Innovative Ex-Situ Activated Iron Solids Treatment & Enhanced Iron Oxide Recovery From Various Types of High Flow Acidic Mine Drainage

FINAL REPORT

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Department of Environmental Protection
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EXECUTIVE SUMMARY

Widespread historic deep coal mining in eastern and western Pennsylvania has created numerous large underground reservoirs of ferrous iron-laden acidic mine drainage (AMD). These contaminated deep mine reservoirs (non-point sources) typically discharge at very high volumes (1 to 50 million gallons per day) and at single or multi-point locations into the surface waters of Pennsylvania. The high flow AMD discharges cause aesthetic and water quality degradation of the receiving surface water to levels that do not meet water quality standards (e.g., pH, metals and benthic habitat destruction) or the waters designated uses.

Treatment of the high flow AMD discharges has been attempted historically using conventional lime-based treatment, as well as numerous other active methods (reverse osmosis, distillation, liquid-liquid extraction, etc.), but the high annual chemical, manpower and energy costs, and the disposal costs of a low-density (1-4% solids) and impure sludge limited the number of high flow discharges that can be treated. Passive treatment initially showed promise based on treatment of lower flow discharges, but sizing requirements result in very large treatment area (20 to 200 acres) with uncertain performance, and sludge removal that is likely difficult, costly and may require interruption of treatment.

A new and innovative AMD treatment and metal recovery process, known as Activated Iron Solids (AIS) has been developed by Iron Oxide Technologies, LLC (IOT) for a range of AMD chemistries. AIS provides an economical treatment solution for high flow (1 to 30 Million Gallon Per Day) and high ferrous iron (> 20 mg/L) concentration AMD due to the elimination of high cost chemicals (e.g., lime, sodium hydroxide, and various oxidants). The AIS process also allows simplified recovery of a high-density (20 to 30% solids) solid with at least 95% iron oxide purity.

Activated Iron Solids (AIS) is a treatment process (patent pending) that utilizes a recently identified catalytic process associated with the surfaces of iron oxides known as heterogeneous ferrous iron oxidation. In this process dissolved ferrous iron is sorbed to iron oxides and is rapidly oxidized to ferric iron forming new iron oxides. The process requires high concentrations of suspended iron oxides, greater than 500 mg/L, which are achieved through collection and recirculation of the AIS within the treatment system.

A portable two stage, flow through AIS system was developed by IOT and tested at five (5) high flow AMD discharges in both the eastern anthracite and western bituminous coal regions of Pennsylvania that included a range of iron-containing AMD chemistries; pH 5.6 to 6.4, alkalinity 30 to 250 mg/L (includes both net acidic to net alkaline waters), and iron concentrations ranging from 15 to 70 mg/L. The five sites have average flows ranging from a low of 1 MGD (Blue Valley discharge on Toby Creek) to a high of 15 MGD (Scotts Tunnel discharge near Shamokin). The portable system (trailer-loaded) is fully equipped with aeration, mixers, chemical feed, pumps, and controllers.

The pilot studies were conducted from September 2006 through October 2008 at the five sites. The results provide considerable information regarding the AIS Treatment process. The results indicate:

- AIS Treatment effectively oxidizes ferrous iron to less than 0.10 mg/L in short detention times and within a small footprint that is needed for many of the discharges.
- In the case of Blue Valley and Monview-Mathies, AIS was shown to be able to replace chemicals (potassium permanganate and sodium hydroxide) currently used to complete treatment of the discharges.
- AIS ferrous iron oxidation rates were not affected by polymer type and dosing needed to flocculate and settle the precipitated iron.
- Observed oxidation rates by the AIS solids are equal to or greater than predicted using the heterogeneous ferrous iron oxidation model.
- Pulverized limestone ($CaCO_3$) was determined to be an effective source of alkalinity in the AIS reactors for slightly net acidic AMD discharges.
- AIS treatment required the use of a polymer for solids recovery and in the clarifier and to produce effluent total iron approaching 1 mg/L.
- Recovery of iron oxides from the system was demonstrated with solids density approaching 30% and iron oxide purity of approximately 95% with minimal trace metal contamination.

Improvements and modifications to the treatment system were made during the pilot studies to improve overall performance that included:

- Mixers were oriented vertically to provide greater bottom mixing to minimize solids accumulation in the bottom of the reactors.
- Polymer dosing was added to aid in flocculation and settling of the AIS.
- A flocculation tank was added to promote greater particle size and faster settling.
- A new vibratory type doser was identified to effectively dose pulverized limestone.

Based on the results of the pilot study and the heterogeneous ferrous iron oxidation model, conceptual AIS treatment systems were developed for each of the sites to produce effluent iron less than 0.5 mg/L at average flows and 1 mg/L at maximum flows. Treatment costs for the discharges for the full-scale systems will range between of $0.025 and $0.25 per 1,000 gallons of treated water depending on the flow and chemistry (i.e., net alkaline versus net acidic) of the AMD, inclusion of various operating costs, and/or reflection of capital costs.

The results of this AIS AMD treatment study have significant water quality and economical implications for Pennsylvania. The new AIS treatment process can effectively, economically and perpetually treat many high flow AMD discharges that are difficult and costly to treat with existing technologies. Treatment of these large flow discharges will dramatically increase the stream miles in Pennsylvania that can be restored. The byproduct produced by AIS treatment is a high purity, high density iron oxide that may be an economic resource to offset treatment and/or sludge disposal costs. Treatment of the AMD in the AIS process is rapid and maintains the thermal characteristics of the water which may have potential commercial (fishery), industrial (cooling or process water) and energy recovery (geothermal) reuse.

INTRODUCTION

The discharge of acid mine drainage (AMD) to surface waters in Pennsylvania and other eastern coal region states contaminates thousands of miles of waterways resulting in their non-compliance with numerous Pennsylvania Water Quality Standards including, but not limited to, pH, total iron, suspended solids, and aesthetics. The AMD is a result of past (and unregulated) surface and underground coal mining that exposes pyritic minerals to atmospheric oxygen and results in the oxidation and the production of AMD.

Of particular concern is AMD produced in the vast historic and abandoned deep mine workings found throughout the coal region. The pyrite oxidizes to create AMD that collects and is stored in the mine voids forming large underground reservoirs of contaminated AMD. These large underground AMD reservoirs discharge at one or more points, typically from air portals (for air circulation during active operations), water portals/drains (to maintain a minimal water level in the mine during active operations), or from the mine entry. Deep mine discharges tend to be very high flow with elevated ferrous iron but may contain adequate alkalinity for iron removal. The deep mine discharges are often the largest contributor of metal loading in the watershed and/or subbasin. Treatment is mandatory to achieve water quality goals in the receiving stream.

The impact of the high flow AMD discharges on receiving streams is substantial. Input of high flow and ferrous iron AMD to surface waters causes: 1) increase of instream iron concentrations to levels exceeding water quality standards; 2) instream oxidation causes the deposition of iron oxides, known as “yellowboy”, onto stream bottoms smothering aquatic life and causing aesthetic and sediment problems; and 3) oxidation of ferrous iron can cause a decrease in pH to less than 6, a water quality standard. These types of impacts lead to degradation of the receiving waters to conditions that do not meet the waters designated aquatic life, recreational, and water supply uses.

The purpose of this proposed study is to investigate a new and innovative technology, known as AIS Treatment, for ex-situ treatment and enhanced metal recovery of high flow (> 500 gpm, 0.75 MGD) AMD discharges. The study included pilot-scale treatment (25 to 80 gpm) at five (5) locations across Pennsylvania with different AMD chemistries to demonstrate the wide-spread application of AIS treatment. AIS treatment has been investigated in bench-scale studies and a demonstration SBR system. The purpose of this field pilot-scale study is the next step to demonstrate the technology and develop design guidance for full-scale systems. A portable (trailer-loaded) completely equipped (i.e., aeration, mixers, chemical feed, pumps, and controllers) steel tank pilot-scale system was used for the study.

This Final Report provides a summary of the five (5) pilot studies. Each of the five pilot study reports follow this final report and include:

1. Activated Iron Solids Treatment for Saxman Run Acidic Mine Drainage.
2. Activated Iron Solids Treatment for Blue Valley Acidic Mine Drainage.
3. Activated Iron Solids Treatment for Monview-Mathies Acidic Mine Drainage.
4. Activated Iron Solids Treatment for Phillips Run Acidic Mine Drainage.
5. Activated Iron Solids Treatment for Scotts Tunnel Acidic Mine Drainage.

SITE DESCRIPTION & BACKGROUND

There five locations where pilot studies were conducted is depicted in Figure FINAL-1 and included locations in southwest, northcentral and eastern Pennsylvania. The locations were:

1. Blue Valley AMD Discharge – a deep mine portal in the Toby Creek watershed located near Brockway, Pennsylvania. *Partial flow treatment at the Blue Valley AMD Treatment Plant and Fish Culture Station using potassium permanganate as a chemical oxidant.*
2. Lower Saxman AMD Discharge – a deep mine portal on the banks of Saxman Run, a tributary to the Loyalhanna River, located to the north of Latrobe, Pennsylvania. *No current treatment.*
3. Monview-Mathies AMD Discharge – a deep mine entry discharge located on Little Mingo Creek near Monongahela, Pennsylvania. *Treated with sodium hydroxide and settling ponds.*
4. Phillips AMD Discharge – a deep mine portal on the banks of Redstone Creek located to the south of Uniontown, Pennsylvania. *No current treatment*.
5. Scotts Tunnel AMD Discharge – a deep mine drain located in the Shamokin Creek watershed to the west of Kulpmont, Pennsylvania. *No current treatment*

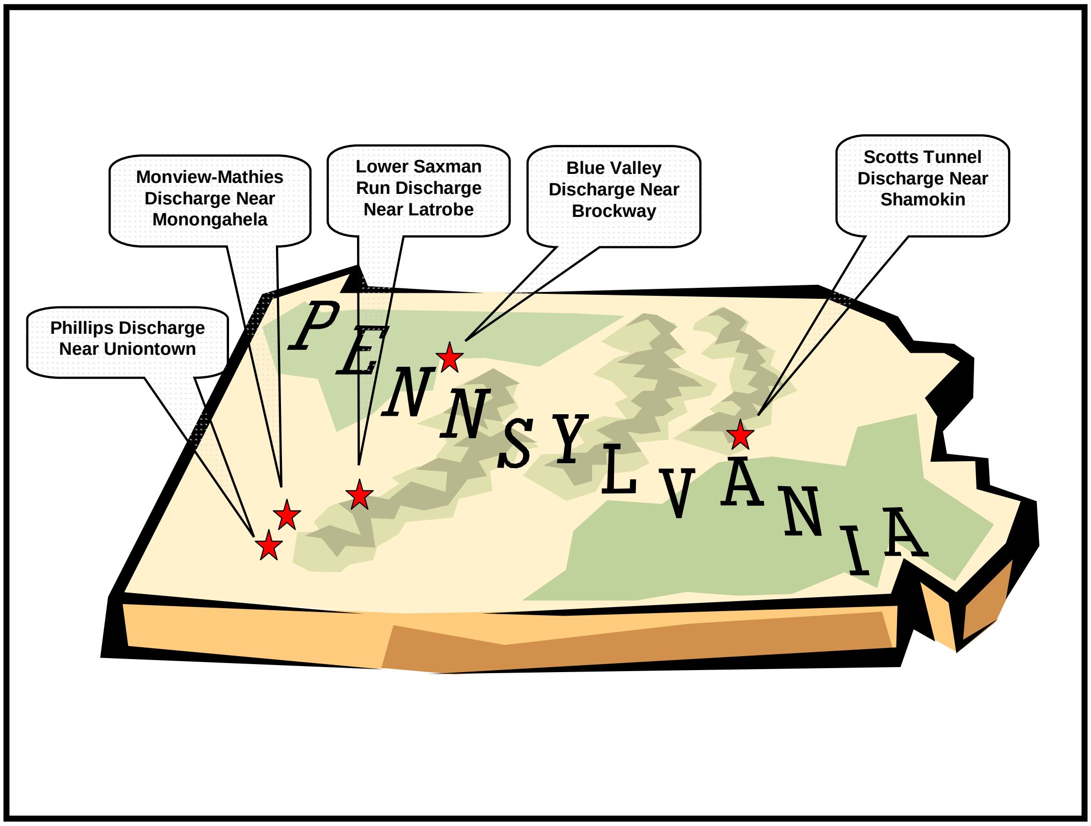

Figure FINAL-1. Locations of the Five Sites for the AIS Treatment Pilot-Scale Studies.

The following provides the technical background information for the pilot study including AMD characteristics of the discharges, background iron oxidation information, and a description of the AIS treatment process.

AMD Characteristics

The chemistry and flows for the discharges investigated in this study are summarized in Table FINAL-1. The discharge flows ranged from 1.0 MGD at Blue Valley to 14.4 MGD at the Scotts Tunnel Discharge. The discharge pH ranged from 5.8 at Scotts Tunnel to 6.8 at Monview-Mathies with the alkalinity in the two discharges ranging from 36 mg/L to 325 mg/L, respectively. Total iron ranged from 14.0 mg/L at Blue Valley to 47.7 mg/L at Phillips. The total iron was comprised almost entirely of dissolved ferrous iron, except for the Monview-Mathies discharge, which had between 4 mg/L and 6 mg/L of particulate ferric iron. All the discharges were low in manganese and aluminum. The metal concentrations along with the alkalinity determined the acidity of the discharges, which ranged from highly alkaline (-270 mg/L) at Monview-Mathies to slightly acidic (+20 mg/L) at Scotts Tunnel. Sulfate concentrations varied from a low of 230 mg/L at Scotts Tunnel to a high of 1,050 at Monview-Mathies. Temperature also varied across the discharges depending on the latitude and elevation with the lowest discharge temperature of 10.0ºC measured at Blue Valley in northcentral Pennsylvania and the highest discharge temperature of 14.9 ºC measured at Phillips in Southwestern Pennsylvania.

Table FINAL-1. Summary of the chemistry and flow for the deep mine discharges investigated in the AIS AMD pilot study.

Location	Max. Flow MGD	Temp ºC	pH	Total Fe mg/L	Fe^{2+} mg/L	Total Al mg/L	Total Mn mg/L	Alkal. mg/L	Acidity mg/L	Sulfate mg/L
Blue Valley	1.0	10.0	6.3	14.0	13.5	<0.5	3.5	200	-130	600
Lower Saxman	8.6	13.2	6.0	33.5	33.0	0.5	4.8	58	+10	510
Monview-Mathies	4.3	13.8	6.8	26.0	21.1	2.0	1.5	325	-270	1,050
Phillips	9.0	14.9	6.1	47.7	47.6	<0.5	3.0	235	-150	600
Scotts Tunnel	14.4	12.1	5.8	22.5	22.3	<0.5	2.5	36	+20	230

Carbon dioxide (CO_2) acidity was calculated to determine the amount of aeration needed to remove the CO_2 and maintain or raise the pH to levels needed for the effective oxidation of ferrous iron in the AIS treatment approach. In aqueous chemistry, CO_2 acidity is present in water as carbonic acid (H_2CO_3). The pH of water (controlled by the carbonate system) is determined by the concentrations of bicarbonate (HCO_3^-), which is alkalinity, and H_2CO_3 according to the following relationship:

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \qquad \text{(FINAL-1)}$$

The pK_a of this equilibrium is 6.4, which would be the pH where the H_2CO_3 and HCO_3^- concentrations would be equal. This means an alkalinity (HCO_3^-) of 30 mg/L (as $CaCO_3$) would require an equal CO_2 acidity (H_2CO_3) of 30 mg/L (as $CaCO_3$) to have a pH of 6.4. The CO_2 acidity was calculated for each of the discharges and ranged from 135 mg/L (as $CaCO_3$) for

Scotts Tunnel to 475 mg/L for the Phillips discharge. The source of this CO_2 acidity is chemical neutralization reactions in the deep mine pool as well as decomposition reactions. The CO_2 acidity is about 100 to 300 times higher than is normally found in surface waters in equilibrium with the atmosphere.

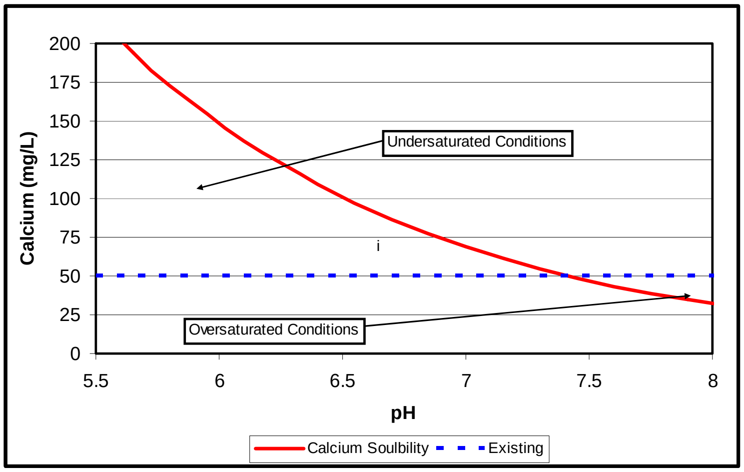

Figure FINAL-2. Calcium solubility in the AMD discharge with respect to pH.

The solubility of calcium and magnesium in the AMD must be evaluated for the various treatment methodologies. pH adjustments may create operation and maintenance issues by precipitating calcium and magnesium. Figure FINAL-1 shows the calcium (calcite) solubility with respect to pH. Oversaturated conditions for calcium is only present at pH greater than 7.5 indicating calcium carbonate (calcite) precipitation is not a significant concern in AIS treatment as the operational pH is typically less than 7. Calcite precipitation will occur in lime (CaO) treatment which raises the pH to greater than 8. At pH greater than 8, magnesium can also be removed as a hydroxide.

An important parameter listed in Table FINAL-1, which is not normally considered, is the temperature of the discharge. Temperature of the water is important because it affects a number of chemical and physical processes in the treatment of AMD. The temperature of the discharges ranged from a low of 10.0°C at Blue Valley to14.9°C at Phillips. Ferrous iron oxidation is affected by temperature oxidation occurring faster at higher temperature, which will affect reactor volumes. This temperature will also affect aeration and settling processes.

Iron Oxidation & Removal in AMD Treatment

The treatment of the high flow deep mine AMD discharges requires iron removal and this iron removal is a multi-step process involving:

1. Oxidation of dissolved ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+});
2. Hydrolysis of ferric iron to form insoluble ferric oxide ($Fe(OH)_3$);
3. Flocculation of tiny (sub micrometer) iron oxide particles to form larger (micrometer) iron oxide particles;
4. Settling of suspended iron oxide particles from solution.

Depending on the type of treatment, one or more of the above processes will control the removal of iron. In passive treatment the oxidation (Step 1) of ferrous iron is very slow and determines iron removal and the size of the passive treatment system. In chemical treatment at high pH (> 8), the settling (Step 4) typically controls iron removal. The new and innovative process, AIS treatment, provides an alternative to passive treatment and chemical treatment that may offer both rapid oxidation and rapid settling, but at acidic pH.

The oxidation of ferrous iron is the first and most crucial step in the removal of iron. Without the oxidation step, ferrous iron would remain in solution (except at very high pH) and removal of iron from AMD would not be possible. There are two types of ferrous iron oxidation in water:

1. ***Homogeneous Ferrous Iron Oxidation (HoFIO)*** **–** is the long established oxidation process occurring in solution and involves the reaction of dissolved ferrous iron (Fe^{2+}) with dissolved oxygen.
2. ***Heterogeneous Ferrous Iron Oxidation (HeFIO)*** **–** is a newly identified oxidation process occurring on the surface of iron oxide solids and involves the sorption of ferrous iron and dissolved oxygen followed by the rapid catalytic oxidation on the surface of the iron oxide.

The first type, HoFIO is the ferrous iron oxidation that occurs in solution and is most commonly associated with passive treatment and conventional (lime-based) chemical treatment of AMD. This process is also the dominate process where aeration is used to add oxygen and raise the pH to greater than 7, a pH where HoFIO will dominate. The long established HoFIO rate equation (Sung & Morgan 1980) is:

$$\text{(FINAL-2)} \quad \textit{HoFIO rate}\ (\mathrm{M \cdot s^{-1}}) = -\delta[\mathrm{Fe(II)}]/\,\delta t = k_{\mathrm{Ho1}} \times [\mathrm{Fe(II)}_{diss}] \times [\mathrm{O_2}]\ /\ \{\mathrm{H+}\}^2$$

The HoFIO equation is complex with the HoFIO rate affected by the ferrous iron concentration $[Fe(II)_{diss}]$, dissolved oxygen $[O_2]$ and pH $\{H^+\}$. Temperature is an integral part of the equation by its affects on the reaction rate constant (k_{Ho2}), with a decrease in temperature causing a decrease in the oxidation rate. The HoFIO equation is a reliable design tool because the equation can be used to predict iron removal for 1) different AMD chemistry, and 2) factors in iron removal under operating conditions (e.g., dissolved oxygen, pH and temperature). The HoFIO model will be used to evaluate ferrous iron oxidation results for the pilot study where only aeration is used in the reactors to increase dissolved oxygen and pH.

Heterogeneous ferrous iron oxidation (HeFIO) is an oxidation process that occurs on iron oxide surfaces and is the oxidation process AIS uses to oxidize ferrous iron. HeFIO is a two step processes that involves: 1) the sorption of ferrous iron to the surface of the iron oxide; 2) rapid oxidation in the presence of dissolved oxygen to form new iron oxides directly on the surface of the iron oxide. Equations and models for the reactions are contained in Dietz (2003). The equations are complex describing both sorption and oxidation process.

$$\text{(FINAL-3)} \quad \textit{HeFIO rate}\ (\mathrm{M \cdot s^{-1}}) = (-\delta[\mathrm{Fe(II)}]/\,\delta t) = (k_{\mathrm{He1}}[\mathrm{O_2}]S_1) + (k_{\mathrm{He2}}[\mathrm{O_2}]S_2)$$

and

$$\text{(FINAL-4)} \qquad S_x = \frac{1 + ([Fe(II)_{diss}] \times K_x^{app})}{[\equiv Fe(III)] \times \Gamma_x \times \{H^+\}^x}$$

where **x** is the reaction (either 1 or 2), $\mathbf{k_{Hex}}$ are the surface oxidation rate constants, $\mathbf{K_x^{app}}$ are the surface complexation constants, and **[≡Fe(III)]** is the AIS concentration (in mg/L). Dietz (2003) determined the various thermodynamic constants for the equations including activation energies and enthalpies, which describe the effects of changing temperature. In current treatment systems (including passive treatment and lime treatment), HeFIO is not very important (< 5% of the ferrous iron oxidation rate) due to the low concentrations of suspended iron oxides (typically less than 10 mg/L). Iron Oxide Technologies, LLC has developed several treatment systems optimizing HeFIO through concentrated suspensions of iron oxide solids in reactor systems. Figure FINAL-2 shows the time required to oxidize and remove ferrous iron from AMD for various treatment methods from bench-scale testing conducted at 15°C on an anoxic AMD discharge. Note the x-axis time scale is logarithmic. At this temperature the detention time required to achieve less than 0.5 mg/L ferrous iron for the passive treatment and passive treatment with pre-aeration tests were 50 and 25 hours, respectively. Lower temperature conditions (e.g., during winter periods) would require additional detention times to complete oxidation. As a comparison, the AIS treatment test required only 20 minutes to achieve 0.5 mg/L, which demonstrates the importance of HeFIO and the ability AIS treatment to achieve rapid oxidation and removal of ferrous iron. AIS treatment is 75 times faster in comparison to pre-aeration/passive treatment and 150 times faster in comparison to passive treatment only. A pH 8 oxidation line is also provided to show AIS ferrous iron oxidation is similar to conventional lime-based treatment: the 0.5 mg/L ferrous iron is expected to occur in 15 to 20 minutes detention time.

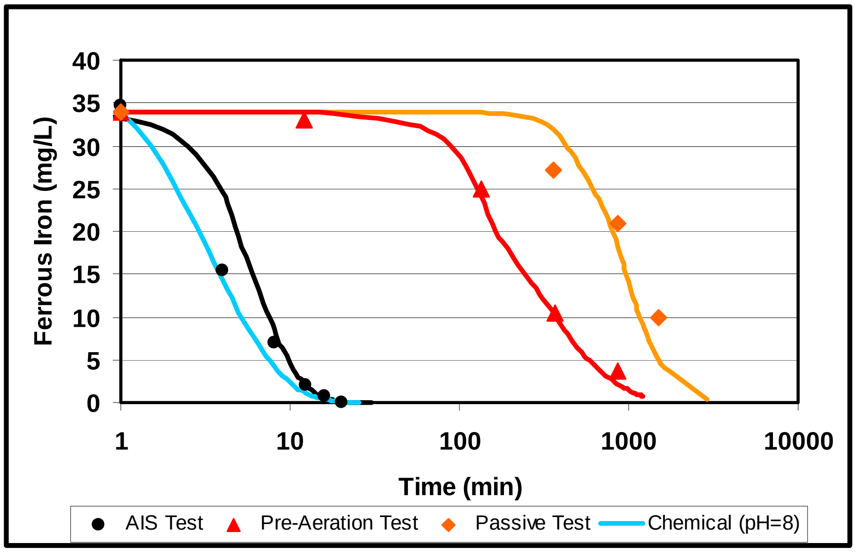

Figure FINAL-3. Bench-scale Results for Activated Iron Solids (AIS), Pre-aeration & Passive Tests

Innovative AIS Treatment

Iron Oxide Technologies, LLC has developed new (patent pending) active treatment approaches collectively known as Activated Iron Solids (AIS) treatment of AMD. AIS treatment has numerous advantages over conventional chemical treatment that can make long term treatment and iron oxide recovery possible at high flow AMD discharges. The AIS treatment advantages over conventional chemical treatment are:

1) Oxidation and removal occur at slightly acidic pH (6-7);
2) Oxidation rates are as fast as conventional chemical treatment;
3) For net alkaline AMD no alkaline chemicals are needed;

4) For net acidic waters, inexpensive pulverized (powder) limestone can be used for the needed alkalinity;
5) Solids produced by the AIS process are high-density (30% solids);
6) Solids are high purity iron oxides (95% iron oxides on a dry weight basis).

These advantages will have a direct effect on treatment costs by eliminating (or minimizing) chemical use and cost, and simplifying operation that will decrease manpower requirements. The innovative active AIS treatment process utilized for this pilot study is the Two-Stage AIS Reactor System (depicted in Figure FINAL-3 through FINAL-5). The changes in the conceptual figures of the Two-Stage AIS Reactor System represent modifications made during the project to improve iron oxide solids removal and AIS recirculation from the initial study at Saxman Run to the final study at Scotts Tunnel.

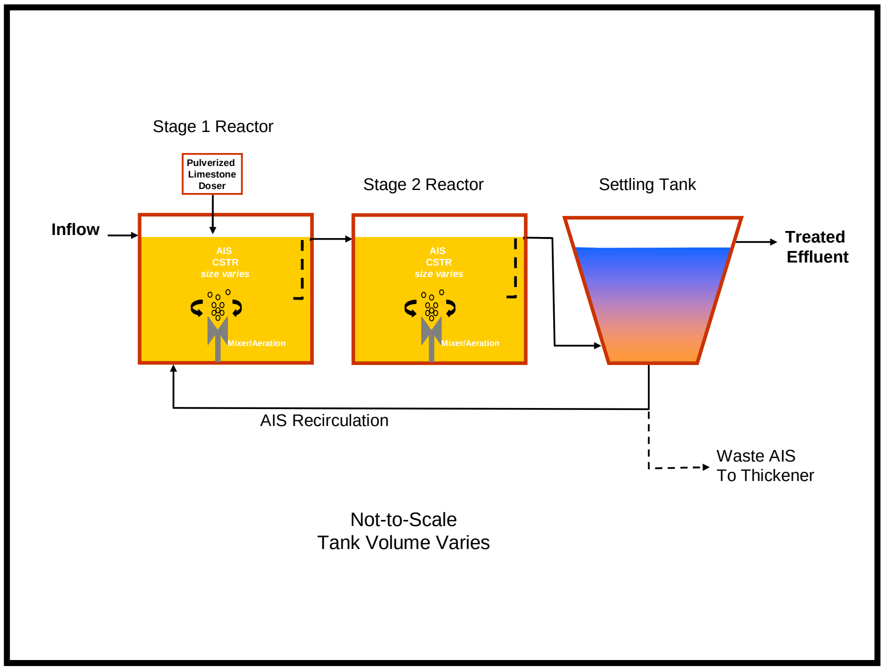

Figure FINAL-4. AMD Treatment in a Two-Stage Flow-Through AIS System.

The AIS treatment system uses high iron oxide concentrations (AIS = 1,500 – 2,500 mg/L) to increase ferrous iron oxidation and removal. The high iron oxide concentrations produce a catalytic environment that promotes ferrous iron oxidation and removal while producing high-density and pure treatment solids (iron oxide solids).

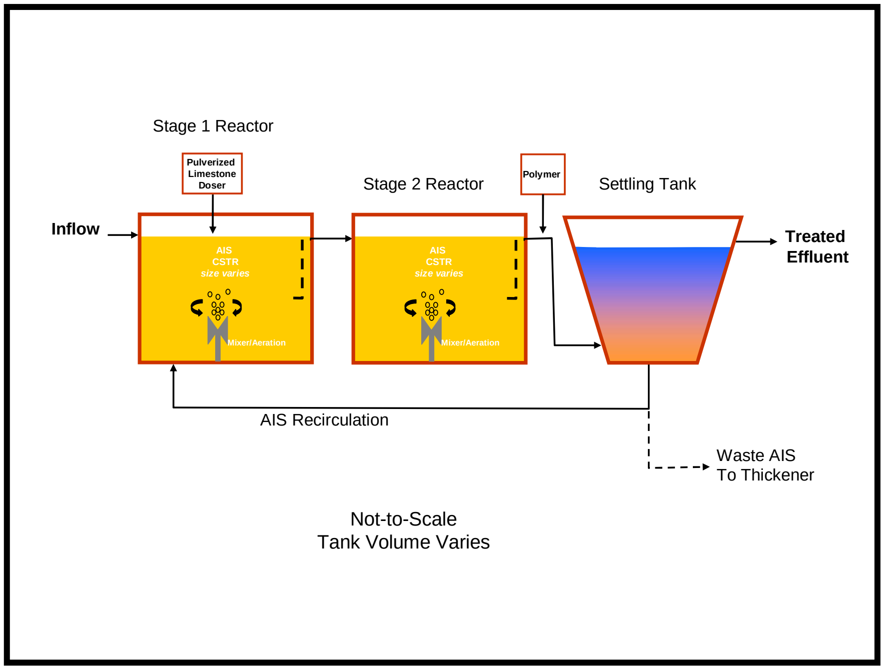

Figure FINAL-5. AMD Treatment in a Two-Stage Flow-Through AIS System showing addition of a polymer prior to settling.

The Two-Stage AIS Reactor system maintains high reactor AIS concentrations through recirculation of solids collected in the clarifier.

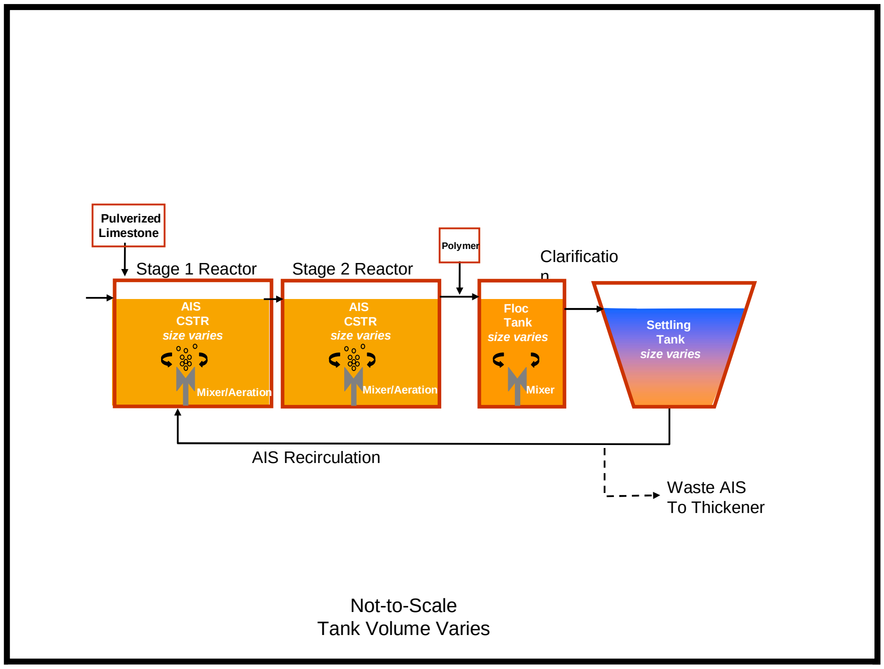

Figure FINAL-6. AMD Treatment in a Two-Stage Flow-Through AIS System showing addition of a polymer and flocculation tank prior to settling.

PILOT STUDIES

Pilot studies were conducted at each of the five (5) locations listed previously. The location for each of the pilot study were identified based on proximity to the discharge, site characteristics, access to the location, and availability of electrical service. In only one case was a generator required and this was at the Phillips location. The locations for each pilot study were:

1. Saxman Run – located on the Latrobe Wastewater Treatment Facility adjacent to a previous project that conveyed the upper Saxman Run discharge to the site and where electrical service was available.
2. Blue Valley – located within the building of the Blue Valley AMD Treatment Facility and Fish Culture Station in the loading dock open area where the discharge could be pumped and electrical service provided from existing service.
3. Monview-Mathies – located between the mine shaft (and discharge) and a maintenance building where temporary electrical service was provided and the discharge was pumped from the mine shaft opening and returned to the existing underground pipe.
4. Phillips – located adjacent to the AMD discharge in a flat area with the access road and pad installed by DEP-BAMR and electrical service provided by a diesel generator.
5. Scotts Tunnel - located adjacent to a discharge on an existing turn off along S.R 61 approximately ½ mile to the west of Kulpmont, PA and on Susquehanna Coal Company property where temporary electrical service was available.

Each site required various degrees on engineering services to develop the site for delivery and placement of the trailer pilot system, installation of electrical service, and installation and setup of the pilot unit. The various activities are summarized in the individual Pilot Study Reports.

Analytical Methods

Analysis for the pilot studies consisted of pH, dissolved oxygen, temperature, total iron, dissolved/ferrous iron, alkalinity and conductivity. pH was measured with an Fisher Scientific

Accumet Portable Meter equipped with a Cole Parmer Accumet combination pH electrode. The pH electrode was calibrated daily prior to use with pH 4.00 and pH 7.00 buffers. Dissolved oxygen (DO) and temperature were measured with an YSI Model 550A DO Meter. The DO Meter was calibrated prior to each use using the air saturation method. Total iron was measured using a Hach Iron Pocket Colorimeter Test Kit (0-3.00 mg/L) using Ferrover reagent after appropriate dilution. Dissolved iron was also measured with the Iron Pocket Colorimeter but after filtration using a syringe and a 0.2 μm syringe filter, and appropriate dilution. Ferrous iron was determined using Hach ferrous iron powder packets and the Hach Iron Pocket Colorimeter. Initial testing on the discharge indicated dissolved iron (filtered sample) equals ferrous iron for the conditions in the Scotts Tunnel AMD. As a result, the dissolved iron test was used to determine ferrous iron. Alkalinity was measured on a 100 mL sample using a Hach Digital Titrator, a 1.600 N sulfuric acid cartridge. Conductivity was measured with an Oakton Conductivity Pen.

Aeration Only Testing

Aeration testing was conducted at several of the locations prior to the AIS testing and included Blue Valley, Monview-Mathies and Scotts Tunnel. The aeration testing was conducted to determine the required detention time and air flow to achieve adequate oxidation of the ferrous iron (dissolved) in the discharge to the insoluble ferric iron. In the case of Scotts Tunnel, aeration testing was also conducted to determine if the addition of an alkaline material (i.e., pulverized limestone) was needed. The results of the aeration could be compared directly to the AIS results to show the benefits of AIS treatment over aeration only. The testing consisted of varying the AMD flow to the treatment system and providing aeration at various air flows.

The results of the aeration only testing from the various pilot studies are summarized in Table FINAL-2. The detention times required to achieve substantial ferrous iron oxidation varied based on a number of factors. Raw water characteristics including pH, alkalinity, and temperature were important in determining the required detention times. The raw water pH and alkalinity determined the amount of carbon dioxide acidity in the water that must be removed to raise the pH to greater than 7 where the ferrous iron oxidation rate is fast. The alkalinity remaining after the iron acidity has been removed is also important in determining the final pH of the water. Temperature affects both the ferrous iron oxidation rate as well as the rate dissolved oxygen is added and carbon dioxide acidity is removed through aeration. The Monview-Mathies discharge had the lowest detention time of the three discharges tested to lower the ferrous iron to less than 0.1 mg/L. This discharge had the highest raw water AMD pH, alkalinity and temperature. The Scotts Tunnel had the longest detention time to oxidize the ferrous iron, which was related to the lower pH resulting from the lower raw water alkalinity and the limited alkalinity remaining after removal of the iron acidity. Overall, the detentions times for aeration only testing required to achieve low ferrous iron at the three locations ranged from 6 hours at Monview-Mathies to greater than 20 hours at Blue Valley and Scotts Tunnel.

The aeration only dissolved iron data was compared to the predictions using the homogeneous iron oxidation model and reactor equations. This was done to evaluate accuracy of the homogeneous iron oxidation model to size aeration only systems. The model results were consistent with the results from the Blue Valley and Monview-Mathies aeration only studies.

The Scotts Tunnel aeration only study had faster oxidation rates (approximately 2 times faster) than the homogeneous model predicted. The Scotts Tunnel AMD discharge has lower salinity in comparison to the other two discharges. Investigators have found lower salinity waters to have faster oxidation rates than higher salinity waters (Millero *et al* 1987). This is related to the ferrous iron equilibrium reactions and the affect ionic strength has on the equilibriums.

Table FINAL-2. Summary of Pilot Study Results where aeration only was used in the Reactors (no AIS).

Study Location	Test	Flow gpm	Det. Time Hrs	Air Flow cfm	pH	Dissolved Oxygen mg/L	Temp. °C	Effluent Alkalinity mg/L	Effluent Diss. Fe mg/L
Blue Valley	A5	3.0	21.1	24	7.44	10.8	12.1	187	0.63
Blue Valley	A4	6.5	9.6	24	7.02	11.0	11.2	195	2.55
Blue Valley	A3	15.0	4.2	24	6.85	11.1	10.4	204	7.75
Monview-Mathies	A1	3.5	18.1	18	8.33	9.6	19.1	350	0.03
Monview-Mathies	A2	9.8	6.4	18	8.13	10.1	17.5	342	0.05
Monview-Mathies	A3	25.0	2.6	18	7.54	10.7	14.8	340	0.25
Scotts Tunnel	A2	2.3	28.4	18	6.35	9.50	18.8	2.9	0.70
Scotts Tunnel	A1	4.4	14.8	18	6.40	10.1	17.2	2.9	1.50
Scotts Tunnel	A3	17.7	3.6	18	6.47	11.0	16.3	25	16.7

Based on the results the homogeneous model can be used to predict aeration only systems to achieve various dissolved ferrous iron concentrations.

AIS Testing

The AIS testing at the five (5) locations covered a broad range of AMD chemistries and operating conditions to determine optimal operating conditions for AIS treatment system for each of the discharges. In the case of the AIS concentration, the target AIS (as total iron) was between 1,500 and 2,500 mg/L in the reactors using recirculation of solids from the clarifier.

To start the pilot system, AIS solids were added to the pilot unit using solids retained from previous pilot studies. In the case of the Blue Valley pilot study, iron oxide solids from the existing Blue Valley AMD treatment system were used. Ferrous iron is oxidized by potassium permanganate at the existing AMD treatment facility. The added iron oxide solids typically resulted in initial reactor AIS concentrations between 400 and 800 mg/L. The addition of iron oxide solids simplified and shortened the start-up time required to accumulate AIS solids in the system (days versus weeks) to the target concentrations.

The initial startup conditions for each of the pilot studies are summarized in the individual reports. The AMD inflow was set based on calculated oxidation rates using the heterogeneous iron oxidation model. The AIS recirculation rate was set at a flow rate to maintain and increase the reactor AIS concentrations based on expected solids in the recirculated flow and the AMD inflow rate. Air flow was set at an estimated rate based on the aeration only studies. The polymer used for the AIS testing was the Ciba Specialty Chemicals Magnafloc® 155, a medium molecular weight low charge anionic acrylamide polymer. This polymer was identified as the most suitable polymer for this application based on testing of multiple polymers at the pilot studies, based on bench testing of the AIS containing reactor water.

Overall the pilot studies indicate the AIS treatment system oxidized the soluble ferrous iron in the AMD discharges to particulate ferric iron in short detention times. The dissolved iron decreased from influent concentrations to less than 0.1 mg/L in the higher AIS concentration tests (> 1,500 mg/L) with effluent concentration dependent on the AMD characteristics and the reactor conditions. The detention times at which this low dissolved iron was achieved ranged from 30 minutes (0.5 hours) at Phillips to 130 minutes (2.2 hours) at Scotts Tunnel. The required detention time varied depending on the influent AMD ferrous iron, temperature, alkalinity and pH. Of the four parameters, the AMD temperature was the most important in determining the needed detention time. The influent AMD alkalinity and pH were important as they affected the reactor pH that could be achieved through aeration. The results of the pilot studies demonstrate the AIS process can achieve effective ferrous iron oxidation to very low concentrations, approaching 100% ferrous iron removal, in short detention times.

Air flow was found to be an important factor in the oxidation process by increasing both dissolved oxygen and pH. Dissolved oxygen is increased through the transport of oxygen in the air to the water. pH is indirectly increased through the removal of dissolved carbonic acid in the water to carbon dioxide in the air. Based on the heterogeneous ferrous iron oxidation model, both the increase in dissolved oxygen and pH substantially increased the ferrous iron oxidation rate. As examples to demonstrate the importance of the dissolved oxygen and pH increase, the heterogeneous model predicts: 1) an increase in dissolved oxygen from 5 to 10 mg/L will double the heterogeneous ferrous iron oxidation rate; and 2) a pH increase of 0.3 will more than triple the heterogeneous ferrous iron oxidation rate.

The results of the AIS pilot study were also used to evaluate the validity of the heterogeneous ferrous iron oxidation model for the sizing AIS reactor systems for the AMD discharge chemistry tested in the pilot studies. The heterogeneous ferrous iron oxidation model was used to predict the oxidation rate (*pseudo*-first order) for the measured conditions in the reactors. The reactor ferrous iron concentration was then estimated using complete mix reactor equations. The results of the comparison are summarized in Table FINAL-3. Based on the measured versus modeled ferrous iron comparisons, the model provides reasonable predictions of the ferrous iron oxidation rates. In addition, the model comparison indicates the polymer used in the pilot studies has no negative impact on the catalytic oxidation process. The results indicate the heterogeneous ferrous iron oxidation model is a valid tool to determine the reactor sizes in an AIS system to treat the range of AMD chemistries tested in the pilot study.

Table FINAL-3 Comparison of AIS Pilot Study Results to the Heterogeneous Ferrous Iron Oxidation Model.

Study Location	Test	AMD Flow gpm	Air Flow cfm	Det. Time Hrs	Ave. Reactor Conditions				Meas. Diss. Fe mg/L	Calc. Diss. Fe mg/L	Diff. Diss. Fe
					pH	D.O. mg/L	Temp. °C	AIS mg/L			
Blue Valley	AIS1	30	8	2.10	6.55	8.2	10.3	1,850	0.71	0.48	+0.23
Blue Valley	AIS3	30	12	2.10	6.65	9.1	10.2	2,170	0.11	0.07	+0.04
Blue Valley	AIS2	30	16	2.10	6.81	9.5	10.3	1,980	0.04	0.06	-0.02
Monview-Mathies	AIS5	25	8	2.60	7.15	8.6	15.0	1,830	0.07	0.01	+0.06
Monview-Mathies	AIS6	40	12	1.64	7.15	9.5	13.9	2,020	0.06	0.01	+0.05
Monview-Mathies	AIS7	60	16	1.08	7.07	9.3	14.4	2,120	0.14	0.01	+0.13
Phillips	AIS4	40	18	1.64	6.65	8.6	15.2	1,980	0.05	0.01	+0.04
Phillips	AIS5	60	18	1.08	6.41	8.2	15.2	2,200	0.00	0.48	-0.48
Phillips	AIS6	80	18	0.80	6.36	7.4	15.4	2,300	0.03	2.3	-2.27
Scotts Tunnel	AIS2	20	18	3.25	6.90	10.5	13.6	2,370	0.06	0.01	+0.05
Scotts Tunnel	AIS3	26	18	2.50	6.61	10.6	13.4	2,340	0.15	0.02	+0.13
Scotts Tunnel	AIS4	40	18	1.62	6.58	10.8	13.2	2,410	0.94	0.27	+0.67

The AMD chemistry for several of the discharges tested in the pilot studies indicated the discharges were net acidic or contained insufficient alkalinity to maintain pH grater than 6.5 (i.e., net alkalinity less than 10 mg/L). In these cases pulverized limestone was tested as a source of alkalinity. Pulverized limestone, also known as agricultural lime, is a fine powder produced from crushing limestone. It is in the form of calcium carbonate ($CaCO_3$) versus hydrated lime and quick lime which are calcium hydroxide ($Ca(OH)_2$) or calcium oxide (CaO), respectively. Pulverized limestone is lower in cost than hydrated lime or quick lime. In the pilot studies where pulverized limestone was used, it was added directly to the first reactor using a powder feed system. The pilot studies indicated the pulverized limestone dissolves providing the alkalinity needed to maintain reactor pH for AIS treatment. In the case of the Scotts Tunnel discharge, the alkalinity produced by the pulverized limestone was greater than 40 mg/L and equated to between 85% and 95% of the measured dose to the pilot unit. This indicates the pulverized limestone, where needed, is an effective material to maintain pH and alkalinity in the AIS treatment process for low net alkalinity or slightly net acidic AMD. The pilot study also identified and developed operating parameters for the needed pulverized limestone dosing technology, a Kraus Gyro Activating Feeder ©, to be used with the AIS process.

The primary objective of the AIS pilot studies was to demonstrate the ability of the AIS process to rapidly oxidized dissolved ferrous iron to an insoluble ferric iron and at slightly acidic pH (6.6 to 7.0). The removal of the particulate iron was a secondary objective of the pilot studies. The initial pilot study demonstrated the need for use of a polymer (anionic) in AIS treatment to produce rapidly flocculating and settling AIS. With the use of a polymer, low effluent total iron concentrations were achieved. Effluent total iron less than 2 mg/L was achieved in tests where a polymer was used with indications an effluent total iron less than 1 mg/L can be achieved under optimal operating conditions (i.e., polymer dose, flocculation and clarifier loading). It is likely effluent total iron less than 1 mg/L can be readily achieved in a full scale AIS treatment system with appropriately designed polymer feed, flocculation/clarifier systems.

IRON OXIDE SOLIDS DISPOSAL/REUSE

The wet solids produced by the AIS treatment process are unique in characteristic, a result of the heterogeneous ferrous iron oxidation process. AIS treatment produces a low volume, high density material, which are 2-4% solids in recirculated/wasted flow and approximately 20-30% solids after 24 hours settling. The purity of iron oxide solids produced by AIS treatment is important for final reuse. Table FINAL-4 contains the analytical results from an AIS sample collected from the Phillips pilot study. The sample had a solids content of 21% after only 6 hours of settling. Additional settling time would increase solids content. Dry weight analysis indicates the sample is nearly all iron (54%), which reflects greater than 95% iron oxides. Calcium is the second largest metal in the sample at 1.4% and equates to a calcium carbonate content of 3.5%. Additional metal analysis indicates the sample has very low trace metal concentrations, which should not limit the disposal or reuse options for the waste solids.

Table FINAL-4: Laboratory Analysis of AIS Sample from the Phillips Pilot Study.

	Unit	Detection Limit	Result	% Content
Solids Content (Wet)	%	0.01		20.8
Dry Weight Basis				
Iron	mg/kg	1	537,500	54
Manganese	mg/kg	1	348	0.03
Aluminum	mg/kg	5	3,580	0.35
Calcium	mg/kg	1	14,200	1.4
Magnesium	mg/kg	1	400	0.04
Sodium	mg/kg	1	160	0.02
Potassium	mg/kg	1	35	<0.01
Silica	mg/kg	1	97	<0.01
Arsenic	mg/kg	1	48	<0.01
Lead	mg/kg	0.25	0.9	<0.01
Selenium	mg/kg	0.25	<0.25	<0.01
Zinc	mg/kg	1	123	0.01

Potential reuse of the AIS solids was investigated. Potential reuse of AIS treatment iron oxides include pigments, metallurgical, environmental, and use in steel production. While there is no documented use identified, there are a number potential uses of the material. The lack of reuse may simply be a result of no readily and high volume supply, because there is no existing AIS treatment system in operation.

Figure FINAL-7 shows a comparison between AIS iron oxides and a commercially available synthetic iron oxide pigment. As can be seen there is minimal differences in physical characteristics between the two samples. To explore pigment reuse further, an AIS sample was provided to LanXESS Corporation located in Pittsburgh, Pennsylvania. Results provided by LanXESS Corporation indicate the iron oxides produced by AIS treatment are unique with properties similar to pigment quality iron oxides. LanXESS Corpration indicated additional processing may be needed for the AIS treatment iron oxides to have similar quality as synthetic or natural iron oxide pigments. The AIS treatment iron oxides are likely to be an acceptable material as a pigment in the masonry industry without any additional processing.

Figure FINAL-7. Comparison of a Synthetic Iron Oxide Pigment to an AIS Treatment Produced Iron Oxide.

Environmental reuse of iron oxides for phosphate sorption in wastewater treatment has been explored by Saint Vincent College (Dr. Daryle Fish) using iron oxides produced by AIS. The results of the study indicated the iron oxides were capable of sorbing/removing phosphate from wastewater. The phosphate removal using the AIS iron oxides directly was about one-tenth the phosphate removal using a stoichiometric equivalent of commercial grade ferric chloride. However, there were no differences between a ferric chloride solution produced by AIS treatment iron oxides and commercial grade ferric chloride at removing phosphate from wastewater. This indicates a potential reuse may be to process the iron oxides into a ferric chloride or ferric sulfate solution for use in wastewater and water treatment.

AIS SYSTEM DESIGNS

The results of the pilot studies were used to develop conceptual AIS treatment systems for the five (5) AMD discharges included in the pilot study. The individual pilot study reports contain the discharge design criteria used for sizing the AIS treatment system, AIS Treatment System layouts on potential sites, and descriptions for the treatment systems.

AIS Treatment Systems – General Design Approach

Based on the pilot study results, the AIS treatment systems typically consist of: 1) Flow measurement; 2) Limestone Dosing where needed; 3) a two-stage reactor system; 4) a clarification system including a polymer feed, circular clarifiers with a flocculation zone and hopper bottoms equipped with solids collection and recirculation; and 5) a solids handling system to concentrate and store solids from the AIS treatment system. A schematic flow path of a typical AIS treatment system is depicted in Figure FINAL-8. Descriptions of the various units follow.

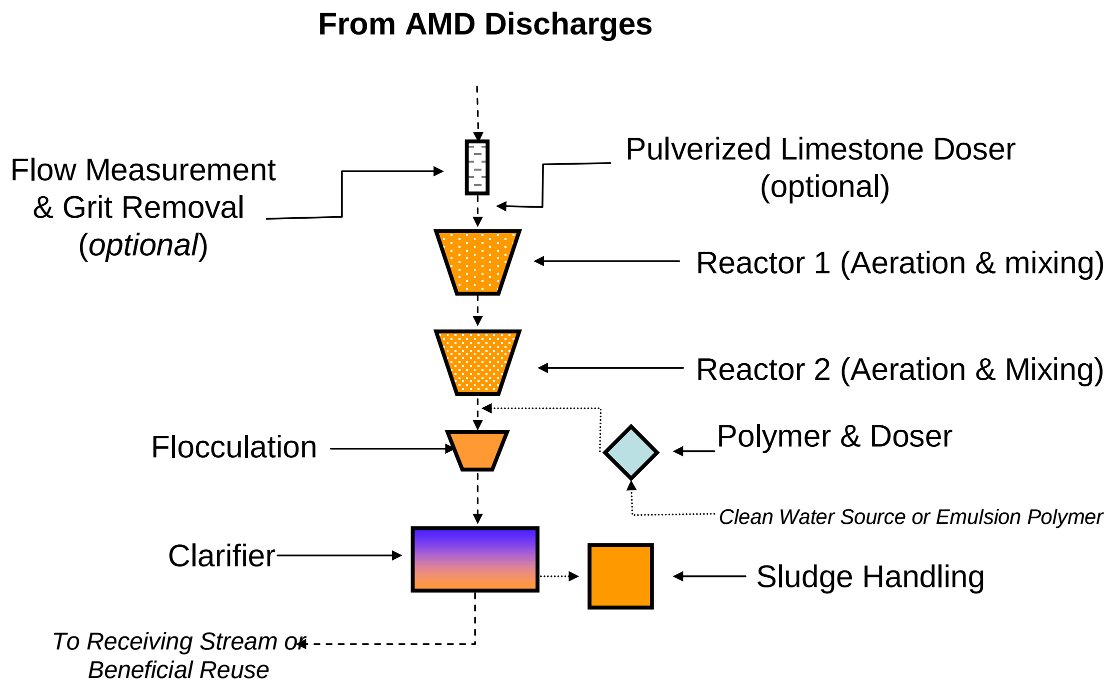

Figure FINAL-8. Typical AIS Treatment System Flow Path.

