IN-LINE AERATION AND TREATMENT OF ACID MINE DRAINAGE: PERFORMANCE AND PRELIMINARY DESIGN CRITERIA

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INTRODUCTION

It is estimated that the U.S. coal mining industry spends over $1 million per day treating acidic mine water so that it can be legally discharged (4).[3] This figure includes the amortized cost of the large water treatment plants (a conventional lime neutralization facility typically costs over $1 million to construct), treatment chemicals (lime, soda ash, sodium hydroxide, flocculant, etc.), maintenance, electric power, and labor.

Although expensive, conventional acid mine drainage (AMD) treatment is a simple process. The water is neutralized, typically to a pH of 8 to 9, and then aerated to oxidize the iron to the Fe^{3+} state, causing precipitation of $Fe(OH)_3$ (Yellowboy) sludge. The water is then separated from the sludge in a series of settling basins or ponds and discharged.

Above a pH of 3.5, the rate of iron oxidation is controlled by dissolved oxygen (DO) and pH. Fully aerated mine water contains about 8 mg/L DO, which is consumed at the rate of 1 mg/L for every 7 mg/L Fe^{+2} oxidized; consequently, the DO initially present can only oxidize 50 to 60 mg/L Fe^{2+} (7). If one assumes, though, that DO is not depleted but instead is maintained at a constant level by continuous aeration, the effect of pH on the rate of iron oxidation can be calculated. Table 1 illustrates the effect of pH on the required aeration time for an initial Fe^{2+} concentration of 100 mg/L. Inspection of the reaction times listed in table 1 reveals why pH is raised to 7.5 or above at most treatment plants to quickly oxidize the ferrous iron.

TABLE 1. - Time required to oxidize 97 pct of 100 mg/L Fe^{2+} at various constant pH's, and constant oxygen saturation (8 mg/L DO)

pH	Time, h
4.5	3.5×10^4
5	3.5×10^3
5.5	3.5×10^2
6	3.5×10^1
6.5	3.5
7	3.5×10^{-1}
7.5	3.5×10^{-2}
8	3.5×10^{-3}
8.5	3.5×10^{-4}

For replenishment of DO in mine water, settling ponds or lagoons are constructed wide and shallow to maximize diffusion of oxygen into the water and thereby increase oxygen transfer from the atmosphere. However, oxygen diffusion is relatively slow (9), so that at many sites supplementary aeration sources are necessary (8). For example, oxygen transfer can be increased by increasing turbulence. This is typically accomplished by incorporating a series of open-channel drops in the flow path of the water. Mechanical aerators can also be used to continuously introduce bubbles of air into the water. This continuous replenishment of DO is effective in maintaining a rapid reaction rate, but it also has disadvantages: a separate aeration tank or basin is required; there are high initial capital costs; and there are operating costs associated with power consumption and maintenance, especially where gypsum precipitation is a problem.

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[3]Underlined numbers in parentheses refer to items in the list of references at the end of this paper.

This report describes a Bureau of Mines-designed treatment system that has been tested at mine sites in Pennsylvania and West Virginia. The in-line aeration and treatment system (ILS) functions in existing AMD pipelines, using energy provided by existing mine water discharge pumps. It appears to be a low-cost alternative to conventional treatment plants and, in fact, appears to accelerate iron oxidation rates. The system has no moving parts and thus has the advantages of low maintenance and operating costs.

UNIT DESCRIPTION

The ILS consists of two off-the-shelf components: a jet pump (3) and a static mixer. Both components can be described as aeration and mixing devices. Jet pumps are simply nozzles that entrain air by Venturi action (fig. 1). The jet pump used is made of polyvinyl chloride (PVC). Water enters under pressure and is converted by the jet pump into a high-velocity stream. This stream then passes through a suction chamber, which is open to the atmosphere. If the system is being used for neutralization as well as aeration, the suction chamber also serves as the injection point for the neutralizing material. Multiple jet pump units may be placed in parallel as long as water pressures of at least 20 psi are maintained.

