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In-Line Aeration and Neutralization System (ILS)—Summary of Eight Field Tests

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IN-LINE AERATION AND NEUTRALIZATION SYSTEM (ILS)--SUMMARY OF EIGHT FIELD TESTS

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ABSTRACT

The Buerau of Mines has developed a pipeline neutralization and aeration system that can be scaled up or down to meet most treatment needs. It consists of a jet pump or educator, which entrains air by Venturi action, and a static mixer, which induces turbulent flow. The system has no moving parts and is designed to utilize the pressure that is generated by existing mine water discharge pumps. The entire system costs significantly less than conventional acid mine drainage (AMD) treatment and appears to be much more efficient than a conventional facility.

INTRODUCTION

One of the most persistent industrial pollution problems in the United States is acid mine drainage (AMD). Many factors influence the quantity and quality of water generated by a mining operation, and it is not unusual for a single mine to treat four million liters of acid drainage per day. Treatment costs per mine can range up to $500,000 per year, with the U.S. coal industry, as a whole, probably spending over $1 million per day to comply with discharge water quality standards. 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.

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This report describes a Bureau of Mines investigation of an alternative, innovative treatment system, and describes the evaluation of this system at various mine sites in Pennsylvania and West Virginia. This new system, called the in-line aeration and treatment system (ILS), can be installed in existing AMD pipelines, using energy provided by existing mine water discharge pumps. It is a low-cost alternative to conventional treatment plants. The system has no moving parts and thus has the advantages of low maintenance and low operating costs.

ACKNOWLEDGMENTS

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BACKGROUND

Acid mine drainage results from the oxidation of pyrite, a mineral commonly found in coal and associated strata, and leaching of other minerals. The drainage is acidic and contains dissolved sulfate, iron, manganese and other ions. Water quality standards imposed on coal mine discharges require neutralization of acidity and removal of iron and manganese in excess of established concentrations. Conventionally, neutralization is easily accomplished by addition of lime, sodium hydroxide, or other alkaline chemicals. The metals are removed as oxides or oxyhydroxides precipitated from the neutralized drainage.

Iron is dissolved in acid mine drainage in the ferrous (Fe^{2+}) and ferric (Fe^{3+}) states; manganese is usually present in the bivalent form (Mn^{2+}). Ferric iron precipitates from near-neutral water as ferric hydroxide:

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3(s) + 3H^+ \qquad (1)$$

and ferrous iron precipitates as an analogous solid at high pH:

$$Fe^{2+} + 2H_2O \rightarrow Fe(OH)_2 + 2H^+. \qquad (2)$$

However, the ferrous hydroxide is unstable with respect to oxidation and converts to the ferric hydroxide shown in equation (1) slowly over time. The preferred treatment consists of oxidation of ferrous iron to the ferric state prior to precipitation:

$$Fe^{2+} + H^+ + 1/4\ O_2 \rightarrow Fe^{3+} + 1/2\ H_2O \qquad (4)$$

Published kinetics experiments (1) conducted at pH values greater than 3.5 showed the rate law:

$$\frac{-d\,[Fe^{2+}]}{dt} = \frac{k\,[Fe^{2+}]\,[O_2\,(aq)]}{[H^+]^2} \qquad (5)$$

$pH = -\log (H$

$10^{pH} = \frac{1}{[H^+]}$

Thus, the rate is very sensitive to pH (-log [H+]), increasing 100-fold for a 1-unit increase in pH. This pH dependence is the reason why conventional treatments raise the polluted mine waters to a pH of about 8.5 to speed the oxidation (2). The rate is linearly dependent on ferrous iron and dissolved oxygen concentrations.

Aeration requirements for oxidation vary, based upon Fe^{2+} concentrations and flow volumes. Even at saturation, mine water generally contains only 8 to 10 mg/l dissolved oxygen (D.O.), which is consumed at the rate of 1 mg/l for every 7 mg/l Fe^{2+} oxidized. To replenish the D.O., settling ponds or lagoons are constructed wide and shallow to maximize diffusion of atmospheric oxygen into the water. However, oxygen diffusion is relatively slow (3), so that at many sites supplementary aeration is necessary. For example, diffusion of atmospheric oxygen into the water can be enhanced by increasing turbulence in the mine water. This is typically accomplished by incorporating a series of open-channel drops in the flow path of the water, which increases the D.O. concentration. Mechanical aerators can also be used to continuously introduce bubbles of air into the water. This continuous replenishment of D.O. is effective in maintaining a rapid iron oxidation reaction rate. However, there are disadvantages associated with mechanical aerators; separate aeration tanks or basins are usually required; there are high initial capital costs; and there are operating costs associated with power consumption and maintenance, especially where gypsum ($CaSO_4 \cdot 2H_2O$) precipitation from treated waters is a problem.

Manganese (Mn) removal can occur in several ways. Initial products of oxygenation at alkaline pH include Mn_3O_4 and β-MnOOH (4). The oxidation process itself is complex and involves autocatalysis (5). Manganese can also be removed from alkaline solution by coprecipitation, as Mn^{2+} sorbed on a solid manganese or iron product. 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 is usually raised to above 10 (typically 10.5) for rapid oxidation and removal of Mn; this adds greatly to the costs of neutralization, produces an effluent that is unacceptably alkaline, and can cause redissolution of iron.

ILS UNIT DESCRIPTION

The ILS consists of two off-the-shelf components: a jet pump (6) 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 in this application is made of polyvinyl chloride (PVC) to resist corrosion. Water enters under pressure and is converted by the jet pump into a high-velocity 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 per jet pump (1.41 kg/cm^2) are maintained.

After passing through the jet pump, the flow of air and liquid enters the static mixer (fig. 2) to aid oxygen dissolution. The static mixer consists of 1-ft (0.3-m) sections of pipe made of copolymer poly propylene resins, laminated with fiberglass. Inside each section is a helical element 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 (0.3-m) sections were used, which provided the contact time of an open 32-ft (9.7-m) pipe because of the induced spiral flow.