Flow Measurement & Grit Removal (optional)

Flow measurement is included in the system. The flow measurement is needed for automated process control. Process control is required to optimize reactor conditions through aeration, pulverized limestone feed, and polymer dose for flocculation, which will have cost benefits in electricity demand and chemical dose. Grit removal (optional) can be incorporated in flow measurement system prior to the reactors to collect coarse solid material that can be contained in the AMD discharge flow from erosion of materials and precipitated solids from the deep mine discharge. The flow measurement can also split the AMD flow where there are two AIS treatment system trains.

Pulverized Limestone Dosing (optional)

Pulverized limestone dosing will be included in the AIS treatment system where alkalinity to complete the oxidation of the ferrous iron as well as maintain an adequate reactor pH for rapid oxidation in the AIS process is needed. A storage silo and pulverized limestone doser (GYRO Vibratory Doser) will be placed on the inflow. The dose rate will be varied based on the measured AMD flow and the needed alkalinity.

Two-Stage Reactors

The two-stage AIS reactor system (Stage 1 and Stage 2) is sized based on the heterogeneous ferrous iron oxidation model, reactor equations, and the pilot study results. Mixing of the reactors is required to suspend the AIS. Top mounted high performance axial flow mixers are recommended. The reactors will also have aeration provided by fine or coarse bubble diffusers using positive displacement blowers. The aeration is needed to add dissolved oxygen and remove excess carbon dioxide in the AMD formed from the reaction of ferrous iron with the AIS. Aeration volume delivered can be adjusted with AMD flow.

Clarification

The clarification system will consist of a polymer dosing, flocculation and clarification. A powdered polymer was identified during the pilot study; Ciba Specialty Chemicals Magnafloc 155, an anionic acrylamide polymer. The polymer reacts with the AIS during flocculation to form large rapidly settling particles. The polymer will be dosed according to flow into the effluent from the Stage 2 Reactors or prior to the flocculation zone of the clarifier. The polymer dosed water will flow into a flocculation tank (for smaller flow system) or a flocculation zone of the clarifier (for larger flows) where high performance variable speed mixers equipped with low shear impellors will promote flocculation of the AIS. Flocculated solids will flow from the flocculation zone into hopper bottom clarifiers where the AIS (i.e., particulate iron) will be settled and collected. The collected AIS will be returned to the reactors or removed to an AIS holding tank using positive displacement cavity pumps.

Solids Handling

An AIS holding tank will receive excess solids from the clarifiers where the solids will be allowed to further thicken with additional settling time. Solids handling facility will concentrate the solids to a wet cake or paste. Solids handling will vary depending on the flow of the discharge, volume of solids produced, a final disposal/reuse of the solids. A solids handling option may consist of: 1) a holding tank with storage capacity between 10 and 15 days; 2) a decant pump to remove clarified water from the top of the solids holding tank and return it to the treatment system; 3) a jet mixer placed in the bottom of the tank to re-suspend the thickened solids to slurry; and 4) a sludge pump to remove the iron oxide slurry from the tank for transport to a disposal or processing site. Alternative solids handling may be acceptable depending on previously sated factors.

ESTIMATED AIS TREATMENT SYSTEM COSTS – CAPITAL & OPERATIONAL

AIS Treatment System capital costs will include plant headworks, silo/doser system (optional), reactor tanks, flocculation clarifiers, water piping, air lines, drop-outs, diffusers, blowers, mixers, pumps polymer makeup and dosing systems, control panels, buildings for housing the control panel, blowers and polymer units, solids handling tanks, and perimeter fence. Backup electrical generators should also be considered to prevent loss of treatment in case of power failure. Operation and maintenance (O&M) costs for the AIS treatment systems will include electricity, pulverized limestone (when used), polymer, solids handling, equipment maintenance (i.e., repairs and replacement), and operating personnel. Electricity is the highest O&M cost for AIS treatment. The second highest cost is solids handling and this cost is likely to vary depending on the final disposal or reuse of the iron oxide solids.

Table FINAL-5 provides a summary of the estimated capital and O&M costs associated for the AIS Treatment System included in the pilot study. The Blue Valley discharge location is a retrofit estimate with capital costs reflecting additional treatment system required at the Blue Valley AMD Treatment System and O&M costs reflecting the change in operational costs. Hayes Run is located in the Toby Creek watershed and is similar to the Blue Valley AMD discharge chemistry. Hayes Run was the original location for the pilot study, but the site was moved to Blue Valley in order to evaluate AIS to eliminate the high cost oxidation chemical (i.e., potassium permanganate) used at the Blue Valley AMD treatment system. Designs for the Hayes Run discharge were developed based on the Blue Valley Results and are summarized in the Blue Valley report. Individual pilot study reports contain a breakdown of the capital and O&M costs.

The treatment costs will vary depending on inclusion of the various AIS treatment system capital and operating costs. Table FINAL-6 summarizes the treatment costs per 1,000 gallons of treated water at the different pilot study locations for the various included costs and assuming average flow conditions. Table Final-6 indicates treatment costs are a function of several factors including the discharge flow, discharge flow variability (i.e., difference between design flow and average flow), and the chemistry of the discharge (i.e., net alkaline versus net acidic). The treatment costs at the Blue Valley site are negative as they reflect a change in operating costs from current treatment using potassium permanganate as an oxidant. Based on the cost analysis AIS treatment costs can be as low as $0.03 per 1000 gallons of treated water where there is beneficial reuse (or a no cost disposal option) of the iron oxide solids. When factoring all the costs of treatment (including 25-year annualized capital costs) the treatment costs remain under $0.30 per 1,000 gallons. Note the treatment costs at the Hayes Run location are higher due to the lower flow of this discharge.

Table FINAL-5. Summary of Estimated Capital, and Annual Operating and Maintenance (O&M) Costs for the AMD Discharges Evaluated in the Pilot Study.

Discharge Location	**Design Flow MGD**	**Capital Costs**	**Annual O&M Costs**		
			Total	**Non-Personnel**	**With Iron Oxide Reuse**
Upper Saxman	10.2	$3,350,000	$287,000	$247,000	$113,000
Blue Valley	0.7	$170,000	-$40,000	NA	NA
Hayes Run	0.5	$585,000	$37,500	$22,500	$11,700
Monview-Mathies	4.3	$1,760,000	$165,000	$135,000	$36,000
Phillips	9.1	$3,140,000	$270,000	$240,000	$50,000
Scotts Tunnel	14.4	$4,650,000	$372,000	$322,000	$140,000

Table FINAL-6. Summary of Estimated AIS Treatment Costs (per 1,000 gallons of treated water) for the AMD Discharges Evaluated in the Pilot Study.

Discharge Location	**Average Flow MGD**	**Treatment Costs (per 1,000 gallons)**		
		Non-Personnel O&M Solids Reuse	**Total O&M**	**Total O&M Annualized Capital Costs**
Upper Saxman	5.1	$0.061	$0.15	$0.23
Blue Valley	0.7	-$0.14	-$0.12	-$0.11
Hayes Run	0.22	$0.10	$0.47	$0.66
Monview-Mathies	2.6	$0.038	$0.17	$0.24
Phillips	5.8	$0.025	$0.13	$0.19
Scotts Tunnel	11.5	$0.033	$0.09	$0.13

SUMMARY

The AIS pilot study results, this summary report, and individual pilot study reports provide considerable information regarding the AIS treatment process. The results indicate:

- AIS treatment effectively oxidizes ferrous iron to concentrations less than 0.1 mg/L in short detention times needed to meet effluent objectives for the discharge.

- AIS treatment solids can be rapidly settled with the addition of a polymer and effluent total iron is likely to be less than 1 mg/L.
- Observed oxidation rates by the AIS solids are consistent with the heterogeneous ferrous iron oxidation model.
- AIS ferrous iron oxidation rates are not affected by polymer dosing.
- Pulverized limestone can be used as an alkalinity source to address the slightly net acidic Scotts Tunnel AMD discharge.

Based on the results of the pilot study and the heterogeneous ferrous iron oxidation model, full-scale AIS treatment system can be developed. The full-scale systems will likely provide the needed cost effective and long term treatment required for high flow AMD with chemistries containing high iron (> 10 mg/L) and net alkaline to slighty acidic. The AIS treatment may also produce iron oxide solids that are marketable and effluent water quality with beneficial use.

RECOMMENDATIONS

Based on the results of the study full-scale AIS treatment should be employed. However, due to the high costs associated with implementing a new full-scale system at a very large flow AMD discharge, an intermediate step should be undertaken. This can be installation of a new AIS treatment system at a smaller AMD flow (e.g., Colbert Breach, ~ 1 MGD, near the Scotts Tunnel discharge, or the Hayes Run discharge) or retrofitting an AIS Treatment system on an existing system (e.g., Blue Valley AMD treatment System). Either alternative would permit evaluation of AIS treatment on a full-scale and continuous operation basis without the high cost (and risk) associated with a large full-scale system. Of the discharges included in this study, the Blue Valley retrofit option would be the lowest cost to construct/install and can potentially lower future treatment costs at the treatment system.

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Activated Iron Solids Treatment Pilot Study for Blue Valley (and Hayes Run) Acidic Mine Drainage

SUMMARY REPORT

Submitted to:

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Bureau of Abandoned Mine Reclamation
Ebensburg, Pennsylvania

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INTRODUCTION

The discharge of acid mine drainage (AMD) to surface waters in Pennsylvania and other eastern coal region states contaminates thousands of miles of waterways resulting in their non-compliance with numerous Pennsylvania Water Quality Standards including, but not limited to, pH, total iron, suspended solids, and aesthetics. The AMD is a result of past (and unregulated) surface and underground coal mining that exposes pyritic minerals to atmospheric oxygen and results in the oxidation and the production of AMD.

Of particular concern is AMD produced in the vast historic and abandoned deep mine workings found throughout the coal region. The pyrite oxidizes to create AMD that collects and is stored in the mine voids forming large underground reservoirs of contaminated AMD. These large underground AMD reservoirs discharge at one or more points, typically from air portals (for recirculation of air in the mine during active operations), water portals/drains (to maintain a minimal water level in the mine during active operations), or from the mine entry. Deep mine discharges tend to be very high flow with elevated ferrous iron but may contain adequate alkalinity for iron removal. The deep mine discharges are often the largest contributor of metal loading in the watershed and/or subbasin. Treatment is mandatory to achieve water quality goals in the receiving stream.

The impact of the high flow AMD discharges on receiving streams is substantial. Input of high flow and ferrous iron AMD to surface waters causes: 1) increase of instream iron concentrations to levels exceeding water quality standards; 2) instream oxidation causes the deposition of iron oxides, known as “yellowboy”, onto stream bottoms smothering aquatic life and causing aesthetic and sediment problems; and 3) oxidation of ferrous iron can cause a decrease in pH to less than 6, a water quality standard. Theses types of impacts lead to degradation of the receiving waters to conditions that do not meet the waters designated aquatic life, recreational, and water supply uses.

Development of new and innovative treatment systems that effectively remove AMD pollutants at substantially lower capital and operating costs is paramount to the watershed restoration efforts across Pennsylvania. AIS treatment has been identified as a potential new and innovative AMD treatment approach to address high flow AMD sources and or AMD treatment where land constraints or effluent objectives dictate active treatment methods.

This report summarizes the Blue Valley AIS pilot study to evaluate the use of AIS treatment to treat AMD sources, specifically the Blue Valley and Hayes Run discharges. The Blue Valley AMD discharge is treated with an active treatment system that utilizes a costly chemical oxidant (potassium permanganate) to remove the iron and the Hayes Run AMD discharge is inadequately treated with a passive system that can not be expanded.

SITE DESCRIPTION & BACKGROUND

There are numerous high flow deep mine discharges with varying concentrations of iron, alkalinity and acidity in the Toby Creek watershed (see Table BV-1). The largest source of AMD is the Brandy Camp deep mine discharge that is currently being actively treated with a lime treatment process. Recent water quality chemistry from the Brandy Camp discharge indicates the discharge has alkalinity but contains ferrous iron concentrations resulting in a net acidic condition. Two other discharges include the Blue Valley and Hayes Run discharges, both of which have initial alkalinity and are net alkaline. The Blue Valley discharge is actively treated with potassium permanganate to oxidize the soluble ferrous iron to an insoluble ferric iron oxide. The potassium permanganate is an expensive chemical oxidant and is one of the highest cost items for the operation of the facility. The Hayes Run discharge is treated with a aerobic pond passive treatment system. This system has poor iron removal due to the AMD characteristics (low pH and temperature) and the limited space available for the passive treatment system.

The purpose of this AIS pilot study in the Toby Creek watershed was to investigate the new and innovative technology as a treatment alternative for both the Blue Valley active treatment system and the Hayes Run passive treatment system. At the Blue Valley location, the AIS treatment system could potentially be retrofitted into the existing treatment system to eliminate or minimize the potassium permanganate chemical oxidant currently being used. The Hayes Run passive treatment system would be replaced by an AIS treatment system that would fit into existing land constraints and provide a better effluent than the existing system. In addition, as the chemistry of the Brandy Camp continues to change, AIS treatment may be a potential alternative retrofit treatment approach replacing the high cost lime-based treatment.

The following provides the technical background information for the pilot study including AMD characteristics at the Blue Valley and Hayes Run discharges, background iron oxidation information, and a brief description of the AIS treatment process.

AMD Characteristics

The AMD discharge chemistry and flow data for the Blue Valley, Hayes Run, and Brandy Camp discharges are summarized in Table BV-1. The Blue Valley and Hayes Run discharges are similar in chemistry and flow; the discharges are both net alkaline with a pH of 6.2. The pH and alkalinity indicate the discharges contain elevated carbon dioxide acidity. The Hayes Run discharge has slightly higher iron concentration, but is within the similar low to moderate ferrous iron concentrations range that will allow comparison of the AIS pilot study results. The data collected at the Blue Valley site will be used to size a treatment system at Hayes Run due to the similarities in discharge chemistry.

Table BV-1: Summary of major deep mine discharges in the Toby Creek watershed.

Location	Max. Flow gpm	pH	Total Fe mg/L	Fe^{2+} mg/L	Total Al mg/L	Total Mn mg/L	Alkalinity mg/L	Calc. Acidity* mg/L	Sulfate mg/L
Blue Valley	750	6.2	14	13.5	<0.5	3.5	170	-138	600
Hayes Run	500	6.2	25	24	<0.5	7.5	125	-85	650
Brandy Camp	1,900	5.2	56	53	6.0	9.0	20	+110	850

* Calc. Acidity value determined after all iron has been oxidized and precipitated.

All the discharges contain predominately ferrous iron (Fe^{2+}), but also small amounts of ferric iron (Fe^{3+}); ferric iron is the difference between total iron and ferrous iron. Given the pH of the waters (pH>5), it is unlikely the discharge contains any dissolved ferric iron (ferric iron is not soluble above a pH of 4). The measurement of ferric iron is probably the result of sample handling and/or laboratory procedures causing entrainment of iron oxide solids into the sample or oxidation of ferrous iron to ferric iron during collection and analysis procedures. The ferrous iron concentration is important since it is the oxidation of ferrous iron that is the controlling step in iron removal from mine drainage.

Alkalinity was evaluated to determine whether there is adequate alkalinity for the removal of iron from the mine drainage. The oxidation and precipitation of 1 mg/L of ferrous iron will consume 1.8 mg/L of alkalinity. The Acidity column in Table BV-1 is the calculated acidity after all iron has been oxidized and precipitated. The negative acidity values indicate the Blue Valley and Hayes Run discharges have excess alkalinity. The positive acidity value for the Brandy Camp discharge indicates there is inadequate alkalinity to complete the oxidation of the iron and that the discharge requires additional alkalinity to complete the treatment.

Carbon dioxide (CO_2) acidity data was also calculated to determine the amount of aeration needed to remove the CO_2 in AIS treatment process and maintain or raise the pH to levels needed for the effective oxidation of ferrous iron in the AIS treatment approach. In aqueous chemistry, carbon dioxide acidity is present in water as carbonic acid (H_2CO_3). The pH of water (controlled by the carbonate system) is determined by the concentrations of bicarbonate (HCO_3^-), which is alkalinity, and H_2CO_3 according to the following relationship:

$$\text{(BV-1)} \qquad H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

The pK_a of this equilibrium is 6.4. This 6.4 would also be the pH at which the H_2CO_3 and HCO_3^- concentrations would be equal. This means an alkalinity (HCO_3^-) of 100 mg/L (as $CaCO_3$) would require an equal CO_2 acidity (H_2CO_3) of 100 mg/L (as $CaCO_3$) to have a pH of 6.4. The CO_2 acidities calculated for the Blue Valley, Hayes Run and Brandy Camp discharges are 275, 200, and 400 mg/L (as $CaCO_3$), respectively. The source of this acidity is chemical neutralization reactions in the deep mine pool as well as decomposition reactions. The CO_2 acidities are between 100 to 500 times higher than is normally found in surface waters in equilibrium with the atmosphere.

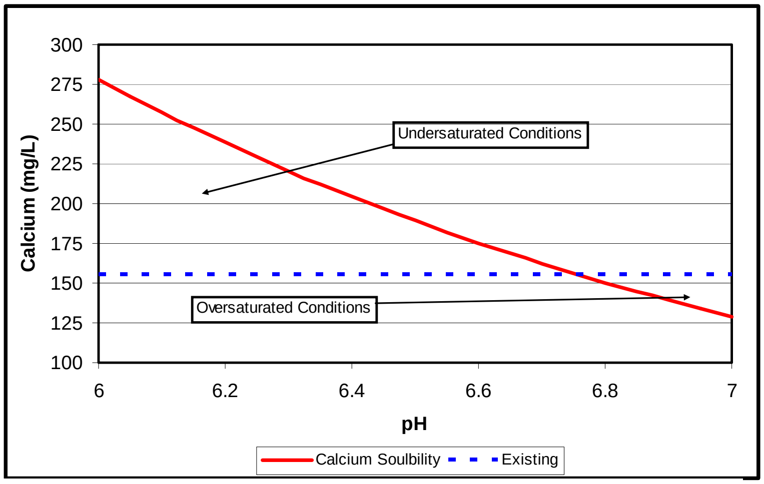


Figure BV-1. Calcium solubility in the AMD discharge with respect to pH.

The solubility of calcium and magnesium in the AMD must be evaluated for the various treatment methodologies. pH adjustments may create operation and maintenance issues by precipitating calcium and magnesium. Figure BV-1 shows the calcium (calcite) solubility with respect to pH for the Blue Valley discharge. Oversaturated conditions at the higher pH indicate calcium (calcite) will precipitate if the pH is increased. This is a potential operation and maintenance issue by creating more solids. This method of calcium precipitation is well known and used in water treatment to soften waters by adding lime (CaO) to raise the pH of water to decrease the solubility and remove calcium (calcite) hardness. At pH greater than 8, magnesium will also be removed as a hydroxide. Calcium and magnesium precipitation in lime-based treatment will increase operation and maintenance by increasing solids handling and disposal. AIS treatment oxidizes ferrous iron at acidic pH (less than 7) and prevents the additional solids volumes associated with calcium and magnesium precipitation compared to lime-based or aeration treatment approaches.

Another important parameter not listed in Table BV-1 is the temperature of the discharges. Temperature of the water is important because it affects a number of chemical and physical processes in the treatment of AMD. The temperature of the Blue Valley and Hayes Run discharges are near 10°C. This is a low temperature that will affect aeration, oxidation and settling processes. As an example, the homogeneous oxidation rate doubles for every 2°C increase in temperature. The heterogeneous oxidation process is similarly affected by temperature. The low temperature of the Blue Valley and Hayes Run discharges require additional detention time (and aeration) to achieve effective oxidation than a discharge with higher temperature. The effects of temperature may explain the poor performance of the Hayes Run passive treatment system which was sized based on a design criteria developed for southwest Pennsylvania discharges where temperatures typically range between 12 to 15°C.

This summarizes the chemistry evaluation for the discharges. As previously indicated this evaluation is an integral component in determining appropriate approaches and methods for treating the AMD. The impacts of the AMD chemistry on the various treatment approaches will be compared in a subsequent section.

Iron Oxidation & Removal in AMD Treatment

The treatment of the Blue Valley and Hayes Run AMD discharges requires iron removal and this iron removal is a multi-step process involving:

1. Oxidation of dissolved ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+});
2. Hydrolysis of ferric iron to form insoluble ferric oxide ($Fe(OH)_3$);
3. Flocculation of tiny (sub micrometer - μm) iron oxide particles to form larger (micrometer - μm) iron oxide particles;
4. Settling of suspended iron oxide particle from solution.

Depending on the type of treatment, one or more of the above processes will control the removal of iron. In passive treatment the oxidation (Step 1) of ferrous iron is very slow and determines iron removal and the size of the passive treatment system. In chemical treatment at high pH (> 8), the settling (Step 4) typically controls iron removal. The new and innovative process, AIS treatment, provides an alternative to passive treatment and chemical treatment.

The oxidation of ferrous iron is the first and most crucial step in the removal of iron. Without the oxidation step, ferrous iron would remain in solution (except at very high pH) and removal of iron from AMD would not be possible. There are two types of ferrous iron oxidation in water:

1. ***Homogeneous Ferrous Iron Oxidation (HoFIO)*** – is the long established oxidation process occurring in solution and involves the reaction of dissolved ferrous iron (Fe^{2+}) with dissolved oxygen.
2. ***Heterogeneous Ferrous Iron Oxidation (HeFIO)*** – is a newly identified oxidation process occurring on the surface of iron oxide solids and involves the sorption of ferrous iron and dissolved oxygen followed by the rapid catalytic oxidation on the surface of the iron oxide.

The first type, HoFIO is the ferrous iron oxidation that occurs in solution and is most commonly associated with passive treatment and conventional (lime-based) chemical treatment of AMD. This process is also the dominate process where aeration is used to add oxygen and raise the pH to greater than 7, a pH where HoFIO will dominate. The long established HoFIO rate equation (Sung & Morgan 1980) is:

(BV-2)

$$R(M \cdot s^{-1}) = -\frac{\partial[Fe(II)_{diss}]}{\partial t} = \frac{k_{Ho2} \times [Fe(II)_{diss}] \times [O_2]}{\{H^+\}^2}$$

The HoFIO equation is complex with the rate (R) affected by the ferrous iron concentration $[Fe(II)_{diss}]$, dissolved oxygen $[O_2]$ and pH $\{H^+\}$. Temperature is an integral part of the equation by its affects on the reaction rate constant (k_{Ho2}), with a decrease in temperature causing a decrease in the oxidation rate. The HoFIO equation is a reliable design tool because the equation can be used to predict iron removal for 1) different AMD chemistry, and 2) factors in iron removal under operating conditions (e.g., dissolved oxygen, pH and temperature). The HoFIO model will be used to evaluate ferrous iron oxidation results for the pilot study where only aeration is used in the reactors to increase dissolved oxygen and pH.

Heterogeneous ferrous iron oxidation (HeFIO) is an oxidation process that occurs on iron oxide surfaces and is the oxidation process AIS uses to oxidize ferrous iron. HeFIO is a two step processes that involves 1) the sorption of ferrous iron to the surface of the iron oxide, 2) rapid oxidation in the presence of dissolved oxygen to form new iron oxides directly on the surface of the iron oxide. Equations and models for the reactions are contained in Dietz (2003). The equations are complex describing both sorption and oxidation process.

(BV-3) HeFIO rate (mol/L-s) = $(-d[Fe(II)]/dt) = (k_{He1}[DO]S_1) + (k_{He2}[DO]S_2)$

and

(BV-4)

$$S_x = \frac{1 + ([Fe(II)_{diss}] \times K_x^{app})}{[\equiv Fe(III)] \times \Gamma_x \times \{H^+\}^x}$$

where **x** is the reaction (either 1 or 2), $\mathbf{k_{Hex}}$ are the surface oxidation rate constants, $\mathbf{K_x^{app}}$ are the surface complexation constants, and **[≡Fe(III)]** is the AIS concentration (in mg/L). Dietz (2003) determined the various thermodynamic constants for the equations including activation energies and enthalpies, which describe the effects of changing temperature. In current treatment systems (including passive treatment and lime treatment), HeFIO is not very important (< 5%) due to the low concentrations of suspended iron oxides (typically less than 5 mg/L). Iron Oxide Technologies, LLC has developed several treatment systems optimizing HeFIO through concentrated suspensions of iron oxide solids in reactor systems. Figure BV-2 shows the time required to oxidize and remove ferrous iron from AMD for various treatment methods from bench-scale testing conducted at 15°C on an anoxic AMD discharge. Note, the x-axis time scale is logarithmic. The detention time required to achieve less than 0.5 mg/L ferrous iron for the passive treatment and passive treatment with pre-aeration tests were 50 and 25 hours, respectively. Critical low-temperature conditions (Average Temp. = 8°C) would require additional detention times (2 to 5 times) to complete oxidation. As a comparison, the AIS treatment test required only 20 minutes to achieve 0.5 mg/L, which demonstrates the importance of HeFIO and the ability AIS treatment to achieve rapid oxidation and removal of ferrous iron. AIS treatment is 75 times faster in comparison to pre-aeration/passive treatment and 150 times faster in comparison to passive treatment only. A pH 8 oxidation line is also provided to show AIS ferrous iron oxidation is similar to conventional lime-based treatment: the 0.5 mg/L ferrous iron is expected to occur in 15 to 20 minutes detention time.

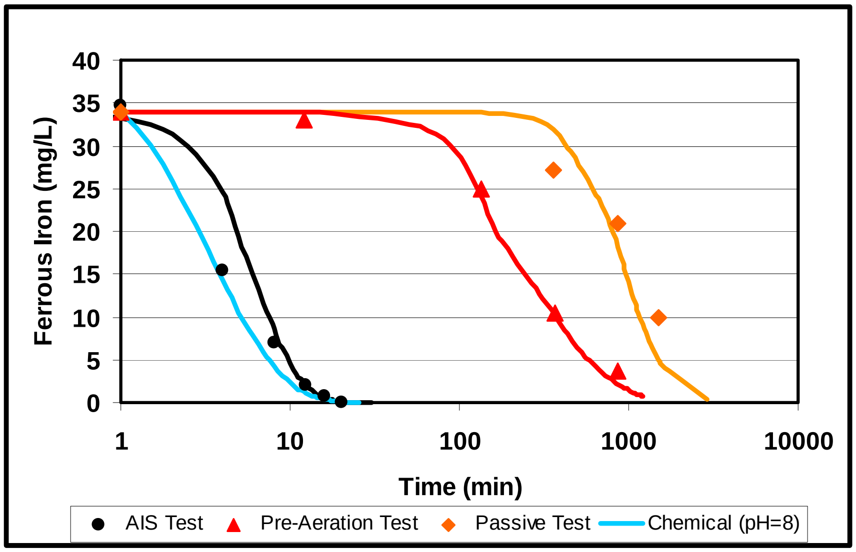


Figure BV-2. Bench-scale Results for Activated Iron Solids (AIS), Pre-aeration & Passive Tests

Innovative AIS Treatment

Iron Oxide Technologies, LLC has developed new (patent pending) active treatment approaches collectively known as Activated Iron Solids (AIS) treatment of AMD. AIS treatment has numerous advantages over conventional chemical treatment that can make long term treatment and iron oxide recovery possible at abandoned mine discharges. The AIS treatment advantages over conventional chemical treatment are:

1) Oxidation and removal occur at slightly acidic pH (6-7);
2) Oxidation rates are as fast as conventional chemical treatment;
3) For net alkaline AMD no alkaline chemicals are needed;

4) For net acidic waters, inexpensive pulverized (powder) limestone can be used for the needed alkalinity;
5) Solids produced by the AIS process are high-density (30% solids);
6) Solids are high purity iron oxides (95% iron oxides on a dry weight basis).

These advantages will have a direct effect on treatment costs by eliminating (or minimizing) chemical use and cost, and simplifying operation that will decrease manpower requirements. The innovative active AIS treatment processes utilized for the pilot study at Blue Valley is the Two-Stage AIS Reactor System (depicted in Figure BV-3). The AIS system uses high iron oxide concentrations (AIS = 1,500 – 2,500 mg/L) to increase ferrous iron oxidation and removal. The high iron oxide concentrations produce a catalytic environment that promotes ferrous iron oxidation and removal while producing high-density and pure treatment solids (iron oxide solids). The Two-Stage AIS Reactor system maintains high reactor AIS concentrations through recirculation of solids collected in the clarifier.

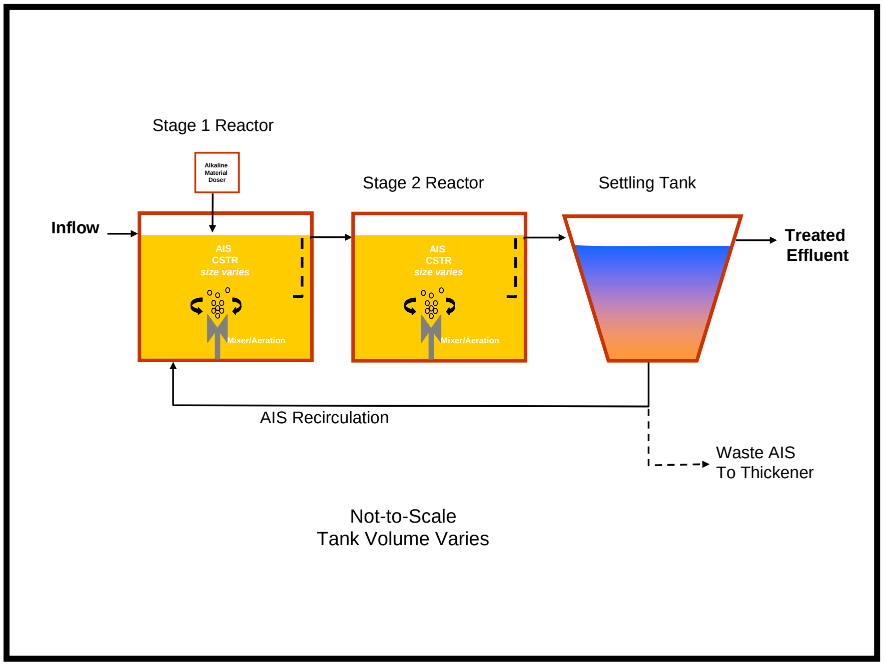


Figure BV-3. AMD Treatment in a Two-Stage Flow-Through AIS System

BLUE VALLEY PILOT STUDY

The pilot system was moved to the Blue Valley AMD treatment & Fish Culture Station in March of 2007. Due to constraints related to tours within the facility, the pilot unit set-up was delayed until April of 2007. Setup of the AIS pilot unit consisted of moving the trailer unit into the building through a delivery access bay. The trailer unit was placed in an open area inside the building between the sludge press and one of the clarifiers in the existing system. The trailer unit was leveled with wooden support pillars at this location. Single phase 230 volt electrical connections were made to the pilot unit control panel from an existing electrical panel within the building. AMD was directed to the pilot unit using a ½ horsepower submersible pump placed in the existing wet well within the building which also contains the pumps for the existing AMD treatment system within the facility. Black 2-inch PVC water line was used to convey the AMD from the wet well to the inlet weir box of the pilot system. The effluent from the pilot unit, along with overflow from the inlet weir box, was conveyed using 4 inch PVC pipe from the pilot treatment system to the overflow wet well in the Blue Valley building.

The Blue Valley pilot study was conducted between April and June 2007. The inflow pump was started on April 5 to fill the tanks and testing was initiated on April 8, 2007. Testing consisted of two phases: 1) aeration only to determine the detention time and aeration requirements to treat the AMD if aeration only was used to raise the pH and oxidize the ferrous iron: and 2) AIS treatment testing to determine the detention time and aeration requirements where AIS treatment was employed, which involves high AIS reactor iron concentrations through solids recirculation from the clarifier.

Analytical Methods

Analysis for the pilot study consisted of pH, dissolved oxygen, temperature, total iron, dissolved iron, alkalinity and periodic conductivity. pH was measured with an Fisher Scientific Accumet Portable Meter equipped with a Cole Parmer Accumet combination pH electrode; except during initial aeration testing where an Oakton pH pen was used. The pH electrode was calibrated daily prior to use with pH 4.00 and pH 7.00 buffers. Dissolved oxygen and temperature were measured with an YSI Model 550A Dissolved Oxygen Meter. The Dissolved Oxygen Meter was calibrated prior to each use using the air saturation method. Total iron was measured using a Hach Iron Pocket Colorimeter Test Kit (0-3.00 mg/L) using Ferrover reagent after appropriate dilution. Dissolved iron was also measured with the Iron Pocket Colorimeter but after filtration using a syringe and a 0.2 μm syringe filter, and appropriate dilution. Ferrous iron was determined using Hach ferrous iron powder packets and the Hach Iron Pocket Colorimeter. Initial testing on the discharge indicated dissolved iron (filtered sample) equals ferrous iron for the conditions in the Blue Valley AMD. As a result, the dissolved iron test was used to determine ferrous iron. Alkalinity was measured on a 100 mL sample using a Hach Digital Titrator, a 1.600 N sulfuric acid cartridge. Conductivity was measured with an Oakton Conductivity Pen.

Aeration Only Testing

Aeration testing at the Blue Valley AMD discharge was conducted between April 8 and May 15, 2007. The testing consisted of varying the AMD flow to the treatment system. Aeration was provided by the blower included with the pilot unit and fine bubble diffuser heads placed in the reactor tanks. Air flow was monitored and set at 23 cfm during the aeration study. AMD flow during the study was varied from a high of 25 gpm to a low of 3 gpm by adjusting the weir plates on the inlet box. The flows to the system equated to a total reactor detention time ranging between 1.6 and 23 hours. The goal of the aeration was to determine the required detention time and air flow to achieve adequate oxidation of the ferrous iron (dissolved) in the discharge to the insoluble ferric iron form. Total iron removal, or solids removal, was not a specific objective of the aeration testing.

The results of the aeration only testing are summarized in Tables BV-2 through BV-6. The raw water chemistry varied slightly during the testing with pH varying from 6.22 to 6.35. Note that initial analysis of pH was with an Oakton pH pen, which overestimated pH by 0.2 to 0.3 pH units compared to the Accumet pH meter and combination electrode. The final pH from the treatment system was dependent on the flow to the system with the lowest effluent pH (6.77) occurring at the maximum tested flow (25 gpm) and the highest effluent pH (7.47) occurring at the lowest tested flow (3 gpm). The higher 40 gpm flow test data was excluded from the pH comparison due to the aforementioned analytical measurement issue with the Oakton pH pen.

Table BV-2: Summary of analytical results from aeration only testing (Test A1) at AMD Flow = 40 gpm and Air Flow = 24 cfm.

Location	pH[1]	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
April 8, 2007						
Raw	6.36	1.86	10.0	10.4	9.8	205
React 1	6.73	9.62	10.0	10.3	9.2	206
React 2	6.94	10.65	10.1	10.2	8.8	202
Effluent	6.91	10.59	10.2	10.2	8.6	205
April 13, 2007						
Raw	6.37	1.95	10.0	11.1	10.2	207
React 1	6.75	9.6	10.1	11.0	10.0	205
React 2	6.95	10.5	10.2	10.9	9.4	202
Effluent	6.94	10.4	10.2	11.1	9.3	200

[1] pH measured with an Oakton Field pH pen

Table BV-3: Summary of analytical results from aeration only testing (Test A2) at AMD Flow = 25 gpm and Air Flow = 24 cfm.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
April 16, 2007						
Raw[1]	6.31	1.84	10.0	11.2	10.8	202
React 1[1]	6.82	10.0	10.0	11.2	10.0	--
React 2[1]	7.14	10.9	10.2	11.1	8.8	203
Effluent[1]	7.12	10.8	10.2	10.8	8.3	--
April 19, 2007						
Raw	6.22	1.80	10.2	10.8	10.4	203
React 1	6.59	10.0	10.3	10.6	9.8	204
React 2	6.76	10.9	10.2	10.5	9.0	203
Effluent	6.77	10.9	10.3	10.2	8.8	203

[1] pH measured with a Oakton Field pH pen

Table BV-4: Summary of analytical results from aeration only testing (Test A3) at AMD Flow = 15 gpm and Air Flow = 24 cfm.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
April 21, 2007						
Raw	6.29	2.05	10.0	11.4	10.6	200
React 1	6.71	10.4	10.2	10.8	9.8	--
React 2	6.88	11.0	10.3	10.6	8.0	204
Effluent	6.89	10.8	10.2	10.55	7.5	--
April 25, 2007						
Raw	6.33	1.98	10.0	11.8	11.0	198
React 1	6.74	10.3	10.2	12.4	9.8	--
React 2	6.86	10.8	10.4	12.3	8.0	--
Effluent	6.87	10.9	10.4	12.0	6.6	188

Table BV-5: Summary of analytical results from aeration only testing (Test A4) at AMD Flow = 6.5 gpm and Air Flow = 24 cfm.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
May 3, 2007						
Raw[1]	6.34	1.84	10.1	10.9	10.7	200
React 1[1]	6.85	10.8	10.7	9.9	7.10	--
React 2[1]	6.96	11.0	11.1	9.1	3.74	192
Effluent[1]	6.92	10.9	11.1	9.0	3.20	--
May 7, 2007						
Raw	6.22	2.01	10.0	11.2	10.9	205
React 1	6.89	10.9	10.8	10.1	6.25	--
React 2	7.02	11.0	11.2	9.4	2.70	192
Effluent	7.03	11.0	11.1	8.5	2.09	--

Table BV-6: Summary of analytical results from aeration only testing (Test A5) at AMD Flow = 3 gpm and Air Flow = 24 cfm.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
May 11, 2007						
Raw	6.35	1.85	10.0	10.3	10.3	209
React 1	7.16	10.7	11.5	8.70	3.45	196
React 2	7.44	10.8	12.1	8.85	0.63	189
Effluent	7.47	10.5	12.0	5.85	0.28	187

Dissolved iron also decreased as a function of detention time in the aeration tanks as a result of oxidation of soluble ferrous iron to insoluble ferric iron. The affects of detention time on dissolved iron concentration (i.e., iron oxidation) is shown in Figure BV-4. The figure shows the effluent dissolved iron concentration decreases non-linearly as the detention time increases. This is an affect of: 1) the length of time the AMD is in the reactor to permit oxidation; and 2) the increase in pH from removal of carbon dioxide acidity through aeration. The pH affect is also related to the detention time in the reactor allowing greater removal of the carbon dioxide acidity. The non-linear relationship in the decrease of dissolved iron with detention time is related to the first-order kinetics of the ferrous iron oxidation. The decrease in alkalinity is also shown which is related to the consumption of alkalinity during the precipitation of the ferric iron, produced from the oxidation of ferrous iron, to insoluble ferric iron hydroxide.

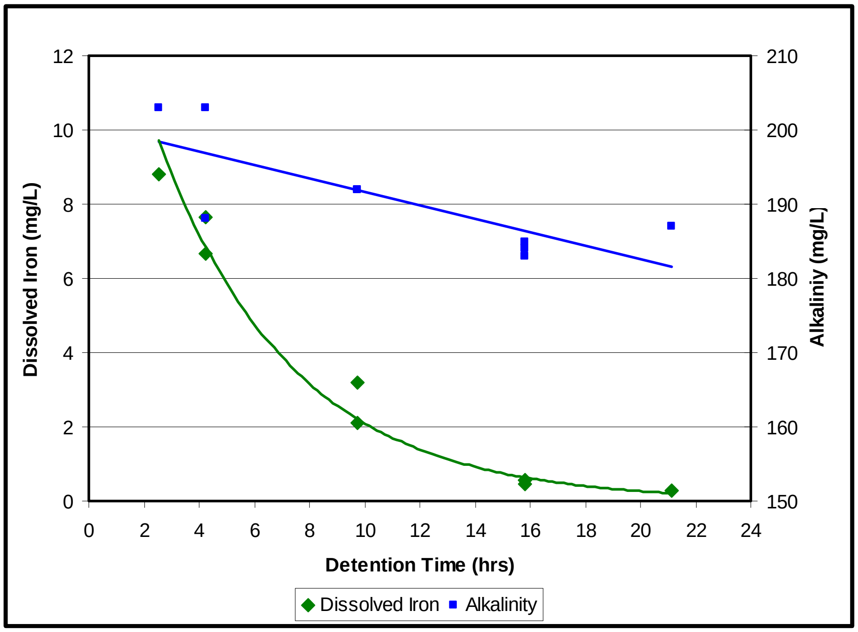


Figure BV-4. Blue Valley Aeration Testing Results; Effluent Dissolved Iron and Alkalinity.

The final evaluation using the aeration only data was to compare the measured dissolved iron to predictions using the homogeneous iron oxidation model and reactor equations. An accurate model will be needed to size an aeration only system. The sampling and analysis conducted in each reactor are summarized in Table BV-7. The calculated dissolved iron concentration for the reactor conditions is also provided in Table BV-7 along with the difference between the measured and calculated dissolved iron values. There was only one value from Reactor 1 where the measured and calculated values differed by more than 1 mg/L. This value may be due to partial mixing at the sampling point in Reactor 1. Overall, the difference between the calculated and measured values averaged less than 0.4 mg/L; removal of the high values decreases the average difference to approximately 0.2 mg/L. This indicates the homogeneous iron oxidation model and the reactor equations can be used to estimate the aeration system size.

Table BV-7: Summary of Iron Oxidation Data From Each Reactor During Aeration Studies Only at Blue Valley and Comparison to the Calculated Dissolved Iron Using the Homogeneous Iron Oxidation Model.

Test	Reactor	Detention Time hrs	pH	Dissolved Oxygen mg/L	Temp. °C	Meas. Diss. Fe mg/L	Calc. Diss. Fe mg/L	Difference Diss. Fe (Meas-Calc)
A2	1	1.27	6.59	10	10.3	9.8	10.2	-0.4
A2	2	1.27	6.76	10.9	10.2	9	9.1	-0.1
A3	1	2.11	6.74	10.3	10.2	9.75	9.9	-0.15
A3	2	2.11	6.86	10.8	10.4	8	8	0
A3	1	2.11	6.7	10.6	10.2	9.2	9.9	-0.7
A3	2	2.11	6.85	11.1	10.4	7.75	7.6	0.15
A4	1	4.87	6.85	10.8	10.7	7.1	6.95	0.15
A4	2	4.87	6.96	11	11.1	3.74	3.45	0.29
A4	1	4.87	6.89	10.9	10.8	6.25	6.55	-0.3
A4	2	4.87	7.02	11	11.2	2.7	2.55	0.15
A5	1	10.56	7.16	10.7	11.5	3.45	1.4	2.05
A5	2	10.56	7.44	10.75	12.1	0.63	0.12	0.51

Based on the model, aeration alone would require approximately 32 hours detention time to decrease dissolved iron to less than 0.1 mg/L. This would require a 1 million gallon aeration tank receiving approximately 4,000 cfm of air. This size aeration system is impractical and no further consideration is warranted.

AIS Pilot Testing

The AIS initial test settings were similar to the current operating conditions at the existing Blue Valley treatment system including polymer type, polymer dose, and AIS concentration. In the case of the AIS concentration, the target was an equal concentration of total iron (or suspended) solids in the reactor using recirculation. This approach was taken to determine the required size of an AIS reactor system to be place before the existing Blue Valley system and using equipment in the existing system including polymer dosing and solids recirculation. An AIS retrofit could then be recommended with minimal modifications to the existing system (e.g., extension of solids recirculation lines from the existing clarifiers and intake AMD piping to the new AIS reactor). In addition, effective demonstration of the AIS process to remove dissolved iron at the Blue Valley site would permit design of a new system for the Hayes Run discharge.

The initial startup conditions for the pilot unit were:

1. Reactor 1 & 2 AIS = 1,500 mg/L (as Fe)
2. Air Flow = 8 cfm – air flow was varied during testing
3. AMD Inflow = 30 gpm
4. AIS Recirculation Rate = 10 gpm
5. Initial Polymer Dose Rate = 55 mL/min (0.5 mg/L of inflow) - *polymer dose was increased during test*

To start the pilot system, AIS solids were added to the pilot unit using solids pumped directly from the existing clarifiers in the Blue Valley system. This was done to test the existing solids to determine if the solids will convert to AIS solids and provide necessary catalytic oxidation. Preliminary bench-scale testing indicated the solids in the clarifiers would convert to AIS solids and provide the needed oxidation of the ferrous iron in the Blue Valley discharge. The use of the solids would simplify start-up by minimizing start-up time to accumulate AIS solids for the reactor system (hours versus months). Air flow was based on the aeration only pilot study results and was set to maintain a dissolved oxygen concentration and pH in the reactors. The AMD inflow was set based on calculated oxidation rates using the heterogeneous iron oxidation model. The 30 gpm flow results in 65 minutes (1.1 hours) detention time in each reactor and a total system detention time (including the clarifier) of 160 minutes (2.7 hours). The AIS recirculation rate was set at a flow rate to maintain the reactor AIS concentrations based on expected solids in the recirculated flow and the AMD inflow rate. The polymer used for the test was the Applied Specialties, Inc. AS-1930, a high molecular weight medium charge anionic acrylamide copolymer. This is the polymer currently used at the Blue Valley treatment system.

The AIS pilot system was started using the above settings on June 18th at 7:30 PM. The pilot unit was operated until June 25th with slight adjustments to vary air flow, solids recirculation rates and polymer dose. The results from various sampling dates (and times) along with operating conditions are contained in Tables BV-8 through BV-11.

The AIS pilot study results indicate the AIS system oxidized the soluble ferrous iron in the Blue Valley discharge to particulate ferric iron. The dissolved iron decreased from an influent concentration of 13 mg/L to less than 0.3 mg/L. Results from the 16 cfm air flow test (shown in Table BV-9 – Test AIS2) produced effluent with dissolved iron less than 0.05 mg/L. This demonstrates the AIS process can achieve the same effective oxidation and ferrous iron removal as the current potassium permanganate chemical treatment employed at the Blue Valley system and will accomplish similar oxidation at the Hayes Run discharge. As shown in the tables, air flow is an important factor in the oxidation process. Based on the results and the heterogeneous model, the air flow increases the oxidation rate through carbonic acid removal which increases pH. The air flow increase from 8 to 16 cfm increases the dissolved oxygen concentration by 1.4 mg/L which with only contributes to a 15% increase in the heterogeneous oxidation rate. In comparison, the same increase in air flow causes a pH increase of 0.3 associated which more than triples (300%) the heterogeneous oxidation rate and is the primary cause of the effluent dissolved iron decrease from 0.6 mg/L to less than 0.05 mg/L.

Table BV-8: Summary of analytical results from AIS pilot testing (Test AIS1) at AMD Flow = 30 gpm and Air Flow = 8 cfm and polymer dose 60 mL/min started on June 18, 2007 at 7:00 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L
11:00 PM on June 18, 2007					
Raw	6.32	1.80	9.9	13.6	13.1
React 1	6.56	7.35	10.5	1,524	2.54
React 2	6.66	8.95	11.0	1,500	0.46
AIS Recirc	--	--	--	7,200	--
4:30 AM on June 19, 2007					
React 1	6.52	7.92	10.2	1,644	4.24
React 2	6.62	8.88	10.4	1,728	0.54
8:30 AM on June 19, 2007					
React 1	6.52	7.30	10.2	1,698	2.24
React 2	6.60	8.83	10.3	1,776	0.75
AIS Recirc	--	--	--	6,240	--
Clarifier	--	--	--	3.65	0.60
1:30 PM on June 19, 2007					
React 1	6.51	7.40	10.2	1,800	2.64
React 2	6.62	8.95	10.4	1,890	0.71
Clarifier	--	--	--	4.00	0.55

Table BV-9: Summary of analytical results from AIS pilot testing (Test AIS2) at AMD Flow = 30 gpm and Air Flow = 16 cfm and polymer dose 65 mL/min started on June 19, 2007 at 2:00 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L
11:00 AM on June 20, 2007					
Raw	6.29	1.75	9.9	13.8	13.2
React 1	6.71	8.79	10.2	2,120	1.00
React 2	6.89	10.35	10.4	1,968	0.07
AIS Recirc	--	--	--	7,840	--
1:30 PM on June 20, 2007					
React 1	6.68	8.80	10.2	1,984	1.01
React 2	6.88	10.30	10.4	2,010	0.04
3:30 PM on June 20, 2007					
React 1	6.71	8.80	10.2	1,960	1.04
React 2	6.91	10.30	10.4	2,000	0.04
AIS Recirc	--	--	--	8,240	--
Clarifier	--	--	--	5.40	0.02

Table BV-10: Summary of analytical results from AIS pilot testing (Test AIS3) at AMD Flow = 30 gpm and Air Flow = 12 cfm and polymer dose 90 mL/min started on June 20, 2007 at 4:30 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L
12:30 PM on June 21, 2007					
Raw	6.35	1.65	9.9	15.4	13.1
React 1	6.60	8.08	10.2	2,070	1.58
React 2	6.71	10.00	10.3	2,120	0.09
AIS Recirc	--	--	--	8,640	--
3:30 PM on June 21, 2007					
React 1	6.62	8.10	10.2	2,170	1.53
React 2	6.72	10.03	10.3	2,180	0.11
Clarifier	--	--	--	5.80	0.07

Table BV-11: Summary of analytical results from AIS pilot testing (Test AIS4) at AMD Flow = 30 gpm and Air Flow = 8 cfm in Reactor 1 only and polymer dose 90 mL/min started on June 21, 2007 at 4:00 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L
9:00 AM on June 22, 2007					
Raw	6.30	1.68	9.9	33.0	13.0
React 1	6.51	7.00	10.1	2,140	2.50
React 2	6.58	8.60	10.2	2,310	0.32
AIS Recirc	--	--	--	10,720	--
Clarifier	--	--	--	5.45	0.29
2:30 PM on June 22, 2007					
React 1	6.58	6.90	10.2	2,350	1.31
React 2	6.47	8.66	10.4	2,600	0.20
Clarifier	6.45	--	--	5.80	0.27

Clarification was not the primary objective of the study. Due to constraints in the design of the system to maintain portability, the trailer system included a compact upflow clarifier. The primary objective of the clarifier was to retain AIS solids for recirculation to the reactors in order to maintain high concentrations of AIS in the reactors for oxidation of ferrous iron. This primary objective was achieved based on maintenance of AIS concentration between 1,500 and 2,500 mg/L through the duration of the AIS pilot study. Effluent monitoring from the clarifier indicated effluent total iron (average = 5 mg/L) was less than influent total iron (average = 14.3 mg/L) which also indicates AIS solids were retained and accumulated in the system.

Particulate iron ranged from 3.0 to 5.8 mg/L in the effluent from the upflow clarifier. The effluent iron concentration was at a hydraulic loading of 1,550 gallons per day per square foot. This is nearly twice the recommended hydraulic loading (800 gpd/ft^2) by the manufacturer (Purestream, Inc.) for the AIS pilot study upflow clarifier. The pilot unit also does not include a flocculation reactor prior to the clarifier as is present in the Blue Valley treatment system. Based on bench testing conducted with the Applied Specialties polymer, longer flocculation time is needed to produce rapidly settling particles that would have lowered effluent total iron from the pilot system clarifier. In addition, a yellowing was observed in the effluent from the system which may be an affect of the polymer used (and possible overdosing) during the testing. Personal communications with a representative of Ciba Specialty Chemicals indicated some polymer formulations can produce a yellowing related to particulate stabilization during polymer overdose. This may have contributed to the observed yellowing as well as the higher effluent total iron during the pilot study. Although similar polymer dose concentrations were used during the pilot study as the current Blue Valley treatment system, operational conditions in the pilot study resulted in slightly higher pH, 6.6 to 6.9 in the pilot unit versus 6.4 to 6.5 in the existing Blue Valley treatment system. This higher pH could result in different polymer requirements in both dose and polymer type (i.e., low charge versus medium charge and/or medium versus high molecular weight). Pilot studies at other AMD discharge locations indicated Magnafloc 155 (Ciba Specialty Chemicals), a medium molecular weight low charge acrylamide polymer produced effective flocculation of the AIS without causing any yellowing. Additional polymer testing after installation of the retrofit AIS reactor would be recommended to identify the appropriate polymer and dose.