After passing through the jet pump, the flow enters the static mixer (fig. 2). The static mixer consists of 1-ft sections of pipe made of copolymer polypropylene resins, laminated together end to end with fiberglass. Inside each

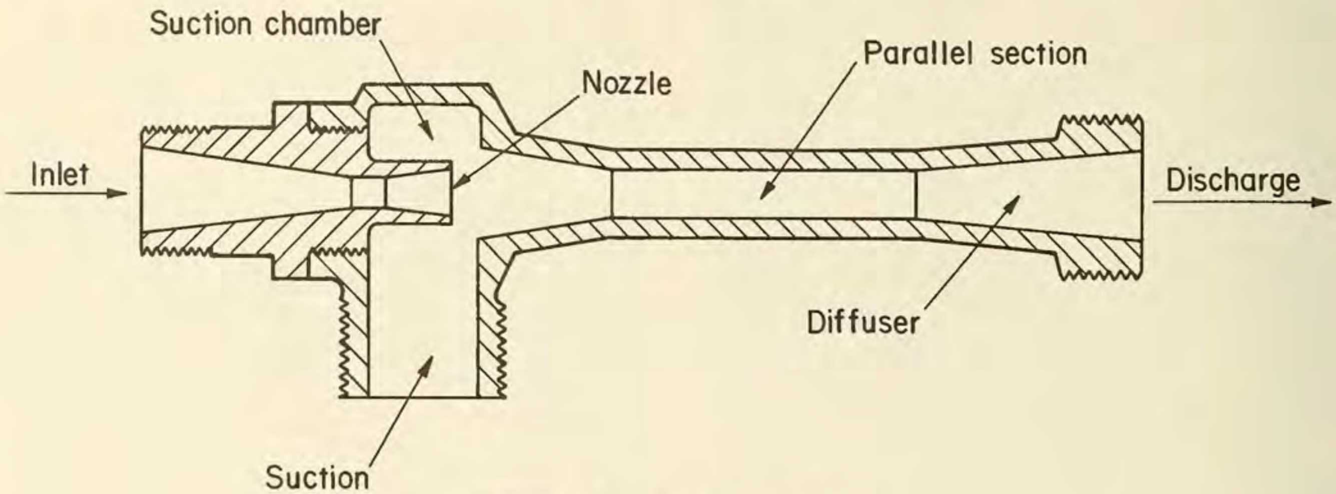

FIGURE 1. - Jet pump diagram.

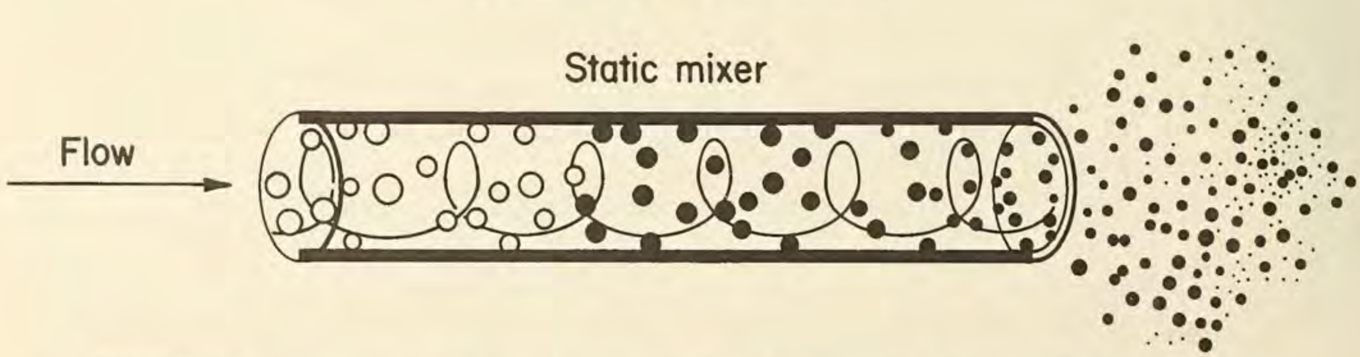

FIGURE 2. - Diagram of the static mixer. Air bubbles are reduced in size by the turbulence, significantly increasing interfacial contact.

section is a 1-ft helix that forces the water to follow a spiral path. Static mixers are used routinely in sewage and industrial waste water treatment plants as vertical airlift aeration and mixing units, but that design was modified somewhat for this horizontal application: each helical unit was rotationally offset 90° from its neighbor, thereby interrupting the corkscrew every foot and enhancing the mixing action. Eight 1-ft sections were used, which provided the contact time of a normal 32-ft pipe because of the induced spiral flow.

