inches of substrate, well A, treatment efficiency of cadmium ranged from 98 to 100%. 91 to 100% was removed at 20 inches of substrate, well B. At 30 inches of substrate, well C, 99 to 100% of Cd was removed. These removals showed a decrease in Cd concentration from 1.0 to below detection limits.

96% of copper was removed in the SS reactor at 50 ml/min. This resulted in a decrease in copper concentration from 15 ppm to 0.6 ppm. In tank 1 of the DS reactor, treatment efficiency of copper reached 97.7%. 100% removal of copper was achieved in tank 2 of the DS reactor at 50 ml/min. Figure 6 shows a graph of treatment efficiency of Cu for the SS and tank 1 and 2 of the DS reactor.

At 10 inches of substrate, well A, 100% removal of copper was achieved by the end of week five. Treatment efficiency dropped slightly between well A and well B to 98% and remained 98% at well C (30 inches of substrate). Copper levels decreased from 14 ppm to less than 1.0 ppm.

95% removal of iron was achieved in the SS reactor at 50 ml/min. Tank 1 of the DS reactor demonstrated 94% removal initially, which dropped to 42% by the end of week five. 92% removal was achieved in tank 2 of the DS reactor at 50 ml/min. Iron levels decreased from 270.0 ppm in the mine drainage to values ranging from 15.0 to 35.0 ppm. Figure 7 shows treatment efficiency of iron for the SS reactor and tanks 1 and 2 of the DS reactor.

At 10 inches of substrate, well A, 90% removal of iron was achieved at 50 ml/min. 89% removal was achieved at 20 inches of substrate, well B. Finally, 91% removal of iron was demonstrated by 30 inches of substrate, well C.

95% removal of lead was achieved in the SS reactor at 50 ml/min. In tank 1 of the DS reactor only 43% removal was demonstrated. Tank 2 of the DS reactor showed 100% removal of Pb at 50 ml/min. Pb concentrations dropped from 0.7 ppm in the mine drainage to less than 0.2 ppm. Figure 8 shows treatment efficiencies of Pb for both reactors.

At 10 inches of substrate, well A, 95% treatment efficiency was achieved. At well B, 20 inches, treatment efficiency dropped to 88%. Finally at well C, 30 inches, 90% treatment efficiency of Pb was achieved.

Treatment efficiency of zinc reached 99.8 in the SS reactor at 50 ml/min. In tank 1 of the DS reactor, 99% removal was initially achieved which dropped to 8% by the end of week five. Tank 2 of the DS reactor demonstrated 99.8% removal of Zn. Concentrations of zinc dropped from 200.0 ppm in the mine drainage to less than 2.0 ppm. Figure 9 shows treatment efficiency of zinc for both reactors.

At 10 inches of substrate, well A, zinc was removed to a 97% treatment efficiency. Well B, 20 inches, showed 99.6% removal of zinc. Finally, 91% treatment efficiency was achieved at 30 inches of substrate, well C.

Manganese removal in the SS reactor effluent reached 97% at 50 ml/min. Tank 1 of the DS reactor demonstrated 90% removal initially, which dropped to 0% removal by the end of week five. 97% removal of Mn was achieved in tank 2 of the DS reactor at 50 ml/min. Concentrations of Mn decreased from 200.0 ppm in the mine drainage to less than 10 ppm in the reactors. Figure 10 shows treatment efficiency of Mn for both reactors.

At 10 inches of substrate, 76% Mn removal was achieved. By 20 inches of substrate, well B, 94% Mn removal was observed. Finally, at well C treatment efficiency of Mn dropped to 80%. Manganese was not considered a primary treatment goal for this experiment because recent studies completed by Wildman and Laudon (1989) and Dugan and Wildman (1992) have shown that pH values must be maintained above neutral for manganese to form Mn(CO_3) precipitate. However, Mn was consistently removed at an efficiency of 95 to 99% in both the SS and DS reactors.