Ferrous Oxidation Kinetic Evaluation

The results of the AIS pilot study were also used to evaluate: 1) the validity of the heterogeneous ferrous iron oxidation model for the sizing of reactor systems; 2) the effects of the polymer on the AIS solids and implications with respect to oxidation rates; and 3) the AIS solids used from the Blue Valley treatment system on the ferrous iron oxidation rates. The heterogeneous ferrous iron oxidation model was used to predict the oxidation rate (*pseudo*-first order) and the ferrous iron concentration in the reactor using complete mix reactor equations. The results of the comparison are summarized in Table BV-12.

Based on the measured versus modeled ferrous iron comparisons in Table BV-12, the model predicts both the oxidation rate and the reactor ferrous iron concentration (remaining after oxidation). The differences ranged from 0.02 to 1.54 mg/L with an average difference of 0.21 mg/L. The 1.54 mg/L appears to be an outlier and removal of this value decreases the range from 0.02 to 0.39 mg/L with an average difference of less than 0.15 mg/L. This indicates the observed oxidation rates during the pilot study are consistent with the model predictions. This also indicates the polymer has negligible impact on the catalytic process and that the Blue Valley iron oxide solids readily convert to AIS. Validation of the model permits use of the heterogeneous ferrous iron oxidation model to determine the adequate size of a retrofit AIS reactor to oxidize ferrous iron for the Blue Valley treatment system and a new and complete AIS system to treat the Hayes Run AMD discharge. The preliminary/conceptual designs of the two systems are summarized in the following sections.

Table BV-12: Summary of Iron Oxidation Data From Each Reactor During AIS Studies at Blue Valley and Comparison to Calculated Dissolved Iron Using the Heterogeneous Iron Oxidation Model (Detention Time for each reactor = 1.05 hrs).

Test	Reactor	pH	Dissolved Oxygen Mg/L	Temp. °C	AIS mg/L	Meas. Diss. Fe mg/L	Calc. Diss. Fe mg/L	Difference Diss. Fe (Meas-Calc)
AIS1	1	6.52	7.92	10.2	1,644	4.24	2.70	1.54
AIS1	2	6.62	8.88	10.4	1,728	0.54	0.52	0.02
AIS1	1	6.52	7.30	10.2	1,698	2.24	2.63	-0.39
AIS1	2	6.6	8.83	10.3	1,776	0.75	0.55	0.2
AIS1	1	6.51	7.40	10.2	1,800	2.64	2.60	0.04
AIS1	2	6.62	8.95	10.4	1,890	0.71	0.48	0.23
AIS2	1	6.71	8.79	10.2	2,120	1.00	1.08	-0.08
AIS2	2	6.89	10.35	10.4	1,968	0.07	0.063	0.007
AIS2	1	6.68	8.80	10.2	1,984	1.01	1.30	-0.29
AIS2	2	6.88	10.30	10.4	2,010	0.04	0.077	-0.037
AIS2	1	6.71	8.80	10.2	1,960	1.04	1.16	-0.12
AIS2	2	6.91	10.30	10.4	2,000	0.04	0.06	-0.02
AIS3	1	6.6	8.08	10.2	2,070	1.58	1.45	0.13
AIS3	2	6.71	10.00	10.3	2,120	0.09	0.082	0.008
AIS3	1	6.62	8.10	10.2	2,170	1.53	1.28	0.25
AIS3	2	6.72	10.03	10.3	2,180	0.11	0.068	0.042
AIS4	1	6.51	7.00	10.1	2,140	2.50	2.35	0.15
AIS4	2	6.58	8.60	10.2	2,310	0.32	0.25	0.07
AIS4	1	6.58	6.90	10.2	2,350	1.31	1.70	-0.39
AIS4	2	6.47	8.66	10.4	2,600	0.2	0.16	0.04

IRON OXIDE SOLIDS DISPOSAL/REUSE

The wet solids produced by the treatment process are important representing the labor needed to handle and process solids and the volume of solids requiring disposal. AIS treatment produces a low volume of solids because the solids density is approximately 20-30% for 24 hour settled AIS. The purity of iron oxide solids produced by AIS treatment may be important for final reuse. Table BV-13 contains the analytical results from an AIS sample collected during the pilot studies. The sample had a solids content of 21% after only 6 hours of settling. Additional settling time would increase solids content. The analytical results the sample is nearly all iron (54%), which reflects greater than 95% iron oxides. Calcium is the second largest metal in the sample at 1.4%, which equates to a calcium carbonate content of 3.5%. Trace metal analysis indicates the sample has very low trace metal concentrations, which should not limit the disposal or reuse options for the waste solids.

Table BV-13: Laboratory Analysis of AIS Sample from the Pilot Study.

	Unit	**Detection Limit**	**Result**	**% Content**
Solids Content (Wet)	%	0.01		20.8
Dry Weight Basis				
Iron	Mg/kg	1	537,500	54
Manganese	Mg/kg	1	348	0.03
Aluminum	Mg/kg	5	3,580	0.35
Calcium	mg/kg	1	14,200	1.4
Magnesium	mg/kg	1	400	0.04
Sodium	mg/kg	1	160	0.02
Potassium	mg/kg	1	35	<0.01
Silica	mg/kg	1	97	<0.01
Arsenic	mg/kg	1	48	<0.01
Lead	mg/kg	0.25	0.9	<0.01
Selenium	mg/kg	0.25	<0.25	<0.01
Zinc	mg/kg	1	123	0.01

AIS SYSTEM DESIGNS

The results of the pilot study will be used to develop two designs: 1) an AIS reactor system to retrofit with the existing Blue Valley AMD treatment system to eliminate the use of potassium permanganate as a chemical oxidant; and 2) a new AIS treatment system to replace the existing passive treatment system at the Hayes Run AMD discharge. The following sections will provide treatment system designs, estimated capital and installation costs, and operating costs for the treatment systems. Due to uncertainties in operation, operational labor will only include a weekly time commitment for normal operation.

Blue Valley Retrofit

The existing Blue Valley AMD treatment system produces a high quality effluent, but requires use of potassium permanganate to oxidize ferrous iron into particulate ferric iron oxide. The potassium permanganate annual costs range between $20,000 and $60,000 depending on the treated flow volume and solids recirculation. The AIS treatment process does not require the use of potassium permanganate which could substantially lower the costs of treating the Blue Valley AMD discharge.

Conversion of the existing Blue Valley treatment system to an AIS treatment system will require installation of a two-stage reactor tank system prior to the existing system. The reactor system will contain aeration and mixers to control the pH and maintain the AIS in suspension. Solids recirculation lines will be added to return AIS solids from the existing clarifiers to the new reactor system. The existing solids pumps will be evaluated to determine whether there is adequate pumping capacity to return and maintain AIS to the reactor system. Greater capacity replacement solids pumps may be needed to operate the new AIS reactor system. The influent AMD line will also be extended to the proposed reactor system to deliver AMD from the wet well.

The location for the proposed AIS reactor system is the vacant room adjacent to the existing treatment system. A two-stage AIS reactor tank with 30,000 gallons can be installed in this available area. The reactor tank system would have the dimensions of 12 feet height, 12 feet width, and 32 feet length with a water level in the tank of 11 feet. This water depth was chosen to allow the effluent from the AIS reactor system to flow by gravity to the remaining Blue Valley treatment system without significant modification; i.e., re-routing of piping only. This reactor tank will fit in the available area and allow access to the tank for routine maintenance.

Side view and cross-section view of the proposed AIS Reactor tank are depicted in Figure BV-5. The new AIS Reactor will be equipped with aeration and mixers. The aeration system will consist of a blower to deliver air, air lines to deliver air from the blower to the tank, and fine bubble diffusers to deliver the air to the AIS reactor tank. The aeration requirement is between 80 and 180 cfm depending on the treated flow (250 to 500 gpm). This air flow is adequate to deliver near saturation of dissolved oxygen (10.4 mg/L) and raise the pH to 6.8 by removal of carbon dioxide acidity in the raw water and produced by the oxidation and precipitation of the ferrous iron. Mixers will be included in the reactors to maintain the AIS in suspension and provide adequate blending of the AMD with the AIS. The mixers will be top mounted with submerged impellors, similar to the mixer used in the flocculation tank but with higher rate pumping impellors to enhance mixing and blending. Figure BV-6 shows the plan view of the proposed retrofit AIS Reactor Tank location and tentative piping locations for inflow of AMD, outflow to existing Blue Valley system, AIS return lines to the reactor system, and the aeration blowers.

The retrofit AIS Reactor Tank ferrous iron oxidation was evaluated based on the detention time of the tank (and the existing Blue Valley treatments system), the heterogeneous ferrous iron oxidation model, and the results of the pilot study. Based on this information the retrofit AIS Reactor Tank is expected to produce an effluent ferrous iron of less than 0.05 mg/L at a flow of 250 gpm and less than 0.20 mg/L at flows of 500 gpm. It is recommended to maintain the potassium permanganate system as a back up as well as a polishing oxidant for AMD treated flows near or in excess of 500 gpm. The estimated potassium permanganate use under these conditions is expected to be less than $50 per month.

The operating costs for the retrofit AIS reactor will be limited to additional electrical costs to operate the proposed blower and mixers. No additional increases in operating costs to the Blue Valley system are anticipated. Decreases in operational costs at the Blue Valley treatment system will be from the elimination/minimization of potassium permanganate usage and modest decreases in sludge volume (due to reduced sludge volume associated with manganese precipitates from potassium permanganate). There may also be benefits associated with the value of the wasted AIS solids (iron oxides) as pigments.

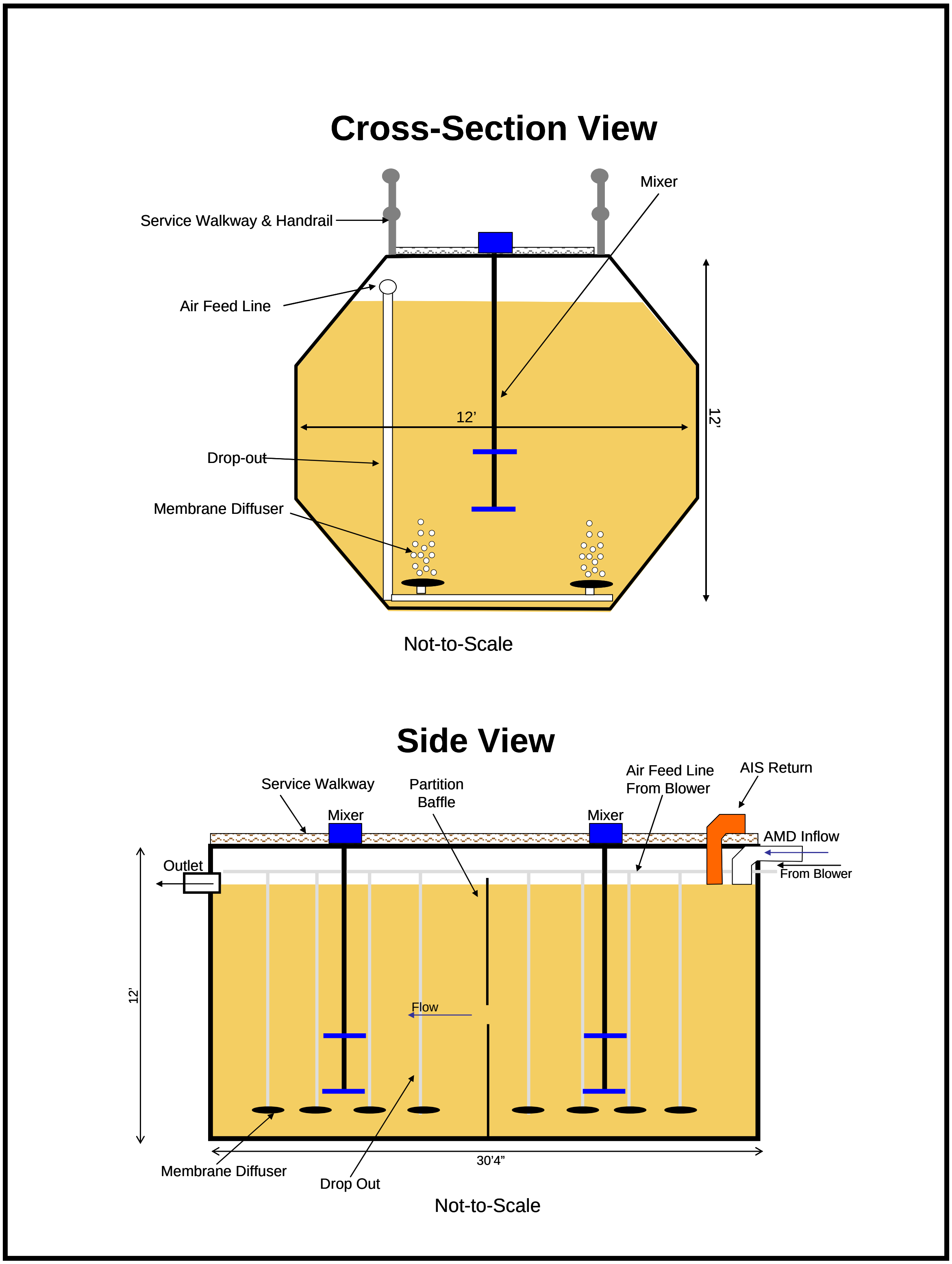
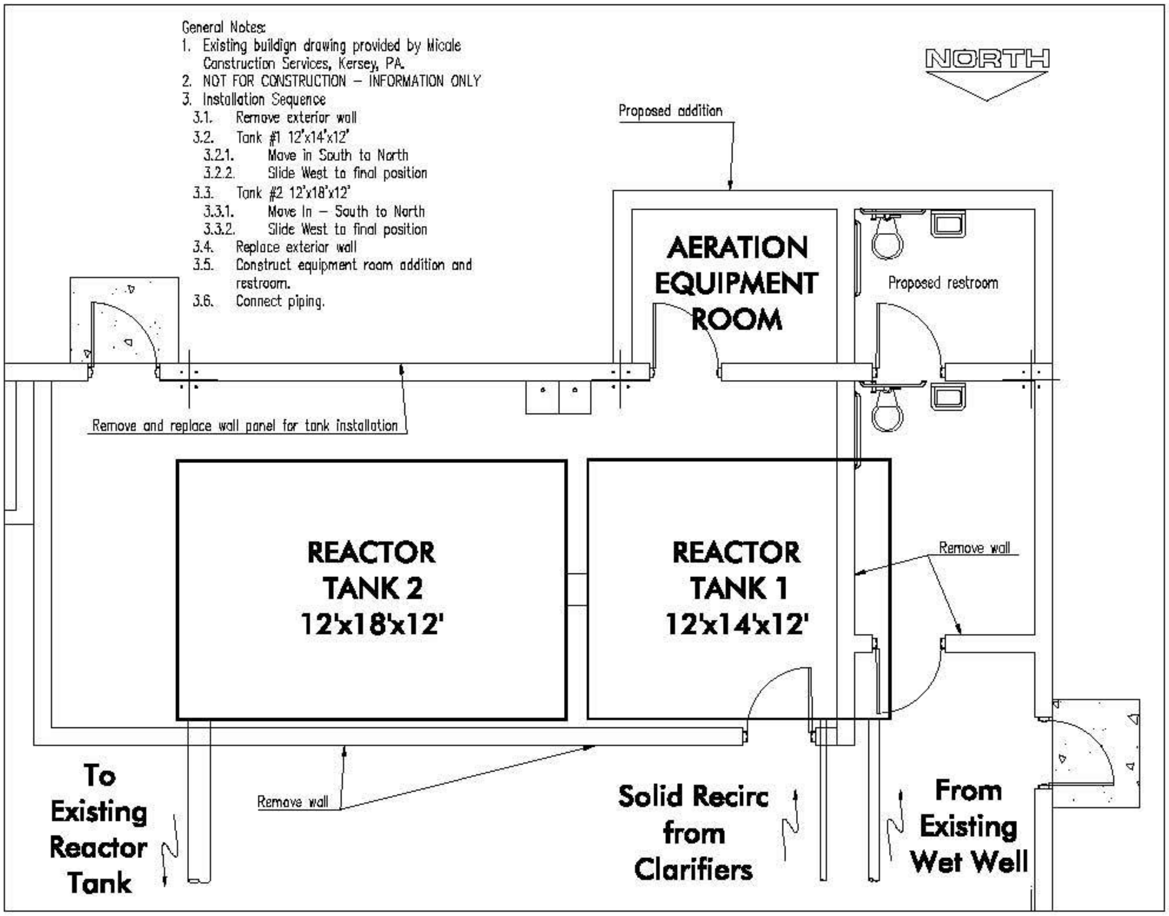


Figure BV-5. Cross-section and side view of the retrofit AIS Reactor for the Blue Valley system.



General Notes:

1. Existing buildign drawing provided by Micale Construction Services, Kersey, PA.
2. NOT FOR CONSTRUCTION – INFORMATION ONLY
3. Installation Sequence
   - 3.1. Remove exterior wall
   - 3.2. Tank #1 12'x14'x12'
     - 3.2.1. Move in South to North
     - 3.2.2. Slide West to final position
   - 3.3. Tank #2 12'x18'x12'
     - 3.3.1. Move In – South to North
     - 3.3.2. Slide West to final position
   - 3.4. Replace exterior wall
   - 3.5. Construct equipment room addition and restroom.
   - 3.6. Connect piping.

Figure BV-6. Blue Valley Treatment System Retrofit

Hayes Run AIS Treatment System

Based on the pilot study results, the AIS treatment system for the Hayes Run AMD discharge will consist of: 1) a two-stage reactor system; 2) a clarification system including a polymer feed, flocculation tank, and horizontal flow hopper clarifiers; and 3) a solids handling system to concentrate and store solids from the AIS treatment system. Table BV-14 summarizes the design information and influent water quality. A schematic flow path of the AIS treatment system is depicted in Figure BV-7. Figure BV-8 shows a conceptual AIS treatment system layout at the existing Hayes Run AMD discharge site.

Table BV-14: Summary of design information for the Hayes Run AMD discharge AIS treatment system.

Estimated Flow (gpm)		**Influent Water Quality**			
Average	**Maximum**	**pH**	**Total Al mg/L**	**Ferrous Fe mg/L**	**Alkalinity mg/L**
150	350	6.2	<0.5	28	125

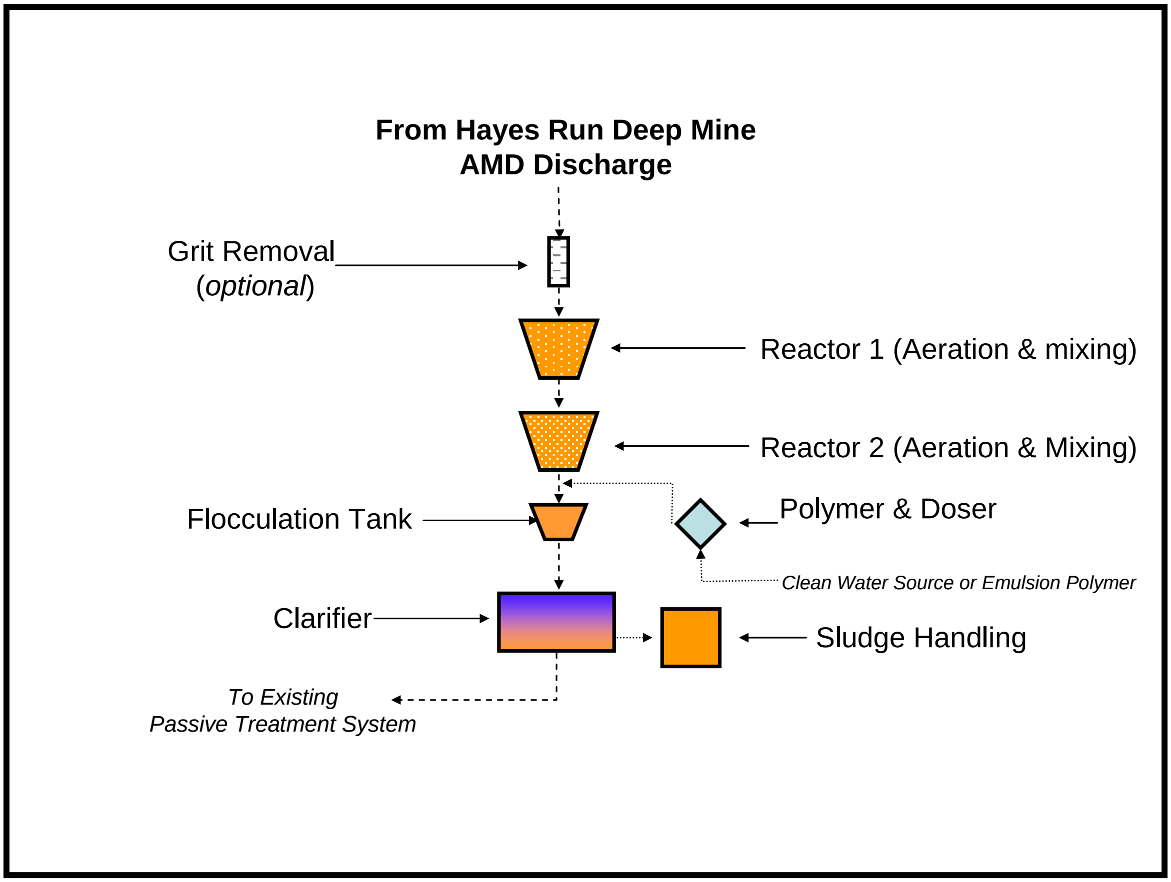


Figure BV-7. Hayes Run AMD Discharge Treatment System Flow Path

Figure BV-8. Hayes Run Conceptual AIS Treatment System Layout

The design criteria and effluent water quality for the Hayers Run AIS treatment system were determined based on the heterogeneous ferrous iron oxidation model kinetic rates and results of the AIS pilot study. Table BV-15 summarizes the design criteria for the Hayes Run AMD AIS treatment system and the anticipated effluent water quality. The expected performance of the Hayes Run AIS treatment system is near complete removal under average flow conditions (> 98% iron removal) and maximum flow conditions (> 95% iron removal). This effluent quality should eliminate the impacts of the Hayes Run AMD discharge on the receiving water. In addition, the effluent quality from the system should permit use of the existing passive treatment pond for recreational fishing and/or fish culture.

Table BV-15: Summary of design information and anticipated effluent water quality of the Hayes Run AIS treatment system.

Condition	Flow gpm	Reactor 1 DT Hrs	Reactor 2 DT hrs	Clarifier ft/d	Anticipated Effluent Quality pH	 Total Fe mg/L	 Alkalinity mg/L
Average	150	1.5	1.5	35	6.8	<0.5	75
Maximum	350	0.7	0.7	80	6.6	<1.0	75

Flow Measurement & Grit Removal

Flow measurement will be included in the design of the system. This flow will be used in the control panel for automated process control. Process control is required to optimize reactor conditions through aeration and polymer dose for flocculation. Both controls will have cost benefits in electricity demand and chemical dose. Grit removal will be incorporated in flow measurement system prior to the reactors to collect solid material that is likely contained in the discharge flow. The coarse material to be removed is from erosion of materials from the deep mine and precipitated solids from the AMD in the collection pipes.

Reactors

The two-stage AIS reactor system follows the flow measurement. The AIS reactors are sized based on the heterogeneous ferrous iron oxidation model, reactor equations, and the pilot study results. The Stage 1 Reactor will contain 90 minutes (1.5 hours) of detention time at average and 40 minutes (0.7 hours) of detention time at maximum flow, the design flow. The reactors will contain top mounted high performance axial flow mixers to suspend the AIS. The reactors will also have aeration provided by fine bubble diffusers using positive displacement blowers. The aeration is needed to remove excess carbon dioxide in the Hayes Run AMD and formed from the reaction of ferrous iron with the AIS. Aeration volume delivered will be based on AMD flow in order to maintain the pH and dissolved oxygen required for the AIS process.

Clarification

The clarification system will consist of a polymer dosing system, flocculation tank and hopper bottom clarifiers. A polymer was identified during the pilot study. The polymer reacts with the AIS during flocculation to form large rapidly settling particles. The powder polymer identified is a medium molecular weight, low charge anionic acrylamide polymer (Magnafloc 155, Ciba Specialty Chemicals). However, due to the variable AMD flow, low dose of the polymer, and lack of clean water supply, an oil emulsion polymer with an extended shelf life should be considered for use in the clarification system. A polymer should be identified during the design phase of the Hayes Run AIS treatment system. The polymer will be dosed at the outlet of the Stage 2 Reactor. The polymer dosed water will flow into a flocculation tank with a detention time of 30 minutes at average flow and 10 minutes at maximum flow. A top mounted high performance variable speed mixer equipped with a radial flow impeller to promote flocculation and minimize shear will mix the flocculation tank. Flocculated solids will flow from the flocculation tank into horizontal flow hopper bottom clarifiers. The hoppers will contain positive displacement cavity pumps to recirculate AIS to the reactors and remove accumulated solids to an AIS holding tank.

Solids Handling

An AIS holding tank will receive excess solids from the clarifiers where the solids will be allowed to further thicken with additional settling time. The Hayes Run AIS treatment system will produce an average volume of AIS to be wasted daily between 200 and 300 gallons per day (6% solids). However, the solids handling facility will concentrate the solids to a final volume between 50 and 100 gallons per day (20% solids). The solids handling will consist of a holding tank with storage capacity between 60 and 100 days. The holding tank will be equipped with a decant pump to remove clarified water from the top of the solids holding tank and return it to the treatment system. Solids will accumulate in the bottom of the tank until the tank is full which corresponds to approximately 50% of the total volume of solids. A jet mixer placed in the bottom of the tank will be used to periodically and at the time for transport to the disposal site re-suspend the thickened solids to slurry. A submersible pump will be used to remove the slurry from the tank for transport to a disposal or processing site.

ESTIMATED AIS TREATMENT SYSTEM COSTS – CAPITAL & OPERATIONAL

Blue Valley – Estimated Costs

The Blue Valley retrofit AIS Treatment System capital costs will include reactor tanks, air lines, drop-outs, diffusers, blowers, mixers and a control panels. Table BV-16 provides an estimate of the capital costs associated for the retrofit Blue Valley AIS Reactor. Actual costs of an AIS Treatment System may be higher or lower depending on a number of factors related to installation limitations. The estimated cost for the installation is $35,000 which results in a total estimated cost for the retrofit reactor and installation of approximately $200,000.

Table BV-16: Blue Valley AMD Discharge AIS Treatment System Preliminary Equipment List & System Cost[1]

Item No.	Item Description	Number
1	**Control System (Analog)**	**1**
2	**AIS Treatment System – IOT, Inc.**	
	a. 17,500 & 12,500 gallon Reactor Tanks (mix & aeration)	2
	b. 3-5 H.P Top Mounted Mixers (incl. mounts)	3
	c. 7.5 H.P. Blower (180 cfm)	2
	d. Access stairway, handrail, full grating	1
Estimated System Cost		**$156,000**
Estimated Freight		**$10,000**
Estimated Total Equipment Cost		**$166,000**

[1] Costs reflect January 2008 pricing for equipment and freight

The operating costs associated with the retrofit AIS reactor tank are summarized in Table BV-17. The operating costs are associated with electricity usage to operate the blower and mixers. The AIS reactor tank will lower/eliminate the potassium permanganate use at the Blue Valley system. Based on a consumption of 25-45 lbs/day of potassium permanganate for the expected AMD flow range to be treated with no solids recirculation and at a cost of $2.50 per pound, yields an annual potassium permanganate cost of $40,000 to $60,000 per year. This cost can be eliminated by the use of the AIS treatment methodology. This results in a net annual savings in operating costs of $30,000 to $50,000/yr and indicates the costs of the retrofit will be recovered in 4 to 6 years. In addition, eliminating the use of potassium permanganate may enhance the value of the solids recovered from the treatment system with a potential value (after processing) of $0.05/lb (as iron oxide). This iron oxide reuse would eliminate operating costs associated with solids handling and disposal, thereby providing additional decreases in the Blue Valley treatment system operating costs.

Table BV-17: Blue Valley AIS Treatment System Operating Cost Estimate

Item	**Cost $/yr**
O&M Electricity ($/yr)	$7,350
Potassium Permanganate ($/yr)[1]	-$40,000 to -$60,000
Polymer Use ($/yr)	No Change
Solids Disposal ($/yr)	No Change
Equipment Maintenance ($/yr)	$1,000
Personnel O&M Costs ($/yr)	No Change
Change in Operating Costs ($/yr)	**-30,000 to -$50,000**
Potential Iron Oxide Reuse (@ $0.05/lb)	***+$2,000***

[1] Range based on average and maximum flow treated with no solids recirculation.

Hayes Run – Estimated Costs

The Hayes Run AIS Treatment System capital costs will include reactor tanks, clarifiers, water piping, air lines, drop-outs, diffusers, blowers, mixers, control panels, buildings for housing the control panel and blowers, solids handling tanks, and perimeter fence. Backup electrical generators should also be considered to prevent loss of treatment in case of power failure.

Table BV-18 provides an estimate of the capital costs associated for the 0.5 MGD (350 gpm) Hayes Run AIS Treatment System. Actual costs of an AIS Treatment System may vary depending on a number of factors related to final effluent quality goals and the site conditions. In addition to the treatment system costs, there will be costs associated with site development, treatment system installation, control/polymer building installation, and perimeter fencing. The estimated cost for these items is $75,000 which results in a total estimated cost for the treatment system and installation of $585,000.

Table BV-18: Hayes Run AMD Discharge AIS Treatment System Preliminary Equipment List & System Cost[1]

Item No.	Item Description	Number
1	**Control System**	
	a. PLC Unit	1
	b. pH/Turbidity/Flow Monitors	1
2	**AIS Treatment System – IOT, Inc.**	
	a. 14,000 gallon Reactor Tanks (mix & aeration)	2
	b. 3.5 H.P Top Mounted Mixers (incl. mounts)	4
	c. 5 H.P. Blower	3
	d. 6,000 gallon Flocculation Tank	1
	e. 3 H.P. Top Mounted Flocculation Mixer	1
	f. 400 sq. ft. Hopper Bottom Clarifiers	2
	g. 0.5 H.P. AIS Recirculation and WAIS Pumps	8
	h. 2 L/min (max.) Polymer Doser Pump	2
4	**Sludge Handling System – IOT, Inc.**	
	a. 10,000 gallon AIS Holding Tank	1
	b. 10 H.P. Jet Mixer	1
	c. 3 H.P. Rail Mounted Decant Pump	1
	d. 5 H.P. Sludge Discharge Pump	1
Estimated System Cost		**$485,000**
Estimated Freight		**$25,000**
Estimated Total Equipment Cost		**$510,000**

[1] Costs reflect January 2008 pricing for equipment and freight

Table BV-19 provides an estimate of O&M Costs for the Hayes Run AIS Treatment system and includes labor, operating and maintenance costs. Also provided is the value of the iron oxide solids produced and the direct effect this beneficial reuse will have on the O&M costs by removing disposal costs and offsetting other operating costs. Depending on a number of factors, the annual O&M costs at the Hayes Run treatment system will be between $12,000 and $34,000.

Table BV-19: Hayes Run AIS Treatment System Operating Cost Estimate

Item	Cost $/yr
O&M Electricity ($/yr)	$12,500
Polymer Use ($/yr)	$1,000
Solids Disposal ($/yr)	$7,000
Equipment Maintenance ($/yr)	$2,000
Personnel O&M Costs ($/yr)	*$10,000-$20,000*
Total O&M Costs ($/yr)	**$37,500**[1]
Non-Personnel O&M Costs ($/yr)	**$22,500**
Potential Iron Oxide Reuse (@ $0.05/lb)	***+$3,800***
BALANCE of O&M Costs	***$11,700***

[1] using personnel O&M cost of $15,000/yr

The treatment costs will vary depending on inclusion of the various Hayes Run system capital and operating costs. Using the annual operating cost (labor not included) of $22,500 for the Hayes Run system equates to a cost of $0.28 per 1,000 gallons of treated water. If sludge disposal costs are removed and an iron oxide revenue option is identified, the treatment costs decrease to treatment costs to $0.10 per 1,000 gallons. The total treatment cost for the Hayes Run AMD discharge using the AIS treatment process, includes annualized capital costs (25-year basis) and all O&M costs ($37,500 per year), is $0.66 per 1,000 gallons of treated AMD.

SUMMARY

The Blue Valley AIS pilot study results and this summary report provide considerable information regarding the AIS Treatment process. The results indicate:

- AIS Treatment effectively oxidizes ferrous iron in short detention times needed to meet effluent objectives for both the Blue Valley and Hayes Run AMD.
- AIS ferrous iron oxidation rates are not affected by polymer dosing.
- Observed oxidation rates by the AIS solids are consistent with the heterogeneous ferrous iron oxidation model.
- Wasted iron oxide solids in the current Blue Valley Treatment System convert to AIS solids.

Based on the results of the pilot study and the heterogeneous ferrous iron oxidation model, AIS treatment systems were developed including:

- An AIS reactor system to retrofit into the existing Blue Valley Treatment System that will eliminate and/or minimize the use of the chemical oxidant, potassium permanganate, and not affect the performance of the remaining treatment system.
- A new complete AIS treatment system for the Hayes Run AMD discharge that will produce an effluent iron less than 0.5 mg/L at average flows and 1 mg/L at maximum flows.

The retrofit AIS reactor system at the Blue Valley location will decrease annual operating costs by between $30,000 and $50,000 per year depending on the treated flow and iron oxide reuse. This is a substantial decrease in operating costs with the retrofit costs recovered in 3 to 6 years.

The Hayes Run treatment system will have a capital cost of $585,000 with an annual operating cost between $12,000 and $37,500 depending on inclusion of labor and solids reuse. The treatment costs for the Hayes Run discharge range between of $0.06 and $0.33 per 1,000 gallons of treated water depending on inclusion of various operating costs and reflection of capital costs in the estimate.

The AIS Treatment approach offers the potential for iron recovery and reuse from the treated AMD and with solids characteristics that offer a significant potential for beneficial reuse. Investigations indicate there is substantial potential for the solids to be used in the pigment industry. This investigation is ongoing.

REFERENCES

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Activated Iron Solids Treatment Pilot Study for Monview-Mathies Acidic Mine Drainage

SUMMARY REPORT

Submitted to:

Department of Environmental Protection
Bureau of Abandoned Mine Reclamation
Ebensburg, Pennsylvania

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INTRODUCTION

The discharge of acid mine drainage (AMD) to surface waters in Pennsylvania and other eastern coal region states contaminates thousands of miles of waterways resulting in their non-compliance with numerous Pennsylvania Water Quality Standards including, but not limited to, pH, total iron, suspended solids, and aesthetics. The AMD is a result of past (and unregulated) surface and underground coal mining that exposes pyritic minerals to atmospheric oxygen and results in the oxidation and the production of AMD.

Of particular concern is AMD produced in the vast historic and abandoned deep mine workings found throughout the coal region. The pyrite oxidizes to create AMD that collects and is stored in the mine voids forming large underground reservoirs of contaminated AMD. These large underground AMD reservoirs discharge at one or more points, typically from air portals (for recirculation of air in the mine during active operations), water portals/drains (to maintain a minimal water level in the mine during active operations), or from the mine entry. Deep mine discharges tend to be very high flow with elevated ferrous iron but may contain adequate alkalinity for iron removal. The deep mine discharges are often the largest contributor of metal loading in the watershed and/or subbasin. Treatment is mandatory to achieve water quality goals in the receiving stream.

The impact of the high flow AMD discharges on receiving streams is substantial. Input of high flow and ferrous iron AMD to surface waters causes: 1) increase of instream iron concentrations to levels exceeding water quality standards; 2) instream oxidation causes the deposition of iron oxides, known as “yellowboy”, onto stream bottoms smothering aquatic life and causing aesthetic and sediment problems; and 3) oxidation of ferrous iron can cause a decrease in pH to less than 6, a water quality standard. Theses types of impacts lead to degradation of the receiving waters to conditions that do not meet the waters designated aquatic life, recreational, and water supply uses.

Development of new and innovative treatment systems that effectively remove AMD pollutants at substantially lower capital and operating costs is paramount to the watershed restoration efforts across Pennsylvania. AIS (Activated Iron Solids) treatment has been identified as a potential new and innovative AMD treatment approach to address high flow AMD sources and or AMD treatment where land constraints or effluent objectives dictate active treatment methods.

This report summarizes the Monview-Mathies AIS pilot study to evaluate the use of AIS treatment to treat AMD deep mine source. The Monview-Mathies AMD discharge is treated with sodium hydroxide solution, a costly chemical, to raise the pH in order to remove the iron.

SITE DESCRIPTION & BACKGROUND

The Monview-Mathies AMD discharge is a high flow discharge that emanates from a bond forfeiture deep mine in Washington County, Pennsylvania. The discharge chemistry emanating from the deep mine is summarized in Table MM-1. At the deep mine opening, and for several hundred feet into the deep mine, the discharge flows by gravity in a channel along the mine entry floor. At the mine opening the AMD discharge is collected in a collection box and conveyed by an underground pipe. Recent water quality chemistry from the Monview-Mathies discharge indicates the discharge has alkalinity well in excess of the acidity associated with the ferrous iron contained in discharge and is net alkaline. Due to the gravity flow in the mine entrance, the discharge also contains dissolved oxygen concentrations ranging from 4 to 7 mg/L. The mine water travels approximately 1,500 feet in the underground pipe to a lined open water basin where the iron oxides are formed and settled. The mine water passes through a second open water pond for additional iron removal prior to discharge to the receiving stream, Mingo Creek, which is a trout stocked fishery.

The Monview-Mathies discharge is treated with liquid sodium hydroxide (30% solution) in order to raise the pH to a level ($pH > 7.5$) where soluble ferrous iron is rapidly oxidized to an insoluble ferric iron oxide. Liquid sodium hydroxide is fed into the pipe approximately 50 feet from the mine entrance. The dose rate is set manually based on flow measurements. The sodium hydroxide solution is an expensive chemical and is the highest cost items for the treatment of the Monview-Mathies discharge at an average annual cost in excess of $50,000 per year.

The purpose of this AIS pilot study at the Monview-Mathies discharge was to investigate a new and innovative technology as a treatment alternative for Monview-Mathies discharge. The following provides the technical background information for the pilot study including AMD characteristics (and implications on treatment) at the Monview-Mathies discharge, background iron oxidation information, and a brief description of the AIS treatment process. Also included is a brief description of aeration and its implications on treatment of the Monview-Mathies discharge.

AMD Characteristics

The AMD discharge chemistry and flow data for Monview-Mathies discharge is summarized in Table MM-1. The discharge contains predominately ferrous iron (Fe^{2+}), but also small amounts of ferric iron (Fe^{3+}); ferric iron is the difference between total iron and ferrous iron. Given the pH of the waters ($pH > 5$), it is unlikely the discharge contains any dissolved ferric iron (ferric iron is not soluble above a pH of 4). The presence of ferric iron in the discharge is likely the result of aeration and oxidation of the ferrous iron during transport in the deep mine entry. Aeration of the mine discharge is indicated by the presence of dissolved oxygen (DO) in the discharge, see Table MM-1. The remaining ferrous iron concentration is important since it is the oxidation of ferrous iron that is the controlling step in iron removal from mine drainage.

Table MM-1: Summary of the Monview-Mathies deep mine discharge water quality characteristics.

Average Flow gpm	Max. Flow gpm	pH	Total Fe mg/L	Fe^{2+} mg/L	Total Al mg/L	Total Mn mg/L	Alkalinity mg/L	Calc. Acidity* mg/L	Sulfate mg/L	DO mg/L
1,800	3,000	6.6	30	22	2.0	1.5	325	-270	1,050	7

* Calc. Acidity value determined after all iron has been oxidized and precipitated.

Alkalinity was evaluated to determine whether there is adequate alkalinity for the removal of iron from the mine drainage. The oxidation and precipitation of 1 mg/L of ferrous iron will consume 1.8 mg/L of alkalinity. The Acidity column in Table MM-1 is the calculated acidity after all iron has been oxidized and precipitated. The negative acidity value indicates the Monview-Mathies discharge has excess alkalinity in an amount greater than 250 mg/L.

Carbon dioxide (CO_2) acidity data was also calculated to determine the amount of aeration needed to remove the CO_2 in AIS treatment process and maintain or raise the pH to levels needed for the effective oxidation of ferrous iron in the AIS treatment approach. In aqueous chemistry, carbon dioxide acidity is present in water as carbonic acid (H_2CO_3). The pH of water (controlled by the carbonate system) is determined by the concentrations of bicarbonate (HCO_3^-), which is alkalinity, and H_2CO_3 according to the following relationship:

$$\text{(MM-1)} \qquad H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

The pK_a of this equilibrium is 6.4. This 6.4 would also be the pH at which the H_2CO_3 and HCO_3^- concentrations would be equal. This means an alkalinity (HCO_3^-) of 100 mg/L (as $CaCO_3$) would require an equal CO_2 acidity (H_2CO_3) of 100 mg/L (as $CaCO_3$) to have a pH of 6.4. The CO_2 acidities calculated for the Monview-Mathies discharge is 190 mg/L (as $CaCO_3$). The source of this acidity is chemical neutralization reactions in the deep mine pool as well as decomposition reactions. The CO_2 acidities are 200 times higher than is normally found in surface waters in equilibrium with the atmosphere.

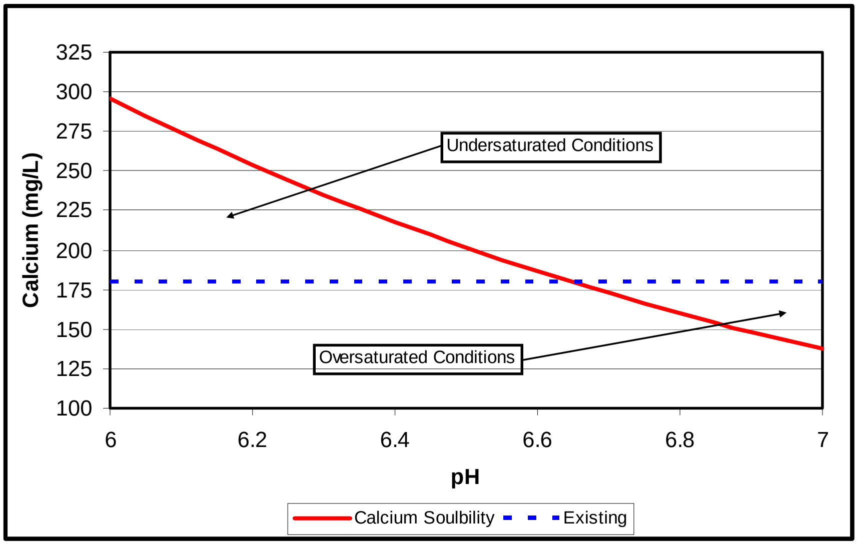


Figure MM-1. Calcium solubility in the AMD discharge with respect to pH.

The solubility of calcium and magnesium in the AMD must be evaluated for the various treatment methodologies. pH adjustments may create operation and maintenance issues by precipitating calcium and magnesium. Figure MM-1 shows the predicted calcium (calcite) solubility with respect to pH for the Monview-Mathies discharge. Oversaturated conditions at the higher pH indicate calcium (calcite) will precipitate if the pH is increased. This is a potential operation and maintenance issue by creating more solids. This method of calcium precipitation is well known and used in water treatment to soften waters by adding lime (CaO) to raise the pH of water to decrease the solubility and remove calcium (calcite) hardness. At pH greater than 8, magnesium will also be removed as a hydroxide. Calcium and magnesium will also precipitate where sodium hydroxide is used for pH adjustment, as is the current treatment at Monview-Mathies, which can increase operation and maintenance by increasing solids handling and disposal. AIS treatment oxidizes ferrous iron at acidic pH (less than 7) and minimizes the additional solids volumes associated with calcium and magnesium precipitation compared to lime, sodium hydroxide, or aeration treatment approaches.

Another important parameter not listed in Table MM-1 is the temperature of the discharges. Temperature of the water is important because it affects a number of chemical and physical processes in the treatment of AMD. The temperature of the Monview-Mathies discharge is near 13.4°C. This is moderate temperature for a deep mine discharge that will affect aeration, oxidation and the settling process. As an example, the homogeneous oxidation rate doubles for every 2°C increase in temperature. The heterogeneous oxidation process is similarly affected by temperature.

The chemistry evaluation for the discharge is an integral component in determining appropriate approaches and methods for treating the AMD. The impacts of the AMD chemistry on the various treatment approaches will be compared in a subsequent section.

Iron Oxidation & Removal in AMD Treatment

The treatment of the Monview-Mathies AMD discharge requires iron removal and this iron removal is a multi-step process involving:

1. Oxidation of dissolved ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+});
2. Hydrolysis of ferric iron to form insoluble ferric oxide ($Fe(OH)_3$);
3. Flocculation of tiny (sub micrometer - μm) iron oxide particles to form larger (micrometer - μm) iron oxide particles;
4. Settling of suspended iron oxide particles from solution.

Depending on the type of treatment, one or more of the above processes will control the removal of iron. In passive treatment the oxidation (Step 1) of ferrous iron is very slow and determines iron removal and the size of the passive treatment system. In chemical treatment at high pH (> 8), the settling (Step 4) typically controls iron removal. The new and innovative process, AIS treatment, provides an alternative to passive treatment and chemical treatment.

The oxidation of ferrous iron is the first and most crucial step in the removal of iron. Without the oxidation step, ferrous iron would remain in solution (except at very high pH) and removal of iron from AMD would not be possible. There are two types of ferrous iron oxidation in water:

1. ***Homogeneous Ferrous Iron Oxidation (HoFIO)*** – is the long established oxidation process occurring in solution and involves the reaction of dissolved ferrous iron (Fe^{2+}) with dissolved oxygen.
2. ***Heterogeneous Ferrous Iron Oxidation (HeFIO)*** – is a newly identified oxidation process occurring on the surface of iron oxide solids and involves the sorption of ferrous iron and dissolved oxygen followed by the rapid catalytic oxidation on the surface of the iron oxide.

The first type, HoFIO is the ferrous iron oxidation that occurs in solution and is most commonly associated with passive treatment and conventional (lime-based) chemical treatment of AMD. This process is also the dominate process where aeration is used to add oxygen and raise the pH to greater than 7, a pH where HoFIO will dominate. The long established HoFIO rate equation (Sung & Morgan 1980) is:

$$\text{(MM-2)} \quad HoFIOrate(M \cdot s^{-1}) = -\frac{\partial[Fe(II)_{diss}]}{\partial t} = \frac{k_{Ho2} \times [Fe(II)_{diss}] \times [O_2]}{\{H^+\}^2}$$

The HoFIO equation is complex with the rate (R) affected by the ferrous iron concentration $[Fe(II)_{diss}]$, dissolved oxygen $[O_2]$ and pH $\{H^+\}$. Temperature is an integral part of the equation by its affects on the reaction rate constant (k_{Ho2}), with a decrease in temperature causing a decrease in the oxidation rate. The HoFIO equation is a reliable design tool because the equation can be used to predict iron removal for 1) different AMD chemistry, and 2) factors in iron removal under operating conditions (e.g., dissolved oxygen, pH and temperature). The HoFIO model will be used to evaluate ferrous iron oxidation results for the pilot study where only aeration is used in the reactors to increase dissolved oxygen and pH.

Heterogeneous ferrous iron oxidation (HeFIO) is an oxidation process that occurs on iron oxide surfaces and is the oxidation process AIS uses to oxidize ferrous iron. HeFIO is a two step processes that involves 1) the sorption of ferrous iron to the surface of the iron oxide, 2) rapid oxidation in the presence of dissolved oxygen to form new iron oxides directly on the surface of the iron oxide. Equations and models for the reactions are contained in Dietz (2003). The equations are complex describing both sorption and oxidation process.

$$\text{(MM-3)} \quad \textit{HeFIO rate } (M \cdot s^{-1}) = (-\delta[Fe(II)]/\,\delta t) = (k_{He1}[O_2]S_1) + (k_{He2}[O_2]S_2)$$

and

$$\text{(MM-4)} \qquad S_x = \frac{1 + ([Fe(II)_{diss}] \times K_x^{app})}{[\equiv Fe(III)] \times \Gamma_x \times \{H^+\}^x}$$

where **x** is the reaction (either 1 or 2), $\mathbf{k_{Hex}}$ are the surface oxidation rate constants, $\mathbf{K_x^{app}}$ are the surface complexation constants, and **[≡Fe(III)]** is the AIS concentration (in mg/L). Dietz (2003) determined the various thermodynamic constants for the equations including activation energies and enthalpies, which describe the effects of changing temperature. In current treatment systems (including passive treatment and lime treatment), HeFIO is not very important (< 5%) due to the low concentrations of suspended iron oxides (typically less than 5 mg/L). Iron Oxide Technologies, LLC has developed several treatment systems optimizing HeFIO through concentrated suspensions of iron oxide solids in reactor systems. Figure MM-2 shows the time required to oxidize and remove ferrous iron from AMD for various treatment methods from bench-scale testing conducted at 15°C on an anoxic AMD discharge. Note, the x-axis time scale

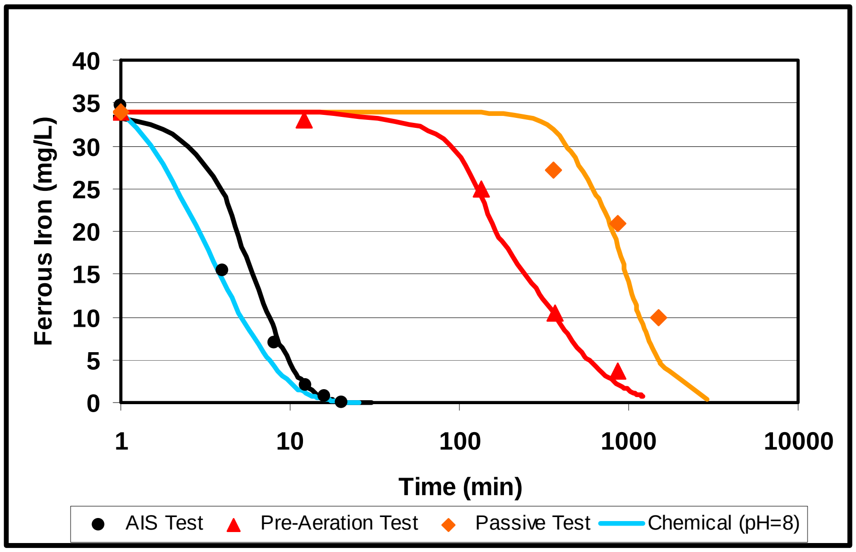


Figure MM-2. Bench-scale Results for Activated Iron Solids (AIS), Pre-aeration & Passive Tests

is logarithmic. The detention time required to achieve less than 0.5 mg/L ferrous iron for the passive treatment and passive treatment with pre-aeration tests were 50 and 25 hours, respectively. Critical low-temperature conditions (Average Temp. = 8°C) would require additional detention times (2 to 5 times) to complete oxidation. As a comparison, the AIS treatment test required only 20 minutes to achieve 0.5 mg/L, which demonstrates the importance of HeFIO and the ability AIS treatment to achieve rapid oxidation and removal of ferrous iron. AIS treatment is 75 times faster in comparison to pre-aeration/passive treatment and 150 times faster in comparison to passive treatment only. A pH 8 oxidation line is also provided to show AIS ferrous iron oxidation is similar to conventional lime-based treatment: the 0.5 mg/L ferrous iron is expected to occur in 15 to 20 minutes detention time.

Innovative AIS Treatment

Iron Oxide Technologies, LLC has developed new (patent pending) active treatment approaches collectively known as Activated Iron Solids (AIS) treatment of AMD. AIS treatment has numerous advantages over conventional chemical treatment that can make long term treatment and iron oxide recovery possible at abandoned mine discharges. The AIS treatment advantages over conventional chemical treatment are:

1) Oxidation and removal occur at slightly acidic pH (6-7);
2) Oxidation rates are as fast as conventional chemical treatment;
3) For net alkaline AMD no alkaline chemicals are needed;
4) For net acidic waters, inexpensive pulverized (powder) limestone can be used for the needed alkalinity;
5) Solids produced by the AIS process are high-density (30% solids);
6) Solids are high purity iron oxides (95% iron oxides on a dry weight basis).

These advantages will have a direct effect on treatment costs by eliminating (or minimizing) chemical use and cost, and simplifying operation that will decrease manpower requirements. The innovative active AIS treatment processes utilized for the pilot study at Monview-Mathies is the Two-Stage AIS Reactor System (depicted in Figure MM-3). The AIS system uses high iron oxide concentrations (AIS = 1,500 – 2,500 mg/L) to increase ferrous iron oxidation and removal. The high iron oxide concentrations produce a catalytic environment that promotes ferrous iron oxidation and removal while producing high-density and pure treatment solids (iron oxide solids). The Two-Stage AIS Reactor system maintains high reactor AIS concentrations through recirculation of solids collected in the clarifier.