PERFORMANCE CHARACTERISTICS

AERATION OF NEAR-NEUTRAL MINE WATERS

The ILS was first tested as an aeration unit at a mine site in Greene County, PA. Influent Fe^{2+} levels were erratic but often exceeded 100 mg/L at near-neutral pH. As an alternative to mechanical aeration, the ILS was installed at the end of the discharge pipe from the underground mine.

Monitoring the discharge from the site began on the fourth day after installation of the ILS. Ferrous iron concentrations dropped from 10 to 20 mg/L before installation of the ILS to 0.2 to 0.9 mg/L. Total iron concentrations fell from over 20 mg/L to less than 2 mg/L.

Subsequent aeration tests were conducted with more acidic water. Iron oxidation continued to be impressive despite an influent pH of 4.6 to 5.6. Figure 3 is a graph of average Fe^{2+} values for all samples of pH 5.5 ±0.2. Although very little iron oxidation occurred in the ILS, the discharge from the first pond (24-h detention time) averaged only 6 mg/L Fe^{2+}. This represents not only much greater iron oxidation than without the ILS at this pH, but also a much faster rate than expected in oxygen-saturated water (table 1). A more detailed analysis of this topic may be found in RI 8868 (2).

SIMULTANEOUS NEUTRALIZATION AND AERATION

The suction port of the jet pumps can be used for addition of neutralizing chemicals without significantly interfering with air intake. Field tests were conducted at actual mine sites using sodium hydroxide (NaOH), quick lime (CaO), or hydrated lime ($Ca(OH)_2$), with the latter two added as slurries. The effluent pH was easily adjusted in each case, and the violent mixing action of the ILS minimized excessive lime use.

Tables 2-4 allow the comparison of actual NaOH or lime consumption with theoretical "best case" neutralization. The theoretical values are derived assuming optimal efficiency (90 pct for CaO, 95 pct for $Ca(OH)_2$, and 99 pct for NaOH) and a pH endpoint of 8.3 (5); our experience indicates that conventional treatment plants use 25 pct more lime than these calculated values.

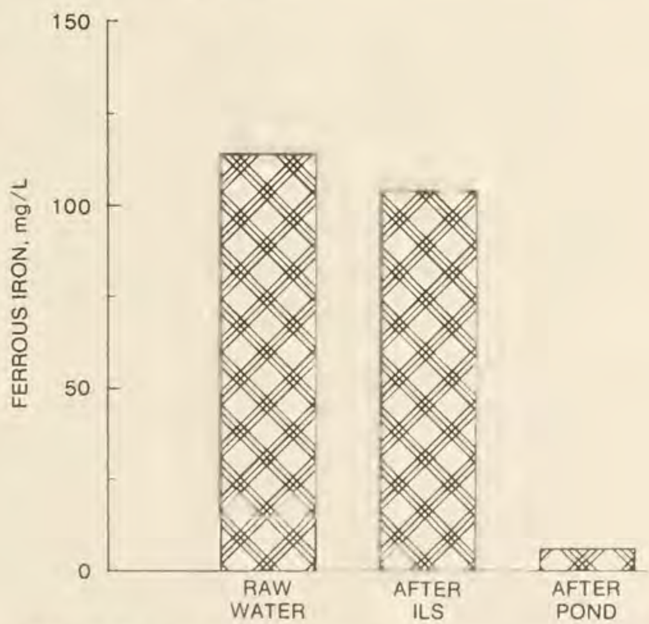

FIGURE 3. - Effect of the ILS as an aeration system on average Fe^{2+} concentration at pH 5.5 ±0.2 at the Greene County, PA, site. Pond has a 24-h detention time.