The jet pump is the key component in this treatment system. The performance characteristics of the jet pump allows the ILS to be flexible in terms of flow rates, operating water pressures, and air intake capacities. For each operating water pressure there exists a corresponding flow rate and air suction capacity at standard conditions. Values for all increase as pressure increases. Back pressure on the jet pump significantly reduces air suction capacities and actually eliminates the venturi action, especially at the lower operating water pressures [pressure range 20 to 200 psi (1.4 to 14.1 kg/cm^2)]. Table 1

Table 1. - Performance characteristics of a single 3 in (7.6 cm) jet pump with and without back pressure

Operating water pressure		Air suction capacity at standard conditions[1] (SCFM) and (l/s)			
		Back Pressure			
(psi)	kg/cm^2	0 (psi)	0 (kg/cm^2)	5 (psi)	0.35 (kg/cm^2)
20	1.4	41.4	18.5	0	0
30	2.1	47.3	21.2	14.8	6.6
40	2.8	53.3	23.8	29.6	13.2
50	3.5	62.1	27.8	44.4	19.9
60	4.2	71.0	31.8	59.2	26.5

[1] Standard conditions implies SCFM (at 14.696 psia and 60°F) or l/s (760 mmHg and 0°C) (7).

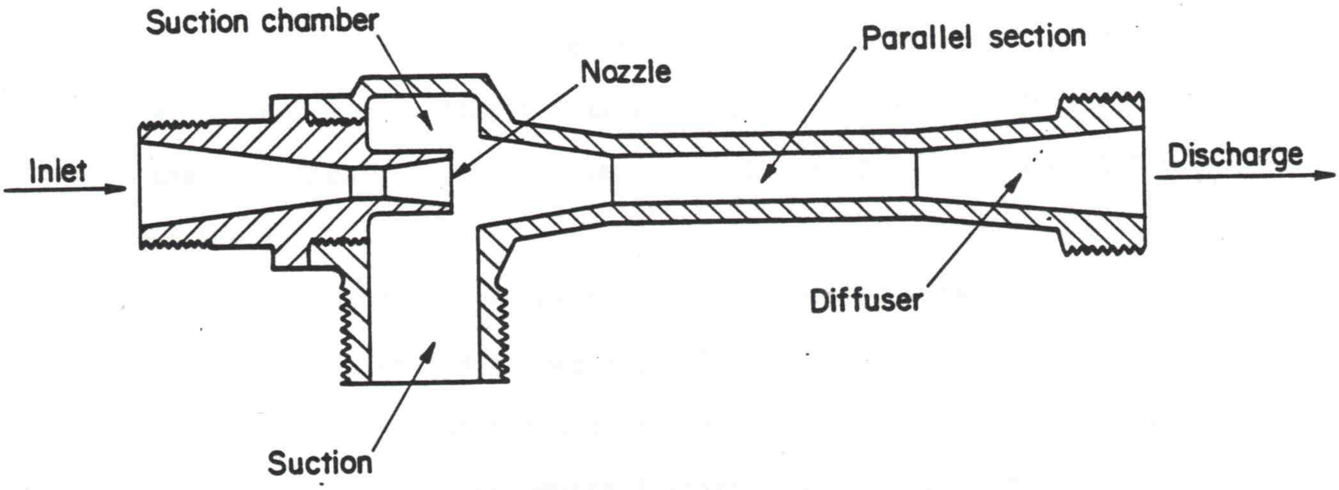

FIGURE 1. - Jet pump diagram.

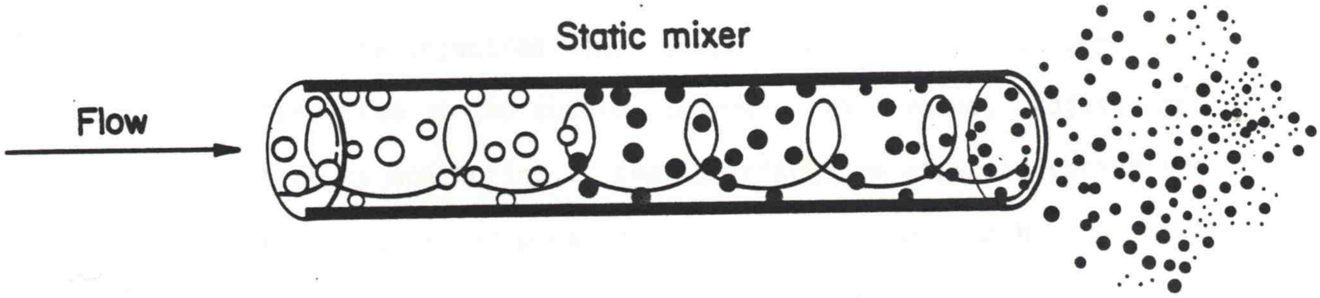

FIGURE 2. - Static mixer diagram.

shows performance characteristics of the 3 in (7.6 cm) in PVC pump used in ILS prototypes.

GENERAL PROCEDURES

Certain procedures and equipment were common to all ILS tests. System installation, testing, water sampling, and analytical procedures, however, were site specific.

System installation at each site involved attaching the 4 in (10.2 cm) inlet line of the ILS to a water feed line capable of providing adequate water pressure to operate the ILS. Two ILS prototypes were used in the testing operations. One prototype was a 2-jet pump system and the other a 3-jet pump system (see figure 3), both of which used 1 or 2 static mixers connected in series. The diameters of the jet pumps and static mixers were 3 and 12 in (7.6 and 30.5 cm), respectively.