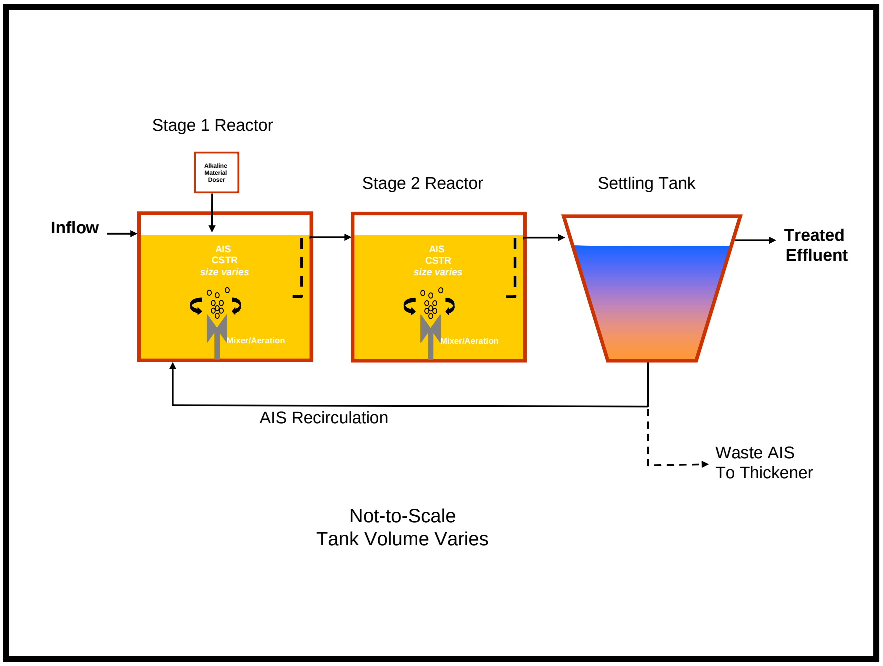


Figure MM-3. AMD Treatment in a Two-Stage Flow-Through AIS System

MONVIEW-MATHIES PILOT STUDY

The pilot system was moved to the Monview-Mathies site in July 2007 and setup for operation during the week of July 23, 2008. Setup of the AIS pilot unit consisted of: 1) providing electrical service to the site; 2) moving the trailer unit to the location; 3) set up of the pilot system; and 4) placement of a pump at the mine entrance and piping to convey the mine drainage to the pilot unit. The trailer unit was placed in an open area adjacent to the abandoned maintenance building for the mine site and near the location where electrical service was provided. The trailer unit was leveled with wooden support pillars at this location. Single phase 230 volt electrical connections were made to the pilot unit control panel from an existing electrical panel within the building. The mine drainage was directed to the pilot unit using a ½ horsepower submersible pump placed in the collection box located at the entrance to the deep mine that directs the mine drainage into an underground pipe to convey it to the treatment ponds. Collapsible 4-inch water line was used to convey the AMD from the submersible pump to the inlet weir box of the pilot system. The effluent from the pilot unit, along with overflow from the inlet weir box, was also conveyed using collapsible 4-inch water line from the pilot treatment system to the grated man-hole access manhole in the existing underground mine drainage pipeline and conveyed with the existing mine drainage to the treatment ponds. Therefore, no new discharge point was created by the pilot study.

The Monview-Mathies pilot study was conducted during July and August 2007. The inflow pump was started on July 23rd to fill the tanks and testing was initiated on July 31st, 2007. Testing consisted of two phases: 1) aeration only to determine the detention time and aeration requirements to treat the AMD if aeration only was used to raise the pH and oxidize the ferrous iron: and 2) AIS treatment testing to determine the detention time and aeration requirements where AIS treatment was employed, which involves high AIS reactor iron concentrations through solids recirculation from the clarifier.

Analytical Methods

Analysis for the pilot study consisted of pH, dissolved oxygen, temperature, total iron, dissolved iron, alkalinity and periodic conductivity. pH was measured with an Fisher Scientific Accumet Portable Meter equipped with a Cole Parmer Accumet combination pH electrode; except during initial aeration testing where an Oakton pH pen was used. The pH electrode was calibrated daily prior to use with pH 4.00 and pH 7.00 buffers. Dissolved oxygen and temperature were measured with an YSI Model 550A Dissolved Oxygen Meter. The Dissolved Oxygen Meter was calibrated prior to each use using the air saturation method. Total iron was measured using a Hach Iron Pocket Colorimeter Test Kit (0-3.00 mg/L) using Ferrover reagent after appropriate dilution. Dissolved iron was also measured with the Iron Pocket Colorimeter but after filtration using a syringe and a 0.2 μm syringe filter, and appropriate dilution. Ferrous iron was determined using Hach ferrous iron powder packets and the Hach Iron Pocket Colorimeter. Initial testing on the discharge indicated dissolved iron (filtered sample) equals ferrous iron for the conditions in the Monview-Mathies AMD. As a result, the dissolved iron test was used to determine ferrous iron. Alkalinity was measured on a 100 mL sample using a Hach Digital Titrator, a 1.600 N sulfuric acid cartridge. Conductivity was measured with an Oakton Conductivity Pen.

Aeration Only Testing

Aeration testing at the Monview-Mathies AMD discharge was conducted between July 31 and August 3, 2007. The testing consisted of varying the AMD flow to the treatment system. Aeration was provided by the blower included with the pilot unit and fine bubble diffuser heads placed in the reactor tanks. Air flow was monitored and set at 17 cfm during the aeration study. AMD flow during the study was varied from a low of 3.5 gpm to a high of 24.6 gpm by adjusting the weir plates on the inlet box. The flows to the system equated to a total reactor detention time ranging between 2.7 and 20 hours. The goal of the aeration was to determine the required detention time and air flow to achieve adequate oxidation of the ferrous iron (dissolved) in the discharge to the insoluble ferric iron form. Total iron removal, or solids removal, was not a specific objective of the aeration testing.

The results of the aeration only testing are summarized in Tables MM-2 through MM-4. The raw water chemistry was consistent during the aeration testing with pH varying from 6.81 to 6.85. The final pH from the treatment system was dependent on the flow to the system with the lowest effluent pH (7.54) occurring at the maximum tested flow (~25 gpm) and the highest effluent pH (8.33) occurring at the lowest tested flow (3 gpm). Iron oxidation, or ferrous iron removal, followed the pH relationship with greater removal occurring at the longer detention time. However, even the maximum flow tested resulted in a low effluent ferrous iron from the second reactor of 0.37 mg/L.

Table MM-2: Summary of analytical results from aeration only testing (Test A1) at AMD Flow = 3.5 gpm and Air Flow = 17 cfm, started on July 31, 2007 at 4:00 PM.

Location	pH[1]	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
3:00 PM on August 1, 2007						
Raw	6.86	7.05	14.1	26.6	18.1	382
React 1	7.75	9.75	17.8	32.0	0.05	--
React 2	8.07	9.66	18.9	37.6	0.10	350
8:30 PM on August 1, 2007						
Raw	6.84	7.01	13.5	27.4	18.5	384
React 1	7.94	9.84	17.8	40.2	0.05	354
React 2	8.33	9.64	19.1	41.2	0.10	350
Effluent	--	--	--	5.5	--	--

Table MM-3: Summary of analytical results from aeration only testing (Test A2) at AMD Flow = 9.8 gpm and Air Flow = 17 cfm, started on August 1, 2007 at 9:00 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
9:30 AM on August 2, 2007						
Raw	6.83	7.40	14.1	26.6	19.4	382
React 1	7.62	10.3	15.0	27.2	0.31	342
React 2	8.01	10.4	15.7	30.2	0.03	--
4:30 PM on August 2, 2007						
Raw	6.85	7.30	14.0	25.8	18.1	384
React 1	7.67	10.3	16.4	26.1	0.16	--
React 2	8.13	10.1	17.5	27.5	0.01	342

Table MM-4: Summary of analytical results from aeration only testing (Test A3) at AMD Flow = 25 gpm and Air Flow = 17 cfm, started on August 2, 2007 at 5:30 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
9:00 AM on August 3, 2007						
Raw	6.81	7.37	13.8	26.0	18.1	380
React 1	7.18	10.3	13.9	26.1	5.06	346
React 2	7.54	10.8	13.9	26.2	0.37	341
Effluent				6.10	0.12	--
12:30 PM on August 3, 2007						
Raw	6.81	7.37	13.9	26.5	18.3	380
React 1	7.15	10.2	14.2	26.0	4.85	--
React 2	7.51	10.7	14.8	26.2	0.25	340

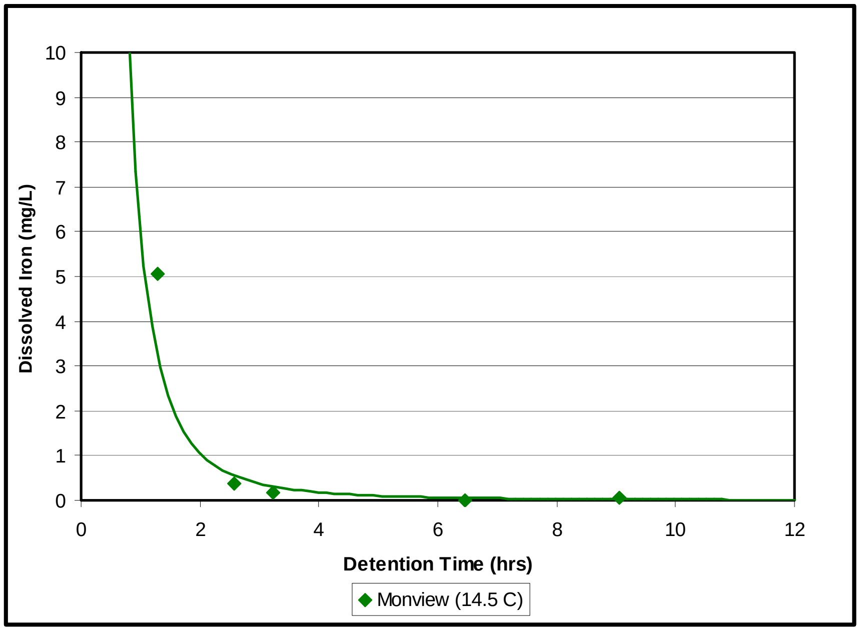


Figure MM-4. Monview-Mathies Aeration Testing Results; Effluent Dissolved Iron.

Dissolved iron also decreased as a function of detention time in the aeration tanks as a result of oxidation of soluble ferrous iron to insoluble ferric iron. The affects of detention time on dissolved iron concentration (i.e., iron oxidation) is shown in Figure MM-4. The figure shows the effluent dissolved iron concentration decreases non-linearly as the detention time increases. This is an affect of: 1) the length of time the AMD is in the reactor to permit oxidation; and 2) the increase in pH from removal of carbon dioxide acidity through aeration. The pH affect is also related to the detention time in the reactor allowing greater removal of the carbon dioxide acidity. The non-linear relationship in the decrease of dissolved iron with detention time is related to the first-order kinetics of the ferrous iron oxidation.

The final evaluation using the aeration only data was to compare the measured dissolved iron to predictions using the homogeneous iron oxidation model and reactor equations. An accurate model will be needed to size an aeration only system. The sampling and analysis conducted in each reactor are summarized in Table MM-5. The calculated dissolved iron concentration for the reactor conditions is also provided in Table MM-5 along with the difference between the measured and calculated dissolved iron values. Overall the difference between the measured and calculated averaged less than 0.1 mg/L and most of the differences were less than 0.1 mg/L. This indicates the homogeneous iron oxidation model and the reactor equations can be used to estimate the aeration system size.

Table MM-5: Summary of Iron Oxidation Data From Each Reactor During Aeration Studies Only and Comparison to the Calculated Dissolved Iron Using the Homogeneous Iron Oxidation Model.

Test	Reactor	Detention Time Hrs	pH	Dissolved Oxygen mg/L	Temp. °C	Meas. Diss. Fe mg/L	Calc. Diss. Fe mg/L	Difference Diss. Fe (Meas-Calc)
A1	1	1.29	7.18	10.3	13.9	5.06	5.5	0.44
A1	2	1.29	7.54	10.8	13.9	0.37	0.45	-0.08
A2	1	3.23	7.67	10.3	16.4	0.16	0.15	0.01
A2	2	3.23	8.13	10.1	17.5	0.01	<0.001	<0.01
A3	1	9.05	7.94	9.8	17.8	0.05	0.052	-0.002
A3	2	9.05	8.33	9.6	19.2	0.01	<0.001	<0.01

Although not a specific objective of the aeration only testing, solids removal was evaluated and polymers were tested during the aeration studies. Due to constraints in pilot system size a non-optimal clarifier. This clarifier was selected to collect and return AIS during testing and not to optimize solids removal. Solids removal evaluation was done to assist in the design of an of the solids removal component in an aeration only treatment system. As can be seen in the Table MM-2 through MM-4, effluent iron less than 6 mg/L was typically achieved during the testing. This effluent required the addition of a polymer to improve flocculation and particle settling. The polymer was identified through bench testing of Reactor 2 effluent and various polymers and doses. The optimal polymer identified for flocculation of aeration treated water was the Ciba Specialty Chemicals Magnafloc 10. This is a medium molecular weight nonionic acrylamide polymer. The bench testing also indicated a flocculation step would improve formation of larger and faster settling particles. *Subsequent testing at the Phillips pilot study also determined the mixer used to disperse the polymer imparted too great of shear and formed smaller difficult to settle particles and may have contributed to effluent iron in excess of 3 mg/L during aeration only testing.*

An aeration only system was estimated based on the aeration data from the pilot study and temperature of 13.5°C, which likely represents a winter time minimum temperature in the reactor (i.e., discharge temperature and heat loss in the reactor). Based on the model, an aeration only system would require approximately 6 hours detention time to decrease dissolved iron to less than 0.3 mg/L. This would require a 1.1 million gallon aeration tank receiving approximately 2,000 cfm of air at maximum flow conditions. Clarifiers would also be required to remove and collect the iron oxides formed from the aeration treatment of the Monview-Mathies discharge. This treatment option will be further evaluated under “Treatment System Alternatives”.

AIS Pilot Testing

The initial startup conditions for the pilot unit were:

1. Reactor 1 & 2 AIS = 900 mg/L (as Fe)
2. Air Flow = 0 cfm – air flow was varied during testing
3. AMD Inflow = 25 gpm
4. AIS Recirculation Rate = 5 gpm
5. Initial Polymer Dose Rate = 105 mL/min (0.5 mg/L of inflow) - *polymer dose was increased during test*

To start the pilot system, AIS were added to the pilot unit using iron oxide solids collected from the Blue Valley treatment system. The Blue Valley solids were previously proven to convert to AIS during the Blue Valley pilot study. The use of the solids would simplify start-up by minimizing start-up time to accumulate AIS solids for the reactor system (hours versus months). Initial AIS concentrations were less than the target operating conditions but were adequate to demonstrate AIS treatment as well as allow rapid accumulation of AIS to the target AIS concentration (~2,000 mg/L). Air flow was initially set at 0 cfm due to the high pH and presence of dissolved oxygen in the mine drainage. Air flow was used in later tests to evaluate treatment improvement in the presence of aeration. The AIS was kept in suspension using mixers included in the reactor tanks. The initial AMD inflow was set based on the maximum flow tested during the aeration only testing. The AIS recirculation rate was set at a flow rate to maintain the reactor AIS concentrations based on expected solids in the recirculated flow and the AMD inflow rate. The polymer used for initially in the pilot study was the Applied Specialties, Inc. AS-1930, a high molecular weight medium charge anionic acrylamide copolymer. Additional polymer testing was conducted during the initial testing to identify optimal polymer type; specifically, polymer molecular weight and charge density. This was conducted because of yellowing of the discharge associated with the AS-1390, which could be due to excessive charge or chemical composition of the AS-1930 copolymer.

The AIS pilot system was started using the above settings on August 5th at 3:00 PM. The pilot unit was operated until August 24th with adjustments to vary inflow, air flow, solids recirculation rates, AIS concentration, and polymer type/dose. The results from various sampling dates (and times) along with operating conditions are contained in Tables MM-6 through MM-11.

All the AIS pilot study results indicate the AIS system oxidized the soluble ferrous iron in the Monview-Mathies discharge to particulate ferric iron. The dissolved iron decreased in all tests from the influent concentration range of 18 to 20 mg/L to effluent dissolved iron ranging from 0.01 to 2.1 mg/L. The effluent dissolved iron concentration varied based on a number of operating and reactor conditions including AIS concentration, pH, temperature and dissolved oxygen.

Pilot study results from AIS Test1 (Table MM-6) and AIS Test2 (Table MM-7) were initial tests to accumulate AIS in the system and to evaluate the polymer type and dose. The tests also showed dissolved iron can be removed from the Monview-Mathies AMD in the AIS pilot system without aeration because of the presence of dissolved oxygen in the influent water. Polymer evaluation conducted during the two tests involved different polymers which included the Applied Specialties Copolymer AS-1390 and Ciba Specialty Chemicals Maganafloc 10, a medium molecular weight and nonionic polymer. A third polymer was identified during the initial AIS testing that was the optimal polymer for the AIS process, which was the Ciba Specialty Chemicals Magnafloc 155, a medium molecular weight low charge anionic polymer. During the initial testing the dissolved iron increased during the use of the AS-1390 copolymer. A yellowing of the effluent was also observed. The results suggest the AS-1390 polymer may slightly interfere with the AIS catalytic oxidation properties as well as produce undesirable effluent characteristics, particularly if overdosed. It is also noteworthy, the elevated effluent total iron may have been due to the use of this polymer as well as excessive mixing during polymer dispersion (*identified during the Phillips pilot study*) as was observed during aeration only testing.

Table MM-6: Summary of analytical results from AIS pilot testing (Test AIS1) at AMD Flow = 25 gpm, Air Flow = 0 cfm (mixing only) and polymer dose 100 mL/min started on August 5, 2007 at 3:00 PM.

Location	**pH**	**Dissolved Oxygen** mg/L	**Temperature** °C	**Total Iron** mg/L	**Dissolved Iron** mg/L
8:00 PM on August 5, 2007					
Raw	6.48	6.83	13.5	26.2	18.4
React 1	6.64	5.10	14.5	970	0.86
React 2	6.70	5.24	15.7	970	0.26
AIS Recirc	--	--	--	10,800	--
9:30 AM on August 6, 2007					
Raw	6.84[1]	6.90	13.8		
React 1	6.83[1]	5.10	14.2	890	2.24
React 2	6.85[1]	4.50	14.7	860	0.75
AIS Recirc	--	--	--	11,520	--
Clarifier	--	--	--	16.1	--

[1] Electrode failure, measured with pH pen

Table MM-7: Summary of analytical results from AIS pilot testing (Test AIS2) at AMD Flow = 25 gpm and Air Flow = 0 cfm and polymer dose 100 mL/min started on August 10, 2007 at 10:30 AM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L
7:00 PM on August 10, 2007					
Raw	6.68	6.9	13.6	27.9	19.8
React 1	6.73	5.7	14.7	610	1.80
React 2	6.79	5.3	15.2	640	0.65
AIS Recirc	--	--	--	2,180	--
Clarifier	6.82	--	--	14.6	--
10:30 AM on August 11, 2007					
Raw	6.75	7.5	14.3	28.0	19.1
React 1	6.83	6.3	14.2	640	4.54
React 2	6.90	5.8	14.4	650	1.78
AIS Recirc	--	--	--	8,240	--
6:30 PM on August 11, 2007					
Raw	6.71	7.6	13.4	27.2	19.2
React 1	6.80	6.4	14.3	772	3.60
React 2	6.84	5.8	14.4	744	1.30
AIS Recirc	--	--	--	3,440	--
Clarifier	--	--	--	8.15	1.20
10:00 AM on August 12, 2007					
React 1	6.80	6.3	14.2	810	3.90
React 2	6.86	5.9	14.3	780	1.41
4:00 PM on August 12, 2007					
Raw	6.68	7.5	13.9	27.7	19.0
React 1	6.78	6.0	14.9	810	3.10
React 2	6.83	5.7	15.4	800	1.09
AIS Recirc	--	--	--	3,600	
Clarifier	--	--	--	8.35	1.21
9:00 AM on August 13, 2007					
Raw	6.70	7.3	13.8	29.3	20.3
React 1	6.82	6.0	14.0	830	4.62
React 2	6.84	5.6	14.1	850	2.12
AIS Recirc				3,940	
Clarifier				8.35	1.59

Table MM-8 contains low inflow results conducted at approximately 5 gpm. This low flow testing was conducted during an interim period while polymer samples for the identified Magnafloc 155 were obtained for subsequent testing, which took approximately one (1) week. The pilot system was run continuously during this period to accumulate additional AIS for AIS testing at higher flow rates and at the target reactor AIS concentration. Similar to previous testing this low flow period was conducted with no aeration and mixing only in the reactors. The results show the AIS process can lower dissolved iron to non-detectable levels (<0.02 mg/L) with no indications the dissolved iron will increase over time. In addition, the total iron from the clarifier approached 5 mg/L and likely could have been lower using less mixing to disperse the polymer and the optimal polymer type/dose.

Table MM-8: Summary of analytical results from AIS pilot testing (Test AIS3) at AMD Flow = 5 gpm and Air Flow = 0 cfm and polymer dose 25 mL/min started on August 13, 2007 at 10:00 AM. (for long term operation and while new polymer, Magnafloc 155, is obtained).

Location	**pH**	**Dissolved Oxygen** mg/L	**Temperature** °C	**Total Iron** mg/L	**Dissolved Iron** mg/L
6:30 PM on August 15, 2007					
Raw	6.65	7.2	13.6	28.3	19.3
React 1	7.11	6.9	17.2	700	0.62
React 2	7.19	7.3	17.7	680	0.01
Clarifier	--	--	--	5.7	0.01
7:00 PM on August 17, 2007					
Raw	6.67	7.1	13.4	28.2	21.0
React 1	7.05	6.5	18.1	580	0.23
React 2	7.17	6.8	19.1	580	0.02
Clarifier	--	--	--	4.2	0.02
8:00 AM on August 20, 2007					
Raw	6.64	7.0	13.2	29.7	20.9
React 1	6.97	5.7	15.2	590	0.60
React 2	7.14	6.8	16.0	630	0.04
Clarifier	--	--	--	5.5	0.04

High flow testing was resumed on August 20, 2008 with the use of Magnafloc 155. Initial testing (Test AIS4) was conducted at 25 gpm, no air flow, and a reactor AIS concentration of 1,700 mg/L and are summarized in Table MM-9. The initial AIS concentration was nearly twice the AIS concentration in previous tests indicating the pilot system accumulated iron oxides during the low flow period. Over the 36 hours of this test, reactor AIS concentration increased to the target 2,000 mg/L, an increase of nearly 20%. The no air flow testing decreased the dissolved iron concentration to less than 1 mg/L from the influent concentration of 21 mg/L.

Table MM-9: Summary of analytical results from AIS pilot testing (Test AIS4) at AMD Flow = 25 gpm and Air Flow = 0 cfm and polymer dose 105 mL/min started on August 20, 2007 at 11:30 AM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L
2:30 PM on August 20, 2007					
React 1	6.92	6.0	14.8	1,700	0.55
React 2	6.97	5.9	15.3	1,700	0.10
AIS Recirc	--	--	--	5,520	--
Clarifier	--	--	--	15.9	--
9:30 AM on August 21, 2007					
Raw	6.67	6.7	13.6	30.6	21.0
React 1	6.79	5.8	14.1	1,720	2.98
React 2	6.81	5.1	14.1	1,840	0.77
AIS Recirc	6.45	--	--	8,400	--
12:30 PM on August 21, 2007[1]					
React 1	6.77	5.7	14.5	1,690	2.84
React 2	6.86	5.3	14.7	1,790	0.58
Clarifier	6.82	5.1	14.7	10.2	0.85
7:00 PM on August 21, 2007					
Raw	6.65	6.9	13.6	30.2	21.1
React 1	6.79	5.7	14.6	1,990	2.64
React 2	6.83	5.3	14.9	1,860	0.76
AIS Recirc	--	--	--	6,000	--
Clarifier	--	--	15.0	11.4	0.91

[1] Switch over to new polymer at 11:30 AM, Ciba Magnafloc 155

Test AIS5 was conducted with similar operating conditions as Test AIS4 except aeration was provided at 8 cfm, 0.3 cfm per gpm. The results of the Test AIS5 are summarized in Table MM-10. As shown in the Table MM-9 and MM-10, air flow is an important factor in the oxidation process through increases in the dissolved oxygen concentration and increase in pH. Aeration increases pH through carbonic acid removal. The air flow increase from 0 to 8 cfm nearly doubles the dissolved oxygen concentration from 5 mg/L to nearly 10 mg/L and increased pH from 6.8 to 7.2. The heterogeneous oxidation rate model indicates the changes would increase the ferrous iron oxidation rate by a factor of 2 and 6, respectively. The increases in oxidation rates are reflected in the effluent dissolved iron concentration decrease from 0.6 mg/L to less than 0.05 mg/L, greater than ten-fold decrease.

Table MM-10: Summary of analytical results from AIS pilot testing (Test AIS5) at AMD Flow = 25 gpm and Air Flow = 8 cfm in Reactor 1 only and polymer dose 115 mL/min started on August 21, 2007 at 8:00 PM.

Location	**pH**	**Dissolved Oxygen** mg/L	**Temperature** °C	**Total Iron** mg/L	**Dissolved Iron** mg/L
11:15 AM on August 22, 2007					
Raw	6.67	7.1	13.9	29.9	20.7
React 1	7.10	9.3	14.7	1,870	0.46
React 2	7.21	9.5	14.9	1,790	0.07
AIS Recirc	--	--	--	4,500	--
Clarifier	--	--	--	8.40	0.06
5:00 PM on August 22, 2007					
Raw	6.65	6.9	13.9	28.6	19.5
React 1	7.11	9.2	15.1	1,860	0.24
React 2	7.20	9.5	15.4	1,780	0.09
AIS Recirc	--	--	--	4,500	--
Clarifier	--	9.6	15.5	8.05	0.04

Table MM-11: Summary of analytical results from AIS pilot testing (Test AIS6) at AMD Flow = 40 gpm and Air Flow = 12 cfm and polymer dose 150 mL/min started on August 22, 2007 at 6:00 PM.

Location	**pH**	**Dissolved Oxygen** mg/L	**Temperature** °C	**Total Iron** mg/L	**Dissolved Iron** mg/L
8:30 AM on August 23, 2007					
Raw	6.63	7.2	13.4	28.3	21.1
React 1	7.09	9.5	13.8	1,990	0.62
React 2	7.20	9.9	13.9	2,050	0.06
AIS Recirc	--	--	--	5,560	--
Clarifier	--	--	--	15.0	0.07
12:30 PM on August 22, 2007[1]					
React 1	7.05	9.2	15.1	2,100	0.58
React 2	7.14	9.5	15.4	2,250	0.08
AIS Recirc	--	--	--	6,760	--
Clarifier	--	9.6	15.4	7.4	0.04

[1] *Polymer dose increase to 200 mL/min*

During Test AIS6 the inflow was increased to 40 gpm from the 25 gpm inflow rate in the previous test. Polymer dose and air flow rate were proportionally increased during the test. The results of Test AIS6 are summarized in Table MM-11. The dissolved iron removal in Test AIS6 are similar to Test AIS5 with dissolved iron decreasing to less than 0.05 mg/L. In fact, Test AIS6 showed dissolved iron removal was nearly complete in the first reactor indicating the oxidation rates and the effectiveness of AIS process had improved compared to the previous test. This suggests the process may have less interferences or improved AIS surface area, associated with the Magnafloc 155 polymer compared to the AS-1390 polymer due to formation of new AIS solids that eliminate the interference of the AS-1390 polymer. The improved oxidation rates were also observed at the Phillips discharge pilot study which was conducted exclusively with the Magnafloc 155.

During Test AIS7 the inflow was increased once again from the 40 gpm to 60 gpm inflow rate. Polymer dose rate was increased proportionally during the test. Air flow rate was increased from 12 cfm to 16 cfm, which is approximately 0.25 cfm per gpm. The results of Test AIS7 are summarized in Table MM-12. The dissolved iron removal in Test AIS6 was similar to Test AIS5 with dissolved iron decreasing to less than 0.05 mg/L. In fact, Test AIS7 showed dissolved iron removal was nearly complete in the first reactor indicating the oxidation rates and the effectiveness of AIS process had improved compared to the previous test. This suggests the process may have less interferences or improved AIS surface area, associated with the Magnafloc 155 polymer compared to the AS-1390 polymer due to formation of new AIS solids that eliminate the interference of the AS-1390 polymer. The improved oxidation rates were also observed at the Phillips discharge pilot study which was conducted exclusively with the Magnafloc 155.

Table MM-12: Summary of analytical results from AIS pilot testing (Test AIS7) at AMD Flow = 60 gpm and Air Flow = 16 cfm in Reactor 1 only and polymer dose 250 mL/min started on August 23, 2007 at 2:00 PM.

Location	**pH**	**Dissolved Oxygen** mg/L	**Temperature** °C	**Total Iron** mg/L	**Dissolved Iron** mg/L
2:00 PM on August 24, 2007					
Raw	--	7.0	13.7	--	--
React 1	7.00	9.2	14.4	2,100	0.93
React 2	7.11	9.5	14.5	2,000	0.17
AIS Recirc	--	--	--	5,760	--
Clarifier	--	9.7	14.7	8.25	0.16
7:30 PM on August 24, 2007					
Raw	6.65	6.9	13.5	29.3	21.0
React 1	7.01	9.2	14.1	2,050	1.14
React 2	7.14	9.4	14.4	2,150	0.14
AIS Recirc	--	--	--	7,160	--
Clarifier	--	9.6	15.5	5.20	0.21

Clarification was not the primary objective of the study. Due to constraints in the design of the system to maintain portability, the trailer system included a compact upflow clarifier. The primary objective of the clarifier was to retain AIS solids for recirculation to the reactors in order to maintain high concentrations of AIS in the reactors for oxidation of ferrous iron. This primary objective was achieved based on the increase in the AIS concentration from 800 mg/L to greater than 2,000 mg/L during high flow testing and the maintenance of AIS concentrations between 2,000 and 2,500 mg/L during the high flow testing. AIS was actually wasted during later high flow tests to prevent additional accumulation of AIS in excess of the desired operating range. Effluent monitoring from the clarifier indicated effluent total iron (average = 8 mg/L) was less than influent total iron (average = 30 mg/L) which also indicates AIS solids were retained and accumulated in the system.

Particulate iron ranged from 4.0 to 15 mg/L in the effluent from the upflow clarifier during all tests. It was later determined the mixer used to disperse the polymer during high flow tests sheared particles creating small stable particles that would not settle. In addition, early testing with the AS-1390 caused yellowing of the effluent and may have contributed to higher effluent iron. Despite the clarification issues, the effluent iron concentration at high flow tests was typically between 5 and 8 mg/L and at a hydraulic loading of greater than 2,500 gallons per day per square foot. This is over three times the recommended hydraulic loading (800 gpd/ft^2) by the manufacturer (Purestream, Inc.) for the AIS pilot study upflow clarifier. The pilot unit also does not include a flocculation reactor prior to the clarifier, which would also enhance settling characteristics of the AIS. Based on bench testing conducted with the Maganafloc 155, longer flocculation time would produce larger rapidly settling particles. This would have lowered effluent total iron from the pilot system clarifier.

Ferrous Oxidation Kinetic Evaluation

The results of the AIS pilot study were also used to evaluate: 1) the validity of the heterogeneous ferrous iron oxidation model for the sizing of reactor systems; 2) the effects of the polymer on the AIS solids and implications with respect to oxidation rates; and 3) the AIS solids used from the Blue Valley treatment system on the ferrous iron oxidation rates. The heterogeneous ferrous iron oxidation model was used to predict the oxidation rate (*pseudo*-first order) and the ferrous iron concentration in the reactor using complete mix reactor equations. The results of the comparison are summarized in Table MM-13.

Based on the measured versus modeled ferrous iron comparisons in Table MM-13, the model predicts both the oxidation rate and the reactor ferrous iron concentration (remaining after oxidation). The differences ranged from 0.05 to 3.6 mg/L with an average difference of 1.00 mg/L. There was a period in the middle of the pilot study where the differences were the greatest. This period coincides with the use of the AS-1390 polymer which was suspected to interfere with the AIS solids. Later high flow tests using the Magnafloc 155 polymer were more consistent with the model predictions. The range of differences was between 0.05 and 0.89 mg/L during the high flow tests (Test AIS5, AIS6 and AIS7). The average difference during the high flow tests was 0.30 mg/L indicating the model reasonably predicts the performance in the pilot unit. This validation of the heterogeneous ferrous iron oxidation model permits its use to determine the adequate size of an AIS system to treat the Monview-Mathies AMD discharge. The preliminary/conceptual design of the system is summarized in the following sections.

Table MM-13: Summary of Iron Oxidation Data From Each Reactor During AIS Studies and Comparison to Calculated Dissolved Iron Using the Heterogeneous Iron Oxidation Model.

Test	Reactor	pH	Dissolved Oxygen mg/L	Temp. °C	AIS mg/L	Meas. Diss. Fe mg/L	Calc. Diss. Fe mg/L	Difference Diss. Fe (Meas-Calc)
AIS1	React 1	6.64	5.1	14.5	970	0.86	2.00	-1.14
AIS1	React 2	6.70	5.2	15.7	970	0.26	0.12	0.14
AIS2	React 1	6.73	5.7	14.7	608	1.80	1.75	0.05
AIS2	React 2	6.79	5.3	15.2	640	0.65	0.12	0.53
AIS2	React 1	6.83	6.3	14.2	645	4.54	1.10	3.44
AIS2	React 1	6.80	6.4	14.3	772	3.6	1.20	2.4
AIS2	React 2	6.90	5.8	14.4	652	1.78	0.10	1.68
AIS2	React 2	6.84	5.8	14.4	744	1.30	0.10	1.2
AIS2	React 1	6.80	6.3	14.2	810	3.90	1.10	2.8
AIS2	React 1	6.78	6.0	14.9	810	3.10	1.00	2.1
AIS2	React 2	6.86	5.9	14.3	780	1.41	0.05	1.36
AIS2	React 2	6.83	5.7	15.4	800	1.09	0.04	1.05
AIS2	React 1	6.82	6.0	14.0	830	4.62	1.00	3.62
AIS4	React 1	6.92	6.0	14.8	1,700	0.55	0.29	0.26
AIS4	React 1	6.79	5.8	14.1	1,720	2.98	0.57	2.41
AIS4	React 1	6.77	5.7	14.5	1,690	2.84	0.58	2.26
AIS4	React 1	6.79	5.7	14.6	1,990	2.64	0.47	2.17
AIS4	React 2	6.81	5.1	14.1	1,840	0.77	0.02	0.75
AIS4	React 2	6.86	5.3	14.7	1,790	0.58	0.02	0.56
AIS4	React 2	6.83	5.3	14.9	1,860	0.76	0.01	0.75
AIS5	React 1	7.10	9.3	14.7	1,870	0.46	0.065	0.395
AIS5	React 1	7.11	9.2	15.1	1,860	0.24	0.066	0.174
AIS5	React 2	7.21	9.5	14.9	1,790	0.07	0.01	0.06
AIS5	React 2	7.20	9.5	15.4	1,780	0.09	0.01	0.08
AIS6	React 1	7.09	9.5	13.8	1,990	0.62	0.14	0.48
AIS6	React 1	7.05	9.2	15.1	2,100	0.58	0.11	0.47
AIS6	React 2	7.20	9.9	13.9	2,050	0.06	0.01	0.05
AIS6	React 2	7.14	9.5	15.4	2,250	0.08	0.01	0.07
AIS7	React 1	7.00	9.2	14.4	2,100	0.93	0.25	0.68
AIS7	React 1	7.01	9.2	14.1	2,050	1.14	0.25	0.89
AIS7	React 2	7.11	9.5	14.5	2,000	0.17	0.01	0.16
AIS7	React 2	7.14	9.4	14.4	2,150	0.14	0.01	0.13

IRON OXIDE SOLIDS DISPOSAL/REUSE

The wet solids produced by the treatment process are important representing the labor needed to handle and process solids and the volume of solids requiring disposal. AIS treatment produces a low volume of solids because the solids density is approximately 20-30% for 24 hour settled AIS. The purity of iron oxide solids produced by AIS treatment may be important for final reuse. Table MM-14 contains the analytical results from an AIS sample collected during the pilot studies. The sample had a solids content of 21% after only 6 hours of settling. Additional settling time would increase solids content. The analytical results the sample is nearly all iron (54%), which reflects greater than 95% iron oxides. Calcium is the second largest metal in the sample at 1.4%, which equates to a calcium carbonate content of 3.5%. Trace metal analysis indicates the sample has very low trace metal concentrations, which should not limit the disposal or reuse options for the waste solids.

Table MM-14: Laboratory Analysis of AIS Sample from the Pilot Study.

	Unit	**Detection Limit**	**Result**	**% Content**
Solids Content (Wet)	%	0.01		20.8
Dry Weight Basis				
Iron	mg/kg	1	537,500	54
Manganese	mg/kg	1	348	0.03
Aluminum	mg/kg	5	3,580	0.35
Calcium	mg/kg	1	14,200	1.4
Magnesium	mg/kg	1	400	0.04
Sodium	mg/kg	1	160	0.02
Potassium	mg/kg	1	35	<0.01
Silica	mg/kg	1	97	<0.01
Arsenic	mg/kg	1	48	<0.01
Lead	mg/kg	0.25	0.9	<0.01
Selenium	mg/kg	0.25	<0.25	<0.01
Zinc	mg/kg	1	123	0.01

AIS SYSTEM DESIGNS

The results of the pilot study will be used to develop two designs: 1) a new AIS reactor system to replace the existing caustic soda chemical treatment; and 2) a modified aeration treatment system utilizing new aeration tanks followed by the existing settling ponds. A third option was also evaluated that uses a pond aeration system in the existing settling pond followed by installation of a new settling pond to collect the precipitated iron oxide solids The following sections will provide treatment system designs, estimated capital and installation costs, and operating costs for the various treatment options. Due to uncertainties in operation, operational labor will only include a weekly time commitment for normal operation.

Monview-Mathies AIS Treatment System

Based on the pilot study results, the AIS treatment system for the Monview-Mathies AMD discharge will consist of: 1) a two-stage reactor system; 2) a clarification system including a polymer feed, flocculation tank, and circular clarifiers; and 3) a solids handling system to concentrate and store solids from the AIS treatment system. Table MM-15 summarizes the design information and influent water quality. A schematic flow path of the AIS treatment system is depicted in Figure MM-5. Figure MM-6 shows a conceptual AIS treatment system layout at the existing Monview-Mathies AMD discharge site.

Table MM-15: Summary of design information for the Monview-Mathies AMD discharge AIS treatment system.

Estimated Flow (gpm)		**Influent Water Quality**				
Average	**Maximum**	**pH**	**Total Al mg/L**	**Ferrous Fe mg/L**	**Total Fe mg/L**	**Alkalinity mg/L**
1,800	3,000	6.6	<0.5	20	30	350

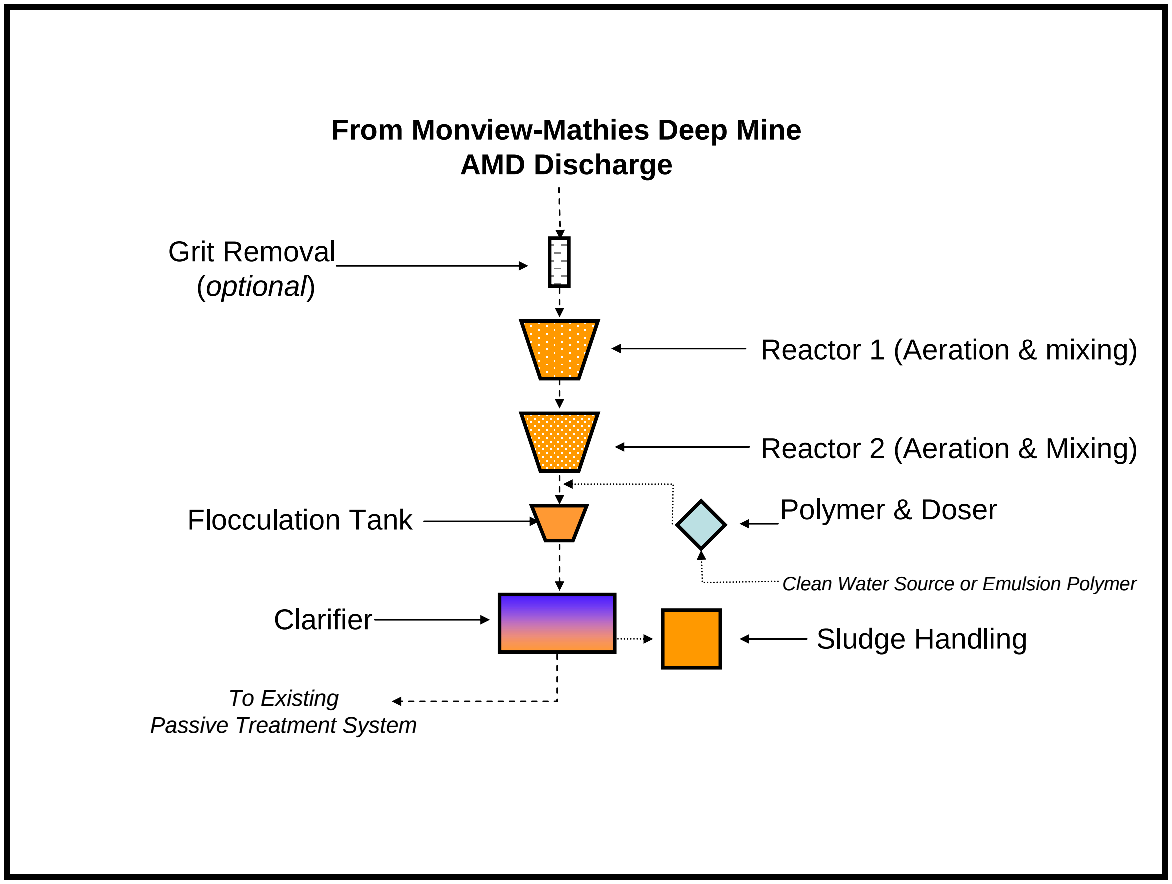
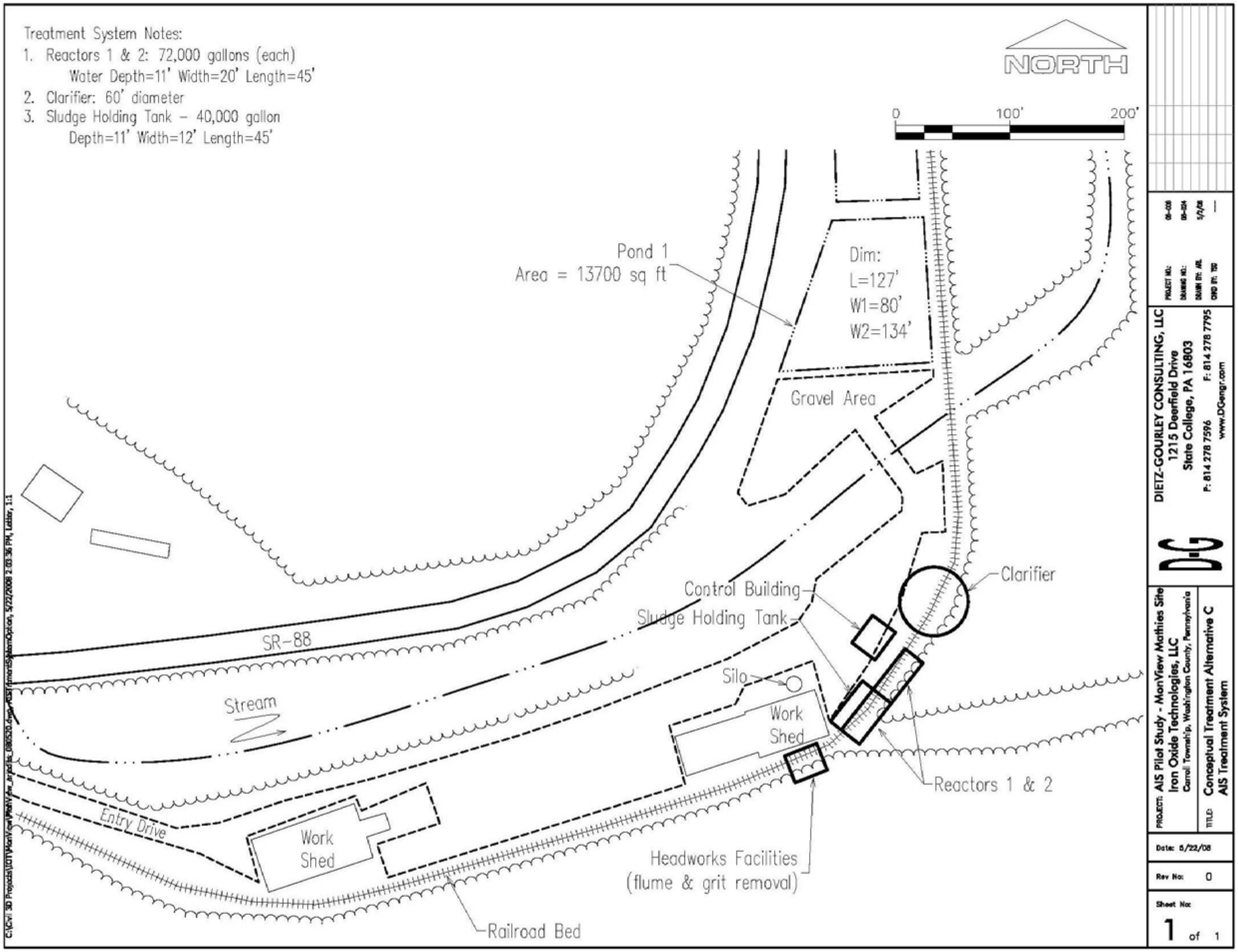


Figure MM-5. Monview-Mathies AMD Discharge AIS Treatment System Flow Path

Figure MM-6. Monview-Mathies Conceptual AIS Treatment System Layout



Treatment System Notes:

1. Reactors 1 & 2: 72,000 gallons (each)
   Water Depth=11' Width=20' Length=45'
2. Clarifier: 60' diameter
3. Sludge Holding Tank – 40,000 gallon
   Depth=11' Width=12' Length=45'

The design criteria and effluent water quality for the Monview-Mathies AIS treatment system were determined based on the heterogeneous ferrous iron oxidation model kinetic rates and results of the AIS pilot study. Table MM-16 summarizes the design criteria for the Monview-Mathies AMD AIS treatment system and the anticipated effluent water quality. The expected performance of the Monview-Mathies AIS treatment system is near complete removal under average flow conditions (< 0.5 mg/L of Fe) and maximum flow conditions (< 2 mg/L of Fe). This effluent quality should meet the required effluent limits for Monview-Mathies AMD discharge. In addition, the effluent quality from the system should permit use of the existing passive treatment pond for recreational fishing and/or fish culture.

Table MM-16: Summary of design information and anticipated effluent water quality of the Monview-Mathies AIS treatment system.

Condition	Flow gpm	Reactor 1 DT Hrs	Reactor 2 DT Hrs	Clarifier ft/hr	Anticipated Effluent Quality pH		
					pH	Total Fe mg/L	Alkalinity mg/L
Average	1,800	0.7	0.7	35	7.0	<0.5	325
Maximum	3,000	0.4	0.4	80	6.8	<2.0	325

Flow Measurement & Grit Removal

Flow measurement will be included in the design of the system. This flow will be used in the control panel for automated process control. Process control is required to optimize reactor conditions through aeration and polymer dose for flocculation. Both controls will have cost benefits in electricity demand and polymer dose. Grit removal will be incorporated in flow measurement system prior to the reactors to collect solid material that is likely contained in the discharge flow. The coarse material to be removed is from erosion of materials from the deep mine and precipitated solids from the AMD in the collection pipes.

Reactors

The two-stage AIS reactor system follows the flow measurement. The AIS reactors are sized based on the heterogeneous ferrous iron oxidation model, reactor equations, and the pilot study results. The Stage 1 Reactor will contain 42 minutes (0.7 hours) of detention time at average and 24 minutes (0.4 hours) of detention time at maximum flow, the design flow. The reactors will contain top mounted high performance axial flow mixers to suspend the AIS. The reactors will also have aeration provided by fine bubble diffusers using positive displacement blowers. The aeration is needed to remove excess carbon dioxide in the Monview-Mathies AMD and formed from the reaction of ferrous iron with the AIS. Aeration volume delivered will be based on AMD flow in order to maintain the optimal pH and dissolved oxygen required for the AIS process.

Clarification

The clarification system will consist of a polymer dosing system, flocculation zone circular clarifiers. A polymer was identified during the pilot study. The polymer reacts with the AIS during flocculation to form large rapidly settling particles. The powder polymer identified is a medium molecular weight, low charge anionic acrylamide polymer (Magnafloc 155, Ciba Specialty Chemicals). The polymer will be dosed at the outlet of the Stage 2 Reactor. The polymer dosed water will flow into the flocculation zone of the clarifier. High performance variable speed mixers equipped with radial flow impellers to promote flocculation and minimize shear will mix the flocculation tank. Flocculated solids will flow from the flocculation zone into horizontal flow hopper bottom circular clarifiers. The hoppers are equipped with solids collection systems to remove settled solids for recirculation of the AIS to the reactors or removal of accumulated solids to an AIS holding tank.

Solids Handling

An AIS holding tank will receive excess solids from the clarifiers where the solids will be allowed to further thicken with additional settling time. The Monview-Mathies AIS treatment system will produce an average volume of AIS to be wasted daily between 2,500 and 3,000 gallons per day (6% solids). However, the solids handling facility will concentrate the solids to a final volume between 800 and 1,000 gallons per day (20% solids). The solids handling will consist of a holding tank with storage capacity between 30 and 60 days. The holding tank will be equipped with a decant pump to remove clarified water from the top of the solids holding tank and return it to the treatment system. Solids will accumulate in the bottom of the tank until the tank is full which corresponds to approximately 50% of the total volume of solids. A jet mixer placed in the bottom of the tank will be used to periodically and at the time for transport to the disposal site re-suspend the thickened solids to slurry. A submersible pump will be used to remove the slurry from the tank for transport to a disposal or processing site.

ESTIMATED AIS TREATMENT SYSTEM COSTS – CAPITAL & OPERATIONAL

The Monview-Mathies AIS Treatment System capital costs will include reactor tanks, clarifiers, water piping, air lines, drop-outs, diffusers, blowers, mixers, control panels, buildings for housing the control panel and blowers, solids handling tanks, and perimeter fence. Backup electrical generators should also be considered to prevent loss of treatment in case of power failure.

Table MM-17 provides an estimate of the capital costs associated for the 4.3 MGD (3,000 gpm) Monview-Mathies AIS Treatment System. Actual costs of an AIS Treatment System may vary depending on a number of factors related to final effluent quality goals and the site conditions. In addition to the treatment system costs, there will be costs associated with site development, treatment system installation, control/polymer building installation, and perimeter fencing. The estimated cost for these items is $160,000 which results in a total estimated cost for the treatment system and installation of $1,760,000.

Table MM-17: Monview-Mathies AMD Discharge AIS Treatment System Preliminary Equipment List & System Cost[1]

Item No.	Item Description	Number
1	**Control System**	
	a. PLC Unit	1
	b. pH/Turbidity/Flow Monitors	1
	c. Operation Building	1
2	**AIS Treatment System – IOT, Inc.**	
	a. 72,000 gallon Reactor Tanks (mix & aeration)	2
	b. 5 H.P Top Mounted Mixers (incl. mounts)	8
	c. 25 H.P. Blower & Aeration Equipment	2
	D 2,200 sq. ft. Flocculation Clarifiers	1
	e. 15 H.P. AIS Recirculation and WAIS Pumps	2
	f. Polymer Dosing System	1
4	**Sludge Handling System – IOT, Inc.**	
	a. 80,000 gallon AIS Holding Tank	1
	b. 40 H.P. Jet Mixer	1
	c. 3 H.P. Rail Mounted Decant Pump	1
	d. 5 H.P. Sludge Discharge Pump	1
Estimated System Cost		**$1,520,000**
Estimated Freight		**$80,000**
Estimated Total Equipment Cost		**$1,600,000**

[1] Costs reflect January 2008 pricing for equipment and freight

Table MM-18 provides an estimate of O&M Costs for the Monview-Mathies AIS Treatment system and includes labor, operating and maintenance costs. Also provided is the value of the iron oxide solids produced and the direct effect this beneficial reuse will have on the O&M costs by removing disposal costs and offsetting other operating costs. Depending on a number of factors, the annual O&M costs at the Monview-Mathies treatment system will be between $35,000 and $165,000.