TABLE 2. - NaOH use at site 2—Braxton County, WV

Test run	Raw pH	Net acidity of raw water, mg/L	Flow, gal/min	Na in raw water, mg/L	Na in treated water, mg/L	Treated pH	Theoretical NaOH use, lb/min	Actual NaOH use, lb/min
SINGLE TREATMENT								
1...	3.2	3,784	521	22	1,243	5.1	13.4	5.3
2...	3.3	3,951	469	22	1,216	5.3	12.6	4.7
3...	3.2	3,784	543	23	1,000	5.2	14.0	4.4
4...	3.2	4,022	533	23	1,176	5.0	14.6	5.1
5...	2.7	3,689	385	27	1,634	6.6	9.7	5.2
6...	2.6	3,689	533	23	1,094	4.9	13.4	4.8
7...	2.5	3,713	530	23	1,209	4.9	12.9	5.2
8...	2.8	3,677	261	35	1,779	6.8	6.5	3.8
9...	2.9	3,641	345	35	3,558	12.8	8.5	10.1
DOUBLE TREATMENT								
10..	4.8	75	543	1,860	1,865	8.4	0.3	0.03
11..	4.6	89	475	1,831	2,193	11.3	.3	1.4
12..	4.6	87	340	1,865	2,021	9.9	.2	.4
13..	4.6	95	523	1,728	2,175	10.7	.4	1.9
14..	4.6	71	475	1,514	2,153	10.6	.2	2.5
15..	4.3	68	337	1,888	1,872	8.6	.1	.04

TABLE 3. - Lime use at site 3—Armstrong Country, PA

Sample	Raw pH	Net acidity of raw water, mg/L	Flow, gal/min	Ca in raw water, mg/L	Ca in treated water, mg/L	Treated pH	Theoretical lime use, lb/min	Actual lime use, lb/min
1...	2.7	830	363	284	1,078	11.7	1.7	4.4
2...	3.0	753	363	271	268	3.1	1.5	.0
3...	3.0	830	363	277	618	7.3	1.7	1.9
4...	3.0	791	363	279	671	8.8	1.6	2.2
5...	2.9	830	363	287	608	5.7	1.7	1.8
6...	N/A	791	363	280	692	8.8	1.6	2.3
7...	2.9	830	363	286	617	6.9	1.7	1.8

TABLE 4. - Lime use at site 4—Westmoreland County, PA

Sample	Raw pH	Net acidity of raw water, mg/L	Flow, gal/min	Ca in raw water, mg/L	Ca in treated water, mg/L	Treated pH	Theoretical lime use, lb/min	Actual lime use, lb/min
1.....	5.6	973	469	445	1,015	8.4	2.6	4.1
2.....	5.7	877	457	454	1,020	7.7	2.3	4.0
3.....	5.4	1,010	457	424	1,057	7.0	2.6	4.5
4.....	5.4	1,040	469	419	1,164	6.9	2.8	5.4
5.....	5.6	942	542	451	749.8	6.6	2.9	2.5
6.....	5.5	1,012	485	425	901	7.0	2.8	3.5
7.....	5.5	1,062	485	421	909	6.9	2.9	3.3
8[1]....	5.4	986	485	420	1,018	7.1	2.7	4.5
9.....	5.4	1,018	485	405	948	7.0	2.8	4.1
Plant[2]	4.8	1,280	1,450	421	1,081	8.2	10.5	[3]14.7 [4]19.1

[1]Fe and Mn in filtered samples were within effluent standards.
[2]Normal plant operation.
[3]Measured by chemical analysis.
[4]Physically measured dry feed.