Testing procedures generally varied operating water pressures and alkalinity addition (pH); however, only pH variations were performed at several sites where pumps had a single operating pressure capacity. Lime slurry addition, for neutralization, was done by pumping out of a slurry mix tank and into the suction chamber of the jet pump. NaOH was injected into the suction chamber either by a metering pump or gravity feed. All alkaline injection lines (except when a metering pump was used) were throttled at the suction chamber with a valve. Adjustments in pH were made by monitoring at the ILS discharge after adjusting the alkaline feed rate. Water pressure adjustments were made by controlling engine speed (rpm), at those sites where diesel powered pumps were used. Operating pressures used in the testing procedures ranged between 20 and 60 psi (1.4 and 4.2 kg/cm^2). Pressure and pH are the key operating parameters in the ILS. Latest testing used a 4x4 test matrix at

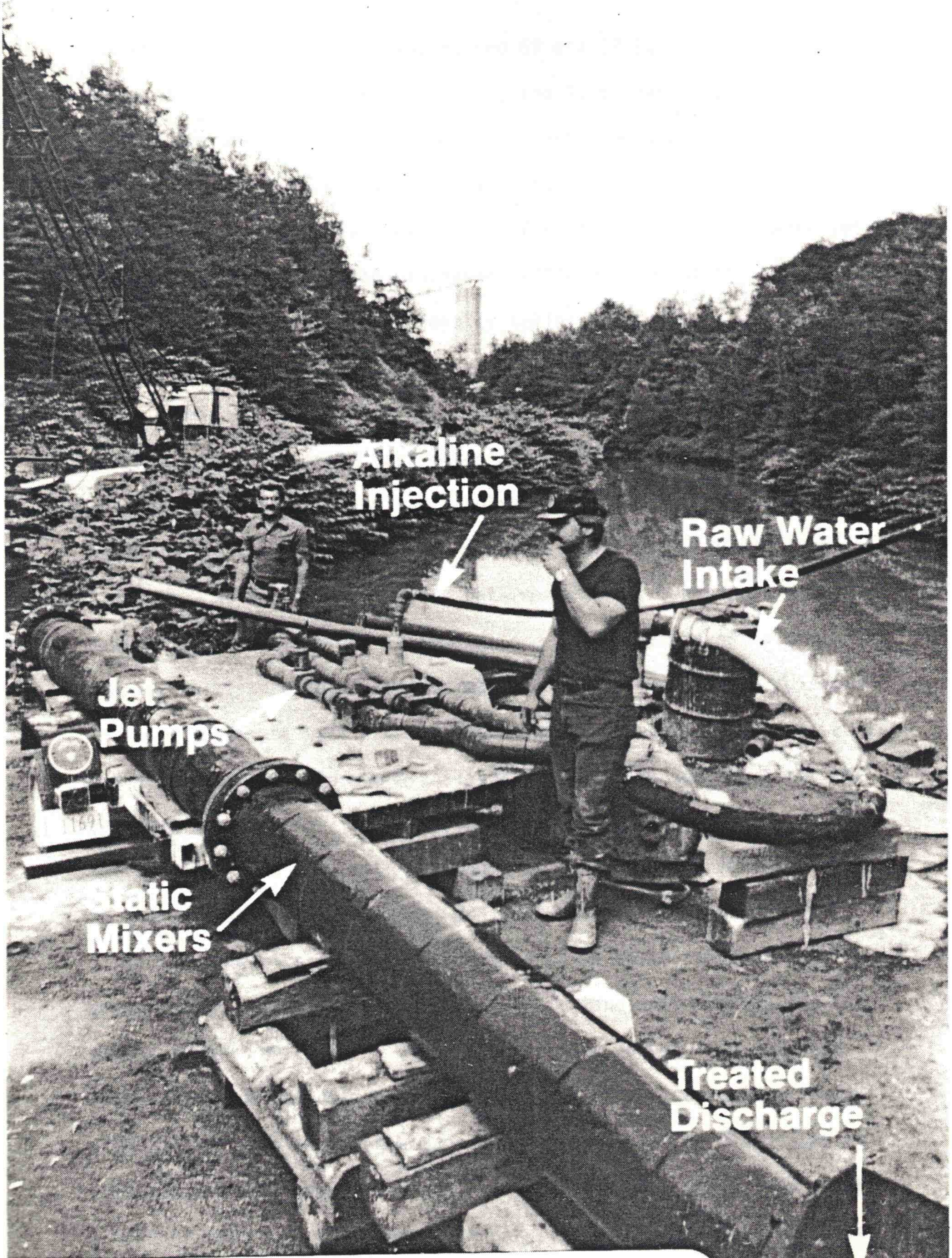

Figure 3. - Portable 3-jet pump ILS

operating pressures of 30, 40, 50 and 60 psi (2.1, 2.8, 3.5, and 4.2 kg/cm^2) and pH values of 6, 7, 8, and 9, to evaluate system performance and determine optimal treatment conditions.

Three sampling locations were available on both ILS prototypes: (1) raw water (before the jet pump), (2) after the jet pump (between jet and static mixer), and (3) ILS discharge (effluent from static mixers). Additional samples were occasionally collected at inlets and outlets to raw water ponds, settling ponds, or clarifiers. Dissolved oxygen (D.O.), pH, and temperature measurements were made in the field. All samples were iced at the test sites and refrigerated.

In general, water sampling involved taking an acidified (using hydrochloric acid) and unacidified water sample at every sampling location. Analytical procedures determined metal concentrations on several types of samples. Fe^{2+}, Mn, and Fe were analyzed in acidified samples to measure total concentrations in solution and precipitated. The acid serves to halt iron oxidation and to dissolve precipitated iron and manganese. Samples were analyzed for the same species after the two-step treatment of (1) filtering through 0.45 μm filters and (2) acidifying to pH 1 with hydrochloric acid. The former step was used to simulate settling of solids; again, the latter step halted Fe^{2+} oxidation. Results from these analyses allow calculation of the distribution of the metals between solution and solid phases and the extent of Fe^{2+} oxidation. Supernatant liquid, drawn from extended samples and then acidified, was analyzed to determine residual metals after sludge settling (these samples are equivalent to field samples used to determine regulatory compliance). The only exceptions to this procedure were two sites where the water analysis was being performed by a coal company and samples were not acidified in the field. In these cases, water samples were delivered directly to the lab and were quickly analyzed. In addition, for quality assurance, some duplicate grab samples, which included field acidified samples, were taken and analyzed by the Bureau's lab.