Table MM-18: Monview-Mathies AIS Treatment System Operating Cost Estimate

Item	**Cost $/yr**
O&M Electricity ($/yr)	$42,500
Polymer Use ($/yr)	$7,500
Solids Disposal ($/yr)	$75,000
Equipment Maintenance ($/yr)	$10,000
Personnel O&M Costs ($/yr)	*$20,000-$40,000*
Total O&M Costs ($/yr)	**$135,000**[1]
Non-Personnel O&M Costs ($/yr)	**$165,000**
Potential Iron Oxide Reuse (@ $0.05/lb)	***+$24,000***
BALANCE of O&M Costs	***$36,000***

[1] using personnel O&M cost of $20,000/yr

The AIS treatment costs will vary depending on inclusion of the various Monview-Mathies system capital and operating costs. Using the annual operating cost (labor not included) of $135,000 for the Monview-Mathies system equates to a cost of $0.14 per 1,000 gallons of treated water. If sludge disposal costs are removed and an iron oxide revenue option is identified, the treatment costs decrease to treatment costs to $0.04 per 1,000 gallons. The total treatment cost for the Monview-Mathies AMD discharge using the AIS treatment process, includes annualized capital costs (25-year basis) and all O&M costs ($165,000 per year), is $0.24 per 1,000 gallons of treated AMD.

The AIS treatment system was developed to provide a high quality effluent limit that typically will result in an effluent total iron less than 1 mg/L. The AIS treatment system can be modified resulting in reduced treatment costs if higher iron in the effluent can be tolerated without causing NPDES permit violations.

Monview-Mathies Aeration Only Treatment Option

The pilot study aeration testing provided results indicting the treatment of the Monview-Mathies discharge can be accomplished with aeration only. Aeration accomplishes treatment by oxidizing the soluble ferrous to insoluble ferric iron through 1) increase in the AMD pH by removal of excess carbon dioxide; and 2) providing additional dissolved oxygen to the AMD. For the Monview-Mathies AMD the pH increase causes a 100-fold increase in the rate compared to an approximate 2-fold increase associated with the dissolved oxygen. The following provides a summary of three (3) alternatives to accomplish treatment of the Monview-Mathies AMD discharge using aeration only. The three aeration alternatives are:

1. A complete replacement system (similar to the AIS treatment system) but with no solids recirculation)
2. A partial replacement using aeration tanks prior to the existing settling basins; and
3. A new and innovative, in-situ pond aeration system known as Lasaire Aeration.

Complete Aeration Treatment System option

The Monview-Mathies Complete Aeration Treatment System option is similar to the AIS Treatment system except the reactor tanks are equipped with aeration only (no mixers) and there is no recirculation of solids. Based on the pilot study results, the aeration only treatment option requires 2,000 cfm and 1.1 million gallons of reactor volume to lower the dissolved ferrous iron to less than 0.3 mg/L. This would allow the system to meet the total iron limits. Treatment volume and air flow can be adjusted if higher effluent dissolved iron will meet the required effluent limits. All other system components would be the similar to the AIS treatment system discussed above. The conceptual layout of the Complete Aeration Treatment System is depicted on Figure MM-7 and shows the system to have a substantially larger footprint than the AIS treatment system option.

Figure MM-7. Monview-Mathies Conceptual Complete Aeration Treatment System Layout

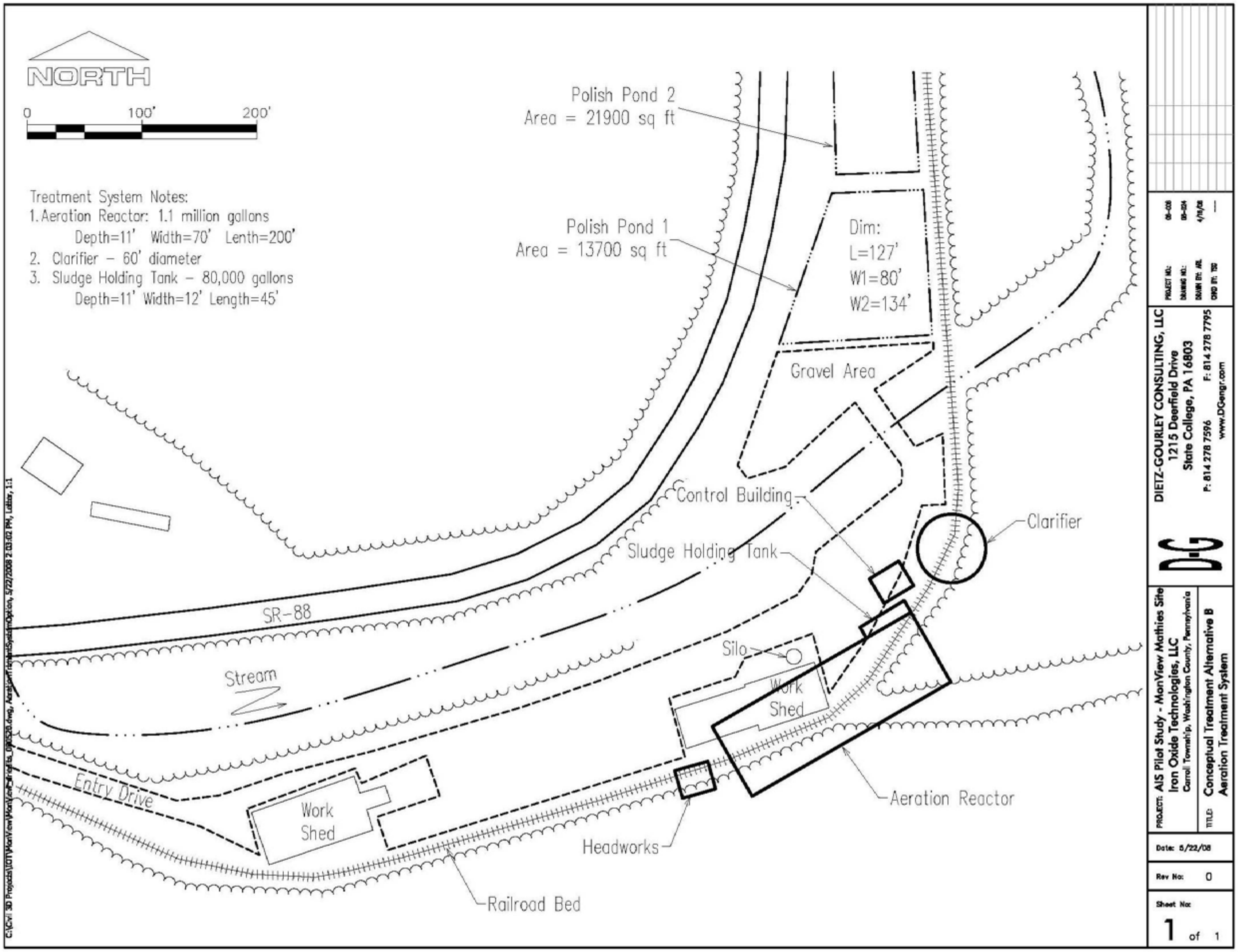


Table MM-19 provides an estimate of the capital costs associated for the 4.3 MGD (3,000 gpm) Monview-Mathies Aeration Treatment System. Actual costs of an AIS Treatment System may vary depending on a number of factors related to final effluent quality goals and the site conditions. In addition to the treatment system costs, there will be costs associated with site development, treatment system installation, control/polymer building installation, and perimeter fencing. The estimated cost for these items is $160,000 which results in a total estimated cost for the treatment system and installation of $2,620,000.

Table MM-19: Monview-Mathies AMD Discharge Complete Aeration Treatment System Preliminary Equipment List & System Cost[1]

Item No.	Item Description	Number
1	**Control System**	
	a. PLC Unit	1
	b. pH/Turbidity/Flow Monitors	1
	c. Operation Building	1
2	**Complete Aeration Treatment System – IOT, Inc.**	
	a. 1.1 million gallon aeration tanks (mix & aeration)	1
	b. 50 H.P. Blower & Aeration Equipment	3
	c. 1,500 sq. ft. Flocculation Clarifiers	1
	d. 15 H.P. Waste Sludge Pumps	2
	e. Polymer Dosing System	1
4	**Sludge Handling System – IOT, Inc.**	
	a. 80,000 gallon AIS Holding Tank	1
	b. 40 H.P. Jet Mixer	1
	c. 3 H.P. Rail Mounted Decant Pump	1
	d. 5 H.P. Sludge Discharge Pump	1
Estimated System Cost		**$2,400,000**
Estimated Freight		**$60,000**
Estimated Total Equipment Cost		**$2,460,000**

[1] Costs reflect January 2008 pricing for equipment and freight

Table MM-20 provides an estimate of O&M Costs for the Monview-Mathies AIS Treatment system and includes labor, operating and maintenance costs. Also provided is the value of the iron oxide solids produced and the direct effect this beneficial reuse will have on the O&M costs by removing disposal costs and offsetting other operating costs. Depending on a number of factors, the annual O&M costs at the Monview-Mathies aeration treatment system will be between $125,000 and $160,000.

Table MM-20: Monview-Mathies Complete Aeration Treatment System Operating Cost Estimate	
Item	**Cost $/yr**
O&M Electricity ($/yr)	$33,500
Polymer Use ($/yr)	$7,500
Solids Disposal ($/yr)	$75,000
Equipment Maintenance ($/yr)	$10,000
Personnel O&M Costs ($/yr)	*$20,000-$40,000*
Total O&M Costs ($/yr)	**$156,000**[1]
Non-Personnel O&M Costs ($/yr)	**$126,000**

[1] using personnel O&M cost of $30,000/yr

The aeration system treatment costs will vary depending on inclusion of the various Monview-Mathies system capital and operating costs. Using the annual operating cost (labor not included) of $126,000 for the Monview-Mathies system equates to a cost of $0.13 per 1,000 gallons of treated water. The solids produced by the system would likely have lower value than the AIS process due to iron oxide solid contamination with calcium carbonate precipitates, this may also increase sludge handling costs. The total treatment cost for the Monview-Mathies AMD discharge using the aeration treatment process, includes annualized capital costs (25-year basis) and all O&M costs ($156,000 per year), is $0.28 per 1,000 gallons of treated AMD. The overall treatment costs are modestly more expensive than the AIS treatment approach. The aeration only treatment system and the AIS treatment system treatment costs are similar.

Aeration Tank Existing Settling Pond Option

An alternative to the full aeration treatment system is to utilize the existing treatment ponds for settling of the particulate iron and install an aeration system to oxidize the dissolved ferrous iron prior to the ponds. This approach would eliminate the capital costs associated with the clarifiers and the sludge handling system. Based on the elimination of these systems the capital costs for the aeration reactor would be decreased to approximately $1,500,000.

Electricity costs associated with operation would decrease slightly by removing the power demand of the clarifier and the sludge handling equipment. Sludge handling and disposal costs would likely increase due greater labor intensive efforts to remove the sludge from the pond on a periodic basis versus an automated continuous removal approach. Table MM-21 summarizes the anticipated operating costs for the aeration system that utilizes existing treatment ponds for solids removal. Polymer costs have been included to aid in clarification during periods of high flow to improve solids settling.

The aeration system in combination with the existing settling ponds treatment costs will vary depending on inclusion of the various Monview-Mathies system capital and operating costs. Using the annual operating cost (labor not included) of $138,500 for the Monview-Mathies system equates to a cost of $0.15 per 1,000 gallons of treated water. The solids produced by the system would likely have lower value than the AIS process due to iron oxide solid contamination with calcium carbonate precipitates, this may also increase sludge handling costs. The total treatment cost for the Monview-Mathies AMD discharge using the aeration treatment process, includes annualized capital costs (25-year basis) and all O&M costs ($148,500 per year), is $0.22 per 1,000 gallons of treated AMD. The overall treatment costs are slightly less expensive than the complete aeration system due to lower capital costs.

Table MM-21: Monview-Mathies partial Aeration Treatment System Operating Cost Estimate

Item	**Cost $/yr**
O&M Electricity ($/yr)	$27,500
Polymer Use ($/yr) – *optional*	$3,500
Solids Disposal ($/yr)	$100,000
Equipment Maintenance ($/yr)	$7,500
Personnel O&M Costs ($/yr)	*$20,000-$40,000*
Total O&M Costs ($/yr)	**$148,500**[1]
Non-Personnel O&M Costs ($/yr)	**$138,500**

[1] using personnel O&M cost of $20,000/yr

Lasaire Aeration and New Settling Pond Treatment Option

The final aeration option utilizes a newly identified aeration technology known as Lasaire aeration that is currently being tested at several AMD sites in Pennsylvania. This aeration system can be placed in a new or retrofitted into the existing pond. This permits utilizing greater water volumes (i.e., detention times) contained in the pond to lower the needed aeration; air volume required is a function of system detention time air flow decreasing as reactor detention time increases.

Ponds can be constructed at a much lower cost than concrete aeration tanks, as long as there are no land area constraints. In the case of the Monview-Mathies discharge and treatment site available land area is not a constraint for an aeration system. There are also existing ponds that can be utilized for the Lasaire aeration system with new additional ponds constructed to settle the iron from aerated water. By utilizing the existing pond for the Lasaire aeration system and installing new additional ponds to settle the iron from the aerated AMD the capital costs can be greatly reduced. Figure MM-8 provides a conceptual layout of the Lasire Asration system showing the new pond for solids removal.

Table MM-22 summarizes the additional capital costs for installation of the Lasaire Aeration system in the existing pond and construction of new settling ponds at the site. The estimated total cost of $475,000 for this approach includes all labor and installation.

Figure MM-8. Monview-Mathies Conceptual Layout for the Retrofit Lasaire Aeration System and New Settling Pond.

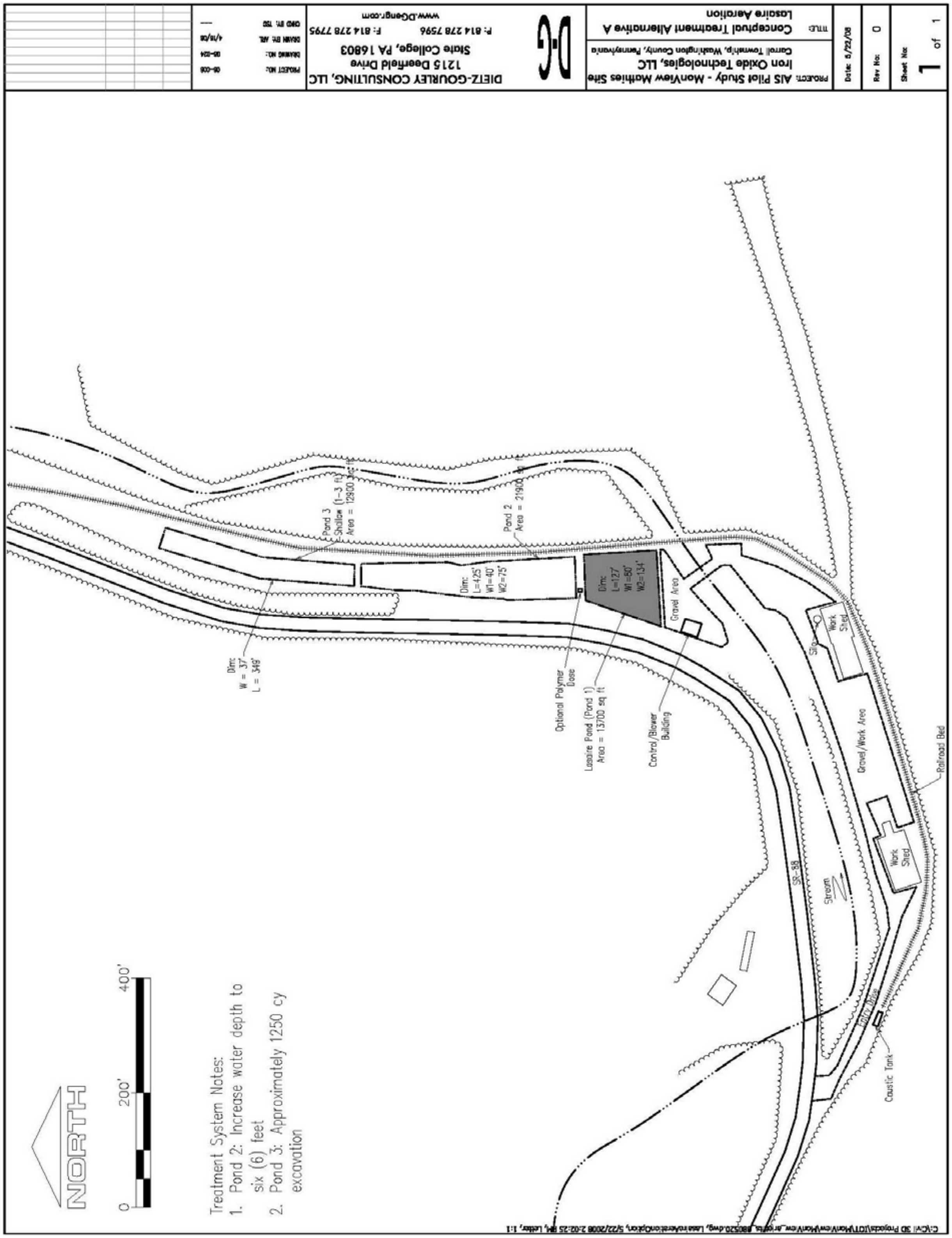


Table MM-22: Monview-Mathies AMD Discharge Lasaire Aeration Treatment System Preliminary Equipment List & System Cost[1]

Item No.	Item Description	Number
1	**Control System**	
	a. Control panel	1
	b. Flow Monitor	1
	c. Operation Building	1
2	**Lasaire Aeration System – IOT, Inc.**	
	a. Complete Aeration System for 0.7 acre pond	1
	b.20 H.P. Blower & Aeration Equipment	3
	c. Polymer Dosing System (optional)	1
3	**New Ponds (37 ft width/350 feet length)**	
	a. Excavation	1
	b. Synthetic Liner	1
	c. Piping	1
Estimated System Cost		**$450,000**
Estimated Freight		**$25,000**
Estimated Total Cost		**$475,000**

[1] Costs reflect January 2008 pricing for equipment and freight

The electricity required for this aeration is substantially less than the other alternatives for several reasons including: 1) longer detention times decrease the required air volume (and horsepower) to accomplish the required pH adjustment through carbon dioxide removal; 2) with additional pond treatment the required increase in pH (and carbon dioxide removal) is lower than the other aeration options as iron oxidation and removal will occur in the additional ponds versus the straight aeration systems that require near complete oxidation at the effluent from the aeration reactor. Solids handling (i.e., sludge removal and disposal) will be greater in this aeration option due to the dredging costs associated with periodic solids removal from the ponds. Consideration should be given in the design for additional ponds to be included in the system for the periodic sludge removal periods. Table MM-23 summarizes the anticipated operating costs for the Lasaire aeration system. Polymer costs have been included to aid in clarification during periods of high flow to improve solids settling.

Table MM-23: Monview-Mathies Lasaire Aeration Treatment System Operating Cost Estimate

Item	Cost $/yr
O&M Electricity ($/yr)	$14,000
Polymer Use ($/yr) – *optional*	*$3,500*
Solids Disposal ($/yr)	$100,000
Equipment Maintenance ($/yr)	$3,500
Personnel O&M Costs ($/yr)	*$20,000-$40,000*
Total O&M Costs ($/yr)	**$141,000**[1]
Non-Personnel O&M Costs ($/yr)	**$121,000**

[1] using personnel O&M cost of $20,000/yr

The Lasaire aeration system in combination with the existing and new settling ponds will have treatment costs that will vary depending on inclusion of the various Monview-Mathies system capital and operating costs. Using the annual operating cost (labor not included) of $121,000 for the Monview-Mathies system equates to a cost of $0.13 per 1,000 gallons of treated water. The solids produced by the system would likely have lower value than the AIS process due to iron oxide solid contamination with calcium carbonate precipitates, this may also increase sludge handling costs. The total treatment cost for the Monview-Mathies AMD discharge using the aeration treatment process, includes annualized capital costs (25-year basis) and all O&M costs ($121,000 per year), is $0.14 per 1,000 gallons of treated AMD. The overall treatment costs are less expensive than the complete aeration system due to lower capital costs.

SUMMARY

The AIS pilot study results and this summary report provide considerable information regarding the AIS Treatment process. The results indicate:

- AIS Treatment effectively oxidizes ferrous iron in short detention times needed to meet effluent objectives for the Monview-Mathies AMD.
- AIS ferrous iron oxidation rates are not affected by polymer dosing.
- Observed oxidation rates by the AIS solids are consistent with the heterogeneous ferrous iron oxidation model.

Based on the results of the pilot study and the heterogeneous ferrous iron oxidation model, an AIS treatment system was developed for the Monview-Mathies AMD discharge that will produce an effluent iron less than 0.5 mg/L at average flows and 2 mg/L at maximum flows. The Monview-Mathies treatment system will have a capital cost of $1,500,000 with an annual operating cost between $36,000 and $165,000 depending on inclusion of labor and solids reuse. The treatment costs for the Monview-Mathies discharge range between of $0.04 and $0.24 per 1,000 gallons of treated water depending on inclusion of various operating costs and reflection of capital costs in the estimate.

The AIS Treatment approach offers the potential for iron recovery and reuse from the treated AMD and with solids characteristics that offer a significant potential for beneficial reuse. Investigations indicate there is substantial potential for the solids to be used in the pigment industry. This investigation is ongoing.

Alternatives to AIS treatment were also developed for the Monview-Mathies discharge involving aeration only approaches including a full aeration treatment system, a combination of aeration tanks and the existing settling ponds, and a new in-situ Lasaire aeration system followed by existing and additional aerobic/settling ponds. The Lasaire aeration option was the lowest cost treatment option with estimated capital costs of $450,000 and estimated annual operating costs of $20,000, excluding solids handling and disposal. The selection of the best treatment approach will depend on short and long term goals of treatment and iron oxide solids recovery, disposal and reuse.

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Activated Iron Solids Treatment Pilot Study for Phillips Acidic Mine Drainage

SUMMARY REPORT

Submitted to:

Department of Environmental Protection
Bureau of Abandoned Mine Reclamation
Ebensburg, Pennsylvania

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June 6, 2008

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INTRODUCTION

The discharge of acid mine drainage (AMD) to surface waters in Pennsylvania and other eastern coal region states contaminates thousands of miles of waterways resulting in their non-compliance with numerous Pennsylvania Water Quality Standards including, but not limited to, pH, total iron, suspended solids, and aesthetics. The AMD is a result of past (and unregulated) surface and underground coal mining that exposes pyritic minerals to atmospheric oxygen and results in the oxidation and the production of AMD.

Of particular concern is AMD produced in the vast historic and abandoned deep mine workings found throughout the coal region. The pyrite oxidizes to create AMD that collects and is stored in the mine voids forming large underground reservoirs of contaminated AMD. These large underground AMD reservoirs discharge at one or more points, typically from air portals (for air circulation during active operations), water portals/drains (to maintain a minimal water level in the mine during active operations), or from the mine entry. Deep mine discharges tend to be very high flow with elevated ferrous iron but may contain adequate alkalinity for iron removal. The deep mine discharges are often the largest contributor of metal loading in the watershed and/or subbasin. Treatment is mandatory to achieve water quality goals in the receiving stream.

The impact of the high flow AMD discharges on receiving streams is substantial. Input of high flow and ferrous iron AMD to surface waters causes: 1) increase of instream iron concentrations to levels exceeding water quality standards; 2) instream oxidation causes the deposition of iron oxides, known as “yellowboy”, onto stream bottoms smothering aquatic life and causing aesthetic and sediment problems; and 3) oxidation of ferrous iron can cause a decrease in pH to less than 6, a water quality standard. Theses types of impacts lead to degradation of the receiving waters to conditions that do not meet the waters designated aquatic life, recreational, and water supply uses.

Development of new and innovative treatment systems that effectively remove AMD pollutants at substantially lower capital and operating costs is paramount to the watershed restoration efforts across Pennsylvania. AIS (Activated Iron Solids) treatment has been identified as a potential new and innovative AMD treatment approach to address high flow AMD sources and or AMD treatment where land constraints or effluent objectives dictate active treatment.

This report summarizes the Phillips AIS pilot study to evaluate the use of AIS treatment to treat the Phillips AMD discharge to Redstone Creek near Uniontown in Fayette County, PA.

SITE DESCRIPTION & BACKGROUND

The Phillips AMD discharge is a high flow deep mine discharge in the Redstone Creek watershed with characteristics summarized in Table PH-1. The Phillips discharge is the largest source of AMD in the watershed comprising greater than 90% of the AMD loading in the watershed.

The purpose of this AIS pilot study on the Phillips AMD discharge was to investigate the new and innovative AIS technology as a treatment alternative for conventional lime-based active treatment or passive treatment. The following provides the technical background information for the pilot study including AMD characteristics at the Phillips AMD discharge, background iron oxidation information, and a brief description of the AIS treatment process.

AMD Characteristics

The historic AMD discharge chemistry and flow data for the Phillips AMD discharge are summarized in Table PH-1. Recent data collected during the pilot study are summarized in Table PH-2. The historic data for the Phillips discharge indicates the AMD is net alkaline with a pH between 6.0 and 6.8. Recent data from the pilot study indicates the Phillips discharge has a pH of 6.12 and is net alkaline. The pH and alkalinity indicate the discharge contains elevated carbon dioxide acidity with the recent data indicating a calculated concentration exceeding 400 mg/L. The Phillips discharge has elevated iron concentrations with a historic average ferrous iron concentration of 61 mg/L compared to the 48 mg/L concentration measured during the pilot study. The historic flow and the more recent chemistry will be used to size a treatment system.

Table PH-1: Historic Phillip Mine AMD Discharge Characteristics (1998-2004).

Condition	Flow gpm	pH	Total Fe mg/L	Fe^{2+} mg/L	Total Mn mg/L	Alkalinity mg/L	Calc. Acidity* mg/L	CO_2 Acidity mg/L	Sulfate mg/L
Average	4054	6.0	68	61	3.0	226	-98	540	600
Maximum	6325	6.8	69	63	3.6	217	-85	83	650
Minimum	1681	6.6	67	48	2.6	237	-112	143	850

* Calc. Acidity value determined after all iron has been oxidized and precipitated.

Table PH-2: Phillip Mine AMD Discharge Characteristics from Pilot Study.

Temperature °C	Dissolved Oxygen mg/L	pH	Total Fe mg/L	Fe^{2+} mg/L	Alkalinity mg/L	Calc. Acidity* mg/L	CO_2 Acidity mg/L
14.9	0.24	6.13	47.7	47.6	238	-150	425

* Calc. Acidity value determined after all iron has been oxidized and precipitated.

Historic data indicates the Phillips discharge contains predominately ferrous iron (Fe^{2+}), but also small amounts of ferric iron (Fe^{3+}); ferric iron is the difference between total iron and ferrous iron. Given the pH of the waters (pH>5), it is unlikely the discharge contains any dissolved ferric iron (ferric iron is not soluble above a pH of 4). The measurement of ferric iron is probably the result of sample handling and/or laboratory procedures causing entrainment of iron oxide solids into the sample or oxidation of ferrous iron to ferric iron during collection and analysis procedures. This is supported by the pilot study testing of the Phillips discharge which only shows an average difference of 0.1 mg/L between total and ferrous iron. The ferrous iron concentration is important since it is the oxidation of ferrous iron that is the controlling step in iron removal from mine drainage.

Alkalinity was evaluated to determine if there is adequate alkalinity in the AMD for the removal of iron from the mine drainage. The oxidation and precipitation of 1 mg/L of ferrous iron will consume 1.8 mg/L of alkalinity. The Acidity column in Table PH-1 and PH-2 is the calculated acidity after all iron has been oxidized and precipitated. The negative acidity values indicate the Phillips discharge has excess alkalinity.

Carbon dioxide (CO_2) acidity data was also calculated to determine the amount of aeration needed to remove the CO_2 in AIS treatment process and maintain or raise the pH to levels needed for the effective oxidation of ferrous iron in the AIS treatment approach. In aqueous chemistry, carbon dioxide acidity is present in water as carbonic acid (H_2CO_3). The pH of water (controlled by the carbonate system) is determined by the concentrations of bicarbonate (HCO_3^-), which is alkalinity, and H_2CO_3 according to the following relationship:

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \qquad \text{(PH-1)}$$

The pK_a of this equilibrium is 6.4. This 6.4 would also be the pH at which the H_2CO_3 and HCO_3^- concentrations would be equal. This means an alkalinity (HCO_3^-) of 100 mg/L (as $CaCO_3$) would require an equal CO_2 acidity (H_2CO_3) of 100 mg/L (as $CaCO_3$) to have a pH of 6.4. The CO_2 acidity calculated for the Phillips discharge is 425 mg/L (as $CaCO_3$), based on monitoring of the discharge during the pilot study. The source of this acidity is chemical neutralization reactions in the deep mine pool as well as decomposition reactions. The CO_2 acidity is about 200 times higher than is normally found in surface waters in equilibrium with the atmosphere.

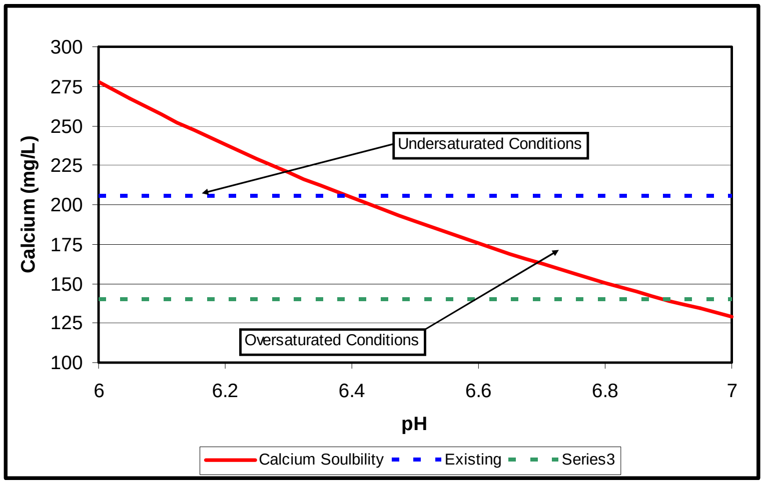


Figure PH-1. Calcium solubility in the AMD discharge with respect to pH.

The solubility of calcium and magnesium in the AMD must be evaluated for the various treatment methodologies. pH adjustments may create operation and maintenance issues by precipitating calcium and magnesium. Figure PH-1 shows the calcium (calcite) solubility with respect to pH for the Phillips discharge. Oversaturated conditions at the higher pH indicate calcium (calcite) will precipitate if the pH is increased. This is a potential operation and maintenance issue by creating more solids. This method of calcium precipitation is well known and used in water treatment to soften waters by adding lime (CaO) to raise the pH of water to decrease the solubility and remove calcium (calcite) hardness. At pH greater than 8, magnesium will also be removed as a hydroxide. Calcium and magnesium precipitation in lime-based treatment will increase operation and maintenance by increasing solids handling and disposal. AIS treatment oxidizes ferrous iron at acidic pH (less than 7) and prevents the additional solids volumes associated with calcium and magnesium precipitation compared to lime-based or aeration treatment approaches.

Another important parameter listed in Table PH-2 is the temperature of the discharge. Temperature of the water is important because it affects a number of chemical and physical processes in the treatment of AMD. The temperature of the Phillips discharge is 14.9°C. This temperature will affect aeration, oxidation and the settling processes. As an example, the homogeneous oxidation rate doubles for every 2°C increase in temperature. The heterogeneous oxidation process is similarly affected by temperature. The temperature of the Phillips discharge is similar to other deep mine discharges in southwestern Pennsylvania.

The chemistry evaluation for the discharges is an integral component in determining appropriate approaches and methods for treating the AMD. The impacts of the AMD chemistry on the various treatment approaches will be compared in a subsequent section.

Iron Oxidation & Removal in AMD Treatment

The treatment of the Phillips AMD discharge requires iron removal and this iron removal is a multi-step process involving:

1. Oxidation of dissolved ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+});
2. Hydrolysis of ferric iron to form insoluble ferric oxide ($Fe(OH)_3$);
3. Flocculation of tiny (sub micrometer - μm) iron oxide particles to form larger (micrometer - μm) iron oxide particles;
4. Settling of suspended iron oxide particles from solution.

Depending on the type of treatment, one or more of the above processes will control the removal of iron. In passive treatment the oxidation (Step 1) of ferrous iron is very slow and determines iron removal and the size of the passive treatment system. In chemical treatment at high pH (> 8), the settling (Step 4) typically controls iron removal. The new and innovative process, AIS treatment, provides an alternative to passive treatment and chemical treatment.

The oxidation of ferrous iron is the first and most crucial step in the removal of iron. Without the oxidation step, ferrous iron would remain in solution (except at very high pH) and removal of iron from AMD would not be possible. There are two types of ferrous iron oxidation in water:

1. ***Homogeneous Ferrous Iron Oxidation (HoFIO) –*** is the long established oxidation process occurring in solution and involves the reaction of dissolved ferrous iron (Fe^{2+}) with dissolved oxygen.
2. ***Heterogeneous Ferrous Iron Oxidation (HeFIO) –*** is a newly identified oxidation process occurring on the surface of iron oxide solids and involves the sorption of ferrous iron and dissolved oxygen followed by the rapid catalytic oxidation on the surface of the iron oxide.

The first type, HoFIO is the ferrous iron oxidation that occurs in solution and is most commonly associated with passive treatment and conventional (lime-based) chemical treatment of AMD. This process is also the dominate process where aeration is used to add oxygen and raise the pH to greater than 7, a pH where HoFIO will dominate. The long established HoFIO rate equation (Sung & Morgan 1980) is:

$$\text{(PH-2)} \quad \textit{HoFIO rate}\ (\mathrm{M \cdot s^{-1}}) = -\delta[\mathrm{Fe(II)}]/\ \delta t = k_{\mathrm{Ho1}} \times [\mathrm{Fe(II)}_{\mathit{diss}}] \times [\mathrm{O_2}] / \{\mathrm{H+}\}^2$$

The HoFIO equation is complex with the HoFIO rate affected by the ferrous iron concentration $[Fe(II)_{diss}]$, dissolved oxygen $[O_2]$ and pH $\{H^+\}$. Temperature is an integral part of the equation by its affects on the reaction rate constant (k_{Ho2}), with a decrease in temperature causing a decrease in the oxidation rate. The HoFIO equation is a reliable design tool because the equation can be used to predict iron removal for 1) different AMD chemistry, and 2) factors in iron removal under operating conditions (e.g., dissolved oxygen, pH and temperature). The HoFIO model will be used to evaluate ferrous iron oxidation results for the pilot study where only aeration is used in the reactors to increase dissolved oxygen and pH.

Heterogeneous ferrous iron oxidation (HeFIO) is an oxidation process that occurs on iron oxide surfaces and is the oxidation process AIS uses to oxidize ferrous iron. HeFIO is a two step processes that involves 1) the sorption of ferrous iron to the surface of the iron oxide, 2) rapid oxidation in the presence of dissolved oxygen to form new iron oxides directly on the surface of the iron oxide. Equations and models for the reactions are contained in Dietz (2003). The equations are complex describing both sorption and oxidation process.

$$\text{(PH-3)} \qquad \textit{HeFIO rate}\ (\mathrm{M} \cdot \mathrm{s}^{-1}) = (-\delta[\mathrm{Fe(II)}]/\ \delta t) = (k_{He1}[O_2]S_1) + (k_{He2}[O_2]S_2)$$

and

$$\text{(PH-4)} \qquad S_x = \frac{1+([Fe(II)_{diss}]\times K_x^{app})}{[\equiv Fe(III)]\times\Gamma_x\times\{H^+\}^x}$$

where **x** is the reaction (either 1 or 2), $\mathbf{k_{Hex}}$ are the surface oxidation rate constants, $\mathbf{K_x^{app}}$ are the surface complexation constants, and **[≡Fe(III)]** is the AIS concentration (in mg/L). Dietz (2003) determined the various thermodynamic constants for the equations including activation energies and enthalpies, which describe the effects of changing temperature. In current treatment systems (including passive treatment and lime treatment), HeFIO is not very important (< 5%) due to the low concentrations of suspended iron oxides (typically less than 5 mg/L). Iron Oxide Technologies, LLC has developed several treatment systems optimizing HeFIO through concentrated suspensions of iron oxide solids in reactor systems. Figure PH-2 shows the time required to oxidize and remove ferrous iron from AMD for various treatment methods from bench-scale testing conducted at 15°C on an anoxic AMD discharge. Note, the x-axis time scale is

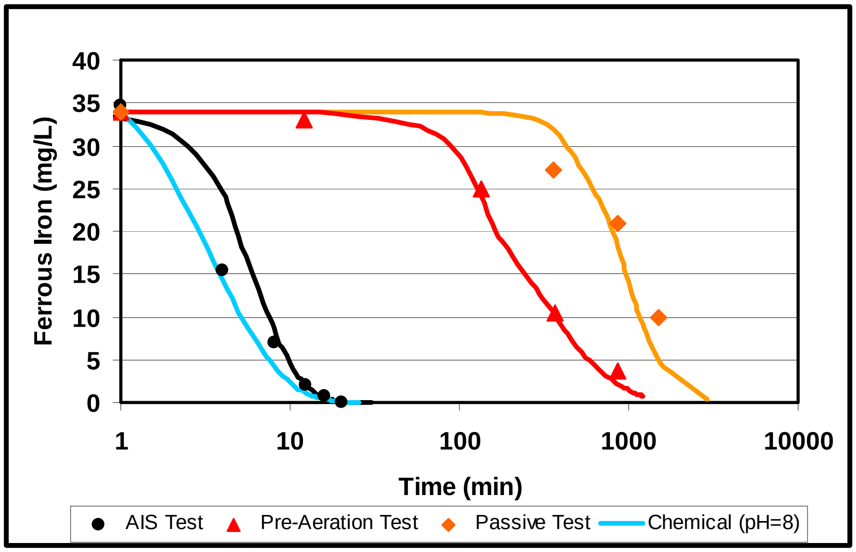


Figure PH-2. Bench-scale Results for Activated Iron Solids (AIS), Pre-aeration & Passive Tests

logarithmic. The detention time required to achieve less than 0.5 mg/L ferrous iron for the passive treatment and passive treatment with pre-aeration tests were 50 and 25 hours, respectively. Critical low-temperature conditions (Average Temp. = 8°C) would require additional detention times (2 to 5 times) to complete oxidation. As a comparison, the AIS treatment test required only 20 minutes to achieve 0.5 mg/L, which demonstrates the importance of HeFIO and the ability AIS treatment to achieve rapid oxidation and removal of ferrous iron. AIS treatment is 75 times faster in comparison to pre-aeration/passive treatment and 150 times faster in comparison to passive treatment only. A pH 8 oxidation line is also provided to show AIS ferrous iron oxidation is similar to conventional lime-based treatment: the 0.5 mg/L ferrous iron is expected to occur in 15 to 20 minutes detention time.

Innovative AIS Treatment

Iron Oxide Technologies, LLC has developed new (patent pending) active treatment approaches collectively known as Activated Iron Solids (AIS) treatment of AMD. AIS treatment has numerous advantages over conventional chemical treatment that can make long term treatment and iron oxide recovery possible at abandoned mine discharges. The AIS treatment advantages over conventional chemical treatment are:

1) Oxidation and removal occur at slightly acidic pH (6-7);
2) Oxidation rates are as fast as conventional chemical treatment;
3) For net alkaline AMD no alkaline chemicals are needed;
4) For net acidic waters, inexpensive pulverized (powder) limestone can be used for the needed alkalinity;
5) Solids produced by the AIS process are high-density (30% solids);
6) Solids are high purity iron oxides (95% iron oxides on a dry weight basis).

These advantages will have a direct effect on treatment costs by eliminating (or minimizing) chemical use and cost, and simplifying operation that will decrease manpower requirements. The innovative active AIS treatment processes utilized for the pilot study at Phillips is the Two-Stage AIS Reactor System (depicted in Figure PH-3). The AIS system uses high iron oxide concentrations (AIS = 1,500 – 2,500 mg/L) to increase ferrous

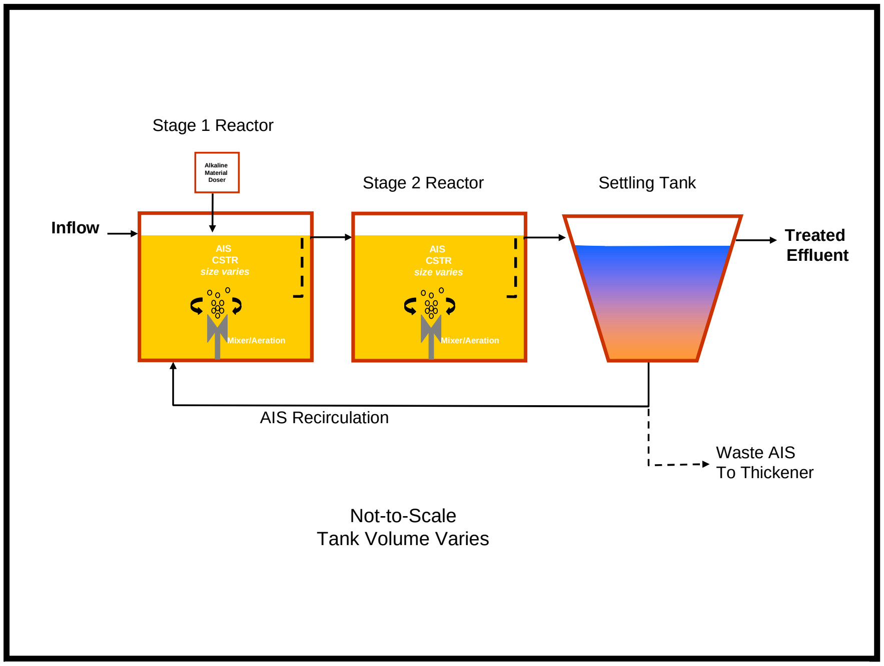


Figure PH-3. AMD Treatment in a Two-Stage Flow-Through AIS System

iron oxidation and removal. The high iron oxide concentrations produce a catalytic environment that promotes ferrous iron oxidation and removal while producing high-density and pure treatment solids (iron oxide solids). The Two-Stage AIS Reactor system maintains high reactor AIS concentrations through recirculation of solids collected in the clarifier.

PHILLIPS PILOT STUDY

A location was identified for the pilot study adjacent to the discharge along Redstone Creek. There was a limited access trail located behind Kurosky's Garage along Route 51 North. A right-of-way was obtained by DEP-BAMR from the land owner (Paul Kurosky). DEP-BAMR improved the access road and installed a stone staging pad for the pilot system in Summer 2007 using materials purchased through this contract.

The pilot system was moved to the Phillips AMD discharge site on September 6, 2007. Setup of the system was completed on September 18th and pilot system testing was initiated on September 19th. Setup of the AIS pilot unit consisted of moving the trailer unit onto the pad and leveling the trailer unit with wooden support pillars. AMD was directed to the pilot unit using a 1 horsepower submersible pump placed in the existing discharge channel and 4-inch flat pipe was used to convey the AMD from the discharge channel to the inlet weir box of the pilot system. The effluent from the pilot unit, along with overflow from the inlet weir box, was conveyed back to the AMD discharge channel from the pilot treatment system using 4-inch flat pipe. No electrical service was available at this site. Electricity for the pilot unit and inlet pumps was provided by a portable trailer 25 KVA diesel generator. Single phase 230 volt electrical connections were made to the pilot unit control panel from the diesel generator.

The Phillips pilot study was conducted during September and October 2007. The inflow pump was started on September 18, 2007 to fill the tanks and testing was initiated on September 19, 2007. AIS for startup of the pilot unit were transported from the previous testing location (Monview-Mathies), however additional AIS needed to be accumulated for the pilot testing at the Phillips site. Pilot testing at Phillips consisted of two phases: 1) initial low flow operation to accumulate the needed AIS: and 2) AIS treatment pilot testing to determine the detention time and aeration requirement which involves high AIS reactor concentrations through solids recirculation from the clarifier.

Analytical Methods

Analysis for the pilot study consisted of pH, dissolved oxygen, temperature, total iron, dissolved iron, alkalinity and periodic conductivity. pH was measured with an Fisher Scientific Accumet Portable Meter equipped with a Cole Parmer Accumet combination pH electrode. The pH electrode was calibrated daily prior to use with pH 4.00 and pH 7.00 buffers. Dissolved oxygen (DO) and temperature were measured with an YSI Model 550A DO Meter. The DO Meter was calibrated prior to each use using the air saturation method. Total iron was measured using a Hach Iron Pocket Colorimeter Test Kit (0-3.00 mg/L) using Ferrover reagent after appropriate dilution. Dissolved iron was also measured with the Iron Pocket Colorimeter but after filtration using a syringe and a 0.2 μm syringe filter, and appropriate dilution. Ferrous iron was determined using Hach ferrous iron powder packets and the Hach Iron Pocket Colorimeter.

Initial testing on the discharge indicated dissolved iron (filtered sample) equals ferrous iron for the conditions in the Phillips AMD. As a result, the dissolved iron test was used to determine ferrous iron. Alkalinity was measured on a 100 mL sample using a Hach Digital Titrator, a 1.600 N sulfuric acid cartridge. Conductivity was measured with an Oakton Conductivity Pen.

AIS Pilot Testing

The AIS test settings covered a broad range of operating conditions to determine optimal operating conditions for the Phillips AIS treatment system including varying polymer dose, AIS concentration, and aeration. In the case of the AIS concentration, the target was an AIS (as total iron) of greater than 1,500 mg/L in the reactors using recirculation of solids from the clarifier. The initial startup conditions for the pilot unit were:

1. Reactor 1 & 2 AIS ~ 500 mg/L (as Fe)
2. Air Flow = 18 cfm – air flow was varied during testing
3. AMD Inflow = 6 gpm
4. AIS Recirculation Rate = 5 gpm
5. Initial Polymer Dose Rate = 17 mL/min (0.5 mg/L of inflow) - *polymer dose was increased during test*

To start the pilot system, AIS solids were added to the pilot unit using solids retained in the pilot system from the previous Monview-Maties pilot study. The use of the solids from the Monview-Mathies pilot study simplified and shortened start-up time to accumulate AIS solids for the reactor system (days versus weeks). This was imperative because of the use of a portable generator for electrical service to operate the pilot unit. Initial air flow was based on previous aeration only studies with the pilot system and was set to maintain a dissolved oxygen concentration and pH in the reactors. The initial AMD inflow was set based on calculated oxidation rates using the heterogeneous iron oxidation model. The 6 gpm flow results in an initial 5.5 hour detention time in each reactor and a total system detention time (including the clarifier) of 12 hours. The AIS recirculation rate was set at a flow rate to maintain and increase the reactor AIS concentrations based on expected solids in the recirculated flow and the AMD inflow rate. The polymer used for the test was the Ciba Specialty Chemicals Magnafloc® 155, a medium molecular weight low charge anionic acrylamide polymer. This polymer was identified as the most suitable polymer for this application based on testing of multiple polymers at the previous Monview-Mathies pilot study.

The AIS pilot system was started using the above settings on September 19th at 4:30 PM. The pilot unit was operated until October 5th with periodic adjustments to vary AMD flow, air flow, solids recirculation rates, and polymer dose. Typically, adjustments involved increasing AMD flow to the pilot unit which also resulted in increasing solids recirculation rates and polymer dose. The results from various sampling dates (and times) along with operating conditions are contained in Tables PH-3 through PH-9. There were two minor operating issues during the pilot study involving: 1) a mixer stopped operating due to a rag impingement on the impellor , and 2) breakdown of the diesel generator. The system had to be temporarily shutdown in both instances, approximately 6 hours to remove a rag from the mixer impellor and 24 hours until a replacement generator was delivered and operational.

Overall the AIS pilot study results indicate the AIS system oxidized the soluble ferrous iron in the Phillips discharge to particulate ferric iron. The dissolved iron decreased from an influent concentration of 48 mg/L to less than 0.1 mg/L in the higher AIS concentration tests. This demonstrates the AIS process can achieve the effective ferrous iron oxidation to very low concentrations approaching 100% ferrous iron removal. Air flow is an important factor in the oxidation process by increasing both dissolved oxygen and pH. Dissolved oxygen is increased through the transport of oxygen in the air to the water. pH is indirectly increased through the removal of dissolved carbonic acid in the water to carbon dioxide in the air. Based on the heterogeneous model, both the increase in dissolved oxygen and pH, substantially increased the ferrous iron oxidation rate. Dissolved oxygen concentrations increased from 0.2 mg/L to greater than 9 mg/L and the pH increased by greater than 1 pH unit in low inflow tests and 0.4 pH units in high inflow tests. As an example to demonstrate the importance of the pH change, a pH increase of 0.3 will more than triple (300%) the heterogeneous ferrous iron oxidation rate.

Table PH-3 summarizes initial operation of the AIS pilot study. The initial operation was conducted at a lower flow rate (6 gpm) to accumulate AIS solids for subsequent higher flow testing and to collect oxidation and aeration rate data for the AIS process. The initial AIS concentrations in the reactors (Total Iron ~ 450 mg/L) were the startup solids in the system from the Monview-Mathies pilot testing. As can be seen in the following tables, the AIS treatment removed nearly all the ferrous iron in the Phillips discharge at the low flow tests. Also at the flow and aeration rate used in the tests the pH of the in the reactors increased to slightly greater than 7.

Table PH-3: Summary of analytical results from Phillips AIS pilot testing (Test AIS1) at AMD Flow = 6 gpm and Air Flow = 12 cfm and polymer dose 20 mL/min started on September 19, 2007 at 4:30 PM.

Location	**pH**	**Dissolved Oxygen mg/L**	**Temperature °C**	**Total Iron mg/L**	**Dissolved Iron mg/L**
9:00 AM on September 20, 2007					
Raw	6.18	0.3	14.9	48.2	47.8
React 1	6.95	9.6	15.3	450	1.60
React 2	7.48	10.1	15.8	440	0.07
Clarifier	7.52	10.0	15.8	6.0	0.07
6:00 PM on September 20, 2007 (increased flow to 10 gpm @ 1:30 PM)					
Raw	6.18	0.3	15.1	48.2	48.2
React 1	6.83	8.9	16.8	510	0.35
React 2	7.19	9.6	17.3	580	0.01
Clarifier	--	--	--	5.25	0.01
12:30 PM on September 21, 2007					
Raw	6.05	0.25	15.4	47.8	48.8
React 1	6.63	9.0	16.0	450	0.33
React 2	6.98	9.8	16.2	430	0.05
Clarifier	7.05	9.9	16.3	5.0	0.06

Table PH-4 shows results of the Test AIS2 conducted at a slightly higher flow (10 gpm) which was also conducted to increase the AIS solids in the system and evaluate kinetic process in the system. As shown in the table, the AIS were approximately 1,300 mg/L at the start of TEST AIS2 showing Test AIS1 increased the AIS concentration (450-1,300 mg/L) in the treatment system. The oxidation of the ferrous iron during Test AIS2 was near complete with effluent less than 0.05 mg/L, 99.9% removal. The pH was increased to slightly greater than 7 during the test in the reactors from the aeration provided.

Table PH-4: Summary of analytical results from Phillips AIS pilot testing (Test AIS2) at AMD Flow = 10 gpm and Air Flow = 12 cfm and polymer dose 30 mL/min started on September 24, 2007 at 4:00 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L
9:00 AM on September 25, 2007					
Raw	6.12	0.2	15.0	47.2	47.0
React 1	6.85	9.0	15.5	1,260	0.05
React 2	7.10	10.1	15.6	1,250	0.07
AIS Recirc	--	--	--	3,640	--
Clarifier	7.05	10.1	15.6	5.90	0.07
6:30 PM on September 25, 2007					
React 1	6.83	8.7	17.1	1,420	0.05
React 2	7.11	9.6	17.6	1,150	0.02
AIS Recirc	--	--	--	2.200	--
Clarifier	7.07	9.6	17.6	5.30	0.02
9:30 AM on September 26, 2007					
Raw	6.10	0.2	15.0	47.6	47.6
React 1	6.73	8.7	15.6	1,320	0.06
React 2	7.06	9.7	16.1	1,350	0.03
AIS Recirc	--	--	--	2,800	--
Clarifier	7.04	9.8	16.1	7.05	0.03

Table PH-5 shows results of the Test AIS3 conducted at double the flow used in Test AIS 2. This is a high flow conducted to evaluate AIS treatment at a higher flow and intermediate to the heterogeneous model estimates for ferrous iron oxidation in the pilot system. This will provide an initial evaluation of the potential interferences, or reduced oxidation, in the presence of the polymer (Magnafloc 155). Also note the AIS concentration increased from 1,400 mg/L at the start of Test AIS3 to near 1,700 mg/L at the end of the test. Similar to previous tests the oxidation of the ferrous iron during Test AIS3 was near complete with effluent less than 0.05 mg/L, 99.9% removal. The pH during the higher flow rate (20 gpm) was approximately 6.8. The flow rate was decreased to 10 gpm for a period of 5 days to evaluate the long term effectiveness of the treatment process. As shown in the table, the oxidation continued and the accumulation of AIS occurred as the final AIS concentrations approached 2,000 mg/L.