Table 2 represents a two-stage process, usig NaOH to treat mine water with high acidity and high iron. Samples 1 through 9 represent a single treatment pass through the ILS from pond 1 to pond 2 (initially empty before the test). Samples 10 through 15 represent water pumped from pond 2 through the ILS to pond 3 36 h after the first treatment. Effluent water from the two-stage treatment met effluent standards. Actual NaOH usage was calculated from the difference in sodium concentrations in unfiltered, acidified samples of treated and raw water. Theoretical NaOH requirement was calculated by Lovell's equations (5). NaOH use was approximately half of that theoretically required. However, iron was precipitated as both $Fe(OH)_3$ and $Fe(OH)_2$ in the first step of the treatment. As explained later, $Fe(OH)_2$ will eventually oxidize, adding acidity to the pond water.

Table 3 summarizes the results of a field test using $Ca(OH)_2$. This operation did not allow a quantitative comparison with actual consumption of lime by the conventional water treatment plant, but the plant operator felt that lime usage was reduced enough to design an ILS to replace the existing system. Except at high pH (sample 1), the ILS values met discharge criteria and approached the theoretical optimal values for lime consumption. As discussed later, both iron and manganese were reduced to effluent levels at a discharge pH as low as 6.9, indicating that greater potential cost savings can be obtained.

Table 4 presents the results of a field test using CaO slurry to neutralize water being pumped from an underground mine pool. Owing to the high levels of dissolved iron (over 500 mg/L), the ILS unit could not oxidize all of the iron in a single pass; as at the NaOH site (table 2), some of the iron precipitated as $Fe(OH)_2$. Water sample 8, which met discharge standards after filtration, can be used for comparing actual costs with those for operation of the conventional treatment plant (table 4, bottom row). Since flow through the ILS is one-third that of normal plant operation, the observed lime use of 4.5 lb/min at pH 7.1 must be scaled up to 13.5 lb/min. This is within 1 pct of the amount of lime consumed in neutralizing acidity during operation of the conventional treatment plant (as calculated from chemical analysis) but is 30 pct more efficient than actual lime use, as measured during normal plant operation. Analysis of the sludge during operation of the conventional treatment plant confirms that a lot of unreacted lime is being wasted, especially in the aeration basin, owing to insufficient mixing action.

IRON OXIDATION

During field testing of the ILS, it became apparent that iron oxidation was proceeding much faster than anticipated. At low pH (4.6 to 5.5), iron oxidation was accelerated by a factor of 10 to 400; at near-neutral pH (6.9 to 7.5), iron oxidation was accelerated by as much as 1,000 (2). Figure 3 illustrates iron oxidation at the Greene County, PA, test site; 98.7 pct of the 190 mg/L Fe^{2+} in the influent water was oxidized in the 4-s transit time in the ILS. Most of this oxidation apparently occurred in the jet pump section of the ILS since water samples collected between the jet pump and the static mixer had an average pH of 6.7 and an Fe^{2+} concentration of only 4.8 mg/L. To obtain such rapid iron oxidation in a conventional water treatment system, the pH would have to be raised to at least 8.5.

However, the iron oxidation capacity of the existing ILS design is limited. As influent Fe^{2+} concentrations approach 300 mg/L, the efficiency of the system decreases. Tables 5 and 6 document field trials with average influent Fe^{2+} concentrations of 965 and 527 mg/L, respectively. The amount of Fe^{2+} oxidized during transit through the ILS ranged between 283 and 479 mg/L using NaOH (table 5) and between 163 and 345 mg/L using CaO (table 6). The amount of Fe^{2+} oxidized was calculated as the difference between Fe^{2+} concentrations in acidified, unfiltered samples of raw and treated water. The