Extended samples were collected in conjunction with the 4x4 test matrix. This was a test procedure designed to simulate pond detention and utilized a floating platform with 16 holes cut into it. As samples from each pH-pressure combination were generated, a sample was placed into a bucket or barrel and placed into a hole in the floating platforms, which allowed the samples to be maintained at the temperature of the pond. The weather was good during these tests and dilution from rain was not a problem. Water samples were classified as initial or extended, where the extended sampling periods ranged between 1 and 6 days.

Two static mixers were used at several sites, for a performance comparison of single versus double mixers or for maximum mixing without a performance comparison. The second mixer, when used, was installed in series with the first mixer by bolting flanged ends together with a rubber gasket between the two. Contact time of the AMD in the ILS ranged between 4 and 10 s depending on the number of static mixers being used (1 or 2).

SUMMARY OF TEST RESULTS

Individual summaries of data from the eight field sites at which the ILS has been tested are presented below. Each summary includes the following information: (1) raw water quality, (2) site description, (3) test procedures, and (4) test results.

Site 1

TABLE 2. - Conditions at Site 1

Site Description:		Ave. Raw Water Quality	
Operation	Deep Mine	pH	4.5
Raw Water	Mine pool	acidity	810 mg/l
Sludge Settling	Pond	Fe^{2+}	190 mg/l
Aeration	None	Fe	260 mg/l
Neutralization	NaOH	Mn	None
Normal Flow	350 gpm (22 l/s)	D.O.	7.6 mg/l

Historically, this first ILS test site required no treatment. However, the water quality deteriorated to a point which required aeration only for a few months, but then deterioration continued and neutralization and aeration become required. The ILS was installed at the site during the transition, which allowed for testing the ILS as an aeration system only and as an aeration and neutralization system using NaOH gravity fed into a jet pump.

The source of water pressure at this site, which operated a 2 jet pump and 1 static mixer ILS, was an electric mine-discharge pump. The pump was located 600 ft (183 m) across the surface from the treatment site and 600 ft (183 m) down the mine shaft. The electric pump was not capable of providing variable pressures; consequently, tests were run at a constant 40 psi (2.8 kg/cm^2).

Sampling procedures at this site, for the aeration test, involved a comparison of the site discharge water quality (before and after ILS installation). 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, which ranged from 10 to 20 mg/l before installation of the ILS dropped 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. At influent pH's of 4.6 to 5.6, very little iron oxidation was observed at the ILS discharge. However, the pond discharge (24-h detention time) contained only an average of 6 mg/l Fe^{2+}, about 67% less than before the ILS was installed.

In the aeration and neutralization tests, the sampling procedures focused on the reactions taking place within the ILS. The average values from four sets of water samples, collected at the three ILS sampling ports, are listed in Table 2A. Nearly all of the Fe^{2+} (97.5 pct) was oxidized as the water passed through the jet pumps. Only settling of ferric hydroxide was needed to bring the ILS discharge into compliance with water quality standards. A more detailed analysis of this test series may be found in Bureau of Mines RI 8868 (8).

TABLE 2A. - Effect of simultaneous in-line neutralization and aeration on water quality during flow through the ILS--Site 1

Parameter[1]	Before treatment	After jet pumps	After static mixer
pH[2]....................mg/L	4.5	6.7	6.9
Acidity or alkalinity[3]..mg/L	-810	+45	+70
Ferrous iron...........mg/L	190	4.8	2.4
Total iron.............mg/L	260	95	40

[1] All values are averages.
[2] Geometric average (9).
[3] (-) indicates acidity; and (+) indicates alkalinity.

Site 2

TABLE 3. - Conditions at Site 2

Site Description:		Average Raw Water Quality			
		First treatment		Second treatment	
Operation	Stripping	pH	2.8	pH	4.6
Raw Water	Pond	acidity	3772 mg/l	acidity	80.9 mg/l
Sludge Settling	Pond	Fe^{2+}	965 mg/l	Fe^{2+}	18.3 mg/l
Aeration	None	Fe	1011 mg/l	Fe	28.5 mg/l
Neutralization	NaOH	Mn	68.4 mg/l	Mn	10.8 mg/l
Normal Flow	50 gpm	SO_4	6290 mg/l	SO_4	5883 mg/l
	(3.1 l/s)	Na	29 mg/l	Na	1781 mg/l
		D.O.	4.9 mg/l	D.O.	5.7 mg/l

A double treatment operation took place at this site using a 3-pond water handling system. A diesel powered, submersible hydraulic pump operated the 3-jet pump ILS which used both single and double static mixers. Sodium hydroxide was gravity fed into the jet pump. Various pH-pressure combinations were scheduled for this site [pH 6 to 9 and 20 to 60 psi (1.4 to 4.2 kg/cm^2)]. Water was pumped through the ILS from pond 1 (raw water) into an empty pond 2 as the first treatment. The second treatment then pumped water, again through the ILS, from pond 2 into pond 3 after a 36 h detention period. The ILS was operated at back pressures ranging between approximately 5 and 10 psi.

Water sampling procedures were directed at not only those chemical reactions taking place within the ILS, but those in the settling pond as well. Ponding effects on water quality were determined from the raw water samples in the second treatment, since the same water was also the effluent from the first treatment.

Due to limitations in the NaOH gravity feed rate, pH values could not be raised above 6.8 regardless of pressure during the first treatment. A minimum of 31 pct (pH 5-5.0 psi), a maximum of 48 pct (pH 6.6-60 psi) and an average of 39 pct of the initial Fe^{2+} iron concentrations were oxidized at the ILS discharge from the various pH-pressure combinations. The D.O. concentration in all first treatment samples at the ILS discharge was essentially zero, thus indicating demand was greater than supply. The presence of 1 or 2 static mixers appeared to have no influence on water quality. Also, Mn values at the ILS discharge, remained equivalent to those in the raw water.

The water quality shown under the second treatment (table 3) indicates over a 98 pct Fe removal after a 36 h pond detention at a pH less than 7, following the initial treatment. Also, over an 80 pct reduction in Mn concentrations is presented.

The second treatment operation was able to put the water to within effluent standards. A full range of pH values was easily obtainable and D.O. values averaged 5.7 and 6.8 mg/l in the ILS influent and effluent, respectively. A more detailed analysis of this site and sites 3 and 4 may be found in BuMines IC 9029 (10).