Table PH-5: Summary of analytical results from Phillips AIS pilot testing (Test AIS3) at AMD Flow = 20 gpm and Air Flow = 18 cfm and polymer dose 40 mL/min started on September 26, 2007 at 10:00 AM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L
9:00 AM on September 27, 2007					
Raw	6.12	0.2	15.2	47.0	46.6
React 1	6.57	8.0	15.3	1,410	0.06
React 2	6.82	9.7	15.5	1,380	0.04
AIS Recirc	--	--	--	4,760	--
1:00 PM on September 27, 2007					
React 1	6.59	7.8	15.9	1,730	0.04
React 2	6.84	9.5	16.2	1,780	0.06
AIS Recirc	--	--	--	5,360	--
Clarifier	6.85	9.6	16.2	9.50	0.06
9:00 AM on October 2, 2007 (flow lowered to 10 gpm on 9/29 @ 2:00 PM)					
Raw	6.15	0.2	14.8	48.0	46.0
React 1	6.75	9.0	15.4	1,760	0.02
React 2	7.05	9.9	15.5	1,990	0.01
AIS Recirc	--	--	--	3,400	--
Clarifier	7.07	10.0	15.5	3.65	0.01

Table PH-6 shows results of the Test AIS4 conducted at an inflow of 40 gpm, twice the flow used in Test AIS 2. This is a high flow conducted to evaluate AIS treatment at a flow predicted by the heterogeneous model to achieve the threshold for ferrous iron oxidation in the pilot system. This test was intended to provide near complete removal of ferrous iron but with Reactor 1 containing measurable ferrous iron in the dissolved form. The AIS concentration in the Test AIS4 was at the target operational condition of 2,000 mg/L. The AIS was maintained during the test by wasting AIS solids periodically from the clarifier or Reactor 2. The results show the oxidation/removal of the ferrous iron by the pilot system during Test AIS3 was near complete with effluent less than 0.05 mg/L in the effluent. The Reactor 2 effluent also had a dissolved ferrous iron concentration less than 0.1 mg/L which was lower than expected, based on the heterogeneous model. The pH during this higher flow rate (40 gpm) also decreased from the previous test to approximately 6.7. Based on the results, the flow to the pilot system was increased to evaluate ferrous iron oxidation/removal by the pilot system at higher flows and shorter reactor detention times.

Table PH-6: Summary of analytical results from Phillips AIS pilot testing (Test AIS4) at AMD Flow = 40 gpm and Air Flow = 18 cfm and polymer dose 85 mL/min started on October 2, 2007 at 10:00 AM.

Location	**pH**	**Dissolved Oxygen mg/L**	**Temperature °C**	**Total Iron mg/L**	**Dissolved Iron mg/L**
4:00 PM on October 2, 2007					
Raw	6.15	0.2	14.8	48.0	46.0
React 1	6.55	7.5	15.4	2,590	0.06
React 2	6.75	9.5	15.6	2,250	0.01
Clarifier	--	--	--	9.3	0.01
---- Generator Breakdown, Restarted on October 3, 2007 at 10:00 AM ----					
7:00 PM on October 3, 2007					
Raw	6.17	0.3	14.8	47.6	48.5
React 1	6.45	7.5	15.2	1,920	0.07
React 2	6.72	9.6	15.3	2,210	0.01
AIS Recirc	--	--	--	5,360	--
Clarifier	6.68	9.7	15.4	10.5	0.01
8:15 AM on October 4, 2007					
React 1	6.55	7.6	14.8	2,150	0.06
React 2	6.73	9.6	14.8	1,860	0.05
AIS Recirc	--	--	--	5,320	--
Clarifier	6.75	9.6	14.8	15.1	0.04
1:00 PM on October 4, 2007					
React 1	6.50	7.5	15.6	1,940	0.05
React 2	6.69	9.5	15.8	1,850	0.02
AIS Recirc	--	--	--	4,920	--
Clarifier	6.67	9.5	15.8	8.75	0.03
5:00 PM on October 4, 2007					
Raw	6.17	0.25	14.9	47.2	46.8
React 1	6.53	7.4	15.4	1,780	0.04
React 2	6.75	9.4	15.7	1,870	0.02
AIS Recirc	--	--	--	5,200	--
Clarifier	6.75	9.6	15.7	5.35	0.03

The high flow testing conducted at influent AMD flow of 60 gpm in Test AIS5 and 80 gpm in Test AIS6 are summarized in Table PH-7 and PH-8, respectively. The AIS concentrations during the tests ranged between 2,100 and 2,500 mg/L (as Fe). The respective total detention times in the two reactors during the tests are 65 and 50 minutes. The detention times in these tests are lower than predicted by the heterogeneous model and should result in elevated dissolved ferrous iron in the reactors as well as the clarifier. However, the results indicate dissolved ferrous iron was almost completely removed throughout the pilot unit to levels less than 0.05 mg/L. This oxidation/removal is well in excess of anticipated performance by the pilot system and the AIS process. While the dissolved iron is completely removed, total ferrous iron tests (includes the sorbed ferrous fraction) indicate there is between 10 and 15 mg/L of ferrous iron sorbed to the AIS in Reactor 1. This sorbed ferrous iron is gradually oxidized in Reactor 2 and the clarifier resulting in the return AIS to Reactor 1 that has little sorbed ferrous iron and is in a condition that will rapidly remove ferrous iron from the influent AMD through sorption and oxidation. It is also noteworthy that the oxidation/removal of the dissolved ferrous iron occurred at pH between 6.3 and 6.5, a relatively low pH for the oxidation of ferrous iron and only 0.2 units greater than the influent pH.

Table PH-7: Summary of analytical results from Phillips AIS pilot testing (Test AIS5) at AMD Flow = 60 gpm and Air Flow = 18 cfm and polymer dose 140 mL/min started on October 4, 2007 at 5:30 PM.

Location	**pH**	**Dissolved Oxygen mg/L**	**Temperature °C**	**Total Iron mg/L**	**Dissolved Iron mg/L**
8:30 AM on October 5, 2007					
React 1	6.40	6.6	14.9	2,600	0.11
React 2	6.65	8.8	15.0	2,200	0.03
AIS Recirc	--	--	--	5,400	--
Clarifier	6.62	9.1	15.0	14.5	0.05
1:00 PM on October 5, 2007					
Raw	6.11	0.2	14.9	49.6	49.8
React 1	6.32	6.9	15.2	2,120	0.06
React 2	6.51	8.8	15.3	2,250	0.00
AIS Recirc	--	--	--	6,640	--
Clarifier	6.47	--	--	5.15	0.03
5:30 PM on October 5, 2007					
React 1	6.35	6.9	15.3	2,190	0.02
React 2	6.56	8.8	15.4	2,500	0.01
AIS Recirc	--	--	--	7,440	--
Clarifier	6.52	8.8	15.4	6.25	0.01

Table PH-8: Summary of analytical results from Phillips AIS pilot testing (Test AIS6) at AMD Flow = 80 gpm and Air Flow = 18 cfm and polymer dose 180 mL/min started on October 5, 2007 at 6:00 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L
8:00 AM on October 6, 2007					
React 1	6.32	6.1	14.8	2,100	0.09
React 2	6.40	8.3	14.9	2,600	0.04
AIS Recirc	--	--	--	10,300	--
Clarifier	6.38	--	15.0	5.8	0.04
10:30 AM on October 6, 2007					
Raw	6.10	0.2	15.0	47.4	47.6
React 1	6.30	5.8	15.2	2,600	0.04
React 2	6.51	8.4	15.3	2,300	0.03
AIS Recirc	--	--	--	9,200	--
Clarifier	6.47	8.4	15.4	1.05	0.01
12:30 PM on October 6, 2007					
React 1	6.28	6.4	15.4	2,100	0.05
React 2	6.44	8.4	15.5	2,500	0.02
AIS Recirc	--	--	--	11,000	--
Clarifier	6.36	8.5	15.5	7.0	0.02

Test AIS7 was the final test conducted at the Phillips site and is summarized in Table PH-9. The flow for this test was conducted at 10 gpm a flow rate consistent with average loading rate on the clarifier. This was done based on operational conditions (i.e., AIS concentration, polymer dose rate, polymer mixing) for solids removal in the clarifier. As shown in the table, dissolved ferrous iron is completely removed. In addition, the clarifier operated more effectively lowering the total effluent iron to less than 2 mg/L. This demonstrates the clarifier can achieve adequate effluent iron under the optimal loading and operating conditions.

Table PH-9: Summary of analytical results from Phillips AIS pilot testing (Test AIS7) at AMD Flow = 10 gpm and Air Flow = 10 cfm and polymer dose 33 mL/min started on October 6, 2007 at 2:00 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L
3:30 PM on October 7, 2007					
React 1	6.83	8.7	17.2	1,770	0.00
React 2	7.15	9.6	17.7	1,770	0.00
AIS Recirc	--	--	--	4,800	--
Clarifier	7.20	9.7	17.5	1.95	0.00

Effluent total iron was tested during the pilot study; however, clarification was not the primary objective of the study. Due to constraints in the design of the system to maintain portability, the trailer system included a compact upflow clarifier. The primary objective of the clarifier was to retain AIS solids for recirculation to the reactors in order to maintain high concentrations of AIS in the reactors for oxidation of ferrous iron. This primary objective was achieved based on maintenance of AIS concentration between 1,500 and 2,500 mg/L during the high flow testing of the AIS pilot study. In fact, AIS was wasted during the later tests to prevent accumulation of solids in the clarifier and reactors. Despite the limitations, effluent monitoring from the clarifier indicated effluent total iron (average = 5 mg/L) was less than influent total iron (average = 48 mg/L), indicating AIS solids were retained and accumulated in the system. Higher effluent concentrations during early testing were due to particle shear, identified during testing, by the mixer used to disperse the polymer into the effluent from Reactor 2 (prior to the clarifier). Subsequent testing yielded lower effluent iron. The final testing yielded a total iron less than 2 mg/L from the clarifier.

The effluent total iron concentrations achieved during the high flow testing were at a hydraulic loading of 3,100 to 4,200 gallons per day per square foot. This is in excess of four times the recommended hydraulic loading (800 gpd/ft^2) by the manufacturer (Purestream, Inc.) for the AIS pilot study upflow clarifier. The final test where less than 2 mg/L was achieved occurred at a hydraulic loading of 510 gallons per day per square foot. The pilot unit does not include a flocculation reactor prior to the clarifier, which is recommended where polymers are used. Based on bench testing conducted with the Magnafloc 155 polymer, longer flocculation time is needed to produce larger rapidly settling particles and to remove smaller difficult to settle particles. Bench testing using this approach achieved less than 1 mg/L of total iron after short (less than 5 minutes) flocculation and settling times.

Ferrous Oxidation Kinetic Evaluation

The results of the AIS pilot study were also used to evaluate: 1) the validity of the heterogeneous ferrous iron oxidation model for the sizing of reactor systems at the Phillips site; and 2) the effects of the polymer on the AIS solids and implications with respect to sorption and oxidation rates. The heterogeneous ferrous iron oxidation model was used to predict the oxidation rate (*pseudo*-first order) and the ferrous iron concentration in the reactors using complete mix reactor equations. The results of the comparison are summarized in Table PH-10.

Based on the measured versus modeled ferrous iron comparisons in Table PH-10, the model over predicts both the reactor ferrous iron concentration (remaining after sorption/oxidation) and under predicts the oxidation rate. In other words, ferrous iron removal was much faster during the Phillips AIS pilot study than the model predicted. The differences ranged from -3.06 to +1.32 mg/L. The +1.32 mg/L is the highest over prediction error and appears to be an outlier that is likely due to initial startup conditions in the pilot system. The next over prediction error is +0.069 mg/L, a value representing a near zero error.

Table PH-10: Summary of Iron Oxidation Data From Each Reactor During AIS Studies at Phillips and Comparison to the Calculated Dissolved Iron Using the Heterogeneous Iron Oxidation Model.

Test	**Reactor**	**pH**	**Dissolved Oxygen** **Mg/L**	**Temp.** **°C**	**AIS** **mg/L**	**Meas. Diss. Fe** **mg/L**	**Calc. Diss. Fe** **Mg/L**	**Difference Diss. Fe** **(Meas-Calc)**
AIS1	1	6.95	9.6	15.3	450	1.6	0.28	+1.32
AIS1	2	7.48	10.1	15.8	440	0.07	0.001	+0.069
AIS1	1	6.83	8.9	16.8	510	0.35	0.66	-0.31
AIS1	2	7.19	9.6	17.3	580	0.01	0.002	+0.008
AIS1	1	6.63	9.0	16.0	450	0.33	1.15	-0.82
AIS1	2	6.98	9.8	16.2	430	0.06	0.010	+0.05
AIS2	1	6.85	9.0	15.5	1260	0.05	0.34	-0.29
AIS2	1/2	6.95	9.3	15.8	1,320	0.03	0.0014	+0.0286
AIS2	1/2	6.97	9.2	17.3	1,280	0.02	0.0009	+0.0191
AIS2	1/2	6.90	9.2	15.8	1,330	0.06	0.0013	+0.0587
AIS3	1/2	6.70	8.8	15.4	1,400	0.04	0.025	+0.015
AIS3	1/2	6.71	8.6	16.0	1,750	0.06	0.013	+0.047
AIS4	1/2	6.65	8.5	15.5	2,420	0.01	0.05	-0.04
AIS4	1/2	6.58	8.6	15.2	2,060	0.01	0.13	-0.12
AIS4	1/2	6.64	8.6	14.8	2,000	0.05	0.10	-0.05
AIS4	1/2	6.60	8.5	15.7	1,900	0.02	0.12	-0.10
AIS4	1/2	6.58	8.4	15.6	1,820	0.02	0.16	-0.14
AIS5	1/2	6.52	7.7	15.0	2,400	0.03	0.48	-0.45
AIS5	1/2	6.42	7.8	15.2	2,180	0.03	1.12	-1.09
AIS5	1/2	6.45	7.8	15.4	2,340	0.01	0.72	-0.71
AIS6	1/2	6.36	7.2	14.8	2,350	0.04	3.1	-3.06
AIS6	1/2	6.38	7.1	15.2	2,450	0.03	2.3	-2.27
AIS6	1/2	6.36	6.9	15.4	2,300	0.02	2.8	-2.78
AIS7	1/2	6.99	9.2	17.4	1770	0.01	0.0012	+0.0088

There are a number of predictions by the model where the actual dissolved iron is less than the model estimate that occurred during the short detention time/high flow tests (AIS5 and AIS6) indicating dissolved iron is removed in the pilot unit much faster than the model predicts. This is shown in Figure PH-4 which shows both the difference between the measured and the modeled dissolved iron concentration and the effluent dissolved iron concentration. At the short detention time tests (less than 100 minutes) the model under predicts the actual dissolved iron (i.e., differences are negative). However, the effluent dissolved iron concentration was consistently less than 0.1 mg/L during the high flow tests. The faster dissolved iron removal was unexpected, but was explained based on an analysis of the AIS solids at the completion of the pilot study. The AIS from the Phillips test was found to have a surface area (Langmuir) of 506 square meters per gram. This surface area is more than twice the 230 square meters per gram used to develop the heterogeneous ferrous iron oxidation model (Dietz 2002). This indicates the AIS produced at Phillips is more reactive (more surface area and reaction sites) for removal of dissolved iron resulting in greater dissolved iron removal. Adjusting for this increased surface area in the heterogeneous ferrous iron oxidation model results in measured versus modeled error of less than 0.5 mg/L for the short detention time tests (AIS4 and AIS5).

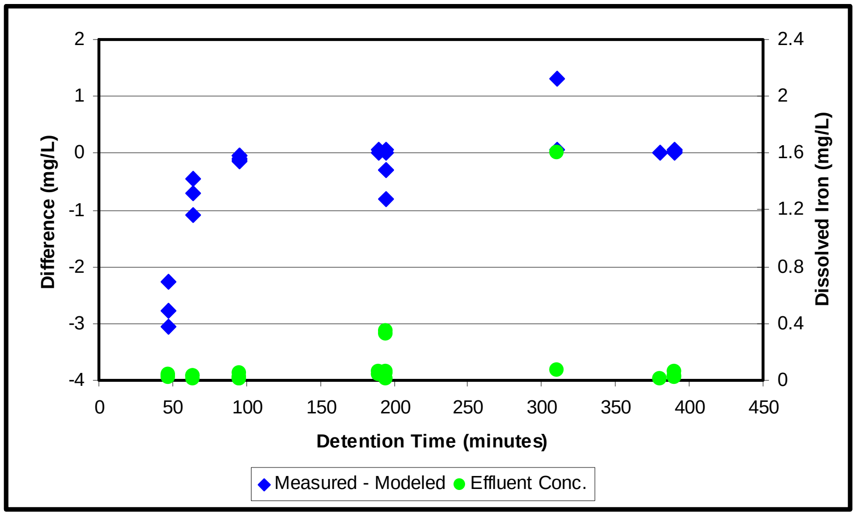


Figure PH-4. Pilot Study Results for Activated Iron Solids (AIS); difference between measured & calculated dissolved iron concentration and effluent dissolved iron concentration.

With the change in surface area in the heterogeneous ferrous iron oxidation model, the observed oxidation rates from the pilot study are consistent with the model predictions. In addition, the results indicate the polymer has no negative impact on the catalytic process. In fact, the polymer may contribute to increased surface area of the AIS thereby enhancing the catalytic properties of the AIS. Validation of the model permits use of the heterogeneous ferrous iron oxidation model to determine the adequate size of an AIS system to treat the Phillips AMD discharge. The preliminary/conceptual design of the Phillips system is summarized in the following sections.

IRON OXIDE SOLIDS DISPOSAL/REUSE

The wet solids produced by the treatment process are important representing the labor needed to handle and process solids and the volume of solids requiring disposal. AIS treatment produces a low volume of solids because the solids density is approximately 20-30% for 24 hour settled AIS. The purity of iron oxide solids produced by AIS treatment may be important for final reuse. Table PH-11 contains the analytical results from an AIS sample collected during the pilot study. The sample had a solids content of 21% after only 6 hours of settling. Additional settling time would increase solids content. The sample is nearly all iron (54%), which reflects greater than 95% iron oxides. Calcium is the second largest metal in the sample at 1.4%, which equates to a calcium carbonate content of 3.5%. Trace metal analysis indicates the sample has very low trace metal concentrations, which should not limit the disposal or reuse options for the waste solids.

Table PH-11: Laboratory Analysis of AIS Sample from the Pilot Study.

	Unit	Detection Limit	Result	% Content
Solids Content (Wet)	%	0.01		20.8
Dry Weight Basis				
Iron	mg/kg	1	537,500	54
Manganese	mg/kg	1	348	0.03
Aluminum	mg/kg	5	3,580	0.35
Calcium	mg/kg	1	14,200	1.4
Magnesium	mg/kg	1	400	0.04
Sodium	mg/kg	1	160	0.02
Potassium	mg/kg	1	35	<0.01
Silica	mg/kg	1	97	<0.01
Arsenic	mg/kg	1	48	<0.01
Lead	mg/kg	0.25	0.9	<0.01
Selenium	mg/kg	0.25	<0.25	<0.01
Zinc	mg/kg	1	123	0.01

AIS SYSTEM DESIGNS

The results of the pilot study will be used to develop an AIS treatment system to treat the Phillips AMD discharge. The following sections will provide treatment system designs, estimated capital and installation costs, and operating costs for the treatment systems.

Phillips AIS Treatment System

Based on the pilot study results, the AIS treatment system for the Phillips AMD discharge will consist of: 1) a two-stage reactor system; 2) a clarification system including a polymer feed, circular clarifiers with a flocculation zone and hopper bottoms equipped with solids collection and recirculation; and 3) a solids handling system to concentrate and store solids from the AIS treatment system. Table PH-12 summarizes the design information and influent water quality. A schematic flow path of the AIS treatment system is depicted in Figure PH-5. Figure PH-6 shows a conceptual AIS treatment system layout at the existing Phillips AMD discharge site.

Table PH-12: Summary of design information for the Phillips AMD discharge AIS treatment system.

Estimated Flow (gpm)		Influent Water Quality			
Average	Maximum	pH	Total Al mg/L	Ferrous Fe mg/L	Alkalinity mg/L
4,000	6,300	6.2	<0.5	60	225

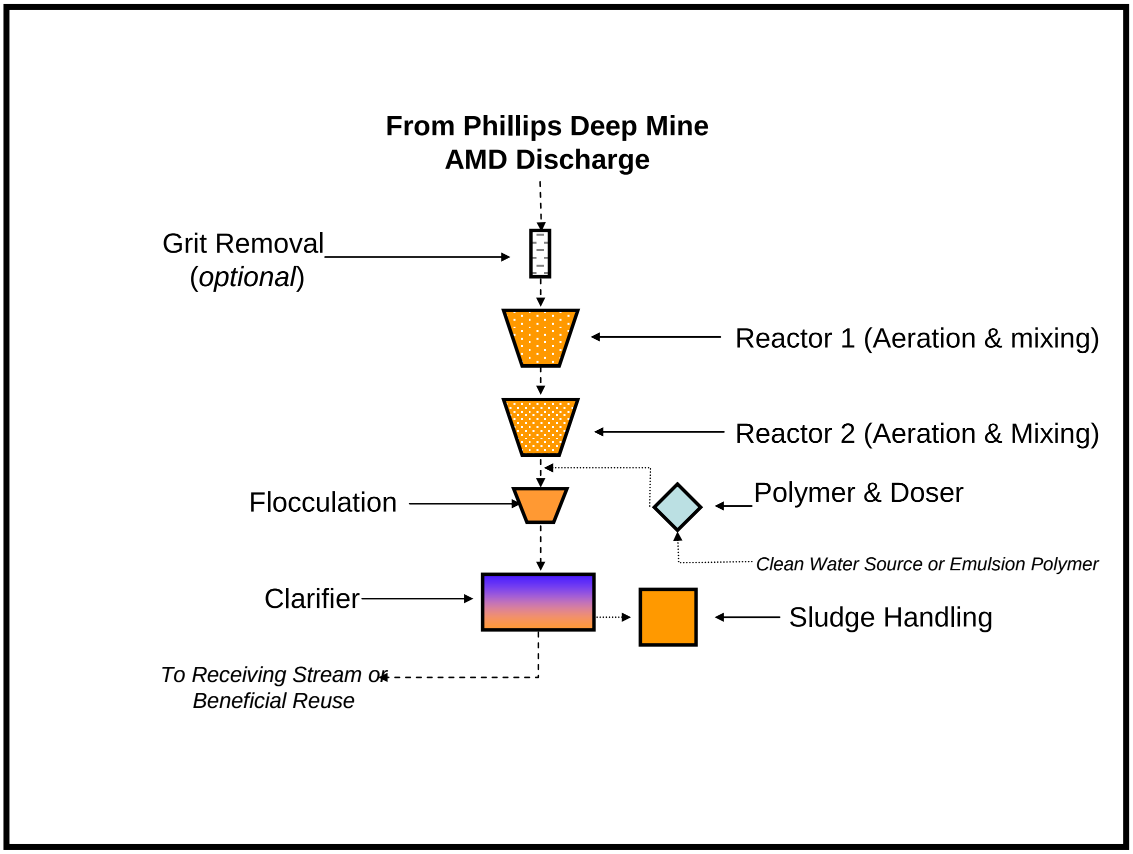


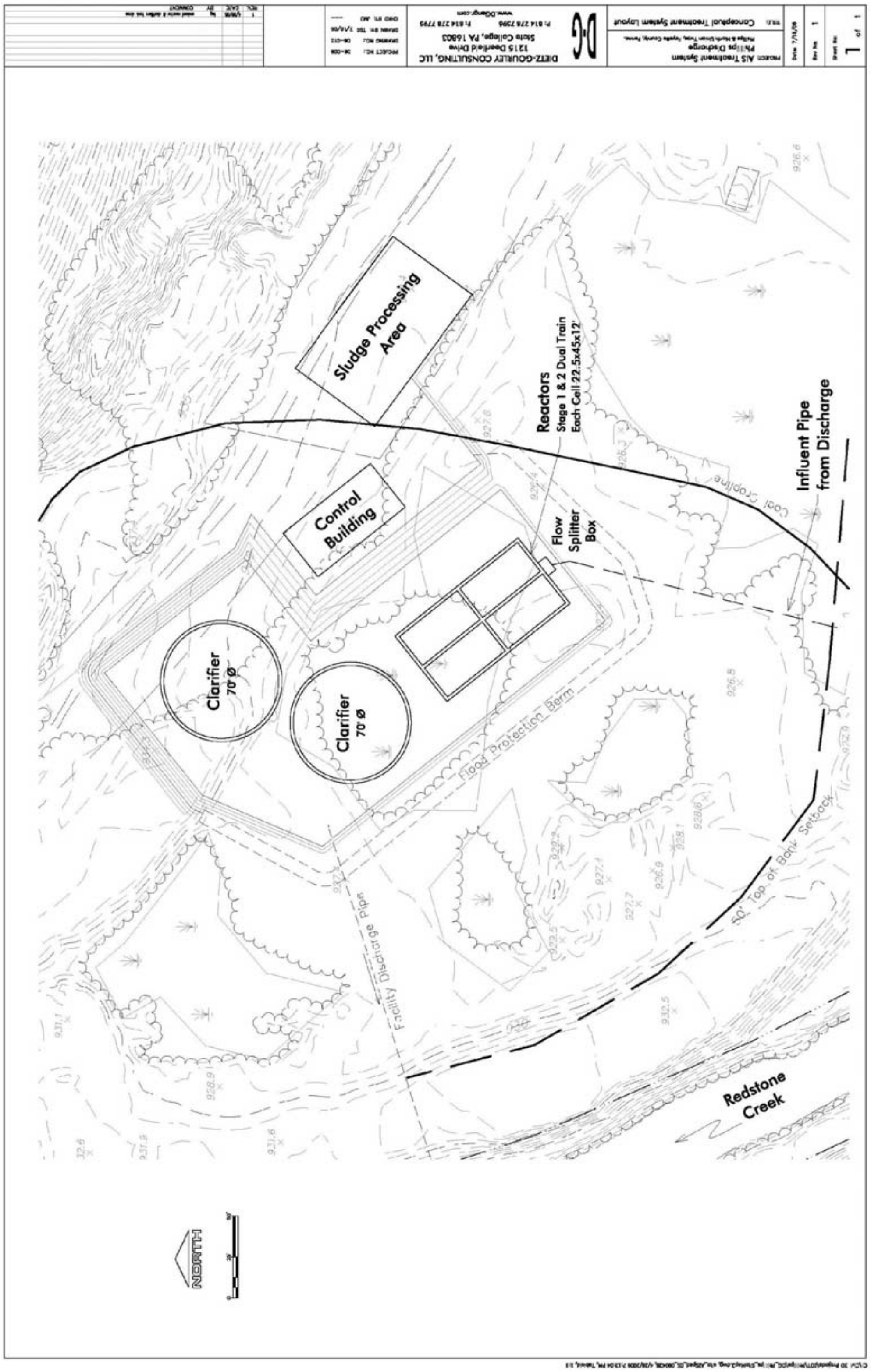
Figure PH-5. Phillips AMD Discharge AIS Treatment System Flow Path

The design criteria and effluent water quality for the Phillips AIS treatment system were determined based on the heterogeneous ferrous iron oxidation model kinetic rates, modified with the results of the AIS pilot study. Table PH-13 summarizes the design criteria for the Phillips AIS treatment system and the anticipated effluent water quality. The expected performance of the Phillips AIS treatment system is near complete removal under average flow conditions (> 99% iron removal) and maximum flow conditions (> 98% iron removal). This effluent quality should eliminate the impacts of the Phillips AMD discharge on Redstone Creek. To augment flexibility in treatment, as well as improve operation and maintenance, a dual train system is recommended. This dual train design would also result in cost savings during low flow periods where both trains are not needed.

Table PH-13: Summary of design information and anticipated effluent water quality of the Phillips Run AIS treatment system.

					Anticipated Effluent Quality			
Condition	**Flow** Gpm	**Reactor 1 DT** Hrs	**Reactor 2 DT** Hrs	**Clarifier** ft/d	**pH**	**Total Fe** mg/L	**Dissolved Fe** mg/L	**Alkalinity** mg/L
Average	4,000	0.6	0.6	50	6.7	<0.5	<0.1	120
Maximum	6,300	0.4	0.4	80	6.5	<1.0	<0.3	120

Figure PH-6. Phillips Conceptual AIS Treatment System Layout



Flow Measurement & Grit Removal

Flow measurement will be included in the design of the system. This flow will be used in the control panel for automated process control. Process control is required to optimize reactor conditions through aeration and polymer dose for flocculation. Both controls will have cost benefits in electricity demand and chemical dose. Grit removal will be incorporated in flow measurement system prior to the reactors to collect solid material that is likely contained in the discharge flow. The coarse material to be removed is from erosion of materials from the deep mine and precipitated solids from the AMD in the collection pipes. The flow measurement will also split the AMD flow to the two AIS treatment system trains.

Reactors

The two-stage AIS reactor system follows the flow measurement. The AIS reactors are sized based on the heterogeneous ferrous iron oxidation model, reactor equations, and the pilot study results. The Stage 1 and Stage 2 Reactors will each contain 36 minutes (0.6 hours) of detention time at average flow and 24 minutes (0.4 hours) of detention time at maximum flow, the design flow. The reactors will contain top mounted high performance axial flow mixers to suspend the AIS. The reactors will also have aeration provided by fine bubble diffusers using positive displacement blowers. The aeration is needed to remove excess carbon dioxide in the Phillips AMD and formed from the reaction of ferrous iron with the AIS. Aeration volume delivered is based on the pilot study results and will be adjusted with AMD flow in order to maintain the pH and dissolved oxygen required for the AIS process.

Clarification

The clarification system will consist of a polymer dosing system, flocculation and clarification. A polymer was identified during the pilot study. The polymer reacts with the AIS during flocculation to form large rapidly settling particles. The powder polymer identified is a medium molecular weight, low charge anionic acrylamide polymer (Magnafloc 155, Ciba Specialty Chemicals). The polymer will be dosed into the effluent from the Stage 2 Reactors or prior to the flocculation zone of the clarifier. The polymer dosed water will flow into a flocculation zone of the clarifier where high performance variable speed mixers equipped with low shear impellors will promote flocculation of the AIS. Flocculated solids will flow from the flocculation zone into hopper bottom clarifiers where the AIS (i.e., particulate iron) will be settled and collected. The collected AIS will be returned to the reactors or removed to an AIS holding tank using positive displacement cavity pumps.

Solids Handling

An AIS holding tank will receive excess solids from the clarifiers where the solids will be allowed to further thicken with additional settling time. The Phillips AIS treatment system will produce an average volume of AIS to be wasted daily between 5,000 and 8,000 gallons per day (6-10% solids). However, the solids handling facility will concentrate the solids to a final average volume of 2,000 to 2,500 gallons per day (20% solids). The solids handling will consist of a holding tank with storage capacity between 20 and 40 days. The holding tank will be equipped with a decant pump to remove clarified water from the top of the solids holding tank and return it to the treatment system. Solids will accumulate in the bottom of the tank until the tank is full which corresponds to approximately 50% of the total volume of solids. A jet mixer placed in the bottom of the tank will be used to periodically and at the time for transport to the disposal or reuse option re-suspend the thickened solids to slurry. A sludge pump will be used to remove the iron oxide slurry from the tank for transport to a disposal or processing site.

ESTIMATED AIS TREATMENT SYSTEM COSTS – CAPITAL & OPERATIONAL

The Phillips AIS Treatment System capital costs will include reactor tanks, flocculation clarifiers, water piping, air lines, drop-outs, diffusers, blowers, mixers, pumps polymer makeup and dosing systems, control panels, buildings for housing the control panel, blowers and polymer units, solids handling tanks, and perimeter fence. Backup electrical generators should also be considered to prevent loss of treatment in case of power failure.

Table PH-14 provides an estimate of the capital costs associated for the 9.0 MGD (6,300 gpm) Phillips AIS Treatment System. Actual costs of an AIS Treatment System may vary depending on a number of factors related to final effluent quality goals and the site conditions. In addition to the treatment system costs, there will be costs associated with site development, treatment system installation, control/polymer building installation, and perimeter fencing. The estimated cost for these items is $350,000 which results in a total estimated cost for the treatment system and installation of $3,140,000.

Table PH-14: Phillips AMD Discharge AIS Treatment System Preliminary Equipment List & System Cost[1]

Item No.	Item Description	Number
1	**Control System**	
	a. PLC Unit	1
	b. pH/Turbidity/Flow Monitors	2
	c. Control Building	**1**
2	**AIS Treatment System – IOT, Inc.**	
	a. 80,000 gallon Reactor Tanks (mix & aeration)	4
	b. 25 H.P Top Mounted Mixers (incl. mounts)	4
	c. 25 H.P. Blower/& Aeration Equipment	3
	f. 3,800 sq. ft. Flocculation Clarifiers	2
	g. 15 H.P. AIS Recirculation and WAIS Pumps	4
	h. 12 L/min (max.) Polymer System	1
4	**Sludge Handling System – IOT, Inc.**	
	a. 80,000 gallon AIS Holding Tank	1
	b. 100 H.P. Jet Mixer	1
	c. 1 H.P. Rail Mounted Decant Pump	1
	d. 15 H.P. Sludge Discharge Pump	1
Estimated System Cost		**$2,690,000**
Estimated Freight		**$100,000**
Estimated Total Equipment Cost		**$2,790,000**

[1] Costs reflect January 2008 pricing for equipment and freight

Table PH-15 provides an estimate of O&M Costs for the Phillips AIS Treatment system and includes labor, operating and maintenance costs. Also provided is the value of the iron oxide solids produced and the direct effect this beneficial reuse will have on the O&M costs by removing disposal costs and offsetting other operating costs. Depending on a number of factors (primarily solids handling/reuse), the annual O&M costs at the Phillips treatment system will be between $50,000 and $270,000.

Table PH-15: Phillips AIS Treatment System Operating Cost Estimate

Item	**Cost $/yr**
O&M Electricity ($/yr)	$105,000
Polymer Use ($/yr)	$20,000
Solids Disposal ($/yr)	$100,000
Equipment Maintenance ($/yr)	$10,000
Personnel O&M Costs ($/yr)	*$20,000-$40,000*
Total O&M Costs ($/yr)	**$270,000**[1]
Non-Personnel O&M Costs ($/yr)	**$240,000**
Potential Iron Oxide Reuse (@ $0.05/lb)	***+$90,000***
BALANCE of O&M Costs	***$50,000***

[1] using personnel O&M cost of $30,000/yr

The treatment costs will vary depending on inclusion of the various Phillips system capital and operating costs. Using the annual operating cost (labor not included) of $240,000 for the Phillips system equates to a cost of $0.11 per 1,000 gallons of treated water. If sludge disposal costs are removed and an iron oxide revenue option is identified, the treatment costs decrease to treatment costs to $0.025 per 1,000 gallons. The total treatment cost for the Phillips AMD discharge using the AIS treatment process, includes annualized capital costs (25-year basis) and all O&M costs ($270,000 per year), is $0.19 per 1,000 gallons of treated AMD.

SUMMARY

The Phillips AIS pilot study results and this summary report provide considerable information regarding the AIS Treatment process. The results indicate:

- AIS Treatment effectively oxidizes ferrous iron in short detention times needed to meet effluent objectives for the Phillips AMD.
- AIS ferrous iron oxidation rates are not affected by polymer dosing.
- Observed oxidation rates by the AIS solids are greater than predicted using the heterogeneous ferrous iron oxidation model, which reflected a greater surface area and reactivity of the AIS at the Phillips site.

Based on the results of the pilot study and the (modified) heterogeneous ferrous iron oxidation model, a modified conceptual AIS treatment system was developed that included:

- A new complete AIS treatment system for the Phillips AMD discharge that will produce an effluent iron less than 0.5 mg/L at average flows and 1 mg/L at maximum flows.
- The AIS treatment system developed based on the pilot study has reactors that are 50% smaller than originally proposed.
- An alternative clarification system to improve removal of particulate iron solids produced by the AIS process that includes:
  - Polymer make-up and feed system
  - Flocculation clarifiers.

The Phillips treatment system will have a capital cost of $2,790,000 with an annual operating cost between $50,000 and $270,000 depending on inclusion of labor and solids reuse. The treatment costs for the Phillips discharge range between of $0.025 and $0.18 per 1,000 gallons of treated water depending on inclusion of various operating costs and reflection of capital costs in the estimate.

The AIS Treatment approach offers the potential for iron recovery and reuse from the treated AMD and with solids characteristics that offer a significant potential for beneficial reuse. Investigations indicate there is substantial potential for the solids to be used in the pigment industry. This investigation is ongoing.

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Activated Iron Solids Treatment Pilot Study for Scotts Tunnel Acidic Mine Drainage

SUMMARY REPORT

Submitted to:

Department of Environmental Protection
Bureau of Abandoned Mine Reclamation
Ebensburg, Pennsylvania

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January 26, 2009

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INTRODUCTION

The discharge of acid mine drainage (AMD) to surface waters in Pennsylvania and other eastern coal region states contaminates thousands of miles of waterways resulting in their non-compliance with numerous Pennsylvania Water Quality Standards including, but not limited to, pH, total iron, suspended solids, and aesthetics. The AMD is a result of past (and unregulated) surface and underground coal mining that exposes pyritic minerals to atmospheric oxygen and results in the oxidation and the production of AMD.

Of particular concern is AMD produced in the vast historic and abandoned deep mine workings found throughout the coal region. The pyrite oxidizes to create AMD that collects and is stored in the mine voids forming large underground reservoirs of contaminated AMD. These large underground AMD reservoirs discharge at one or more points, typically from air portals (for air circulation during active operations), water portals/drains (to maintain a minimal water level in the mine during active operations), or from the mine entry. Deep mine discharges tend to be very high flow with elevated ferrous iron but may contain adequate alkalinity for iron removal. The deep mine discharges are often the largest contributor of metal loading in the watershed and/or subbasin. Treatment is mandatory to achieve water quality goals in the receiving stream.

The impact of the high flow AMD discharges on receiving streams is substantial. Input of high flow and ferrous iron AMD to surface waters causes: 1) increase of instream iron concentrations to levels exceeding water quality standards; 2) instream oxidation causes the deposition of iron oxides, known as “yellowboy”, onto stream bottoms smothering aquatic life and causing aesthetic and sediment problems; and 3) oxidation of ferrous iron can cause a decrease in pH to less than 6, a water quality standard. Theses types of impacts lead to degradation of the receiving waters to conditions that do not meet the waters designated aquatic life, recreational, and water supply uses.

Development of new and innovative treatment systems that effectively remove AMD pollutants at substantially lower capital and operating costs is paramount to the watershed restoration efforts across Pennsylvania. AIS (Activated Iron Solids) treatment has been identified as a potential new and innovative AMD treatment approach to address high flow AMD sources and or AMD treatment where land constraints or effluent objectives dictate active treatment.

This report summarizes the Scotts Tunnel AIS pilot study to evaluate the use of AIS treatment to treat AMD sources, specifically Site SR19, Site SR 20 and Site SR12 discharges, as reported in various Shamokin Creek AMD assessment documents (e.g., Scarlift). The discharges are also known locally as the Scotts Ridge Mine Tunnel, Colbert Mine Breach, and Excelsior Strip Pit Overflow discharges, respectively. None of the discharges are currently treated and are all major AMD sources in the Shamokin Creek watershed.

SITE DESCRIPTION & BACKGROUND

There are numerous high flow deep mine discharges with varying concentrations of iron, alkalinity and acidity in the Shamokin Creek watershed. Three deep mine discharges in the headwaters contribute a large portion of the AMD pollutant loading to Shamokin Creek (see

Table ST-1). The three deep mine discharges are also very similar in chemistry containing high iron and slightly net acidic conditions.

The purpose of this AIS pilot study on the Scotts Tunnel AMD discharge was to investigate the new and innovative AIS technology as a treatment alternative for conventional lime-based active treatment or passive treatment. The following provides the technical background information for the pilot study including AMD characteristics at the Scotts Tunnel (as well as the Colbert Breach and Excelsior discharges), background iron oxidation information, and a brief description of the AIS treatment process.

AMD Characteristics

The historic AMD discharge chemistry and flow data for the Scotts Tunnel, Colbert Breach and Excelsior AMD discharges are summarized in Table ST-1. Recent data collected during the pilot study are summarized in Table ST-2. The historic data for the Scotts Tunnel discharge indicates the AMD is net acidic with an average pH of 5.8. Recent data from the pilot study indicates the Scots Tunnel discharge has a pH of 5.84 with an alkalinity of 36 mg/L. Based on the iron and manganese concentrations the Scotts Tunnel AMD discharge is slightly net acidic (10 mg/L of acidity). The pH and alkalinity indicate the discharge contains elevated carbon dioxide acidity with the recent data indicating a calculated concentration of approximately 100 mg/L. The Scotts Tunnel discharge has elevated iron concentrations with a historic average ferrous iron concentration of 24 mg/L compared to the 22.3 mg/L concentration measured during the pilot study. The historic flow and the more recent chemistry will be used to size a treatment system.

Table ST-1. Summary of three major deep mine discharges in the headwaters of Shamokin Creek watershed.

Location	AMD Rank	% Load	Flow MGD	pH	Total Fe mg/L	Total Al mg/L	Total Mn mg/L	Alkal. mg/L	Acidity mg/L	Sulfate mg/L
Scotts Tunnel	1	22.7	12.3	5.8	24	<0.5	2.5	30	20	230
Excelsior	2	20.3	20.1	5.7	28	<0.5	3.2	30	30	240
Colbert Breach	10	2.2	1.3	6.0	26	<0.5	3.7	38	15	260
Total	**1**	**45.2**	**32.7**	**5.8**	**26**	**<0.5**	**3.2**	**31**	**25**	**240**

Table ST-2: Scotts Tunnel AMD Discharge Characteristics during Pilot Study.

Temperature °C	Dissolved Oxygen mg/L	pH	Total Fe mg/L	Diss. Fe mg/L	Alkalinity mg/L	Calc. Acidity* mg/L	CO_2 Acidity mg/L
12.1	6.0	5.84	22.5	22.3	36	6	135

* Calc. Acidity value determined after all iron has been oxidized and precipitated.

Historic data indicates the Scotts Tunnel contains predominately ferrous iron (Fe^{2+}), but also small amounts of ferric iron (Fe^{3+}); ferric iron is the difference between total iron and ferrous iron. The measurement of ferric iron is probably the result of some minor oxidation of ferrous iron to ferric iron during transport from the deep mine discharge point to the sampling point at the weir, a distance of several hundred feet. The difference measured during the pilot study testing only shows an average difference of 0.2 mg/L between total and dissolved iron indicating the iron concentration in the discharge is ferrous iron. The ferrous iron concentration is important since it is the oxidation of ferrous iron that is the controlling step in iron removal from mine drainage.

Alkalinity was evaluated to determine if there is adequate alkalinity in the AMD for the removal of iron from the mine drainage. The oxidation and precipitation of 1 mg/L of ferrous iron will consume 1.8 mg/L of alkalinity. Table ST-1 contains an analytically measured acidity and Table ST-2 is the calculated acidity after all iron has been oxidized and precipitated. Both the measured and calculated acidity indicates the Scotts Tunnel discharge is slightly acidic and will require the addition of alkalinity in order to complete the oxidation step and have an effluent pH greater than 6.

Carbon dioxide (CO_2) acidity data was also calculated to determine the amount of aeration needed to remove the CO_2 by the AIS treatment process and maintain or raise the pH to levels needed for the effective oxidation of ferrous iron in the AIS treatment approach. In aqueous chemistry, carbon dioxide acidity is present in water as carbonic acid (H_2CO_3). The pH of water (controlled by the carbonate system) is determined by the concentrations of bicarbonate (HCO_3^-), which is alkalinity, and H_2CO_3 according to the following relationship:

$$\text{(ST-1)} \qquad H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

The pK_a of this equilibrium is 6.4. This 6.4 would also be the pH at which the H_2CO_3 and HCO_3^- concentrations would be equal. This means an alkalinity (HCO_3^-) of 30 mg/L (as $CaCO_3$) would require an equal CO_2 acidity (H_2CO_3) of 30 mg/L (as $CaCO_3$) to have a pH of 6.4. The CO_2 acidity calculated for the Scotts Tunnel discharge is 135 mg/L (as $CaCO_3$), based on monitoring of the discharge during the pilot study. The source of this acidity is chemical neutralization reactions in the deep mine pool as well as decomposition reactions. The CO_2 acidity is about 100 times higher than is normally found in surface waters in equilibrium with the atmosphere.

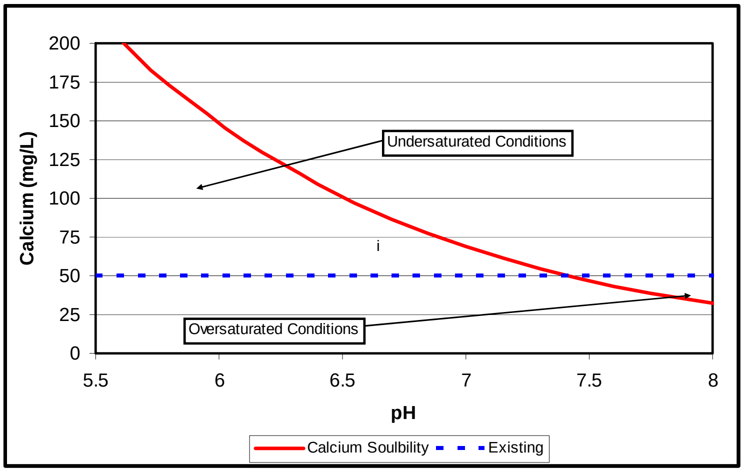

Figure ST-1. Calcium solubility in the AMD discharge with respect to pH.

The solubility of calcium and magnesium in the AMD must be evaluated for the various treatment methodologies. pH adjustments may create operation and maintenance issues by precipitating calcium and magnesium. Figure ST-1 shows the calcium (calcite) solubility with respect to pH for the Scotts Tunnel discharge. Oversaturated conditions are only present at pH approaching 8 indicating calcium (calcite) precipitation is not a significant concern in the treatment of the Scotts Tunnel discharge unless lime (CaO) is used to raise the pH to greater than 8. The increased calcium concentrations and elevated pH will cause calcium (calcite) to precipitate. At pH greater than 8, magnesium can also be removed as a hydroxide. Calcium and magnesium precipitation in lime-based treatment will increase operation and maintenance by increasing solids handling and disposal. AIS treatment oxidizes ferrous iron at acidic pH (less than 7) and prevents the additional solids volumes associated with calcium and magnesium precipitation compared to lime-based or aeration treatment approaches.

Another important parameter listed in Table ST-2 is the temperature of the discharge. Temperature of the water is important because it affects a number of chemical and physical processes in the treatment of AMD. The temperature of the Scotts Tunnel discharge is 12.1°C. This temperature will affect aeration, oxidation and the settling processes. As an example, the homogeneous oxidation rate doubles for every 2°C increase in temperature. The heterogeneous oxidation process is similarly affected by temperature. The temperature of the Scotts Tunnel discharge is similar to the other deep mine discharges in the Shamokin Creek watershed.

The chemistry evaluation for the discharges is an integral component in determining appropriate approaches and methods for treating the AMD. The impacts of the AMD chemistry on the various treatment approaches will be compared in a subsequent section.

Iron Oxidation & Removal in AMD Treatment

The treatment of the Scotts Tunnel AMD discharge requires iron removal and this iron removal is a multi-step process involving:

1. Oxidation of dissolved ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+});
2. Hydrolysis of ferric iron to form insoluble ferric oxide ($Fe(OH)_3$);
3. Flocculation of tiny (sub micrometer) iron oxide particles to form larger (micrometer) iron oxide particles;
4. Settling of suspended iron oxide particles from solution.

Depending on the type of treatment, one or more of the above processes will control the removal of iron. In passive treatment the oxidation (Step 1) of ferrous iron is very slow and determines iron removal and the size of the passive treatment system. In chemical treatment at high pH (> 8), the settling (Step 4) typically controls iron removal. The new and innovative process, AIS treatment, provides an alternative to passive treatment and chemical treatment.

The oxidation of ferrous iron is the first and most crucial step in the removal of iron. Without the oxidation step, ferrous iron would remain in solution (except at very high pH) and removal of iron from AMD would not be possible. There are two types of ferrous iron oxidation in water:

1. ***Homogeneous Ferrous Iron Oxidation (HoFIO)*** – is the long established oxidation process occurring in solution and involves the reaction of dissolved ferrous iron (Fe^{2+}) with dissolved oxygen.
2. ***Heterogeneous Ferrous Iron Oxidation (HeFIO)*** – is a newly identified oxidation process occurring on the surface of iron oxide solids and involves the sorption of ferrous iron and dissolved oxygen followed by the rapid catalytic oxidation on the surface of the iron oxide.

The first type, HoFIO is the ferrous iron oxidation that occurs in solution and is most commonly associated with passive treatment and conventional (lime-based) chemical treatment of AMD. This process is also the dominate process where aeration is used to add oxygen and raise the pH to greater than 7, a pH where HoFIO will dominate. The long established HoFIO rate equation (Sung & Morgan 1980) is:

(ST-2) *HoFIO rate* $(\mathrm{M} \cdot \mathrm{s}^{-1}) = -\delta[\mathrm{Fe(II)}]/ \delta t = k_{\mathrm{Ho1}} \times [\mathrm{Fe(II)}_{diss}] \times [\mathrm{O}_2] / \{\mathrm{H}+\}^2$

The HoFIO equation is complex with the HoFIO rate affected by the ferrous iron concentration $[\mathrm{Fe(II)}_{diss}]$, dissolved oxygen $[\mathrm{O}_2]$ and pH $\{\mathrm{H}^+\}$. Temperature is an integral part of the equation by its affects on the reaction rate constant (k_{Ho2}), with a decrease in temperature causing a decrease in the oxidation rate. The HoFIO equation is a reliable design tool because the equation can be used to predict iron removal for 1) different AMD chemistry, and 2) factors in iron removal under operating conditions (e.g., dissolved oxygen, pH and temperature). The HoFIO model will be used to evaluate ferrous iron oxidation results for the pilot study where only aeration is used in the reactors to increase dissolved oxygen and pH.

Heterogeneous ferrous iron oxidation (HeFIO) is an oxidation process that occurs on iron oxide surfaces and is the oxidation process AIS uses to oxidize ferrous iron. HeFIO is a two step processes that involves 1) the sorption of ferrous iron to the surface of the iron oxide, 2) rapid oxidation in the presence of dissolved oxygen to form new iron oxides directly on the surface of the iron oxide. Equations and models for the reactions are contained in Dietz (2003). The equations are complex describing both sorption and oxidation process.

(ST-3) *HeFIO rate* $(\mathrm{M} \cdot \mathrm{s}^{-1}) = (-\delta[\mathrm{Fe(II)}]/ \delta t) = (k_{\mathrm{He1}}[\mathrm{O}_2]S_1) + (k_{\mathrm{He2}}[\mathrm{O}_2]S_2)$

and

(ST-4)
$$S_x = \frac{1 + ([Fe(II)_{diss}] \times K_x^{app})}{[\equiv Fe(III)] \times \Gamma_x \times \{H^+\}^x}$$

where **x** is the reaction (either 1 or 2), $\mathbf{k_{Hex}}$ are the surface oxidation rate constants, $\mathbf{K_x^{app}}$ are the surface complexation constants, and **[≡Fe(III)]** is the AIS concentration (in mg/L). Dietz (2003) determined the various thermodynamic constants for the equations including activation energies and enthalpies, which describe the effects of changing temperature. In current treatment systems (including passive treatment and lime treatment), HeFIO is not very important (< 5% of the ferrous iron oxidation rate) due to the low concentrations of suspended iron oxides (typically less than 10 mg/L). Iron Oxide Technologies, LLC has developed several treatment systems optimizing HeFIO through concentrated suspensions of iron oxide solids in reactor systems. Figure ST-2 shows the time required to oxidize and remove ferrous iron from AMD for various treatment methods from bench-scale testing conducted at 15°C on an anoxic AMD discharge. Note the x-axis time scale is logarithmic. The detention time required to achieve less than 0.5 mg/L ferrous iron for the passive treatment and passive treatment with pre-aeration tests were 50 and 25 hours, respectively. Critical low-temperature conditions (Average Temp. = 8°C) would require additional detention times (2 to 5 times) to complete oxidation. As a comparison, the AIS treatment test required only 20 minutes to achieve 0.5 mg/L, which demonstrates the importance of HeFIO and the ability AIS treatment to achieve rapid oxidation and removal of ferrous iron. AIS treatment is 75 times faster in comparison to pre-aeration/passive treatment and 150 times faster in comparison to passive treatment only. A pH 8 oxidation line is also provided to show AIS ferrous iron oxidation is similar to conventional lime-based treatment: the 0.5 mg/L ferrous iron is expected to occur in 15 to 20 minutes detention time.