No sulfate removal was observed at 50 ml/min. In fact, sulfate concentration increased in the SS and tanks 1 and 2 of the DS reactor. Sulfate also increased in sampling wells A, B, and C.

Flow of 100 ml/min. At 100 ml/min treatment efficiency for Cd, Cu, Fe, Pb, Zn, and Mn for the SS reactor, tanks 1 and 2 of the DS reactor, and for each sampling well were:

100% of cadmium was removed in the SS reactor at 100 ml/min. In tank 1 of the DS reactor 85% removal of Cd was achieved and 100% Cd removal was achieved in tank 2 of the DS reactor. This removal resulted in a decrease in Cd concentration from 1.0 ppm to below detection limits. See figure 5 for treatment efficiency of Cd at 100 ml/min.

At 10 inches of substrate, 99% removal of Cadmium was achieved. 100% removal of Cd was reached in both wells B and C.

In the SS reactor, 99% removal of copper was achieved at 100 ml/min. Tank 1 of the DS reactor showed 97% Cu removal. Finally, 99% removal of Cu was achieved in tank 2 of the DS reactor at 100 ml/min. Cu concentration decreased from 14 ppm in the mine water to less than 0.5 ppm in the reactors. Figure 6 shows treatment efficiency of Cu.

At 10 inches of substrate, 99% Cu removal was achieved. Well B, 20 inches, and well C, 30 inches showed 99.9% and 99% removal respectively.

At 100 ml/min, treatment efficiency of iron in the SS reactor reached 99%. Tank 1 of the DS reactor showed 33% removal, while 97% Fe removal was achieved in tank 2 of the DS reactor. Concentration of iron dropped from 270.0 ppm in the mine drainage to less than 20.0 ppm in both reactors (see figure 7).

At 10 inches of substrate, treatment efficiency of iron reached 91% at 100 ml/min. This value increased to 95% by well B, 20 inches of substrate. At well C, 30 inches of substrate, 98% iron removal was achieved.

100% removal of lead was achieved by the SS reactor and tanks 1 and 2 of the DS reactor at 100 ml/min. This resulted in a decrease in lead concentration from 0.7 ppm to below detection limits. (see figure 8). 100% treatment efficiency of lead was also achieved for wells A, B, and C.

99.8% of zinc was removed in the SS reactor at 100 ml/min. 0% removal was demonstrated in tank 1 of the DS reactor. Tank 2 of the DS reactor reached 97% Zn removal at 100 ml/min. Zinc concentration decreased from 200.0 ppm in the mine water to less than 2.0 ppm at 100 ml/min (figure 9).

At 10 inches of substrate, 97% Zn removal was observed. This value increased to 99% removal in both well B and well C.

Manganese removal at 100 ml/min in the SS reactor reached 96%. In tank 1 of the DS reactor 0% Mn removal was observed. Tank 2 of the double stage reactor showed 99% Mn removal. Mn concentration dropped from 200.0 ppm in the mine drainage to less than 15.0 in the reactor effluents (see figure 10).

At 10 inches of substrate, 51% Mn removal was observed. This value increased to 94% in well B, 20 inches of substrate. At 30 inches of substrate, well C, 98% Mn removal was achieved.