Site 3

TABLE 4. - Conditions at Site 3

Site Description:

Operation	Preparation/Deep Mine
Raw Water	Pond
Sludge Settling	Pond/Clarifier
Aeration	None
Neutralization	$Ca(OH)_2$
Normal Flow	360 gpm (22.7 l/s)

Ave. Raw Water Quality

pH	2.9
acidity	808 mg/l
Fe^{2+}	77 mg/l
Fe	150 mg/l
Mn	9.6 mg/l
SO_4	2029 mg/l
Ca	281 mg/l
D.O.	8.5 mg/l

An electric pump, with a single pressure (60 psi or 4.2 kg/cm^2) capacity, was used to operate 2 jets in a 3 jet pump ILS (third jet valved closed) using 2 static mixers. Water was pumped out of a raw water holding pond through the ILS into a sludge settling pond, which in turn discharged into a small clarifier. A lime slurry was pumped into one jet pump from an existing paddle mix tank using a small submersible pump. Operating water pressure was constant but pH values in the ILS discharge ranged between 3.1 and 11.7. The ILS was operated at back pressures ranging between approximately 5 and 10 psi.

Water sampling locations included the three sampling ports on the ILS and discharges from the sludge settling pond and clarifier. Filtered, acidified samples showed that the initial Fe^{2+} concentrations were reduced to within effluents limits in the ILS discharge at pH values of 5.7 and up. Mn, however, was not within effluent standards until pH values of 7.3 and up were obtained. Finally, D.O. concentrations in the ILS discharge were equivalent to those in raw water (8.5 mg/l), indicating that an adequate supply of O_2 was available for the demand presented by this site.

Site 4

TABLE 5. - Conditions at Site 4

Site Description:	
Operation	Abandoned Deep Mine
Raw Water	Mine Pool
Sludge Settling	Clarifier
Aeration	Mechanical
Neutralization	$Ca(OH)_2$
Normal Flow	1500 gpm (95 l/s)

Ave. Raw Water Quality	
pH	5.3
acidity	991 mg/l
Fe^{2+}	527 mg/l
Fe	529 mg/l
Mn	14.1 mg/l
SO_4	4835 mg/l
Ca	429 mg/l
D.O.	6.5 mg/l

Raw water was pumped into an existing basin, then pumped through the ILS and discharged via flume into a large clarifier. Of the 10 tests conducted, 5 tests used one static mixer and 5 tests used 2 static mixers. A diesel powered, hydraulic submersible pump operated the 3 jet pump ILS used at this site. Except for 1 of 10 tests, the operating water pressure was kept at 40 psi (2.8 kg/cm^2); the exception was a 50 psi (3.5 kg/cm^2) operating pressure. Neutralization consisted of pumping, from a mix tank, a lime slurry with a small submersible pump to the suction chamber of a jet pump. ILS discharge pH values ranged between 5.9 and 8.4 for the 10 tests. The ILS was operated at back pressures ranging between approximately 5 and 10 psi.

Lab analysis showed that 6 of the 10 tests (2 with 1 static mixer and 4 with 2 static mixers) had pH values of 7 ± 0.1. Fe^{2+} and Mn concentrations in 5 of the 6 tests ranged between 42 and 59 mg/l (average 49 mg/l) and 3.4 to 5.6 mg/l (average 4.5 mg/l), respectively at the ILS discharge. These 5 tests showed an average of 91 pct Fe^{2+} removal and 68 pct Mn removal at a near neutral pH. One of the 6 tests however, proved to be within effluent standards with Fe^{2+} and Mn concentrations of 1.1 and 1.9 mg/l, respectively. Two of the 4 remaining tests had pH's greater than 7 ± 0.1 and 2 tests had pH's lower, none of which completely met effluent standards. The lower pH values, 5.9 and 6.6, resulted in Fe^{2+} and Mn reductions in the ranges of 9 pct (Fe^{2+}) and 1 pct (Mn) and 70 pct (Fe^{2+}) and 15 pct (Mn), respectively. The higher pH values, 7.7 and 8.4, resulted in Fe^{2+} reductions of 98 pct and 99 pct, respectively, and Mn concentrations were less than 2 mg/l at both pH levels. The D.O. concentrations in the ILS discharge were always less than 1 mg/l, regardless of the number of static mixers being used. Again, the number of static mixers used had no apparent effect on effluent water quality.

Site 5

TABLE 6. - Conditions at Site 5

Site Description:		Ave. Raw Water Quality	
Operation	Abandoned Deep Mine	pH	6.7
Raw Water	Underground Mine Pool	acidity	222 mg/l
Sludge Settling	Pond	Fe^{2+}	15.6 mg/l
Aeration	None	Fe	20.2 mg/l
Neutralization	$Ca(OH)_2$	Mn	None mg/l
Normal Flow	500 gpm	SO_4	272 mg/l
	(315 l/s)	D.O.	2.5 mg/l

Although this site conventionally treats mine water with lime, the ILS was installed and functioned as an aeration unit only. A diesel-powered, submersible hydraulic pump fed raw water alone out of an existing lime-raw water mix tank, through the ILS, and into the first of two settling ponds via a flume. Two separate tests were conducted at this site, one in the summer and the other in the fall. Test procedures (in both tests) involved operating the 2-jet-pump ILS at a constant water pressure, 24 h per day without neutralization. In the summer and fall tests, the ILS was operated at 30 and 20 psi (2.1 and 1.4 kg/cm^2), respectively. A difference between the two tests was that the ILS, at 30 psi (2.1 kg/cm^2), was operated only long enough to turn over the first of a 2 pond sludge settling operation (4 days). In the fall, the ILS operated at 20 psi (1.4 kg/cm^2) for a period long enough to turn over both ponds (15 days). Sampling locations included: (1) the ILS, (2) pond 1 discharge, and (3) pond 2 discharge.