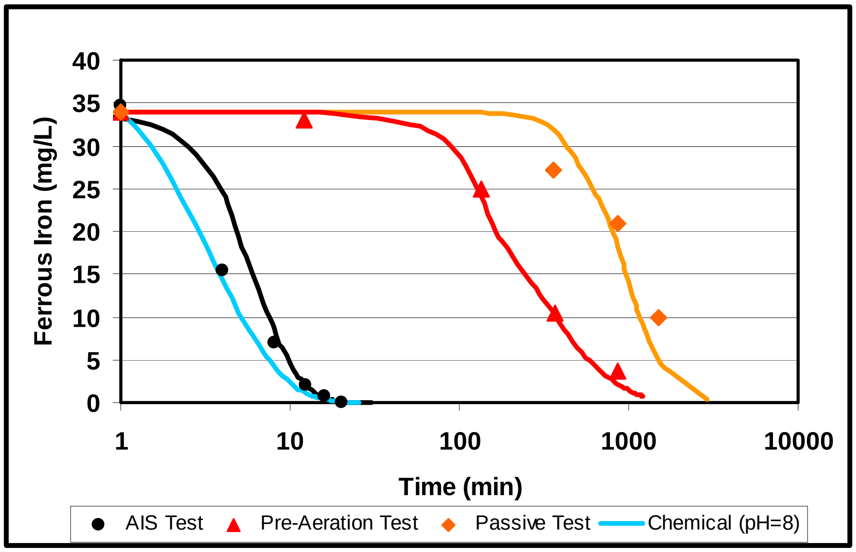

Figure ST-2. Bench-scale Results for Activated Iron Solids (AIS), Pre-aeration & Passive Tests

Innovative AIS Treatment

Iron Oxide Technologies, LLC has developed new (patent pending) active treatment approaches collectively known as Activated Iron Solids (AIS) treatment of AMD. AIS treatment has numerous advantages over conventional chemical treatment that can make long term treatment and iron oxide recovery possible at abandoned mine discharges. The AIS treatment advantages over conventional chemical treatment are:

1) Oxidation and removal occur at slightly acidic pH (6-7);
2) Oxidation rates are as fast as conventional chemical treatment;
3) For net alkaline AMD no alkaline chemicals are needed;
4) For net acidic waters, inexpensive pulverized (powder) limestone can be used for the needed alkalinity;
5) Solids produced by the AIS process are high-density (30% solids);
6) Solids are high purity iron oxides (95% iron oxides on a dry weight basis).

These advantages will have a direct effect on treatment costs by eliminating (or minimizing) chemical use and cost, and simplifying operation that will decrease manpower requirements. The innovative active AIS treatment processes utilized for the pilot study at the Scotts Tunnel discharge is the Two-Stage AIS Reactor System (depicted in Figure ST-3). The AIS system uses high iron oxide concentrations (AIS = 1,500 – 2,500 mg/L) to increase ferrous iron oxidation and removal. The high iron oxide concentrations produce a catalytic environment that promotes ferrous iron oxidation and removal while producing high-density and pure treatment solids (iron oxide solids). The Two-Stage AIS Reactor system maintains high reactor AIS concentrations through recirculation of solids collected in the clarifier.

SCOTTS TUNNEL PILOT STUDY

A location was identified for the pilot study adjacent to the Scotts Tunnel discharge channel near Kulpmont, PA and on Susquehanna Coal Company property. There was a limited access trail accessible from Route 61. Right of access was obtained from Susquehanna Coal Company (Paul Freeman). The access road was improved to permit placement of the pilot unit.

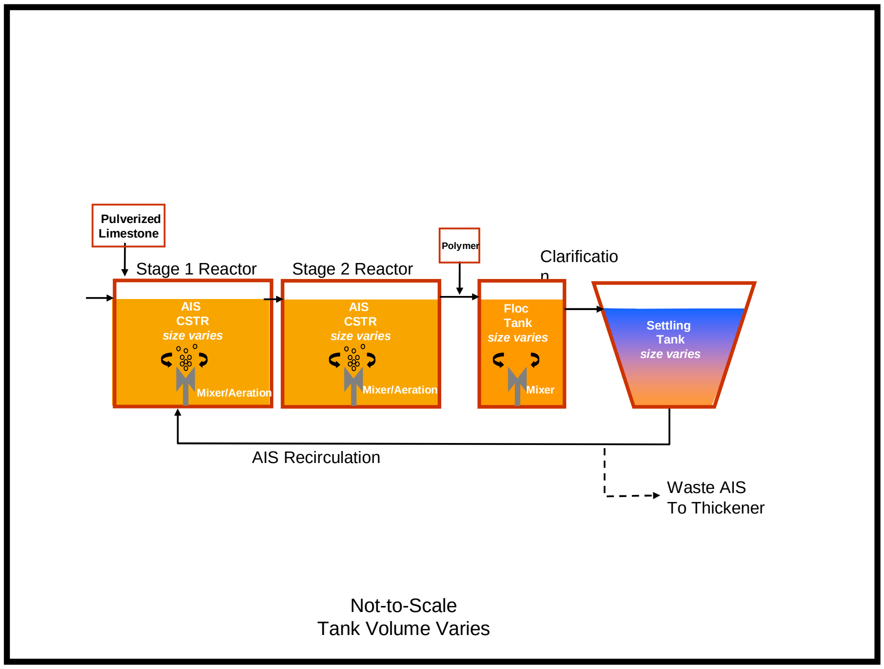

Figure ST-3. AMD Treatment in a Two-Stage Flow-Through AIS System

The pilot system was moved to the Scotts Tunnel AMD discharge site on June 25, 2008. Setup of the system was completed and pilot system testing was initiated on July 7th. Setup of the AIS pilot unit consisted of: 1) moving the trailer unit onto the pad and leveling the trailer unit with wooden support pillars; 2) moving the inclined plate clarifier and placement on concrete pads with a crane; 3) placement of the pulverized lime doser on the pilot unit with a crane; 3) electrical connection of all the equipment to temporary service provided by PP&L Electric Company; 4) installing all mixers, pumps and aeration equipment in the pilot unit; and 5) connecting all required plumbing to and from the pilot unit. AMD was directed to the pilot unit using a one (1) horsepower submersible pump placed in the existing discharge channel and 4-inch flat pipe was used to convey the AMD from the discharge channel to the inlet weir box of the pilot system. The effluent from the pilot unit, along with overflow from the inlet weir box, was conveyed back to the AMD discharge channel from the pilot treatment system using 4-inch flat pipe.

The AIS system used for the Scotts Tunnel Pilot Study included several modifications in order to improve solids removal and control of Return Activated Iron Solids (RAIS). The modifications included: 1) converting the upflow clarifier to a flocculation tank by adding a high efficiency, variable speed, low shear top mounted mixer; 2) re-plumbing the upflow clarifier to allow flow though through the side wall of the tank; 3) adding an inclined plate clarifier (rated for a 25 gpm hydraulic loading) after the flocculation tank; 4) adding a variable speed sludge pump to return AIS from the clarifier hopper to the first reactor; and 5) adding a powder feed unit equipped with a storage hopper to dose pulverized limestone (alkaline material) to the first reactor if additional alkalinity was needed. Figure ST-3 schematic shows the changes made to the pilot unit for the Scotts Tunnel Pilot Study.

The Scotts Tunnel pilot study was conducted during July, August and September 2008. The inflow pump was started on June 28, 2008 to fill the tanks and testing was initiated on July 7, 2008. AIS for startup of the pilot unit were transported from the previous testing location (Phillips discharge), however additional AIS needed to be accumulated for the pilot testing at the Scotts Tunnel. Pilot testing at Scotts Tunnel discharge consisted of two phases: 1) initial operation using aeration only to accumulate additional AIS and evaluate aeration only as a treatment approach: and 2) AIS treatment pilot testing to determine the detention time and aeration requirement which involves high AIS reactor concentrations through solids recirculation from the clarifier. In addition, pulverized limestone dosing was tested as an alkalinity source for the Scotts Tunnel discharge, slightly net acid, to maintain the needed pH (~6.5) for the AIS process.

Analytical Methods

Analysis for the pilot study consisted of pH, dissolved oxygen, temperature, total iron, dissolved iron, alkalinity and periodic conductivity. pH was measured with an Fisher Scientific Accumet Portable Meter equipped with a Cole Parmer Accumet combination pH electrode. The pH electrode was calibrated daily prior to use with pH 4.00 and pH 7.00 buffers. Dissolved oxygen (DO) and temperature were measured with an YSI Model 550A DO Meter. The DO Meter was calibrated prior to each use using the air saturation method. Total iron was measured using a Hach Iron Pocket Colorimeter Test Kit (0-3.00 mg/L) using Ferrover reagent after appropriate dilution. Dissolved iron was also measured with the Iron Pocket Colorimeter but after filtration using a syringe and a 0.2 μm syringe filter, and appropriate dilution. Ferrous iron was determined using Hach ferrous iron powder packets and the Hach Iron Pocket Colorimeter. Initial testing on the discharge indicated dissolved iron (filtered sample) equals ferrous iron for the conditions in the Scotts Tunnel AMD. As a result, the dissolved iron test was used to determine ferrous iron. Alkalinity was measured on a 100 mL sample using a Hach Digital Titrator, a 1.600 N sulfuric acid cartridge. Conductivity was measured with an Oakton Conductivity Pen.

Aeration Only Testing

Aeration testing at the Scotts Tunnel AMD discharge was conducted between July 7 and August 5, 2008. The testing consisted of varying the AMD flow to the treatment system. Aeration was provided by the blower included with the pilot unit and fine bubble diffuser heads placed in the reactor tanks. Air flow was monitored and set at 18 cfm during the aeration study. AMD flow during the study was varied from a high of 45 gpm to a low of 2 gpm by adjusting the weir plates on the inlet box. The flows to the system equated to a total reactor detention time ranging between 1.4 and 32 hours. The goal of the aeration was to determine the required detention time and air flow to achieve adequate oxidation of the ferrous iron (dissolved) in the discharge to the insoluble ferric iron form as well as determine if the addition of an alkaline material (i.e., pulverized limestone) was needed to maintain pH. Total iron removal, or solids removal, was not a specific objective of the aeration testing.

The results of the aeration only testing are summarized in Tables ST-3 through ST-7. The raw water chemistry varied slightly during the testing with pH varying from 5.7 to 5.9. The final pH from the treatment system was dependent on the flow to the system which affected both the CO_2 acidity (removed by aeration) and the effluent alkalinity (depleted by the ferrous iron oxidation and precipitation). The lowest effluent pH (6.30) and alkalinity occurred at the lowest tested flow (2.3 gpm) and the highest effluent pH (6.52) and alkalinity occurred at the highest tested flow (45 gpm). The effluent alkalinity was also the lowest in the low flow test with a measured concentration of 2.9 mg/L. This alkalinity concentration is likely to be too low to maintain an adequate pH (> 6.5) for rapid oxidation in aeration only or passive treatment, as ferrous iron oxidation decreases as pH decreases. The low alkalinity may the also be too low to maintain the pH (>6.5) for the AIS process.

Table ST-3: Summary of results from aeration only testing (Test A1) at AMD Flow = 4.4 gpm and Air Flow = 18 cfm.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
July 9, 2008						
Raw	5.82	6.09	12.1	22.0	23.0	32.5
React 1	6.48	10.65	15.3	22.0	10.4	---
React 2	6.55	10.30	16.5	21.8	2.59	---
Effluent	6.40	10.20	16.2	12.5	1.94	9.0
July 11, 2008						
Raw	5.75	6.08	12.2	21.1	21.2	31.9
React 1	6.33	10.35	15.9	20.6	7.1	10.0
React 2	6.40	10.07	17.2	20.6	1.5	3.6
Effluent	6.25	10.15	16.5	3.5	1.1	2.9

Table ST-4: Summary of results from aeration only testing (Test A2) at AMD Flow = 2.3 gpm and Air Flow = 18 cfm.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
July 14, 2008						
Raw	5.85	5.90	12.1	22.2	22.1	32.6
React 1	6.38	9.69	17.5	20.7	3.3	6.0
React 2	6.35	9.50	18.8	18.0	0.7	3.1
Effluent	6.30	9.40	18.5	2.3	0.4	2.9

Table ST-5: Summary of results from aeration only testing (Test A3) at AMD Flow = 17.7 gpm and Air Flow = 18 cfm.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
July 16, 2008						
Raw	5.74	6.06	12.3	21.5	21.0	31.2
React 1	6.39	10.9	13.3	21.4	19.3	32.7
React 2	6.52	11.0	14.0	20.0	16.3	26.4
Effluent	6.50	10.8	14.0	20.6	15.8	25.0
July 18, 2008						
Raw	5.79	6.08	12.2	21.6	21.6	34
React 1	6.38	11.0	12.8	24.1	19.8	32
React 2	6.47	11.1	13.2	21.6	16.7	28
Effluent	6.44	--	--	21.7	16.2	--

Table ST-6: Summary of results from aeration only testing (Test A4) at AMD Flow = 31 gpm and Air Flow = 18 cfm.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
July 21, 2008						
Raw	5.78	5.99	12.1	22.8	22.8	36
React 1	6.32	10.6	12.4	25.1	20.8	42
React 2	6.51	11.0	12.7	22.5	19.6	36
July 25, 2008						
Raw	5.81	6.10	12.1	23.8	21.7	35
React 1	6.39	10.8	12.4	21.5	21.4	39
React 2	6.52	11.2	12.7	21.7	19.1	36
Effluent	6.50	--	--	21.5	20.1	--

Table ST-7: Summary of results from aeration only testing (Test A5) at AMD Flow = 45 gpm and Air Flow = 18 cfm.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
July 28, 2008						
Raw	5.75	6.12	12.0	22.1	21.7	33
React 1	6.31	10.6	12.1	21.5	21.3	40
React 2	6.49	11.2	12.2	21.2	20.6	37
Effluent	6.52	--	--	20.6	--	--
July 30, 2008						
Raw	5.75	6.04	12.0	21.9	21.1	33
React 1	6.32	10.5	12.1	21.7	20.9	39
React 2	6.49	11.2	12.3	21.2	20.4	40

Dissolved iron decreased as a function of detention time in the aeration tanks as a result of oxidation of soluble ferrous iron to insoluble ferric iron. The affects of detention time on dissolved iron concentration (i.e., iron oxidation) is shown in Figure ST-4. The figure shows the effluent dissolved iron concentration decreases non-linearly as the detention time increases. This is an affect of: 1) the length of time the AMD is in the reactor to permit oxidation; and 2) the increase in pH from removal of carbon dioxide acidity through aeration. The pH affect is also related to the detention time in the reactor allowing greater removal of the carbon dioxide acidity. The non-linear decrease of dissolved iron with detention time is related to the first-order kinetics of the ferrous iron oxidation. The decrease in alkalinity is also shown which is related to the consumption of alkalinity during the precipitation of the ferric iron, produced from the oxidation of ferrous iron, to insoluble ferric iron hydroxide. The concentration decrease is approximately 2 mg/L of alkalinity for every 1 mg/L of ferrous iron oxidized and is consistent with the stoichiometric concentration of 1.8 mg/L of alkalinity for every 1.0 mg/L of ferrous iron oxidized.

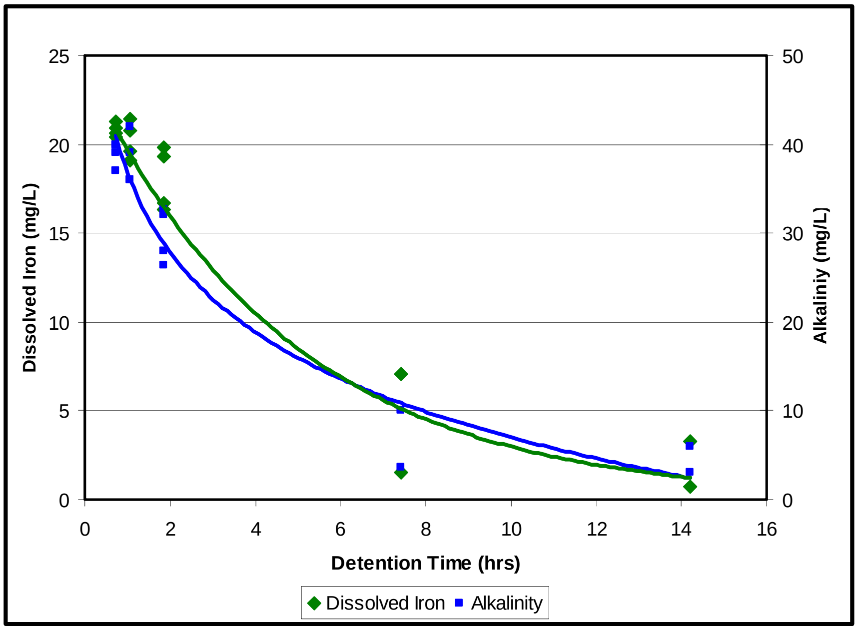

Figure ST-4. Scotts Tunnel AMD Aeration Testing Results; Effluent Dissolved Iron and Alkalinity.

The final evaluation using the aeration only data was to compare the measured dissolved iron to predictions using the homogeneous iron oxidation model and reactor equations. An accurate model will be needed to size an aeration only system. The sampling and analysis conducted in each reactor are summarized in Table ST-8. The calculated dissolved iron concentration for the reactor conditions is also provided in Table ST-8 along with the difference between the measured and calculated dissolved iron values. There were two values, both from Reactor 1, where the measured and calculated values differed by more than 2 mg/L. This value may be from variable pH within the reactor versus the effluent point of sampling. There is also a bias, based on the high number of negative values, indicating the model is under predicting the actual oxidation. This may be a result of the lower conductivity (and salinity) of the Scotts Tunnel AMD discharge; lower salinity waters have been found to have faster oxidation rates than higher salinity waters. An analysis of the ferrous oxidation rates indicates the measured rates area approximately twice as fast as the calculated rates for the reactor conditions. The homogeneous ferrous iron oxidation model and the reactor equations can still be used to estimate the aeration system size employing the observed rate adjustment for the Scotts Tunnel AMD chemistry.

Table ST-8 Summary of Iron Oxidation Data From Each Reactor During Aeration Studies Only at Scotts Tunnel and Comparison to the Calculated Dissolved Iron Using the Homogeneous Iron Oxidation Model.

Test	Reactor	Detention Time Hrs	pH	Dissolved Oxygen mg/L	Temp. °C	Meas. Diss. Fe mg/L	Calc. Diss. Fe mg/L	Difference Diss. Fe (Meas-Calc)
A1	1	7.4	6.33	10.35	15.9	7.1	14.4	-7.3
A1	2	7.4	6.40	10.1	17.2	1.5	3.5	-2.0
A2	1	14.2	6.38	9.69	17.5	3.3	7.7	-4.4
A2	2	14.2	6.35	9.50	18.8	0.7	0.94	-0.2
A3	1	1.8	6.39	10.9	13.3	19.3	19.7	-0.4
A3	2	1.8	6.52	11.0	14.0	16.3	16.7	-0.4
A3	1	1.8	6.38	11.0	12.8	19.8	20.5	-0.7
A3	2	1.8	6.47	11.1	13.2	16.7	18.1	-1.4
A4	1	1.0	6.32	10.6	12.4	20.8	21.2	-0.4
A4	2	1.0	6.51	11.0	12.7	19.6	19.8	-0.2
A4	1	1.0	6.39	10.8	12.4	21.4	21.2	0.2
A4	2	1.0	6.52	11.2	12.7	19.1	20.3	-1.2
A5	1	0.7	6.31	10.6	12.1	21.3	21.4	-0.1
A5	2	0.7	6.49	11.2	12.2	20.6	20.7	-0.1
A5	1	0.7	6.32	10.5	12.1	20.9	21.4	-0.5
A5	2	0.7	6.49	11.2	12.3	20.4	20.3	0.1

Based on the model and using the rate adjustment, aeration alone would require approximately 130 hours detention time to decrease dissolved iron to less than 0.1 mg/L. This is a result of the low initial alkalinity in the Scotts Tunnel AMD which is depleted from the oxidation/precipitation process and results in a low reactor pH (~ 6.4). This detention time and aeration volume is impractical and no further consideration is warranted. The results of the aeration testing also provide indications that passive treatment or passive/active treatment would also require substantial detention times that would be impractical for the large flow of the Scotts Tunnel discharge.

AIS Pilot Testing

The AIS test settings covered a broad range of operating conditions to determine optimal operating conditions for the Scotts Tunnel AIS treatment system including varying pulverized limestone dose, AIS concentration, polymer dose and aeration. In the case of the AIS concentration, the target was AIS (as total iron) greater than 1,500 mg/L in the reactors using recirculation of solids from the clarifier. The initial startup conditions for the pilot unit were:

1. Reactor 1 & 2 AIS ~ 400 mg/L (as Fe)
2. Air Flow = 18 cfm – air flow was varied during testing

3. AMD Inflow = 10 gpm
4. AIS Recirculation Rate = 2.5 gpm
5. Initial Polymer Dose Rate = 20 mL/min (0.5 mg/L of inflow) - *polymer dose was increased during test*
6. Pulverized Limestone Dose = 0 gr/min

To start the pilot system, AIS solids were added to the pilot unit using solids retained from the previous Phillips pilot study. The use of the solids from the Phillips pilot study simplified and shortened start-up time to accumulate AIS solids for the reactor system (days versus weeks). Initial air flow was based on previous aeration only studies with the pilot system and was set to maintain a dissolved oxygen concentration and pH in the reactors. The initial AMD inflow was set based on calculated oxidation rates using the heterogeneous iron oxidation model. The 10 gpm flow results in an initial 3 hour detention time in each reactor and a total system detention time (including the clarifier) of 8 hours. The AIS recirculation rate was set at a flow rate to maintain and increase the reactor AIS concentrations based on expected solids in the recirculated flow and the AMD inflow rate. The polymer used for the test was the Ciba Specialty Chemicals Magnafloc® 155, a medium molecular weight low charge anionic acrylamide polymer. This polymer was identified as the most suitable polymer for this application based on testing of multiple polymers at the previous pilot studies.

The AIS pilot system was started on August 6th at an initial high RAIS flow rate (~15 gpm) in order to break in the new sludge pump (Seepex® sludge pump). The new sludge pump break in period lasted for approximately one week. After the break in period the system was started and operated using the above settings on August 14th at 7:15 PM. No pulverized limestone was dosed during this initial startup period to evaluate the performance of the AIS system with respect to pH and alkalinity and whether the pulverized limestone would be needed. The results of this initial AIS testing (Test AIS1) are provided in Table ST-9. The results indicate the alkalinity was depleted and resulted in a low reactor pH (~6.1). The low reactor pH resulted in a slow ferrous iron oxidation rate in the reactors. This indicates pulverized limestone will be needed in order to maintain a higher pH (6.5 to 6.8) where the AIS process is more effective at ferrous iron oxidation. Pulverized limestone was dosed in all subsequent AIS tests.

The pilot unit was operated with added pulverized limestone until September 26th with periodic adjustments to vary AMD flow, air flow, solids recirculation rates, pulverized limestone dose and polymer dose. Typically, adjustments involved increasing AMD flow to the pilot unit which also resulted in increasing solids recirculation rates, pulverized limestone dose and polymer dose. The system was also run for a period of two weeks after the high AMD flow testing was complete to evaluate long term operation. The results from various sampling dates (and times) along with operating conditions are contained in Tables ST-10 through ST-13. There were two minor operating issues during the pilot study involving: 1) power loss after a severe thunder storm, and 2) the RAIS temporarily stopped during the last week of the study due to clogging of the sludge return line with leaves. That later was due to the location of the pilot unit in a forested area and the fall season during which the study was conducted. The system had to be temporarily shutdown and restarted in both instances.

Table ST-9: Summary of results from Scotts Tunnel AIS pilot testing (Test AIS1) at AMD Flow = 10.5 gpm, Air Flow = 18 cfm, RAIS flow = 2.6 gpm and polymer dose 20 mL/min started on August 14, 2008 at 7:15 PM.
(No Pulverized Limestone Dose)

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
10:00 AM on* August 19, *2008						
Raw	5.90	6.25	12.2	24.1	22.4	--
React 1	6.23	10.5	14.0	392	6.00	--
React 2	6.22	10.8	14.6	400	2.05	--
Clarifier	6.10	--	--	4.6	1.68	5.2
RAIS	--	--	--	1,950	--	--
10:00 AM on August 21, 2008						
React 1	6.16	11.1	13.3	454	6.60	--
React 2	6.15	11.2	13.8	425	2.40	--
Clarifier	6.08	--	--	4.7	1.65	4.6
RAIS	--	--	--	1,520	--	--
2:30 PM on August 22, 2008						
React 1	6.17	10.4	15.2	345	6.20	--
React 2	6.13	10.8	15.9	388	2.14	--
Clarifier	6.10	--	--	--	1.74	1.74
RAIS	--	--	--	1,270	--	4.9

Overall the AIS pilot study results indicate the AIS system oxidized the soluble ferrous iron in the Scotts Tunnel discharge to particulate ferric iron. The dissolved iron decreased from an influent concentration of 22 mg/L to less than 0.1 mg/L in the higher AIS concentration tests. This demonstrates the AIS process can achieve the effective ferrous iron oxidation to very low concentrations approaching 100% ferrous iron removal. Air flow is an important factor in the oxidation process by increasing both dissolved oxygen and pH. Dissolved oxygen is increased through the transport of oxygen in the air to the water. pH is indirectly increased through the removal of dissolved carbonic acid in the water to carbon dioxide in the air and the addition of pulverized limestone, which dissolves to add alkalinity to the treated water in the pilot unit. Based on the heterogeneous model, both the increase in dissolved oxygen and pH, substantially increased the ferrous iron oxidation rate. Dissolved oxygen concentrations increased from 5.8 mg/L to greater than 10 mg/L and the pH increased by approximately 1 pH unit. As an example to demonstrate the importance of the pH change, a pH increase of 0.3 will more than triple (300%) the heterogeneous ferrous iron oxidation rate.

Table ST-10 shows results of the Test AIS2 conducted at a flow 20 gpm and pulverized limestone dose of 2.4 gr/min (the pulverized limestone dose was increased to 4.6 gr/min during Test AIS2). Test AIS2 was conducted to increase the AIS solids in the system and evaluate kinetic process in the system. As shown in the table, the AIS concentration was approximately 850 mg/L at the start of TEST AIS2 and increased to 1,300 mg/L by the end of the seven (7) day test duration. The oxidation of the ferrous iron during Test AIS2 was near complete with effluent less than 0.1 mg/L, 99.5% removal. The pH was increased from 5.9 to slightly greater than 6.8 during the test the reactors from the aeration and pulverized limestone provided. The pulverized limestone was also effective at adding alkalinity, effluent between 40 and 50 mg/L, which was needed to replace the alkalinity consumed from the precipitation of the ferric iron produced from the oxidation of the ferrous iron. Based on the pulverized limestone dose, influent/effluent alkalinity and stoichiometric alkalinity consumed by the oxidation/precipitation of iron, approximately 80 to 90% of the pulverized limestone is dissolved in the pilot system.

Table ST-10: Summary of results from Scotts Tunnel AIS pilot testing (Test AIS2) at AMD Flow = 20 gpm, Air Flow = 18 cfm, Pulverized limestone dose = 2.4 gr/min, RAIS flow = 8 gpm and polymer dose 38 mL/min started on August 28, 2008 at 12:30 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
11:30 AM on August 29, 2008						
Raw	5.95	5.65	12.2	23.3	22.5	40
React 1	6.50	10.7	12.9	880	1.59	
React 2	6.70	11.0	13.2	840	0.12	
0Clarifier	6.67	10.9	13.3	8.00	0.22	27
RAIS	--	--	--	3,360	--	--
8:30 AM on August 31, 2008						
React 1	6.47	10.9	12.4	920	5.08	--
React 2	6.65	11.2	12.5	940	0.78	--
Clarifier	6.58	11.1	12.4	7.80	0.38	25
RAIS	--			3.040	--	--
10:00 AM on September 2, 2008 (Pulverized Limestone dose = 4.6 gr/min)						
Raw	5.85	6.25	12.3	23.0	23.0	39
React 1	6.58	10.6	13.1	1,090	2.38	--
React 2	6.83	11.1	13.3	1,140	0.11	--
Clarifier	6.88	11.1	13.3	3.80	0.04	42
RAIS	--	--	--	3.960	--	--
12:00 PM on September 4, 2008 (Pulverized Limestone dose = 4.6 gr/min)						
React 1	6.60	10.6	14.0	1,260	1.94	--
React 2	6.90	11.1	14.4	1,200	0.04	--
Clarifier	6.95	11.0	14.6	2.80	0.03	49
RAIS	--	--	--	5,600	--	--

Table ST-11 shows results of the Test AIS3 conducted at 26 gpm, a slightly higher flow than Test AIS2. This was the maximum flow the ½ hp intake pump could deliver to the pilot system. The pump was switched to a 1 hp pump for the subsequent higher flow tests. The 26 gpm flow represents the maximum hydraulic loading of the clarifier and was conducted to optimize polymer dose, flocculation tank mixing and clarifier performance. Also note the AIS concentration increased from 1,300 mg/L at the start of Test AIS3 to near 2,300 mg/L at the end of the test. Similar to previous tests the oxidation of the ferrous iron during Test AIS3 was near complete with effluent less than 0.1 mg/L, 99.5% removal. The pH during the higher flow rate (26 gpm) was approximately 6.8. The polymer dose in combination with the flocculation tank mixing yielded a total iron concentration of approximately 2 mg/L. This effluent total iron is at the maximum hydraulic loading for the inclined plate clarifier. Improved iron removal would be expected at hydraulic loading less than this maximum.

Table ST-12 shows results of the Test AIS4 conducted at an inflow of 40 gpm, the maximum flow tested, which is nearly twice the maximum hydraulic loading of the clarifier. This is a high flow test conducted to evaluate AIS treatment at a flow predicted by the heterogeneous model to achieve the threshold for ferrous iron oxidation in the pilot system. This test was intended to provide near complete removal of ferrous iron but with Reactor 2 containing measurable ferrous iron in the dissolved form. The AIS concentration in the Test AIS4 was at the target operational condition of 2,000 to 2,500 mg/L. The AIS was maintained during the test by wasting AIS solids periodically from the return sludge line to Reactor 1. The results show the oxidation/removal of the ferrous iron by the pilot system during Test AIS4 was near complete with effluent less than 1.0 mg/L in the effluent. The pH during this higher flow rate (40 gpm) also decreased from the previous test to approximately 6.7. The results will provide oxidation data that will be useful to evaluate the heterogeneous ferrous iron oxidation model and the required AIS treatment system requirements for the Scotts Tunnel discharge. Effluent total iron increased to greater than 5 mg/L during Test AIS4. However, this is not unexpected since the maximum hydraulic loading for the inclined plate clarifier was exceeded by 150%. The intent of Test AIS4 was to obtain kinetic results for the reactors.

At the completion of the high flow test (Test AIS4) the influent AMD flow was decreased to 20 gpm during Test AIS5. Test AIS5 results are reported in Table ST-13. This test was conducted to evaluate operational conditions and requirements for longer operation of an AIS system. The AIS concentrations during the tests ranged between 2,000 and 2,400 mg/L (as Fe). Ferrous iron was substantially oxidized over the eight (8) day test to less than 0.05 mg/L, or 99.7% oxidation. The pH in the effluent was between 6.9 and 7.1 with an alkalinity ranging between 40 and 60 mg/L. In addition, effluent total iron was maintained at less than 2 mg/L during much of the test. RAIS concentration increased to approximately 25,000 mg/L (or 5% solids) during the test. This was a result of solids accumulation in the hopper of the clarifier as no AIS was wasted over this period.

The effluent total iron concentrations (~ 5 mg/L) during the high flow testing exceeded the maximum recommended hydraulic loading of the inclined plate clarifier. Testing conducted at lower flows achieved less than 2 mg/L total effluent iron. Within the pilot unit there are interactions between the polymer dose, flocculation tank and clarifier. At the lower flow the flocculation tank detention time approached 40 minutes. This is too long a detention time and may have caused flocculation erosion leading to smaller more difficult to settle particles. It is likely improved total iron removal to less than 1 mg/L can be achieved in a full scale system where polymer dose, flocculation time and clarifier size are all optimal.

Table ST-11: Summary of results from Scotts Tunnel AIS pilot testing (Test AIS3) at AMD Flow = 26 gpm, Air Flow = 18 cfm, Pulverized limestone dose = 4.3 gr/min, RAIS flow = 8 gpm and polymer dose 45 mL/min started on September 4, 2008 at 2:30 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
8:30 AM on September 6, 2008 (Polymer dose low due to tubing)						
React 1	6.50	10.6	13.1	1,580	4.30	--
React 2	6.81	11.0	13.4	1,320	0.50	--
Clarifier	6.80	10.9	13.6	7.30	0.17	40
RAIS	--	--	--	5,700	--	--
10:30 AM on September 8, 2008						
Raw	5.88	6.18	12.3	22.3	22.4	38
React 1	6.51	10.9	12.4	1,830	2.59	--
React 2	6.78	11.2	12.5	1,780	0.23	--
Clarifier	6.82	11.1	12.4	5.40	0.03	35
RAIS	--	--	--	7,400	--	--
9:00 AM on September 10, 2008, Power Outage due to Thunderstorm System Restarted at 9:30 AM						
11:00 AM on September 12, 2008						
React 1	6.65	10.7	12.7	2,150	1.96	--
React 2	6.89	11.3	12.9	2,220	0.04	--
Clarifier	6.91	11.2	13.0	6.70	0.04	48
RAIS	--	--	--	8,900	--	--
12:00 PM on September 12, 2008 (Polymer dose = 80 mL/min)						
React 1	6.54	10.4	12.8	2,260	1.08	--
React 2	6.80	11.0	13.0	2,300	0.01	--
Clarifier	6.85	11.0	13.2	2.15	0.03	47
10:00 AM on September 13, 2008 (Polymer dose = 80 mL/min)						
Raw	5.92	6.11	12.1	23.0	22.8	--
React 1	6.45	10.4	12.8	2,390	0.81	--
React 2	6.68	11.2	13.0	2,410	0.10	--
Clarifier	6.70	11.0	13.2	2.00	0.13	50
RAIS	--	--	--	11,800	--	--
3:00 PM on September 13, 2008 (Polymer dose = 80 mL/min)						
React 1	6.50	10.4	13.2	2,380	0.70	--
React 2	6.72	10.8	13.7	2,300	0.15	--
Clarifier	6.73	10.8	14.1	2.35	0.07	43
RAIS	--	--	--	8,640	--	--

Table ST-12: Summary of results from Scotts Tunnel AIS pilot testing (Test AIS4) at AMD Flow = 40 gpm, Air Flow = 18 cfm, Pulverized limestone dose = 8 gr/min, RAIS flow = 8 gpm and polymer dose = 115 mL/min started on September 13, 2008 at 4:00 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
6:30 PM on September 13, 2008						
React 1	6.41	10.4	12.7	2,320	6.35	--
React 2	6.59	11.0	13.0	2,360	0.67	--
Clarifier	6.62	10.8	13.4	1.95	0.52	40
RAIS	--	--	--	13,500	--	--
8:00 AM on September 14, 2008						
React 1	6.39	10.4	12.4	2,430	7.75	--
React 2	6.52	11.1	12.6	2,530	1.99	--
Clarifier	6.53	10.9	12.7	2.54	1.10	40
RAIS	--	--	--	18,000	--	--
1:30 PM on September 14, 2008						
React 1	6.51	10.1	13.3	2,410	4.64	--
React 2	6.82	10.8	13.9	2,610	0.40	--
Clarifier	6.84	10.6	14.3	5.60	0.15	56
RAIS	--	--	--	17,800	--	--
6:00 PM on September 14, 2008						
React 1	6.49	10.2	12.9	2,260	5.74	--
React 2	6.76	10.8	13.4	2,450	0.73	--
Clarifier	6.75	10.6	13.8	5.60	0.27	55
RAIS	--	--	--	17,500	--	--
7:30 AM on September 15, 2008						
React 1	6.48	10.5	12.4	2,320	7.30	--
React 2	6.68	11.0	12.6	2,460	1.18	--
Clarifier	6.71	10.9	12.7	6.30	0.61	44
RAIS	--	--	--	18,400	--	--
12:30 PM on September 15, 2008						
Raw	5.92	6.10	12.1	23.2	23.0	45
React 1	6.49	10.4	13.0	2,520	6.40	--
React 2	6.68	10.9	13.3	2,340	0.94	--
Clarifier	6.75	10.8	13.5	5.25	0.61	42
RAIS	--	--	--	17,000	--	--

Table ST-13: Summary of results from Scotts Tunnel AIS pilot testing (Test AIS5) at AMD Flow = 20 gpm, Air Flow = 18 cfm, Pulverized limestone dose = 4 gr/min, RAIS flow = 3 gpm and polymer dose = 50 mL/min started on September 15, 2008 at 4:00 PM.

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
10:30 AM on September 17, 2008						
React 1	6.56	10.8	12.8	2,050	2.95	--
React 2	6.92	11.4	13.1	1,830	0.07	--
Clarifier	6.85	11.4	12.8	2.20	0.03	35
RAIS	--	--	--	26,000	--	--
9:30 AM on September 19, 2008						
React 1	6.65	11.0	12.3	2,000	1.65	--
React 2	6.94	11.7	12.4	2,080	0.03	--
Clarifier	6.89	11.8	12.3	2.29	0.01	47
RAIS	--	--	--	20,000	--	--
8:15 AM on September 21, 2008						
Raw	5.96	5.85	11.8	23.6	22.9	--
React 1	6.79	10.2	11.9	2,150	1.63	--
React 2	7.15	11.0	11.9	2,260	0.05	--
Clarifier	7.10	10.8	11.9	1.66	0.01	61
RAIS	--	--	--	25,000	--	--
11:00 AM on September 23, 2008						
React 1	6.75	10.0	12.6	2,370	0.79	--
React 2	7.05	10.9	12.7	2,370	0.06	--
Clarifier	7.14	10.6	12.8	1.75	0.01	55
RAIS	--	--	--	23,000	--	--

Ferrous Oxidation Kinetic Evaluation

The results of the AIS pilot study were also used to evaluate the validity of the heterogeneous ferrous iron oxidation model for the sizing AIS reactor systems for the Scotts Tunnel AMD discharge chemistry. The heterogeneous ferrous iron oxidation model was used to predict the oxidation rate (*pseudo*-first order) and the ferrous iron concentration in the reactors using complete mix reactor equations. The results of the comparison are summarized in Table ST-14.

Based on the measured versus modeled ferrous iron comparisons in Table ST-14, the model provides reasonable predictions of the ferrous iron oxidation rates at the intermediate flows tested. However, the model under predicts the ferrous iron oxidation rate during the high flow tests (or shortest reactor detention times) and over predicts at the lower flows (longer detention times). This relationship is shown in Figure ST-4 where the measured minus the calculated ferrous iron concentrations from Reactor 1 are provided along with the average of the overall tests. As can be seen, there is a trend in the data with accurate model predictions at intermediate detention times (i.e., near 0 difference), under prediction at short detention times (i.e., positive differences), and over prediction at longer detention times (i.e., negative differences). The under prediction of the model at short detention times may be due to short circuiting through the reactor and the over predictions at long detention times mat be due to a shift to plug flow reactor characteristics. It is likely this model will be used to estimate reactor size based on the intermediate flows, because of the desired effluent ferrous iron concentration, the model will provide treatment system size estimates for design purposes.

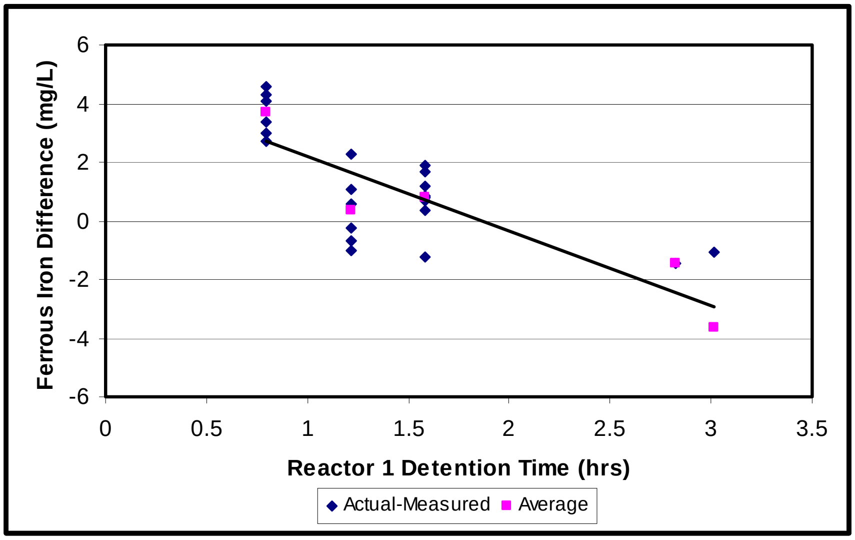

Figure ST-5. Pilot Study Results for Activated Iron Solids (AIS); difference between measured & calculated dissolved iron concentration.

With the change in surface area in the heterogeneous ferrous iron oxidation model, the observed oxidation rates from the pilot study are consistent with the model predictions. In addition, the results indicate the polymer has no negative impact on the catalytic process. Validation of the model permits use of the heterogeneous ferrous iron oxidation model to determine the adequate size of an AIS system to treat the Scotts Tunnel AMD discharge. The preliminary/conceptual design of the Scotts Tunnel system is summarized in the following sections.

Table ST-14: Summary of Iron Oxidation Data From Each Reactor During AIS Studies at the Scotts Tunnel Location and Comparison to the Calculated Dissolved Iron Using the Heterogeneous Iron Oxidation Model.

Test	Reactor	pH	Dissolved Oxygen mg/L	Temp. °C	AIS mg/L	Meas. Diss. Fe mg/L	Calc. Diss. Fe mg/L	Difference Diss. Fe (Meas-Calc)
AIS2	1	6.50	10.7	12.9	880	1.59	2.83	-1.24
AIS2	2	6.70	11.0	13.2	840	0.12	0.09	+0.03
AIS2	1	6.47	10.9	12.4	920	5.08	3.42	+1.66
AIS2	2	6.65	11.2	12.5	940	0.78	0.36	+0.42
AIS2	1	6.58	10.6	13.1	1,090	2.38	1.61	+0.77
AIS2	2	6.83	11.1	13.3	1,140	0.11	0.06	+0.05
AIS2	1	6.60	10.6	14.0	1,260	1.94	1.24	+0.70
AIS2	2	6.90	11.1	14.4	1,200	0.04	0.03	+0.01
AIS3	1	6.50	10.6	13.1	1,580	4.30	2.05	+2.25
AIS3	2	6.81	11.0	13.4	1,320	0.50	0.12	+0.38
AIS3	1	6.51	10.9	12.4	1,830	2.59	1.99	+0.60
AIS3	2	6.78	11.2	12.5	1,780	0.23	0.06	+0.15
AIS3	1	6.65	10.7	12.7	2,150	1.96	0.89	+1.07
AIS3	2	6.89	11.3	12.9	2,220	0.04	0.03	+0.01
AIS3	1	6.54	10.4	12.8	2,260	1.08	1.32	-0.24
AIS3	2	6.80	11.0	13.0	2,300	0.01	0.02	-0.01
AIS3	1	6.45	10.4	12.8	2,390	0.81	1.83	-1.02
AIS3	2	6.68	11.2	13.0	2,410	0.10	0.02	+0.08
AIS3	1	6.50	10.4	13.2	2,380	0.70	1.37	-0.67
AIS3	2	6.72	10.8	13.7	2,300	0.15	0.02	+0.13
AIS4	1	6.41	10.4	12.7	2,320	6.35	3.35	+3.00
AIS4	2	6.59	11.0	13.0	2,360	0.67	0.42	+0.25
AIS4	1	6.39	10.4	12.4	2,430	7.75	3.65	+4.10
AIS4	2	6.52	11.1	12.6	2,530	1.99	0.70	+1.29
AIS4	1	6.51	10.1	13.3	2,410	4.64	1.91	+2.73
AIS4	2	6.82	10.8	13.9	2,610	0.40	0.09	+0.31
AIS4	1	6.49	10.2	12.9	2,260	5.74	2.39	+3.35
AIS4	2	6.76	10.8	13.4	2,450	0.73	0.16	+0.57
AIS4	1	6.48	10.5	12.4	2,320	7.30	2.70	+4.60
AIS4	2	6.68	11.0	12.6	2,460	1.18	0.34	+0.84
AIS4	1	6.49	10.4	13.0	2,520	6.40	2.12	+4.28
AIS4	2	6.68	10.9	13.3	2,340	0.94	0.27	+0.67
AIS5	1	6.56	10.8	12.8	2,050	2.95	1.04	+1.91
AIS5	2	6.92	11.4	13.1	1,830	0.07	0.03	+0.04
AIS5	1	6.65	11.0	12.3	2,000	1.65	0.80	+0.85
AIS5	2	6.94	11.7	12.4	2,080	0.03	0.02	+0.01
AIS5	1	6.79	10.2	11.9	2,150	1.63	0.44	+1.19
AIS5	2	7.15	11.0	11.9	2,260	0.05	0.01	+0.04
AIS5	1	6.75	10.0	12.6	2,370	0.79	0.41	+0.38
AIS5	2	7.05	10.9	12.7	2,370	0.06	0.01	+0.05

IRON OXIDE SOLIDS DISPOSAL/REUSE

The wet solids produced by the treatment process are important representing the labor needed to handle and process solids and the volume of solids requiring disposal. AIS treatment produces a low volume of solids because the solids density is approximately 20-30% for 24 hour settled AIS. The purity of iron oxide solids produced by AIS treatment may be important for final reuse. Table ST-15 contains the analytical results from an AIS sample collected during the Phillips pilot study. The sample had a solids content of 21% after only 6 hours of settling. Additional settling time would increase solids content. The sample is nearly all iron (54%), which reflects greater than 95% iron oxides. Calcium is the second largest metal in the sample at 1.4%, which equates to a calcium carbonate content of 3.5%. Trace metal analysis indicates the sample has very low trace metal concentrations, which should not limit the disposal or reuse options for the waste solids.

Table ST-15: Laboratory Analysis of AIS Sample from the Pilot Study.

	Unit	**Detection Limit**	**Result**	**% Content**
Solids Content (Wet)	%	0.01		20.8
Dry Weight Basis				
Iron	mg/kg	1	537,500	54
Manganese	mg/kg	1	348	0.03
Aluminum	mg/kg	5	3,580	0.35
Calcium	mg/kg	1	14,200	1.4
Magnesium	mg/kg	1	400	0.04
Sodium	mg/kg	1	160	0.02
Potassium	mg/kg	1	35	<0.01
Silica	mg/kg	1	97	<0.01
Arsenic	mg/kg	1	48	<0.01
Lead	mg/kg	0.25	0.9	<0.01
Selenium	mg/kg	0.25	<0.25	<0.01
Zinc	mg/kg	1	123	0.01

AIS SYSTEM DESIGNS

The results of the pilot study will be used to develop an AIS treatment system to treat the Scotts Tunnel AMD discharge. The following sections will provide treatment system designs, estimated capital and installation costs, and operating costs for the treatment systems.

Scotts Tunnel AIS Treatment System

Based on the pilot study results, the AIS treatment system for the Scotts Tunnel AMD discharge will consist of: 1) a two-stage reactor system; 2) a clarification system including a polymer feed, circular clarifiers with a flocculation zone and hopper bottoms equipped with solids collection and recirculation; and 3) a solids handling system to concentrate and store solids from the AIS treatment system. Table ST-16 summarizes the design information and influent water quality. A schematic flow path of the AIS treatment system is depicted in Figure ST-5. Figure ST-6 shows a conceptual AIS treatment system layout at the proposed Scotts Tunnel AMD treatment system site. The proposed location is near the Kulpmont Wastewater Treatment Plant.

Table ST-16: Summary of design information for the Scotts Tunnel AMD discharge AIS treatment system.

Estimated Flow (gpm)		**Influent Water Quality**			
Average	**Maximum**	**pH**	**Total Al mg/L**	**Ferrous Fe mg/L**	**Alkalinity mg/L**
8,000	10,000	5.8	<0.5	23	36

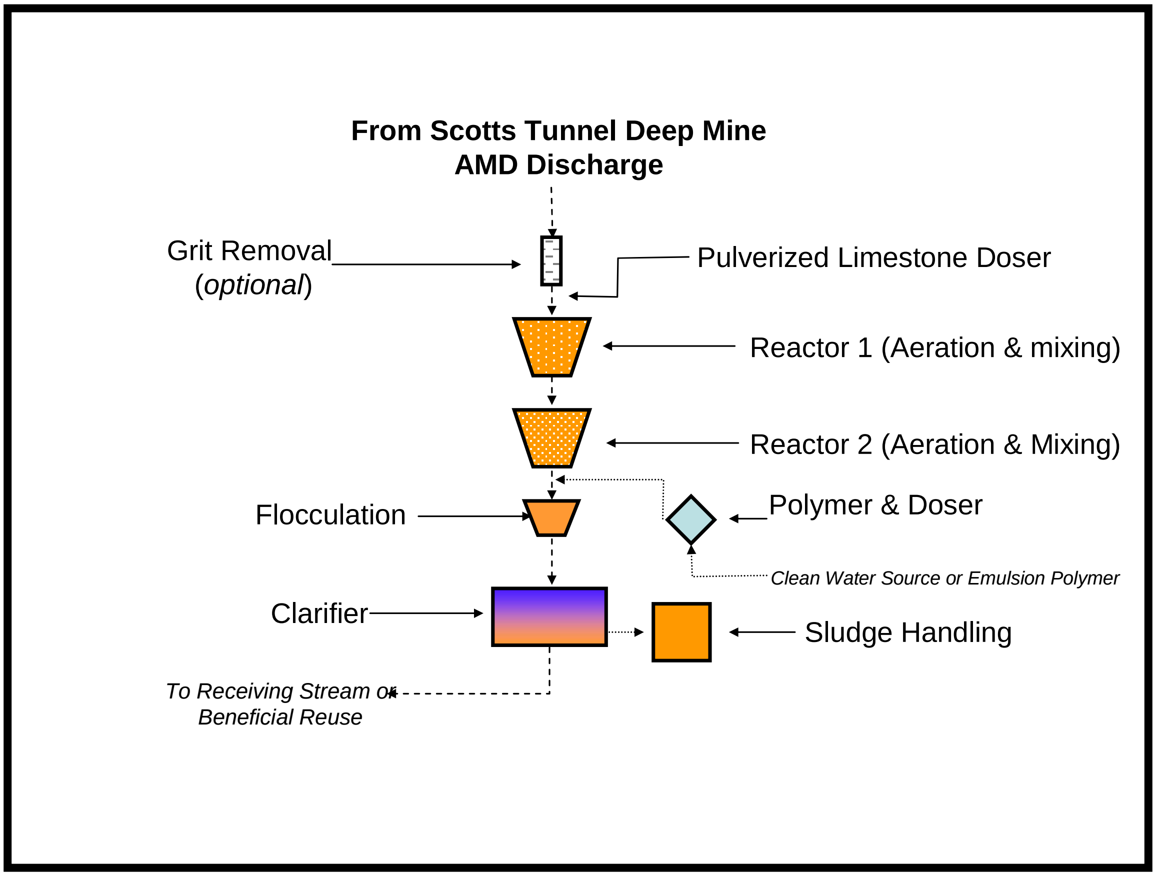

Figure ST-5. Scotts Tunnel AMD Discharge AIS Treatment System Flow Path

The design criteria and effluent water quality for the Scotts Tunnel AIS treatment system were determined based on the heterogeneous ferrous iron oxidation model kinetic rates, modified with the results of the AIS pilot study. Table ST-17 summarizes the design criteria for the Scotts Tunnel AIS treatment system and the anticipated effluent water quality. The expected performance of the Scotts Tunnel AIS treatment system is near complete removal under average flow conditions (> 99% iron removal) and maximum flow conditions (> 98% iron removal). This effluent quality should eliminate the impacts of the Scotts Tunnel AMD discharge on surface waters as well as produce water that may have beneficial reuse. Several potential water reuse applications have been identified that include: 1) a cooling water for the Mt. Carmel Cogeneration Station and 2) as a geothermal source for heating and cooling in the adjacent SEEDCO Industrial Park To augment flexibility in treatment, as well as improve operation and maintenance, a dual train system is recommended. This dual train design would also result in cost savings during low flow periods where both trains are not needed.

Table ST-17: Summary of design information and anticipated effluent water quality of the Scotts Tunnel AIS treatment system.

					Anticipated Effluent Quality			
Condition	**Flow gpm**	**Reactor 1 DT Hrs**	**Reactor 2 DT Hrs**	**Clarifier ft/d**	**pH**	**Total Fe mg/L**	**Dissolved Fe mg/L**	**Alkalinity mg/L**
Average	8,000	1.25	1.25	65	6.7	<0.5	<0.06	40
Maximum	10,000	1.00	1.00	80	6.5	<1.0	<0.1	35

Flow Measurement & Grit Removal

Flow measurement will be included in the design of the system. This flow will be used in the control panel for automated process control. Process control is required to optimize reactor conditions through aeration and polymer dose for flocculation. Both controls will have cost benefits in electricity demand and chemical dose. Grit removal will be incorporated in flow measurement system prior to the reactors to collect solid material that is likely contained in the discharge flow. The coarse material to be removed is from erosion of materials from the deep mine and precipitated solids from the AMD in the collection pipes. The flow measurement will also split the AMD flow to the two AIS treatment system trains.