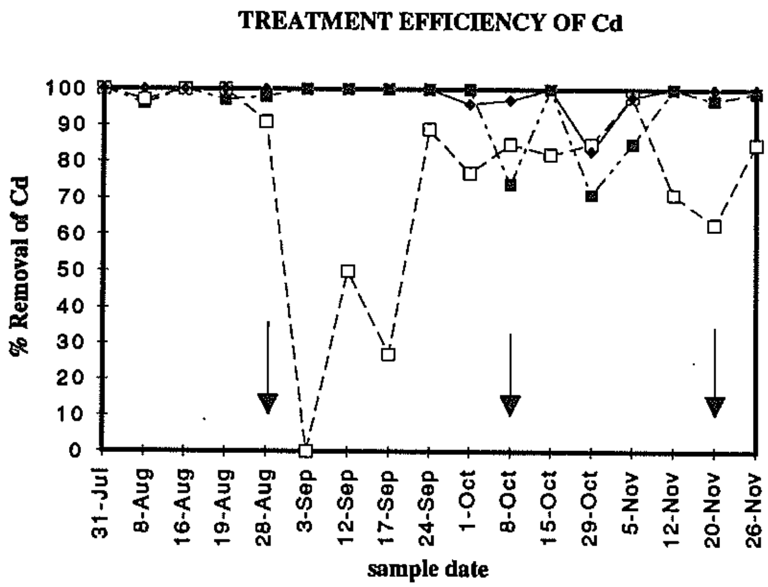

Figure 5: Treatment efficiency of Cd for the SS and DS reactors. Arrows represent increase in flow rate to 100, 200, and 400 ml/min.

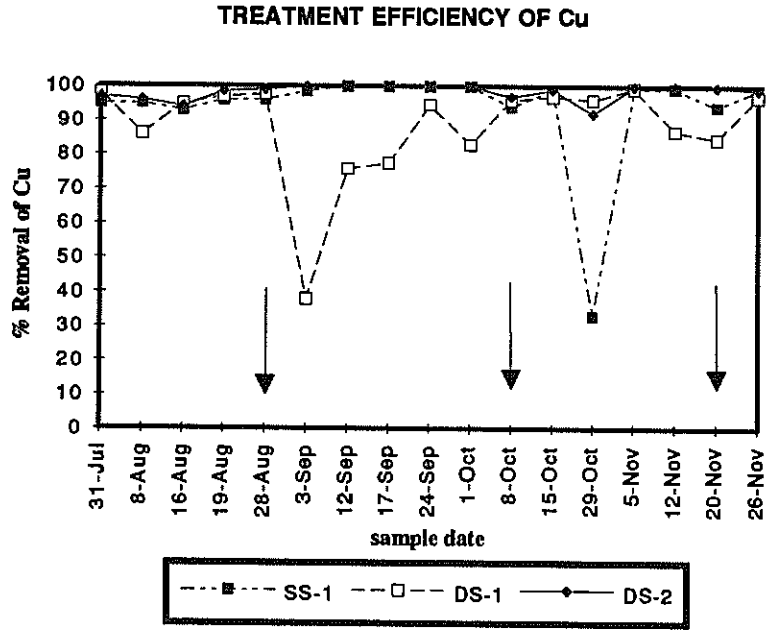

Figure 6: Treatment efficiency of Cu for the SS and Ds reactors. Arrows represent increase in flow rate to 100, 200, and 400 ml/min.

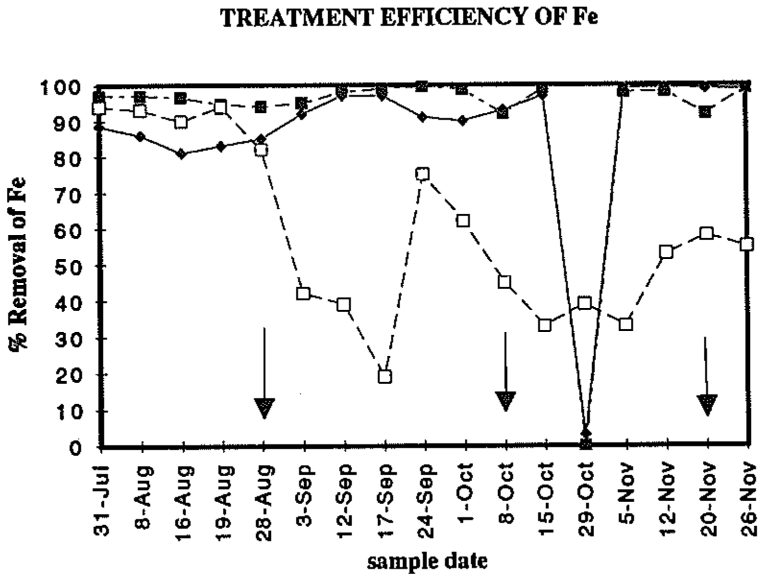

Figure 7: Treatment efficiency of Fe for the SS and DS reactors. Arrows represent increase in flow rate to 100, 200, and 400 ml/min.