In the 30 psi tests, Fe^{2+} concentrations were reduced to within effluent standards in samples collected at the ILS discharge. However, samples taken at the discharge from pond 1 showed an average of 5.9 mg/l total iron. Although analysis showed complete Fe^{2+} oxidation, precipitation apparently was incomplete at that point in the settling operation.

In the 20 psi (1.4 kg/cm^2) tests, Fe^{2+} oxidation was incomplete at the ILS discharge with analysis yielding an average 17.2 mg/l Fe^{2+} concentration. Analysis at the first pond discharge showed 100 pct Fe^{2+} oxidation, with an average total Fe concentration of 4.3 mg/l. Total Fe concentrations in the discharge from pond 2 were within effluent standards.

In both the 30 and 20 psi (2.1 and 1.4 kg/cm^2) tests, the D.O. concentration in the ILS discharge increased to average values of 9.3 and 8.5 mg/l, respectively, thus indicating an adequate supply of O$_2$ for complete Fe^{2+} oxidation.

Site 6

TABLE 7. - Conditions at Site 6

Site Description:		Ave. Raw Water Quality	
Operation	Stripping	pH	3.7
Raw water	Pond	Acidity	510 mg/l
Sludge setting	Pond	Fe^{2+}	< 1 mg/l
Aeration	None	Fe_{tot}	< 1 mg/l
Neutralization	Soda ash briquettes	Mn	181 mg/l
Average flow	50 gpm	SO_4	2475 mg/l
	(3.1 l/s)	D.O.	9.3 mg/l

A diesel powered, hydraulic submersible pump was used throughout the 4x4 test matrix described earlier in the General Procedures Section. Extended sampling procedures, also described in that section, were exercised at this site and the following two sites. Water was pumped from a raw water pond, through the 2-jet-pump ILS, and into the first of a two pond sludge settling operation. NaOH was substituted for soda ash briquettes and was either metered or gravity fed into a jet pump from a large storage tank. Initial samples were collected from the inlet and discharge of the ILS and extended samples were collected daily from the platform floating in the first settling pond. The extended detention period for this site was six days for each pH-pressure combinations.

No sample resulting from treatment within the described pressure-pH matrix was found to be within effluent standards. The average raw water quality for this site shows that iron is insignificant and Mn is the main concern. At pH 6 no reduction was observed in the Mn concentration regardless of pressure. Only a slight Mn reduction (13 pct maximum) was observed in the pH 7 series with relatively little change throughout the extended sampling period. Maximum reductions for tests at pH 8 and 9 in the initial samples were 46 pct and 80 pct, respectively. However, within the pH 8 to 9 range, extended sampling showed further reductions followed by increases in Mn concentrations. With one exception, both test series had maximum reductions on the third day of extended sampling. The exception was lowest on the second day. The maximum Mn reduction (down to 12.3 mg/l) was observed in the pH 9-50 psi combination on day three before it increased to 34.5 mg/l on day six. The average D.O. concentration in the ILS discharge was 8.8 mg/l.

Two additional tests were run, one at pH 10 and 40 psi (2.8 kg/cm^2) and the other at pH 10 and 60 psi (4.2 kg/cm^2). The extended sampling period for these tests was 48 h. The initial sampling in both tests showed only a 16 pct reduction in Mn; however, the 24 h and 48 h extended samples showed almost 100 pct removal (< 1 mg/l).

Site 7

TABLE 8. - Conditions at Site 7

Site Description:		Ave. Raw Water Quality	
Operation	Stripping	pH	3.1
Raw Water	Pond	acidity	382 mg/l
Sludge Settling	Pond	Fe^{2+}	< 1 mg/l
Aeration	None	Fe	23 mg/l
Neutralization	NaOH	Mn	20.4 mg/l
Normal Flow	5 gpm	SO_4	1580 mg/l
	(0.3 l/s)	D.O.	8.4 mg/l

The equipment, sampling, and neutralization were the same as site 6 except that the extended sampling period was 2 days. The testing procedures (test matrix and extended sampling) were also similar to those of the previous site; however, a reduced test matrix was used. Two pH 6 tests were completed, at 40 and 60 psi (2.8 and 4.2 kg/cm^2) and two pH 7 and pH 9 tests were completed at 30 and 50 psi (2.1 and 3.5 kg/cm^2) for a total of 6 tests.

Since the ferrous iron concentrations were < 1 mg/l, as shown above, the Mn represented the only oxygen demand. At pH 6.75 ± 0.5, only 56 pct of the Mn was removed. At the pH 7-30 psi (2.1 kg/cm^2) combination, the initial sampling was slightly over the 2 mg/l legal limit for Mn. However, the 1 and 2 day extended samples fell within compliance with the second day sample showing a slight increase. The pH values in this series were also on the high side, 7.95 ± 0.15. In the 50 psi (3.5 kg/cm^2) run, in which the pH's were consistant at 7.5, the Mn in the initial sample was within effluent standards. However, the 2 extended samples showed the Mn concentrations to increase to over 4 mg/l. Although a pH of 9 was targeted in the field, lab analysis showed the 30 psi (2.1 kg/cm^2) combination to yield pH's slightly less than 7 for the initial and extended samples. Consequently, results were similar to those obtained in the previously mentioned pH 6 tests. In the pH 9-50 psi (pH 9-3.5 kg/cm^2) combination Mn concentrations were reduced to less than 1 mg/l in the initial and extended samples.

Site 8

TABLE 9. - Summary Conditions at Site 8

Site Description:		Ave. Raw Water Quality	
Operation	Stripping	pH	2.9
Raw Water	Pond	acidity	736 mg/l
Sludge Settling	Pond	Fe^{2+}	82 mg/l
Aeration	None	Fe	145 mg/l
Neutralization	NaOH	Mn	121 mg/l
Normal Flow	220 gpm	SO_4	3860 mg/l
	(13.9 l/s)	Na	2.9 mg/l
		D.O.	6.2 mg/l

The same pump and ILS were used at this site as the previous 2 sites (sites 6 and 7). The 4x4 test matrix and extended sampling procedures were exercised as well. A 48 h extended sampling period was observed with samples being taken on 24 h intervals. Water was pumped from a raw water pond, through the ILS, and discharged into a previously emptied sludge settling pond. NaOH was injected into a jet pump with a metering pump.