TABLE 5. - Oxidation site 2--Braxton County, WV

	Single treatment									Double treatment					
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Run 13	Run 14	Run 15
Fe^{2+} oxidized[1]..............mg/L..	342	369	342	283	479	366	451	380	425	12	0	20	19	0	19
Fe^{2+} oxidized...............pct..	37	40	37	31	48	37	45	38	42	34	0	84	83	0	91
Fe^{2+} removed[2]..............mg/L..	615	769	612	581	1,000	723	824	1,000	1,000	34	3.8	24	23	3.8	21
Fe^{2+} removed................pct..	66	83	66	64	100	73	82	100	100	100	100	100	100	100	100
Mn removed (unfiltered)....mg/L..	1	2	0.4	-1.2	0	-1.2	0.3	-0.6	4.3	15.4	3.1	0.6	2.7	2.2	1.9
Mn removed (unfiltered).....pct..	2	3	1	-2	0	-2	0.5	-1	6	58	23	5	20	18	15
Mn removed (filtered)......mg/L..	-2	1	-4	2	67	2	10	67	72	26	14	13	13	12	12
Mn removed (filtered).......pct..	-3	2	-7	2.5	94	3	14	95	100	100	100	100	100	100	100
O_2 consumed.........std ft^3/min..	2.4	2.3	2.4	2.0	2.4	2.6	3.2	1.3	1.9	0.1	0	0.1	0.1	0	0.1
O_2 consumed.............lb/min..	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.1	0.2	0.01	0	0.01	0.01	0	0.01
Effluent pH.....................	5.1	5.3	5.2	5.0	6.6	4.9	4.9	6.8	12.8	8.4	11.3	9.9	10.7	10.6	8.6
Initial Fe^{2+} concentration mg/L..	930	930	930	903	1,000	1,000	1,000	1,000	1,000	34	4	24	23	4	21

[1] Fe^{2+} oxidized as $Fe(OH)_3$.
[2] Fe^{2+} removed as $Fe(OH)_3$ and $Fe(OH)_2$; samples were retained 11 days to simulate settling before analysis.

TABLE 6. - Oxidation site 4--Westmoreland County, PA

	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Fe^{2+} oxidized[1]................mg/L..	243	228	193	163	208	236	345	254	220
Fe^{2+} oxidized..................pct..	44	47	36	31	40	43	62	46	39
Fe^{2+} removed[2].................mg/L..	542	480	489	475	377	494	512	551	522
Fe^{2+} removed...................pct..	98.4	99	92	89	72	89	92	100	92
Mn removed (unfiltered)........mg/L..	1.0	0.6	0.2	1.3	0.2	-0.1	2.2	0.4	0.7
Mn removed (unfiltered).........pct..	7	4	1	9	1	-0.6	15	3	5
Mn removed (filtered)..........mg/L..	12.9	12.3	10.9	9.7	2.2	9.2	10.1	12.8	11.1
Mn removed (filtered)...........pct..	87	90	78	66	15	62	68	87	75
O_2 consumed............std ft^3/min..	1.5	1.4	1.2	1.0	1.5	1.4	2.1	1.5	1.3
O_2 consumed.................lb/min..	0.14	0.12	0.11	0.09	0.13	0.13	0.19	0.14	0.12
Effluent pH.........................	8.4	7.7	7.0	6.9	6.6	7.0	6.9	7.1	7.0
Initial Fe^{2+} concentration.....mg/L..	551	486	532	532	524	553	554	552	565

[1] Fe^{2+} oxidized as $Fe(OH)_3$.
[2] Fe^{2+} removed as $Fe(OH)_3$ and $Fe(OH)_2$.

amount of Fe^{2+} removed was calculated in the same way from unacidified, filtered treated water. Filtering was assumed to approximate settling of iron hydroxides.

At these high levels of influent Fe^{2+}, additional quantities of Fe^{2+} were removed as $Fe(OH)_2$, which produces a green sludge in the ILS effluent at a pH as low as 4.9. $Fe(OH)_2$ is unstable below a pH of about 7; its formation in the ILS suggests that a transient pH of at least 8 (6) exists at the point of alkaline injection and that the dissolution of oxygen cannot match the chemical oxygen demand represented by the Fe^{2+} at that pH. The formation of $Fe(OH)_2$ has both advantages and disadvantages: the precipitation of both sludge forms reduces dissolved iron concentrations, allowing discharge of the effluent water, but the $Fe(OH)_2$ sludge will gradually oxidize to $Fe(OH)_3$, lowering the pH of the sludge and, through diffusion, the effluent water. The difference on tables 5-7 between iron oxidized and iron removed reflects formation and precipitation of $Fe(OH)_2$.