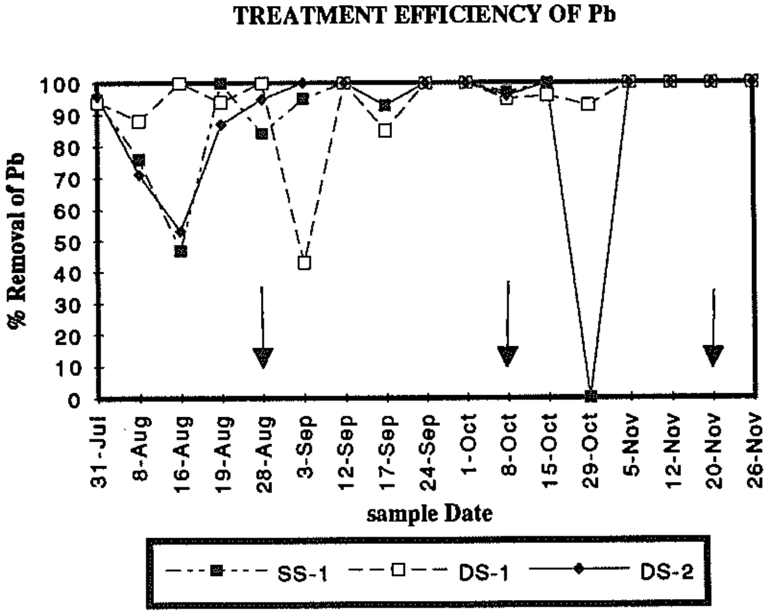

Figure 8: Treatment efficiency of Pb for the SS and Ds reactors. Arrows represent increase in flow rate to 100, 200, and 400 ml/min.

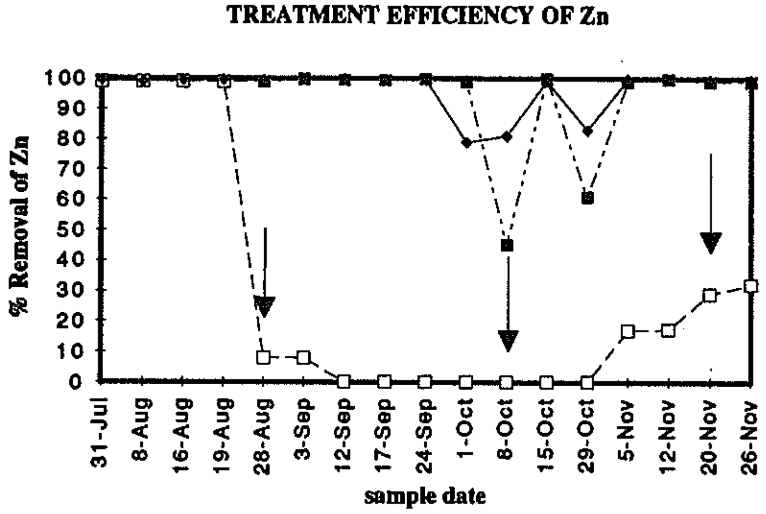

Figure 9: Treatment efficiency of Zn for the SS and DS reactors. Arrows represent increase in flow rate to 100, 200, and 400 ml/min.