With one exception, Fe^{2+} concentrations were reduced to within effluent standards (< 1 mg/l) at pH values of 7.2 and up, regardless of operating pressure in the initial samples. This exception, 30 psi (2.1 kg/cm^2) and pH 8, lab results showed 8 mg/l in the initial sample; however, extended sampling proved this combination, in terms of Fe concentrations, to be within effluent standards. Mn concentrations, in the initial samples, were found not to be within effluent standards until pH values of 8.8 and up were obtained, regardless of pressure. Analysis of the 24 h and 48 h extended samples showed Mn concentrations to increase, with only those initial samples with pH values of 9.1 ± 0.1 remaining within discharge standards. The D.O. concentrations of the treated water varied only by 0.8 mg/l over the 4 operating pressures, with 5.1 mg/l being the average concentration of all the samples.

DISCUSSION

As illustrated in the summary of test results, the ILS is capable of treating a wide range of AMD to within effluent standards. The ILS has been demonstrated to have definite advantages over conventional treatment. The following is a discussion of those advantages and the apparently unique capabilities demonstrated by the In-line system.

Advantages

The ILS has many advantages over conventional treatment methods: (1) the aeration and neutralization steps of conventional treatment are combined into a simultaneous operation, (2) the ILS has no moving parts, consequently, maintenance costs (labor, parts, lubrication, etc.) are significantly reduced, (3) construction of an in-line system does not require skilled labor; although, a qualified electrician may be required at the time of installation if an electric pump is to be newly installed, (4) the ILS has reduced space requirements, (5) simple burial or surface construction which allows for gravity drainage eliminates any adverse freezing problems, (6) this treatment system can easily be made portable, which allows for versatility in surface mining operations. Also, the portable ILS is an excellent system for those short term treatment situations usually encountered in reclamation operations. Mechanical aerators and/or aeration basins and the associated capital, operating, and maintenance costs are eliminated with the ILS. The ILS operates by water pressure, usually provided by an existing mechanical pump; however, given enough elevational difference [46 ft (14 m) or greater] the ILS can be operated by gravitational head pressure.

Capital costs for the ILS are perhaps the most significant advantage of the ILS over conventional treatment. Costs, based on the two prototypes, are as follows: 3 in (7.6 cm) jet pumps are approximately \$800 each and 12 in (30.5 cm) static maxers are approximately \$2,500 each. Each static mixer has an approximate flow capacity of 1,000 gpm (63 l/s). Consequently, the 2 and 3 jet pump components ILS prototypes cost \$4,100 and \$4,900, respectively.

Operation Costs

Operational cost will most likely be the cost of the additional power consumption by the existing mine discharge pump. For example, at site 1, which was the only test site which used an existing mine discharge pump, the additional power cost was calculated to be only 10 pct greater than normal pumping costs (7). The existing deep mine discharge pump at site 5 was operating at full capacity and could not provide the additional pressure [20 psi (1.4 kg/cm^2) and up] necessary to operate the ILS without modifications; consequently, another pump was used for testing purposes. Since a 20 psi (1.4 kg/cm^2) operating pressure was found to be adequate for this site, it was possible to modify to the existing pump at a lower cost.

Neutralization costs

Neutralization cost comparisons were performed at 2 sites (4 and 8), one site using lime and the other sodium hydroxide. At site 4 the flow through the ILS was one-third that of normal plant operation, the observed lime use (with the ILS) of 4.5 lb/min (2 kg/min) at pH 7.1 was scaled up to 13.5 lb/min (6.1 kg/min). This is the same, within 1 pct, as the lime consumed in neutralizing acidity during normal operation of the conventional treatment plant when calculated from chemical analysis but is 30 pct more efficient than actual lime use, as measured from the dry chemical feed in normal plant operation (10). Analysis of the sludge during operation of the conventional treatment plant confirms that a lot of unreacted lime was being wasted, especially in the aeration basin, owing to insufficient mixing action and the relative solubility of lime. At site 8, the average rate of NaOH use in the existing plant for a 6 month period was determined from company records. When compared to those NaOH feed rates in the ILS which put the treated water to within effluent standards, a 29 pct reduction in NaOH use was observed. The ILS feed rates were determined from both field measurements and chemical analysis.

Aeration

Air suction capacity in the ILS increases as the pressure increases; however, the amount of air (21 pct O_2) available in proportion to water (standard cubic foot per minute (SCFM) or liters per second (l/s) per gallon of water) changes very little as shown in Table 3. This fact shows that jet pumps have limited capacities for the amount of air they can inject into the water for dissolution purposes. Oxygen transfer efficiency is the subject of current research; however, the following observations of D.O. concentrations and oxygen consumption can be made. While using the ILS most sites had considerable concentrations of D.O. in the treated effluent even after meeting the Fe^{2+} oxidation demands (10). For example, the D.O. concentration in the raw water at site 5 (2.5 mg/l) was increased up to 10.5 mg/l (average 9.3) after a 4 s contact time in the ILS and oxidizing about 16 mg/l Fe^{2+}. At site 3, the D.O. concentration remained the same (8.5 mg/l) in the ILS influent and effluent after oxidizing 77 mg/l Fe^{2+} in a 10 s contact time. Two sites, however, did not have any residual D.O. in the treated effluent. Sites 2 and 4, which had relatively high Fe^{2+} concentrations, 965 and 529 mg/l, respectively, showed the ILS to have an apparent 300 mg/l Fe^{2+} oxidation limitation (10). However, as mentioned earlier, both sites experienced back pressures on the jet pump. Consequently, air suction capacities were drastically reduced by the 5 to 10 psi (0.35 to 0.70 kg/cm^2) back pressures (see table 10), which according to the jet pump manufacturer's tables can cause loss of suction. Yet at one site Fe^{2+} oxidation, as shown by chemical analysis, shows that over 2 SCFM (0.9 l/s) was consumed in the reactions (<u>10</u>). The source of back pressure in these tests was the 12 in (30.5 cm) static mixer which was flanged down to a 4 in (10.2 cm) discharge line. When the 12 in (30.5 cm) static mixer was completely filled with water and had to push the water through a 4 in (10.2 cm) opening at the end, back pressure developed. Back pressure was removed in the later tests simply by enlarging the discharge line from the static mixer from 4 (10.2) to 6 in (15.2 cm).