The apparent high transient pH in the jet pump may partially explain the extremely high rate of iron oxidation in the ILS. Table 1 indicates that a 1-s pH of 8.5 to 9.0 would be sufficient if DO is continuously replenished; an instantaneous pH over 10 would reduce the required reaction time to milliseconds in whatever fraction of the fluid is at a high pH. It is not known whether the apparent limitation on iron oxidation is due to limited air intake and the rate of oxygen dissolution (from the bubbles into the water), or to limited catalysis by some other mechanism.

Apparent oxidation of dissolved iron in the pond, after ILS treatment, continues to be rapid for several days (1). This apparent effect is caused by fine-ground suspended $Fe(OH)_2$ or $Fe(OH)_3$ particles that are analyzed as dissolved iron in unfiltered samples. These particles slowly settle in the pond, mimicking oxidation and hydrolysis; filtration with a 0.45 µm filter confirms this explanation.

REMOVAL OF MANGANESE

Manganese, when present in mine water at concentrations greater than 4 mg/L, can significantly add to the costs of water treatment. In a conventional treatment plant, the pH must be raised to above 10 (typically 10.5) for rapid oxidation and removal of manganese; this adds greatly to the costs of neutralization, produces an effluent that is unacceptably alkaline, and can cause redissolution of iron. Three of the four field sites where the ILS was tested had manganese problems. Manganese averaged 68 mg/L at the West Virginia site (table 5),

TABLE 7. - Oxidation site 3--Armstrong County, PA

	Run 1[1]	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Fe^{2+} oxidized[2]................mg/L..	6	75	67	74	77	76	78
Fe^{2+} oxidized..................pct..	7	98	94	98	97	99	99
Fe^{2+} removed[3]................mg/L..	0.3	75	70	74	78	77	78
Fe^{2+} removed...................pct..	0.4	99	99	99	98	99	99
Mn removed (unfiltered).......mg/L..	0.2	2.1	0.1	0.4	-0.3	-0.6	-0.4
Mn removed (unfiltered)........pct..	2	21	1	4	-3	-7	-4
Mn removed (filtered).........mg/L..	-0.2	9	9	9	2	9	6
Mn removed (filtered)..........pct..	2	95	91	90	24	99	69
O_2 consumed............std ft^3/min..	0.02	0.4	0.3	0.3	0.4	0.4	0.4
O_2 consumed................lb/min..	0.002	0.03	0.02	0.03	0.03	0.03	0.03
Effluent pH........................	3.1	11.7	7.3	8.8	5.7	8.8	6.9
Initial Fe^{2+} concentration....mg/L..	80.5	75.9	71.3	74.7	79.5	77.3	79.5

[1]Untreated sample, run through ILS without neutralization.
[2]Fe^{2+} oxidized as $Fe(OH)_3$.
[3]Fe^{2+} removed as $Fe(OH)_3$ and $Fe(OH)_2$.

14 mg/L at the Westmoreland County, PA, site (table 6), and about 10 mg/L at the Armstrong County, PA, site (table 7). At all three sites, manganese was reduced to within effluent limits after passage through the ILS.

At the West Virginia site, the first treatment step raised the pH to 4.9 to 6.8 and had little apparent effect on manganese concentrations in unfiltered samples. However, 6 h after discharge to the pond, and despite the low pH, manganese concentrations had fallen to 13.5 mg/L, an 80-pct reduction. Sealed water samples kept in the laboratory showed similar declines in manganese concentrations, with no detectable dissolved manganese present after 11 days of storage.

At the Westmoreland County site, water treated to a pH of 7.1 or greater met effluent standards for manganese after filtration. Filtered samples that had been treated to a pH of 6.9 to 7.0 approached manganese effluent standards (3.1-5.6); it was not possible to collect samples after settling.

At the Armstrong County site, a similar pattern was observed. Fe^{2+} was reduced to below effluent standards at a pH of 5.7 and up, but manganese exceeded effluent limits under pH 7.3. ILS test runs at pH 7.3 or above met effluent standards.