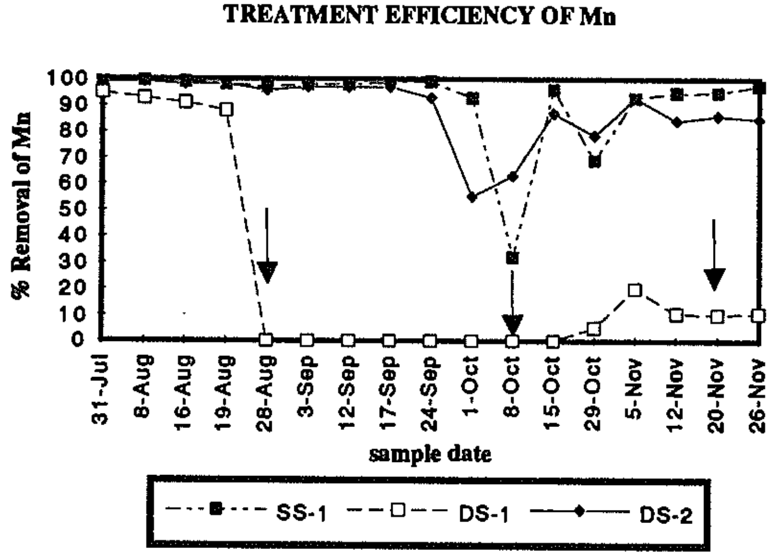

Figure 10: Treatment efficiency of Mn for the SS and Ds reactors. Arrows represent increase in flow rate to 100, 200, and 400 ml/min.

At the beginning of the 100 ml/min flow rate sulfate reduction was observed. In the SS reactor, sulfate concentration dropped from 4,400.0 ppm to less than 3,000.0 ppm. Tank 1 of the double stage reactor showed a slight increase in sulfate concentration. Concentration dropped in tank 2 of the DS reactor from 4,4000.0 ppm in the mine drainage to less than 4,000.0 ppm.

At 10 inches of substrate, sulfate concentration decreased slightly from the mine drainage to 4,000.0 ppm. In well B sulfate concentration increased again to 4,800.0 ppm. Finally, in well C concentration of sulfate dropped below 4,000.0 ppm.

Flow of 200 ml/min. At 200 ml/min, treatment efficiency of the six metals for the SS reactor, tanks 1 and 2 of the DS reactor and the three sampling wells were:

100% removal of cadmium was achieved in the SS reactor at 200 ml/min. Tank 1 of the DS reactor showed only 85% removal while tank 2 of the DS reactor demonstrated 100% Cd removal. Cadmium concentration decreased from 1.0 ppm in the mine drainage to below detection limits in the reactors (see figure 5). At 10 inches of substrate, 97% of cadmium was removed. 100% treatment efficiency of Cd was achieved in both well B and well C at 200 ml/min.

Copper removal reached 99% in the SS reactor at 200 ml/min. Tank 1 of the DS reactor produced 87% copper removal. Finally, tank 2 of the DS reactor demonstrated 99.8% treatment efficiency (see figure 6). At 200 ml/min, Cu concentration decreased from 14.0 ppm to less than 1.0 ppm.

At 10 inches of substrate, well A, 98% copper removal was observed. 99% removal of copper was achieved in both well B and well C at 200 ml/min.

98.2% iron removal was observed in the SS reactor at 200 ml/min. Tank 1 of the DS reactor demonstrated 53% Fe removal. 99% treatment efficiency of Fe was achieved in tank 2 of the DS reactor (see figure 7). Fe concentration decreased from 270.0 ppm to less than 10.0 ppm in both reactors.

At 10 inches of substrate, 94% treatment efficiency of Fe was observed. In well B, 20 inches of substrate, 97% removal of Fe was achieved. Finally, in well C, 30 inches of substrate, Fe was removed 99%.

100% removal of lead was achieved in the SS reactor effluent and in tanks 1 and 2 of the DS reactor (figure 8). Pb concentration decreased from 0.7 ppm in the mine water to below detection limits at the 200 ml/min flow. 100% removal of lead was also achieved in wells, A, B, and C at the 200 ml/min flow rate.

Zinc removal reached 99% in the SS reactor at 200 ml/min. 17% Zn removal was observed in tank 1 of the DS reactor and 99.9% Zn removal in tank 2 of the DS reactor (Figure 9). This resulted in a decrease in Zn concentration from 200.0 ppm to less than 4 in most cases.

At 10 inches of substrate, well A, 95% removal of Zn was achieved. 99% treatment efficiency of Zn was observed in both well B and well C at 200 ml/min.