TABLE 10. - Air suction capacity of a 3-jet pump ILS as a function of pressure (<u>7</u>)

Pressure		Water Flow		Air Flow		Volume air per volume water	
(psi)	kg/cm^2	(gpm)	l/s	(SCFM)	l/s	SCFM/ gal	l air/ l water
20	1.4	291	18.4	124	55.5	0.43	3.0
30	2.1	344	21.7	142	63.5	0.41	2.9
40	2.8	399	25.2	160	71.6	0.40	2.8
50	3.5	439	27.7	180	80.5	0.42	2.9
60	4.2	478	30.2	213	95.3	0.45	3.1

At site 1, the ILS eliminated the need for mechanical aeration, which implies: (1) significantly reduced capital, maintenance, and operating costs, and (2) elimination of the cost to deliver power to this site which previously had none, had this water quality remained the same. The ILS at site 5 eliminated the need for neutralization, thus eliminating associated maintenance and lime costs for this operation.

Finally, as operating pressures were increased, volumes, water velocities, and consequently turbulence in the static mixer(s) were increased. Exactly what influence these variables have in the chemical reactions is the subject of current research efforts as stated earlier.

Ferrous Iron Removal

The kinetics of the Fe^{2+} oxidation occurring in the ILS also is a subject of current research efforts. Thus, quanitative rate data are not yet available. However, some preliminary observations can be made from the field tests.

In terms of Fe^{2+} and Mn oxidation and removal, 4 different treatment situations existed in the field tests. There were 2 aeration only situations, 1 with Mn only, 1 with Fe^{2+} only, and 5 situations with Fe^{2+} and Mn both present.

The aeration situations, sites 1 and 7, showed the Fe^{2+} oxidation process to be completed at either the ILS discharge or after pond detention. At site 7 both cases were observed. At 30 psi (2.1 kg/cm^2) operating water pressure the Fe^{2+}, although at relatively low concentrations, was converted to Fe^{3+} in the 4 s contact time of the ILS. However, at 20 psi (1.4 kg/cm^2), only a low percentage of the initial Fe^{2+} concentration was converted to the Fe^{3+} state at the ILS discharge. But 4 days later at the first pond's discharge the Fe^{2+} was 100 pct removed. At site 1, which had considerably more Fe^{2+} in the near-neutral pH water, 4 days of pond detection was required to oxidize essentially all of the Fe^{2+}.

Site 1, which as described earlier developed into an aeration and neutralization operation, showed the ILS to oxidize 190 mg/l of Fe^{2+} (no Mn at this site) within the 4 s contact time of the treatment system.

At the 5 test sites with Fe^{2+} and Mn present, Fe^{2+} oxidation varied. Sites 3, 7, and 8, had a 100 pct Fe^{2+} oxidation in the ILS discharge, at near-neutral pH values. However, Mn removal to within effluent standards was not always obtained at the neutral pH of these waters and required higher pH values for compliance. In the 2 cases of high Fe^{2+} concentrations of approximately 500 and 1,000 mg/l at sites 2 and 4, respectively, Fe^{2+} oxidation was incomplete at the ILS discharge. However, as previously mentioned in this section, the ILS was operating at a very low air suction capacity resulting from back pressure. Thus, an apparent Fe^{2+} oxidation limitation of 300 mg/l was observed at both sites.

In the one situation, site 6, which had insignificant iron, but a high level of Mn (181 mg/l), little or no effect was observed at the ILS discharge within the pH 6 to 9 range.

Mn Removal

Significant manganese removal occurred at relatively low pH in the ILS treatment. In a conventional system, the pH is usually raised to 9 to 10 to precipitate manganese at an acceptable rate. In contrast, several tests showed compliance with the manganese standard in the ILS discharge at pH values ranging from 7.3 to 9. Manganese was removed at lower pH values when the total iron to manganese ratio was high (15.6 at site 3 and 37.5 at site 4). At site 6, where the iron concentration was near 0, a pH greater than 9.5 was required to meet the manganese standard at the ILS discharge. The apparent dependence of manganese removal at low pH on iron concentrations suggests that a coprecipitation mechanism may be involved. In fact, sorption of Mn^{2+} on ferric hydroxide floc is known to occur (11).

Manganese redissolution was observed in extended samples where the initial pH was less than 9 or 10. The pH generally decreased during the settling time. Since the affinity between Mn^{2+} and $Fe(OH)_3$ increases with pH, this may simply indicate desorption. If manganese removal at low pH is desired, settling pond conditions will have to be monitored carefully to maintain a sufficiently high pH.

CONCLUSIONS

The in-line aeration and neutralization system is a simple and effective method of treating AMD and can reduce treatment costs. Field tests have shown the performance of the ILS to be at least equivalent and in most cases apparently superior to conventional treatment methods in terms of Fe^{2+} and Mn removal. These removal rates are, as previously mentioned, the subject of current research. The ILS has demonstrated several advantages over conventional treatment:

- reduced capital costs,
- reduced operating costs,
- reduced maintenance costs,
- reduced alkalinity costs,
- system can be made portable or permanent,
- no moving parts, easy to install, and easy to operate,
- easy to install,
- easy to operate, and
- electrical power source need not be located at treatment site.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

U.S. Customary Units		International System of Units (SI)	
Abbreviation or unit	Unit of measure	Abbreviation or unit	Unit of measure
psia	pound-force per square inch absolute	cm	centimeters
		m	meters
in	inches	l/s	liters per second
ft	feet	kg	kilograms
gpm	gallon per minute	kg/cm^2	kilograms-force per square centimeter
lb	pounds	l	liter
s	second	µm	micrometers
min	minute		
h	hour		
psi	pounds-force per square inch		
scfm	standard cubic feet per minute		