It appears that manganese was precipitating as very small particles during neutralization and aeration in the ILS. Filtration removed most of these particles; settling removed all of them. It is possible that the transient pH in the jet pump was high enough to allow for rapid formation of MnO_2. Alternatively, it is possible that the manganese is being removed from solution as a coprecipitate on particles of iron hydroxide as they form and swirl in the ILS. It has previously been shown that adsorption of manganese by $Fe(OH)_3$ increases rapidly above pH 8, rising from 0.15 to over 0.6 mol Mn^{2+} per mol Fe^{3+} at pH 8.6 (7).

PRELIMINARY DESIGN SPECIFICATIONS

Three parameters should be considered in the design of the ILS: available water pressure, flow, and influent Fe^{2+} concentration. Table 8 partially summarizes flow capacity of the existing ILS design at various water pressures. In general, adding jet pumps (in parallel) increases capacity. The ILS that was designed and tested by the Bureau had valves on two of the three jet pumps. This allowed for variable flow rates and is a potentially useful feature on sites where surface runoff during storm events determines treatment requirements.

Additional helixors influence flow capacity and may increase oxygen transfer. Increased water pressure increases flow capacity. If flows are above 500 gal/min, larger capacity jet pumps can be substituted or additional jet pumps can be placed in parallel.

If Fe^{2+} levels are above 300 mg/L, a two-stage treatment process may be necessary. This can actually be quite efficient, as shown in tables 2 and 5, and does not necessarily require a second ILS unit. For example, a surface mine can, by installing valves in multiple suction and discharge lines, pump the once-treated water from the first-stage settling pond through the same ILS to another settling pond. Similarly, an

TABLE 8. - Flow rates for the ILS, gallons per minute

Test design	20 psi	30 psi	40 psi	50 psi	64 psi
3 jet pumps in parallel with 1 helixor..	NA	411	469	521	NA
3 jet pumps in parallel with 2 helixors in series..............................	329	317	457	542	NA
2 jet pumps in parallel with 2 helixors in series..............................	NA	261	310	344	363

NA Not available.

underground mine that is intermittently discharging through an ILS unit into a settling pond can pump from the pond through the same ILS to a second settling pond while the underground pump is off. However, if there is continuous flow, then two ILS units and a second pump are necessary. Our tests of the two-step process indicate that a 50-pct reduction in neutralization costs is possible with such a system (table 2).

Actual oxygen consumption rates, as calculated from the amount of iron oxidized during passage through the ILS, are shown on tables 5-7. Air transfer tables provided by the jet pump manufacturer do not appear to correlate with observed oxygen consumption. For example, in our ILS design, sample 2 (table 5) consumed 2.3 std ft^3/min O_2 operating at 40 psi, with three jet pumps in parallel and with 10 psi back pressure; the manufacturer's tables predict 1.5 std ft^3/min per jet or 4.5 std ft^3/min of air intake for the three-jet pump system. Sample 1, operating at 50 psi, consumed 2.4 std ft^3/min O_2; the same tables predict 0 std ft^3/min of air intake under these operating conditions. Actual air flow measurements are needed so that oxygen transfer can be quantified.

Another aspect of system design is cost. The 3-in PVC jet pumps and static mixers cost about $900 and $2,500 each, respectively. Associated PVC plumbing costs about $500. For our tests we purchased a hydraulic pump with a diesel power unit capable of providing pressures up to 50 psi with three jet pumps, but any heavy-duty pump should serve. The total cost is, of course, much less than for construction of a conventional emplaced treatment system. Operating costs should also be low owing to the efficient mixing action, efficient iron oxidation, and lack of moving parts.

There are other advantages. The system is small, and if desired, portable. It requires no electrical power, although it does add slightly to the load on the mine water discharge pump (approximately 10 pct). The basic design is simple and easily modified to cover a wide range of flow and pressure conditions and can operate continuously or intermittently. It can also be dismantled easily for use elsewhere if water treatment is no longer required. Finally, although settling ponds are required, they do not serve as aeration basins and therefore do not require as large an area as would be the case for a conventional treatment plant.

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