Manganese removal in the SS reactor reached 95% during the 200 ml/min flow rate. Tank 1 of the DS reactor demonstrated 10% Mn removal. 84% removal of Mn was achieved in tank 2 of the DS reactor (Figure 10). Mn concentration dropped from 200.0 ppm in the mine drainage to less than 10.0 ppm in the SS reactor and less than 30.0 ppm in the DS reactor.

At 10 inches of substrate, well A, treatment efficiency of Mn reached 62% at 200 ml/min. Mn removal increased to 97% in well B, 20 inches of substrate. Finally, in well C, 30 inches of substrate, 98% removal of Mn was observed.

At 200 ml/min, sulfate concentration decreased substantially from 4,400.0 ppm in the mine drainage to less than 2,500.0 ppm in the SS reactor. Tank 1 of the DS reactor also showed a decrease in sulfate concentration from 4,400.0 to less than 4,000.0 ppm. In tank 2 of the DS reactor, sulfate concentration dropped blow 3,200.0 ppm.

At 10 inches of substrate, sulfate concentration decreased from the mine drainage to less than 3,500.0 ppm. At 20 inches of substrate the concentration of sulfate was below 3,000.0 ppm. Finally, at well C, sulfate concentration dropped significantly to 360.0 ppm.

In figures 5 through 10, two distinct valleys (decrease in treatment efficiency) exist at weeks 11 and 13. This drop in treatment efficiency was explained by two separate contamination incidents where a pipe clogged with iron hydroxide precipitate forced water to flow backwards through the reactors. It was believed that this contamination was minor because weeks preceding and following both incidents showed normal treatment efficiencies. Also, examination of sampling wells A, B, and C at weeks 11 and 13 showed no deviation from normal treatment. This suggests that the contamination that did occur was only surface contamination and the integrity of the substrate within the reactors was not affected.

Conclusions

PMDT treatment without plants or lime additions proved to be a valid method for removing high concentrations of metals from the Eagle Mine acid mine drainage. Treatment was successful at flow rates of 50, 100, and 200 ml/min. Treatment was also successful in an underground environment with temperatures ranging from 2 to 9 degrees Celsius.

A standard student t-test used to determine the probability that the SS and DS reactors were the same showed that metal removal and pH increase for both reactors were equal.

At 50 ml/min and 100 ml/min, both reactors were reducing with a redox potential of -20.0 mv and -30.0 mv respectively. At 200 ml/min a less reducing environment was observed but treatment efficiencies remained successful regardless.

Within the single stage reactor, more than 75% of metal removal occurred within the first 10 inches of substrate (except Mn) at all three flow rates. An increase in treatment continued gradually through the substrate and upwards of 99 to 100% removal was achieved for nearly all metals by 30 inches of substrate.

Treatment of water at well A was consistent throughout the entire experiment at three flow rates. This suggests that a zone of less metal removal at the substrate-mine drainage interface did not migrate through the substrate with time during the seventeen week experiment. This also suggests that after seventeen weeks of operation, the first 10 inches of substrate was still capable of treating as effectively as fresh substrate.

Earlier research (Wildman et al. 1990) suggested that loading rates should be determined based on flow per given area (Q/A). At the Big Five constructed wetland in Idaho Springs, CO, effective treatment was obtained with a loading rate of 0.125 gal/min/100 ft^2. The reactors in this research have shown effective treatment at higher flow rates per given area. Given that treatment efficiencies in the SS reactor (with an area of 14.7 ft^2) and the DS (with an area of 7.06 ft^2) are equal, and the residence time for each reactor is equal, then it appears that volume per flow rate (V/Q), which yields hydraulic residence time, is a more reliable variable for determining loading rates than Q/A (velocity). This in turn suggests that large scale PMDT treatment plants may be built as tall towers rather than shallow, broad wetlands. Space required for treatment would be significantly reduced. The results also show that a substrate consisting of composted cow manure and fresh hay, in an upflow configuration, treated two and four times the flow rate of other systems in the Rocky Mountain Region.

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