Pulverized Limestone Dosing

The Scotts Tunnel AMD discharge will need added alkalinity to complete the oxidation of the ferrous iron as well as maintain an adequate reactor pH for rapid oxidation in the AIS process. A storage silo and pulverized limestone doser (GYRO Vibratory Doser) will be placed on the inflow to Reactor 1. The dose rate will be varied based on the measured AMD flow with an average dose of 2.2 tons per day. The added pulverized limestone will dissolve in the reactors producing alkalinity to sustain the AIS treatment. An average effluent alkalinity of 40 mg/L is anticipated.

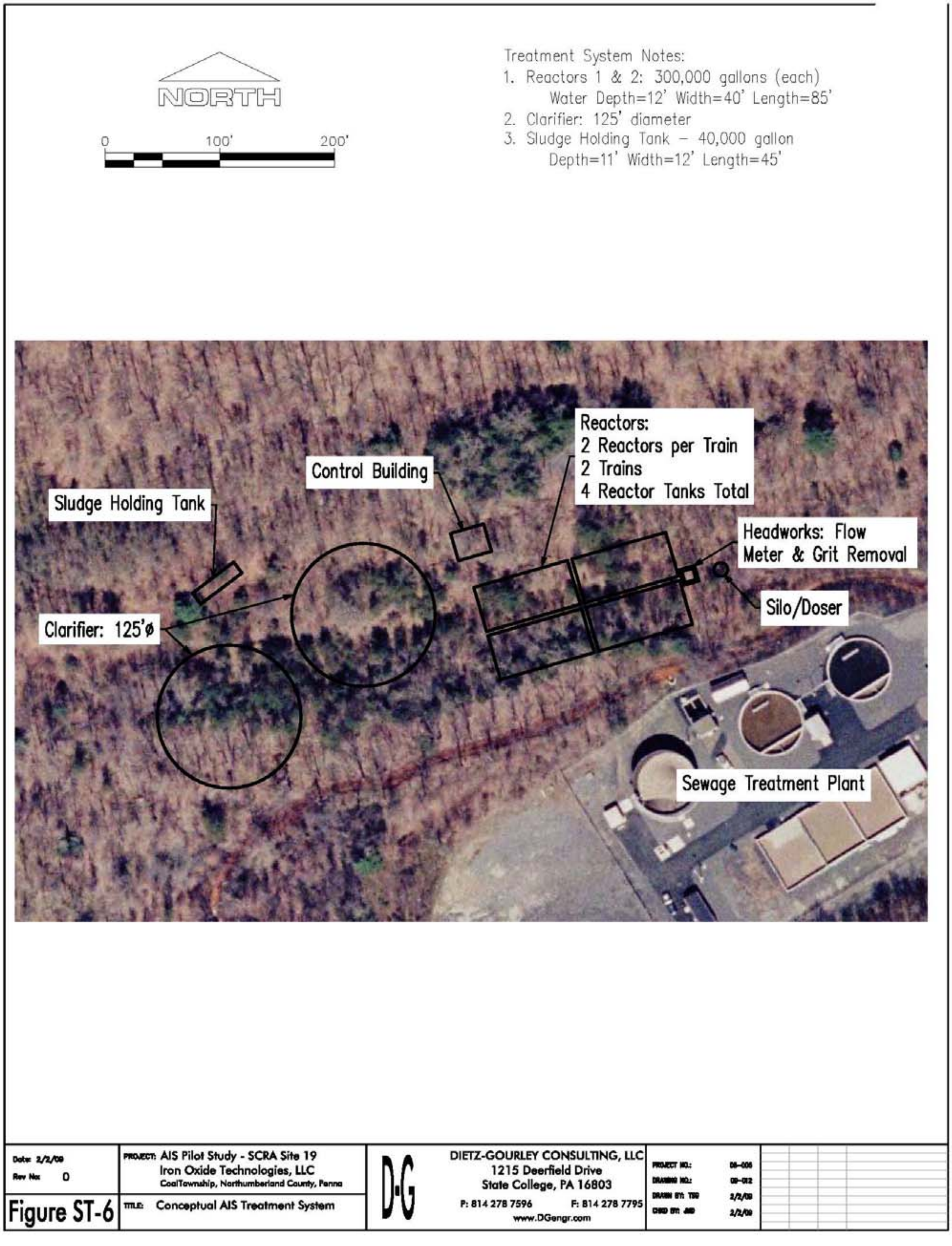

Figure ST-6. Scotts Tunnel Conceptual AIS Treatment System Layout

Reactors

The two-stage AIS reactor system follows the flow measurement. The AIS reactors are sized based on the heterogeneous ferrous iron oxidation model, reactor equations, and the pilot study results. The Stage 1 and Stage 2 Reactors will each contain 60 minutes (1.0 hours) of detention time at average flow and 75 minutes (1.25 hours) of detention time at maximum flow, the design flow. The reactors will contain top mounted high performance axial flow mixers to suspend the AIS. The reactors will also have aeration provided by fine bubble diffusers using positive displacement blowers. The aeration is needed to remove excess carbon dioxide in the AMD and formed from the reaction of ferrous iron with the AIS. Aeration volume delivered is based on the pilot study results and will be adjusted with AMD flow in order to maintain the pH and dissolved oxygen required for the AIS process.

Clarification

The clarification system will consist of a polymer dosing system, flocculation and clarification. A polymer was identified during the pilot study. The polymer reacts with the AIS during flocculation to form large rapidly settling particles. The powder polymer identified is a medium molecular weight, low charge anionic acrylamide polymer (Magnafloc 155, Ciba Specialty Chemicals). The polymer will be dosed into the effluent from the Stage 2 Reactors or prior to the flocculation zone of the clarifier. The polymer dosed water will flow into a flocculation zone of the clarifier where high performance variable speed mixers equipped with low shear impellors will promote flocculation of the AIS. Flocculated solids will flow from the flocculation zone into hopper bottom clarifiers where the AIS (i.e., particulate iron) will be settled and collected. The collected AIS will be returned to the reactors or removed to an AIS holding tank using positive displacement cavity pumps.

Solids Handling

An AIS holding tank will receive excess solids from the clarifiers where the solids will be allowed to further thicken with additional settling time. The Scotts Tunnels AIS treatment system will produce an average volume of AIS to be wasted daily between 6,000 and 12,000 gallons per day (4-8% solids), based on RAIS from pilot study. However, the solids handling facility will concentrate the solids to a final average volume of 1,500 to 2,500 gallons per day (20-30% solids). A solids handling option consists of a holding tank with storage capacity between 10 and 15 days. The holding tank will be equipped with a decant pump to remove clarified water from the top of the solids holding tank and return it to the treatment system. Solids will accumulate in the bottom of the tank until the tank is full which corresponds to approximately 50% of the total volume of solids. A jet mixer placed in the bottom of the tank will be used to periodically and at the time for transport to the disposal or reuse option re-suspend the thickened solids to slurry. A sludge pump will be used to remove the iron oxide slurry from the tank for transport to a disposal or processing site. Alternative solids handling will be evaluated depending on the final disposal and/or reuse of the iron oxides produced by the AIS process.

ESTIMATED AIS TREATMENT SYSTEM COSTS – CAPITAL & OPERATIONAL

The Scotts Tunnel AIS Treatment System capital costs will include plant headworks, silo/doser system, reactor tanks, flocculation clarifiers, water piping, air lines, drop-outs, diffusers, blowers, mixers, pumps polymer makeup and dosing systems, control panels, buildings for housing the control panel, blowers and polymer units, solids handling tanks, and perimeter fence. Backup electrical generators should also be considered to prevent loss of treatment in case of power failure.

Table ST-18 provides an estimate of the capital costs associated for the 14.4 MGD (10,000 gpm) Scotts Tunnel AIS Treatment System. Actual costs of an AIS Treatment System may vary depending on a number of factors related to final effluent quality goals and the site conditions. In addition to the treatment system costs, there will be costs associated with site development, treatment system installation, control/polymer building installation, and perimeter fencing. The estimated cost for these items is $500,000 which results in a total estimated cost for the treatment system and installation of $4,650,000.

Table ST-18: Scotts Tunnel AMD Discharge AIS Treatment System Preliminary Equipment List & System Cost[1]

Item No.	Item Description	Number
1	**Control System**	
	a. PLC Unit	1
	b. pH/Turbidity/Flow Monitors	2
	c. Control Building	1
2	**Pulverized Limestone System**	
	a. 60 ton Storage Silo	1
	b. GYRO Doser	1
3	**AIS Treatment System – IOT, Inc.**	
	a. 300,000 gallon Reactor Tanks (mix & aeration)	4
	b. 35 H.P Top Mounted Mixers (incl. mounts)	4
	c. 45 H.P. Blower/& Aeration Equipment	3
	f. 12,000 sq. ft. Flocculation Clarifiers	2
	g. 25 H.P. AIS Recirculation and WAIS Pumps	4
	h. 12 L/min (max.) Polymer System	1
4	**Sludge Handling System – IOT, Inc.**	
	a. 80,000 gallon AIS Holding Tank	1
	b. 100 H.P. Jet Mixer	1
	c. 1 H.P. Rail Mounted Decant Pump	1
	d. 15 H.P. Sludge Discharge Pump	1
Estimated System Cost		**$3,950,000**
Estimated Freight		**$200,000**
Estimated Total Equipment Cost		**$4,150,000**

[1] Costs reflect January 2008 pricing for equipment and freight

Table ST-19 provides an estimate of O&M Costs for the Scotts Tunnel AIS Treatment system and includes labor, operating and maintenance costs. Also provided is the value of the iron oxide solids produced and the direct effect this beneficial reuse will have on the O&M costs by removing disposal costs and offsetting other operating costs. Depending on a number of factors (primarily solids handling/reuse), the annual O&M costs at the Scotts Tunnel treatment system will be between $140,000 and $370,000.

Table ST-19: Scotts Tunnel AIS Treatment System Operating Cost Estimate

Item	**Cost $/yr**
O&M Electricity ($/yr)	$158,000
Pulverized Limestone Use ($/yr)	$31,000
Polymer Use ($/yr)	$28,000
Solids Disposal ($/yr)	$100,000
Equipment Maintenance ($/yr)	$15,000
Personnel O&M Costs ($/yr)	*$30,000-$50,000*
Total O&M Costs ($/yr)	**$372,000**[1]
Non-Personnel O&M Costs ($/yr)	**$322,000**
Potential Iron Oxide Reuse (@ $0.05/lb)	***+$80,000***
BALANCE of O&M Costs	***$140,000***

[1] using personnel O&M cost of $40,000/yr. Installation not included.

The treatment costs will vary depending on inclusion of the various Scotts Tunnel system capital and operating costs. Using the annual operating cost (labor not included) of $322,000 for the Scotts Tunnel system equates to a cost of $0.08 per 1,000 gallons of treated water. If sludge disposal costs are removed and an iron oxide revenue option is identified, the treatment costs decrease to treatment costs to $0.033 per 1,000 gallons. The total treatment cost for the Scotts Tunnel AMD discharge using the AIS treatment process, includes annualized capital costs (25-year basis) and all O&M costs ($372,000 per year), is $0.13 per 1,000 gallons of treated AMD.

SUMMARY

The Scotts Tunnel AIS pilot study results and this summary report provide considerable information regarding the AIS Treatment process. The results indicate:

- AIS Treatment effectively oxidizes ferrous iron in short detention times needed to meet effluent objectives for the Scotts Tunnel AMD.
- AIS ferrous iron oxidation rates are not affected by polymer dosing.
- Observed oxidation rates by the AIS solids are slightly slower, but consistent with the heterogeneous ferrous iron oxidation model.
- Pulverized limestone can be used as an alkalinity source to address the slightly net acidic Scotts Tunnel AMD discharge.

Based on the results of the pilot study and the (modified) heterogeneous ferrous iron oxidation model, a conceptual AIS treatment system was developed that included:

- A new complete AIS treatment system for the Scotts Tunnel AMD discharge that will produce an effluent iron less than 0.5 mg/L at average flows and 1 mg/L at maximum flows.
- An alternative clarification system to improve removal of particulate iron solids produced by the AIS process that includes:
    - Polymer make-up and feed system
    - Flocculation horizontal flow clarifiers.

The Scotts Tunnel treatment system will have a capital cost of $4,650,000 with an annual operating cost between $140,000 and $370,000 depending on inclusion of labor and solids reuse. The treatment costs for the Scotts Tunnel discharge range between of $0.033 and $0.13 per 1,000 gallons of treated water depending on inclusion of various operating costs and reflection of capital costs in the estimate.

The AIS Treatment approach produces iron oxide solids with characteristics that offer a significant potential for beneficial reuse. Investigations indicate there is substantial potential for the solids to be used in the pigment industry. This investigation is ongoing. Water reuse is also significant potential for the treated water due to the AMD characteristics (< 250 mg/L sulfate) and the location of the treated discharge near 1) a cogeneration facility the could use the treated water as a cooling water source and 2) an industrial park where the water could be used as a geothermal heating/cooling source.

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Activated Iron Solids Treatment Pilot Study for Saxman Run Acidic Mine Drainage

SUMMARY REPORT

Submitted to:

Department of Environmental Protection
Bureau of Abandoned Mine Reclamation
Ebensburg, Pennsylvania

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February 3, 2009

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INTRODUCTION

The discharge of acid mine drainage (AMD) to surface waters in Pennsylvania and other eastern coal region states contaminates thousands of miles of waterways resulting in their non-compliance with numerous Pennsylvania Water Quality Standards including, but not limited to, pH, total iron, suspended solids, and aesthetics. The AMD is a result of past (and unregulated) surface and underground coal mining that exposes pyritic minerals to atmospheric oxygen and results in the oxidation and the production of AMD.

Of particular concern is AMD produced in the vast historic and abandoned deep mine workings found throughout the coal region. The pyrite oxidizes to create AMD that collects and is stored in the mine voids forming large underground reservoirs of contaminated AMD. These large underground AMD reservoirs discharge at one or more points, typically from air portals (for air circulation during active operations), water portals/drains (to maintain a minimal water level in the mine during active operations), or from the mine entry. Deep mine discharges tend to be very high flow with elevated ferrous iron but may contain adequate alkalinity for iron removal. The deep mine discharges are often the largest contributor of metal loading in the watershed and/or subbasin. Treatment is mandatory to achieve water quality goals in the receiving stream.

The impact of the high flow AMD discharges on receiving streams is substantial. Input of high flow and ferrous iron AMD to surface waters causes: 1) increase of instream iron concentrations to levels exceeding water quality standards; 2) instream oxidation causes the deposition of iron oxides, known as “yellowboy”, onto stream bottoms smothering aquatic life and causing aesthetic and sediment problems; and 3) oxidation of ferrous iron can cause a decrease in pH to less than 6, a water quality standard. Theses types of impacts lead to degradation of the receiving waters to conditions that do not meet the waters designated aquatic life, recreational, and water supply uses.

Development of new and innovative treatment systems that effectively remove AMD pollutants at substantially lower capital and operating costs is paramount to the watershed restoration efforts across Pennsylvania. AIS (Activated Iron Solids) treatment has been identified as a potential new and innovative AMD treatment approach to address high flow AMD sources and or AMD treatment where land constraints or effluent objectives dictate active treatment.

This report summarizes the Saxman Run AIS pilot study to evaluate the use of AIS treatment to treat AMD sources, specifically the upper and lower Saxman Run discharges. Neither of the discharges are currently treated and are major AMD sources to Saxman Run as well as the Loyalhanna River.

SITE DESCRIPTION & BACKGROUND

There are numerous high flow, deep mine discharges with varying concentrations of iron, alkalinity and acidity in the Loyalhanna River watershed. There are two deep mine discharges, the Upper and Lower Saxman Run discharges, in the Saxman Run watershed, a tributary to the Loyalhanna River. The Upper and Lower Saxman Run AMD discharges contribute all the AMD pollution loading to Saxman Run, which is severely degraded. The two AMD sources also contribute considerable AMD pollutant load through Saxman Run to the Loyalhanna River causing degradation downstream of the confluence.

The purpose of this AIS pilot study at Saxman Run was to investigate the new and innovative AIS technology as a treatment alternative for conventional lime-based active treatment or passive treatment for the two Saxman Run discharges as well as other discharges in the Loyalhanna River watershed (e.g., the Crabtree AMD discharge). The following provides the technical background information for the pilot study including AMD characteristics at the Saxman Run discharges, background iron oxidation information, and a brief description of the AIS treatment process.

AMD Characteristics

The historic AMD discharge chemistry and flow data for the Saxman Run discharges are summarized in Table SX-1. Recent data collected during the pilot study are summarized in Table SX-2. The two tables indicate the two discharges have changed slightly from historic conditions. The measured total and ferrous iron in the more recent data is lower than the historical data. This may be due to a gradual flushing of the deep mine pools. The discharge chemistry may also have been affected by the construction of a new bridge across Saxman Run. The construction of the bridge abutment foundation intercepted the mine pool and resulted in substantial AMD flow that currently flows into the stream downstream of the bridge through three (3) PVC pipes installed to permit construction of the bridge. The PVC pipes caused the historic location of the Upper Saxman Run discharge to cease flowing. The PVC pipes are now known as the Upper Saxman Run discharge.

Table SX-1. Historic data (2002 – 2004) for the two Saxman Run deep mine discharges. (data obtained from the Loyalhanna Watershed Association – LWA)

Location	Ave. Flow gpm	pH	Total Fe mg/L	Fe^{2+} mg/L	Total Al mg/L	Total Mn mg/L	Alkal. mg/L	"Hot" Acidity mg/L	Sulfate mg/L
Lower	1820	5.7	44.9	39.1	0.5	4.8	55.8	75.8	508
Upper	1710	5.5	45.0	38.9	2.0	5.3	38.7	95.3	552

Table SX-2: Characteristics of the Saxman Run Discharges collected during the pilot study.

Location	Temp. °C	pH	Total Fe mg/L	Diss. Fe mg/L	Alkal. mg/L	Calc. Acidity* mg/L	CO_2 Acidity mg/L
Lower	13.2	6.05	33.5	33.0	58	-15	165
New Upper	13.2	5.70	36.0	36.0	45	+20	250

* Calc. Acidity value determined after all iron has been oxidized and precipitated.

Historic data indicates the Saxman Run contains predominately ferrous iron (Fe^{2+}), but also small amounts of ferric iron (Fe^{3+}); ferric iron is the difference between total iron and ferrous iron. The measurement of ferric iron is probably the result of sampling and handling error resulting in small amounts of ferrous iron oxidation to ferric iron. In addition, the difference between total and dissolved iron measured during the pilot study testing was only 0.5 mg/L. This indicates the iron in the AMD is solely as ferrous iron. The ferrous iron concentration is important since it is the oxidation of ferrous iron that is the controlling step in iron removal from mine drainage.

Alkalinity was evaluated to determine if there is adequate alkalinity in the Saxman Run AMD for the removal of iron from the mine drainage. The oxidation and precipitation of 1 mg/L of ferrous iron will consume 1.8 mg/L of alkalinity. Table SX-1 contains an analytically measured acidity and Table SX-2 is the calculated acidity after all iron has been oxidized and precipitated. The historic data for both the Saxman Run discharges indicate the AMD are net acidic. Recent data from the pilot study indicates the Lower Saxman Run discharge has changed to a pH of 6.05 with an alkalinity of 58 mg/L. Based on the recent iron and manganese concentrations, the Lower Saxman Run AMD discharge is now slightly net alkaline (-15 mg/L of acidity). The Upper Saxman Run AMD discharge has been moved as a result of the bridge construction and has also changed chemistry with lower iron and acidity. However, the Upper Saxman Run discharge is still slightly acidic. Both discharges will require the addition of alkalinity in order to complete the oxidation step and have an effluent pH greater than 6.

The pH and alkalinity indicate the discharge contains elevated carbon dioxide acidity with the recent data indicating a calculated concentration of approximately 165 mg/L. The Saxman Run discharge has elevated iron concentrations with a historic average ferrous iron concentration of 45 mg/L compared to the 33 mg/L concentration measured during the pilot study. The historic flow and the more recent iron data will be used to size a treatment system.

Carbon dioxide (CO_2) acidity data was also calculated to determine the amount of aeration needed to remove the CO_2 by the AIS treatment process and maintain or raise the pH to levels needed for the effective oxidation of ferrous iron in the AIS treatment approach. In aqueous chemistry, carbon dioxide acidity is present in water as carbonic acid (H_2CO_3). The pH of water (controlled by the carbonate system) is determined by the concentrations of bicarbonate (HCO_3^-), which is alkalinity, and H_2CO_3 according to the following relationship:

$$\text{(SX-1)} \qquad H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

The pK_a of this equilibrium is 6.4. This 6.4 would also be the pH at which the H_2CO_3 and HCO_3^- concentrations would be equal. This means an alkalinity (HCO_3^-) of 30 mg/L (as $CaCO_3$) would require an equal CO_2 acidity (H_2CO_3) of 30 mg/L (as $CaCO_3$) to have a pH of 6.4. The CO_2 acidity calculated for the Upper and Lower Saxman Run discharges are 250 and 165 mg/L (as $CaCO_3$), respectively. The source of this acidity is chemical neutralization reactions in the deep mine pool as well as decomposition reactions. The CO_2 acidity in the discharges is about 100 times higher than is normally found in surface waters in equilibrium with the atmosphere.

The solubility of calcium and magnesium in the AMD must be evaluated for the various treatment methodologies. pH adjustments may create operation and maintenance issues by precipitating calcium and magnesium. Figure SX-1 shows the calcium (calcite) solubility with respect to pH for the Saxman Run discharge. Oversaturated conditions are only present at pH above 7 indicating calcium (calcite) precipitation is not a significant concern in the treatment of

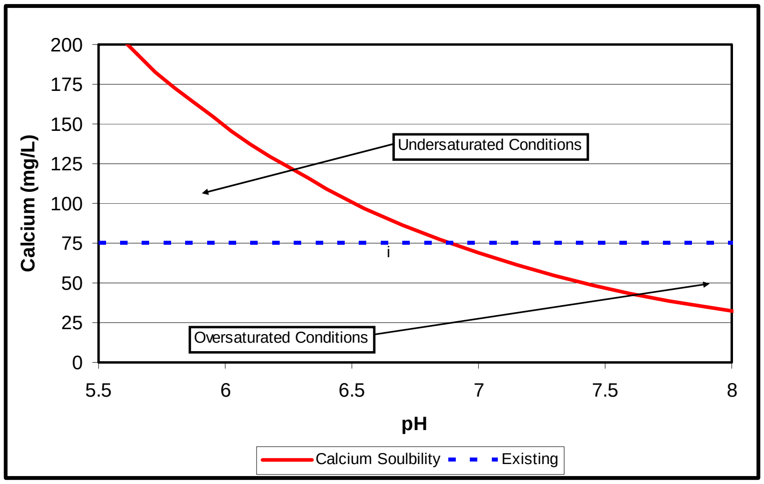


Figure SX-1. Calcium solubility in the AMD discharge with respect to pH.

the Saxman Run discharge unless lime (CaO) is used to raise the pH to greater than 7. The increased calcium concentrations and elevated pH will cause calcium (calcite) to precipitate. At pH greater than 8, magnesium can also be removed as a hydroxide. Calcium and magnesium precipitation in lime-based treatment will increase operation and maintenance by increasing solids handling and disposal. AIS treatment oxidizes ferrous iron at acidic pH (less than 7) and prevents the additional solids volumes associated with calcium and magnesium precipitation compared to lime-based or aeration treatment approaches.

Another important parameter listed in Table SX-2 is the temperature of the discharge. Temperature of the water is important because it affects a number of chemical and physical processes in the treatment of AMD. The temperature of the Saxman Run discharges is 13.2°C. This temperature will affect aeration, oxidation and the settling processes. As an example, the homogeneous oxidation rate doubles for every 2°C increase in temperature. The heterogeneous oxidation process is similarly affected by temperature.

The chemistry evaluation for the discharges is an integral component in determining appropriate approaches and methods for treating the AMD. The impacts of the AMD chemistry on the various treatment approaches will be compared in a subsequent section.

Iron Oxidation & Removal in AMD Treatment

The treatment of the Saxman Run AMD discharges requires iron removal and this iron removal is a multi-step process involving:

1. Oxidation of dissolved ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+});
2. Hydrolysis of ferric iron to form insoluble ferric oxide ($Fe(OH)_3$);
3. Flocculation of tiny (sub micrometer) iron oxide particles to form larger (micrometer) iron oxide particles;
4. Settling of suspended iron oxide particles from solution.

Depending on the type of treatment, one or more of the above processes will control the removal of iron. In passive treatment the oxidation (Step 1) of ferrous iron is very slow and determines iron removal and the size of the passive treatment system. In chemical treatment at high pH (> 8), the settling (Step 4) typically controls iron removal. The new and innovative process, AIS treatment, provides an alternative to passive treatment and chemical treatment.

The oxidation of ferrous iron is the first and most crucial step in the removal of iron. Without the oxidation step, ferrous iron would remain in solution (except at very high pH) and removal of iron from AMD would not be possible. There are two types of ferrous iron oxidation in water:

1. ***Homogeneous Ferrous Iron Oxidation (HoFIO)*** **–** is the long established oxidation process occurring in solution and involves the reaction of dissolved ferrous iron (Fe^{2+}) with dissolved oxygen.
2. ***Heterogeneous Ferrous Iron Oxidation (HeFIO)*** **–** is a newly identified oxidation process occurring on the surface of iron oxide solids and involves the sorption of ferrous iron and dissolved oxygen followed by the rapid catalytic oxidation on the surface of the iron oxide.

The first type, HoFIO is the ferrous iron oxidation that occurs in solution and is most commonly associated with passive treatment and conventional (lime-based) chemical treatment of AMD. This process is also the dominate process where aeration is used to add oxygen and raise the pH to greater than 7, a pH where HoFIO will dominate. The long established HoFIO rate equation (Sung & Morgan 1980) is:

$$\text{(SX-2)} \qquad \textit{HoFIO rate}\ (\mathrm{M} \cdot \mathrm{s}^{-1}) = -\delta[\mathrm{Fe(II)}]/\ \delta t = k_{\mathrm{Ho1}} \times [\mathrm{Fe(II)}_{diss}] \times [\mathrm{O_2}] / \{\mathrm{H+}\}^2$$

The HoFIO equation is complex with the HoFIO rate affected by the ferrous iron concentration $[Fe(II)_{diss}]$, dissolved oxygen $[O_2]$ and pH $\{H^+\}$. Temperature is an integral part of the equation by its affects on the reaction rate constant (k_{Ho2}), with a decrease in temperature causing a decrease in the oxidation rate. The HoFIO equation is a reliable design tool because the equation can be used to predict iron removal for 1) different AMD chemistry, and 2) factors in iron removal under operating conditions (e.g., dissolved oxygen, pH and temperature). The HoFIO model will be used to evaluate ferrous iron oxidation results for the pilot study where only aeration is used in the reactors to increase dissolved oxygen and pH.

Heterogeneous ferrous iron oxidation (HeFIO) is an oxidation process that occurs on iron oxide surfaces and is the oxidation process AIS uses to oxidize ferrous iron. HeFIO is a two step processes that involves 1) the sorption of ferrous iron to the surface of the iron oxide, 2) rapid oxidation in the presence of dissolved oxygen to form new iron oxides directly on the surface of the iron oxide. Equations and models for the reactions are contained in Dietz (2003). The equations are complex describing both sorption and oxidation process.

$$\text{(SX-3)} \qquad \textit{HeFIO rate}\ (\mathrm{M} \cdot \mathrm{s}^{-1}) = (-\delta[\mathrm{Fe(II)}]/\ \delta t) = (k_{\mathrm{He1}}[\mathrm{O_2}]S_1) + (k_{\mathrm{He2}}[\mathrm{O_2}]S_2)$$

and

$$\text{(SX-4)} \qquad S_x = \frac{1 + ([Fe(II)_{diss}] \times K_x^{app})}{[\equiv Fe(III)] \times \Gamma_x \times \{H^+\}^x}$$

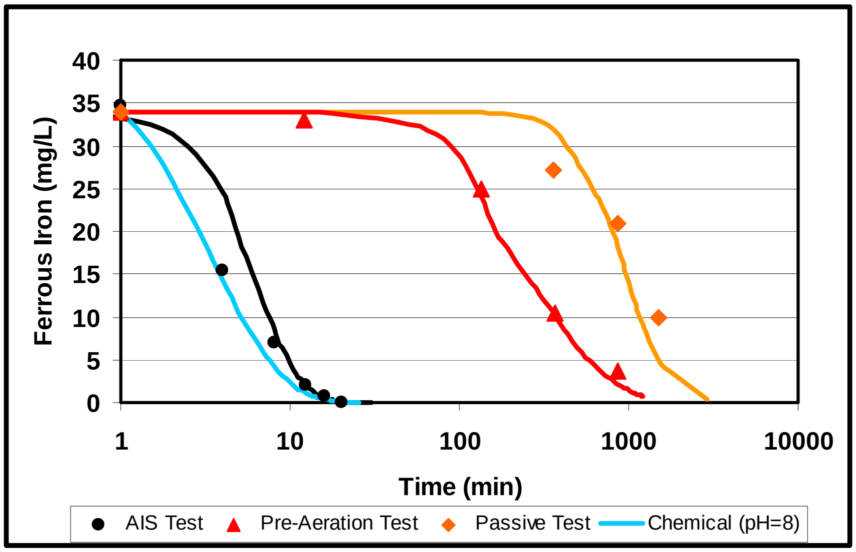


Figure SX-2. Bench-scale Results for Activated Iron Solids (AIS), Pre-aeration & Passive Tests

where **x** is the reaction (either 1 or 2), $\mathbf{k_{Hex}}$ are the surface oxidation rate constants, $\mathbf{K_x^{app}}$ are the surface complexation constants, and $\mathbf{[\equiv Fe(III)]}$ is the AIS concentration (in mg/L). Dietz (2003) determined the various thermodynamic constants for the equations including activation energies and enthalpies, which describe the effects of changing temperature. In current treatment systems (including passive treatment and lime treatment), HeFIO is not very important (< 5% of the ferrous iron oxidation rate) due to the low concentrations of suspended iron oxides (typically less than 10 mg/L). Iron Oxide Technologies, LLC has developed several treatment systems optimizing HeFIO through concentrated suspensions of iron oxide solids in reactor systems. Figure SX-2 shows the time required to oxidize and remove ferrous iron from AMD for various treatment methods from bench-scale testing conducted at 15°C on an anoxic AMD discharge. Note the x-axis time scale is logarithmic. The detention time required to achieve less than 0.5 mg/L ferrous iron for the passive treatment and passive treatment with pre-aeration tests were 50 and 25 hours, respectively. Critical low-temperature conditions (Average Temp. = 8°C) would require additional detention times (2 to 5 times) to complete oxidation. As a comparison, the AIS treatment test required only 20 minutes to achieve 0.5 mg/L, which demonstrates the importance of HeFIO and the ability AIS treatment to achieve rapid oxidation and removal of ferrous iron. AIS treatment is 75 times faster in comparison to pre-aeration/passive treatment and 150 times faster in comparison to passive treatment only. A pH 8 oxidation line is also provided to show AIS ferrous iron oxidation is similar to conventional lime-based treatment: the 0.5 mg/L ferrous iron is expected to occur in 15 to 20 minutes detention time.

Innovative AIS Treatment

Iron Oxide Technologies, LLC has developed new (patent pending) active treatment approaches collectively known as Activated Iron Solids (AIS) treatment of AMD. AIS treatment has numerous advantages over conventional chemical treatment that can make long term treatment and iron oxide recovery possible at abandoned mine discharges. The AIS treatment advantages over conventional chemical treatment are:

1) Oxidation and removal occur at slightly acidic pH (6-7);
2) Oxidation rates are as fast as conventional chemical treatment;
3) For net alkaline AMD no alkaline chemicals are needed;

4) For net acidic waters, inexpensive pulverized (powder) limestone can be used for the needed alkalinity;
5) Solids produced by the AIS process are high-density (30% solids);
6) Solids are high purity iron oxides (95% iron oxides on a dry weight basis).

These advantages will have a direct effect on treatment costs by eliminating (or minimizing) chemical use and cost, and simplifying operation that will decrease manpower requirements. The innovative active AIS treatment processes utilized for the pilot study at the Saxman Run discharge is the Two-Stage AIS Reactor System (depicted in Figure SX-3). The AIS system uses high iron oxide concentrations (AIS = 1,500 – 2,500 mg/L) to increase ferrous iron oxidation and removal. The high iron oxide concentrations produce a catalytic environment that promotes ferrous iron oxidation and removal while producing high-density and pure treatment solids (iron oxide solids). The Two-Stage AIS Reactor system maintains high reactor AIS concentrations through recirculation of solids collected in the clarifier.

SAXMAN RUN PILOT STUDY

A location was identified for the pilot study at the Latrobe Wastewater Treatment Facility in an open area adjacent to the 2002 Growing Greener Project that included collection and piping of the Lower Saxman Run discharge to the Latrobe Wastewater Treatment Facility property, installation of a small-scale ALD on the property, and a temporary AIS demonstration unit. The Lower Saxman Run AMD was available at this location for the pilot study through the installed underground pipe collection system and an intake pump placed in a wet well. A set of valves at the intake and on the Latrobe Wastewater Treatment Facility property regulate flow from the Lower Saxman Run discharge to and around the ALD that was used to test alkalinity addition to the slightly acidic mine water.

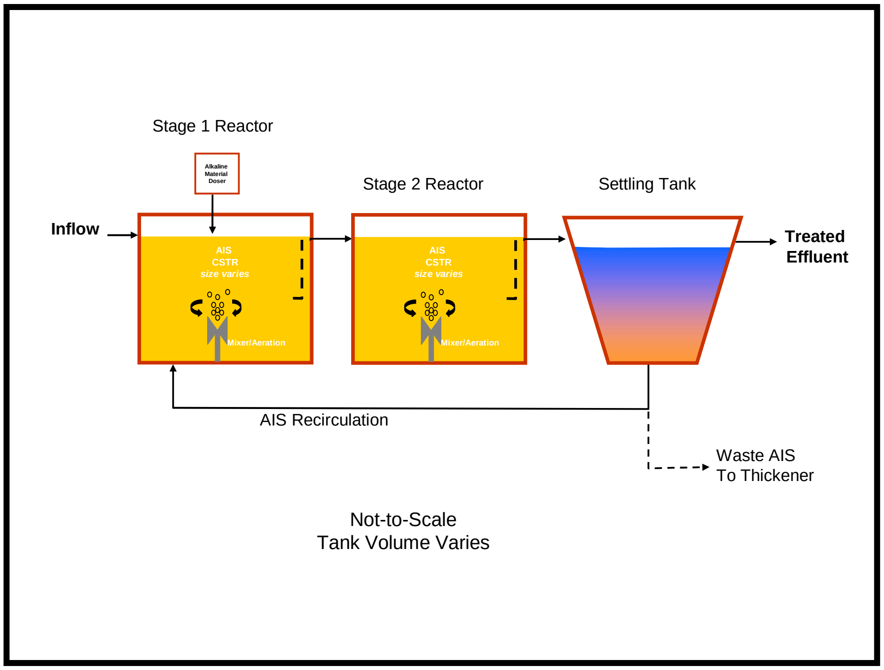


Figure SX-3. AMD Treatment in a Two-Stage Flow-Through AIS System

The Saxman Run location was the first pilot study to be conducted with the portable pilot Two-Stage Flow-Through AIS system. Fabrication of the unit was completed in mid-September and delivery to the Saxman Run AMD discharge site was on September 16, 2006. Because of the historic net acidic conditions or low final alkalinity, a Merrick screw feed doser was also required for the study to deliver pulverized limestone to the system as an alkalinity source. Setup of the AIS pilot unit consisted of: 1) moving the trailer unit onto the pad and leveling the trailer unit with support pillars; 2) placement of the Merrick pulverized limestone doser on the pilot unit with a crane; 3) electrical connection of all the equipment to the on-site service provided by Allegheny Power; 4) installing all mixers, pumps and aeration equipment in the pilot unit; and 5) connecting all required plumbing to and from the pilot unit. The Lower Saxman Run AMD was directed to the pilot unit inlet weir box using the existing wet well, one (1) horsepower submersible pump, and piping for the SBR. The effluent from the pilot unit, along with overflow from the inlet weir box, was conveyed to Saxman Run from the pilot treatment system using 4-inch PVC drain line. Setup of the pilot system was completed on October 1st and initial startup testing of the pilot unit started on October 2nd.

The Saxman Run pilot study was conducted during October and November 2006. This was the first operational test of the pilot flow through system and the configuration of the various components. AIS for startup of the pilot unit were obtained from the adjacent SBR unit by pumping from the sludge holding tank. Pilot testing at the Lower Saxman Run discharge consisted of two phases: 1) initial operation using AMD from the ALD to evaluate operation using net alkaline water produced by pre-treatment in the ALD: and 2) operation using AMD directly from the source (i.e., no pre-treatment by the ALD) with alkalinity added by the Merrick pulverized limestone doser. The pulverized limestone was tested to determine if this is a cost effective alkalinity source for the Saxman Run discharge in order to maintain the needed pH (~6.5) for the AIS process.

Analytical Methods

Analysis for the pilot study consisted of pH, dissolved oxygen, temperature, total iron, dissolved iron, alkalinity and periodic conductivity. pH was measured with an Fisher Scientific Accumet Portable Meter equipped with a Cole Parmer Accumet combination pH electrode. The pH electrode was calibrated daily prior to use with pH 4.00 and pH 7.00 buffers. Dissolved oxygen (DO) and temperature were measured with an YSI Model 550A DO Meter. The DO Meter was calibrated prior to each use using the air saturation method. Total iron was measured using a Hach Iron Pocket Colorimeter Test Kit (0-3.00 mg/L) using Ferrover reagent after appropriate dilution. Dissolved iron was also measured with the Iron Pocket Colorimeter but after filtration using a syringe and a 0.2 μm syringe filter, and appropriate dilution. Ferrous iron was determined using Hach ferrous iron powder packets and the Hach Iron Pocket Colorimeter. Initial testing on the discharge indicated dissolved iron (filtered sample) equals ferrous iron for the conditions in the Saxman Run AMD. As a result, the dissolved iron test was used to determine ferrous iron. Alkalinity was measured on a 100 mL sample using a Hach Digital Titrator, a 1.600 N sulfuric acid cartridge. Conductivity was measured with an Oakton Conductivity Pen.

AIS Pilot Testing

The initial AIS treatment system settings were intended to identify operating conditions for an AIS flow through treatment process that included pulverized limestone dose, AIS concentration/recirculation, and aeration rate. In the case of the AIS, the reactor AIS (as total iron) concentration was achieved by recirculation of solids from the clarifier. The initial startup conditions for the pilot unit were:

1. Reactor 1 & 2 AIS ~ 700 mg/L (as Fe)
2. Coarse Bubble Air Flow = 24 cfm
3. AMD Inflow = 4 gpm
4. AIS Recirculation Rate = 25 gpm
5. Pulverized Limestone Dose = 0 gr/min

To start the pilot system, AIS solids were added to the pilot unit using solids in the sludge holding tank of the adjacent demonstration AIS-SBR system that were collected during the operation of the system. The intent of using the solids from the AIS-SBR was to shorten start-up time to accumulate AIS solids for the reactor system (days versus weeks). Maximum air flow from the blower to the coarse bubble diffusers was selected as an initial setting to evaluate increases in dissolved oxygen concentration and control of pH through carbon dioxide removal. The initial AMD inflow was selected to evaluate initial operation of the various components. The AIS recirculation rate was set at a flow rate based on recommendations of the manufacturer for optimal performance of the floc blanket clarifier.

The AIS pilot system was started on October 4th. No pulverized limestone was dosed during this initial startup because the water source was from the ALD. Pulverized limestone dosing was attempted in subsequent testing at the site to determine if pulverized limestone could be used. Limited data was collected during this first pilot study at the Upper Saxman Run discharge site because a number of operational issues occurred that severely limited the effectiveness of the pilot system. Initial operational issues of a new treatment process are not completely unexpected, but the degree of the operational issues encountered during this first testing substantially affected achieving the objectives for the site. The operational issues encountered at this first pilot study included:

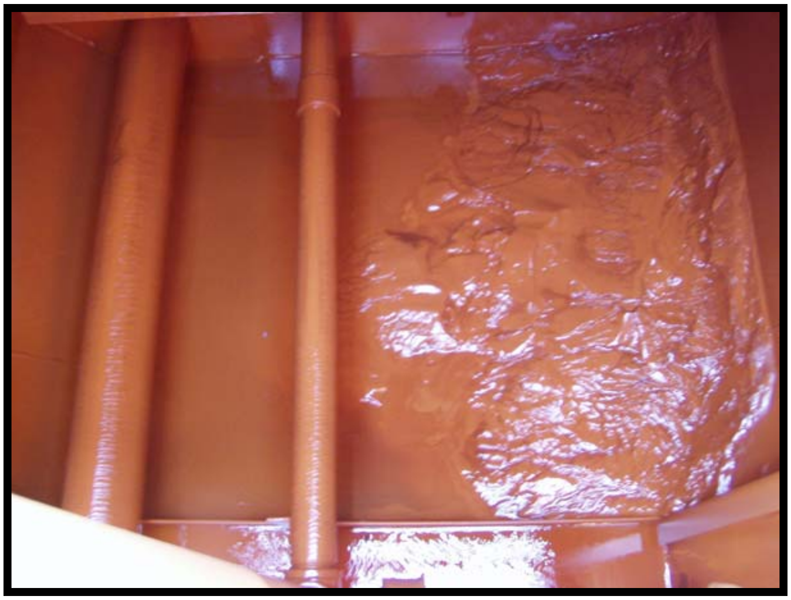


Figure SX-4. AIS solids accumulation in the bottom of Reactor 1 during the Upper Saxman Run pilot study.

1. The mixers were installed in a horizontal configuration that did not adequately mix the bottom of the reactors and caused the accumulation of AIS in the bottom of the reactors (see Figure SX-4) instead of maintaining a high AIS concentration in suspension.
2. Operation guidance for the upflow clarifier provided by the manufacturer was inadequate for the AIS

application.

3. Overflow weir box location in the clarifier may have contributed to short-circuiting causing solids wash-out.
4. Poor flocculation in the floc blanket clarifier did not result in formation of large particles that settled rapidly. It was determined this was a result of a high charge on the iron oxide particles that required a polymer for charge neutralization.
5. The screw feed pulverized limestone doser provided by Merrick Industries would not maintain a consistent dose. The screw feed design is an inadequate configuration for the characteristics of the pulverized limestone.

The first issue substantially limited the ability of the pilot system to operate long term as the AIS concentration in the reactors gradually declined as the solids accumulated in the bottom of the reactor tanks. High flow performance evaluation was also limited because of the loss of solids from the clarifier (and system) at influent flows greater than 10 gpm. Effluent iron was also not acceptable at lower flows (> 10 mg/L) but did not exceed the influent total iron concentration (i.e., solids were not lost).

Table SX-3: Summary of analytical results from Lower Saxman Run AIS pilot testing (Test AIS1) at AMD Flow = 11 gpm, Air Flow = 24 cfm, and RAIS flow = 25 gpm started on October 4, 2006 at 10:00 AM.

(No Pulverized Limestone Dose)

Location	pH	Dissolved Oxygen mg/L	Temperature °C	Total Iron mg/L	Dissolved Iron mg/L	Alkalinity mg/L
2:30 PM on October 5, 2006						
Raw	6.14	3.6	13.2	34.0	34.0	105
React 1	6.80	11.2	13.7	560	1.80	--
React 2	7.07	11.6	13.7	560	0.33	--
Clarifier	7.05	9.5	--	10.6	0.15	47
9:30 AM on October 8, 2006						
Raw	6.16	3.3	13.3	35.2	35.2	105
React 1	6.59	10.7	13.4	400	8.10	--
React 2	6.82	11.4	13.4	400	2.99	--
Clarifier	6.85	11.2	13.3	15.0	2.00	60
2:30 PM on October 10, 2006						
React 1	6.65	10.4	13.5	345	6.20	--
React 2	6.85	10.8	13.5	325	2.14	--
Clarifier	6.82	10.6	13.4	12.0	1.74	55

Due to the operational problems, the performance results at the Lower Saxman Run pilot study were limited. The results of this initial AIS testing (Test AIS1) without pulverized limestone addition and using pre-treated water by the ALD are provided in Table SX-3. The results shown indicate the AIS process can effectively oxidize ferrous iron at rates much greater than would be expected without the presence of AIS. However, the reactor total iron concentration (i.e., AIS) decreased during the test due to the gradual accumulation of solids in the bottom of the reactors. The loss of suspended AIS gradually decreased the oxidation rate of ferrous, as can be seen by the increase in dissolved iron concentrations. Total iron during the test was greater than 10 mg/L which was at a flow of 10 gpm, less than one-half the design flow for the clarifier. Alkalinity decreased from influent to effluent and corresponded to the expected stoichiometric consumption; 1.8 mg/L alkalinity per 1 mg/L of ferrous iron oxidized and precipitated as an iron oxide.

Table SX-4: Summary of analytical results from Saxman Run AIS pilot testing (Test AIS2) at AMD Flow = 20 gpm, Air Flow = 14 cfm, pulverized limestone dose = 2-3 gr/min, and RAIS flow = 50 gpm started on November 1, 2006 at 11:30 AM.

Location	**pH**	**Dissolved Oxygen mg/L**	**Temperature °C**	**Total Iron mg/L**	**Dissolved Iron mg/L**	**Alkalinity mg/L**
4:00 PM on November 2, 2006						
Raw	6.05	4.2	12.7	33.6	33.0	58
React 1	7.07	11.8	12.4	500	0.53	--
React 2	7.20	11.7	12.2	520	0.06	--
Clarifier	7.44	11.1	12.4	39.4	0.05	55
9:30 AM on November 3, 2006						
Raw	6.08	3.2	12.6	32.6	32.6	58
React 1	6.47	9.3	12.4	440	1.30	--
React 2	6.65	9.2	12.5	440	0.45	--
Clarifier	7.02	8.7	12.4	26.4	0.42	45
3:00 PM on November 3, 2006						
React 1	6.99	9.6	12.8	460	0.99	--
React 2	7.08	9.5	12.7	460	0.54	--
Clarifier	7.02	9.2	12.4	30.2	0.21	42
12:00 PM on November 7, 2006 (Flow = 5 gpm)						
Raw	6.04	5.2	12.6	35.2	35.2	61
React 1	6.94	11.0	12.0	260	0.16	--
React 2	7.02	11.5	12.0	250	0.03	--
Clarifier	7.06	11.7	11.6	16.2	0.04	38

The pilot unit was operated with added pulverized limestone from November 2nd through November 7th. The Merrick doser was difficult to operate and maintain a consistent dose. It was determined this type of feed system is inadequate for dosing material with the characteristics of pulverized limestone. To evaluate the use of pulverized limestone as a source of alkalinity and to maintain pH, the mechanical dosed amount was supplemented with manually added pulverized limestone. The results of the AIS testing with added pulverized limestone are provided in Table SX-4. The raw water alkalinity decreased to 58 mg/L, which indicates the Upper Saxman Run discharge is only slightly net acidic; based on a calculated acidity of 62 mg/L for the ferrous iron contained in the raw water, Similar to the previous testing the AIS concentrations were able to oxidize the ferrous iron to low concentrations and fast rates. In addition, based on the effluent alkalinity of 40 to 60 mg/L the added pulverized limestone was able to add alkalinity and maintain pH for the oxidation of ferrous iron and precipitation as an iron oxide.

The AIS pilot study results at the Upper Saxman Run site indicate AIS can oxidize the soluble ferrous iron in the Upper Saxman Run discharge to particulate ferric iron. The dissolved iron decreased from an influent concentration of 34 mg/L to less than 0.1 mg/L in the lower flow AIS concentration tests and showed substantial oxidation at higher flow testing. This demonstrates the AIS process can achieve the effective ferrous iron oxidation to very low concentrations approaching 100% ferrous iron removal. The air flow provided during the test increased both the dissolved oxygen and pH. Dissolved oxygen is increased through the transport of oxygen in the air to the water. pH is indirectly increased through the removal of dissolved carbonic acid in the water to carbon dioxide in the air. Addition of pulverized limestone, which dissolves to add alkalinity, was also shown to be a viable alkaline material for the AIS process.

The effluent total iron concentrations were found to exceed 10 mg/L during the higher flow testing. This high effluent iron is likely a result of poor flocculation of the iron oxides in the clarifier and is related to the positive charge of the iron oxide particles. It is likely improved total iron removal to less than 1 mg/L can be achieved where a polymer is used.

AIS System Modifications

The results of the Lower Saxman Run pilot study indicate several modifications will be needed to achieve the desired operational performance for the pilot system. Unfortunately the modifications could not be made in the field and within the time frame needed to for completion of this pilot study. As a result, the pilot unit was taken out of service in mid-November and transported to a fabricator for modifications. The modifications to the pilot unit for subsequent pilot studies at the remaining AMD discharge sites included:

1. Installation of new mixer mounts to place the mixers in the center of the reactors and in a vertical configuration to provide greater bottom mixing needed to minimize solids accumulation in the bottom of the reactors.
2. Installation of a surface outlet between Reactor 1 and Reactor 2 to permit sampling of the effluent from Reactor 1.
3. Installation of an outlet box from Reactor 2 to permit polymer dosing to aid in flocculation and settling of the AIS prior to the upflow clarifier.
4. Installation of an air flow meter and valves to regulate and monitor air flow to the reactors.
5. Replacement of the screw feed Merrick doser with a vibratory type GYRO doser which was found to be an effective doser at the Scotts Tunnel pilot study for pulverized limestone.

Additional modifications were made to the pilot unit to provide additional improvements to clarification prior to the final pilot study that included:

1. Conversion of the upflow clarifier to a flocculation tank that included a low shear mixer.
2. Addition of an inclined plate clarifer and sludge recirculation pump to the system.

The changes in the pilot unit had dramatic affects on the performance of the Two-Stage Flow Through AIS pilot unit in subsequent studies. The improvements resulted in elimination of AIS accumulation in the bottom of the reactors, retention and accumulation of AIS solids in the pilot system, clarification of total iron to less than 1 mg/L, and operation of the system with reactor AIS concentrations exceeding 2,000 mg/L.

IRON OXIDE SOLIDS DISPOSAL/REUSE

The wet solids produced by the treatment process are important representing the labor needed to handle and process solids and the volume of solids requiring disposal. AIS treatment produces a low volume of solids because the solids density is approximately 20-30% for 24 hour settled AIS. The purity of iron oxide solids produced by AIS treatment may be important for final reuse. Table SX-5 contains the analytical results from an AIS sample collected during the Lower Saxman Run pilot study. The sample had a solids content of 21% after only 6 hours of settling. Additional settling time would increase solids content. The sample is nearly all iron (57%), which reflects greater than 95% iron oxides. Calcium is the second largest metal in the sample at 1.2%, which equates to a calcium carbonate content of 3.0%. Trace metal analysis indicates the sample has very low trace metal concentrations, which should not limit the disposal or reuse options for the waste solids.

Table SX-5: Laboratory Analysis of AIS Sample from the Pilot Study.

	Unit	**Detection Limit**	**Result**	**% Content**
Solids Content (Wet)	%	0.01		20.8
Dry Weight Basis				
Iron	mg/kg	1	565,900	57
Manganese	mg/kg	1	513	0.05
Aluminum	mg/kg	5	2,184	0.22
Calcium	mg/kg	1	12,260	1.23
Magnesium	mg/kg	1	380	0.04
Sodium	mg/kg	1	3.4	<0.01
Potassium	mg/kg	1	131	0.01
Silica	mg/kg	1	205	0.02
Arsenic	mg/kg	1	51	<0.01
Lead	mg/kg	0.15	0.16	<0.01
Selenium	mg/kg	0.25	0.74	<0.01
Zinc	mg/kg	1	462	0.05

AIS SYSTEM DESIGNS

The results of the Lower Saxman Run pilot study could not be used to develop an AIS treatment system to treat the Saxman Run AMD discharge. However, successful pilot studies at Blue Valley, Monview-Mathies, Phillips, and Scotts Tunnel provided substantial data on which to base the design of an AIS system. Reported oxidation rates in the pilot studies were consistent with or faster than the heterogeneous model indicating the model can be used to estimate the reactor sizes for the Saxman Run discharges. The use of pulverized limestone and dose rate were substantiated at the Scotts tunnel pilot study where a GYRO vibratory doser was able to effectively dose pulverized limestone. The following sections provide treatment system designs, estimated capital and installation costs, and operating costs for the Saxman Run AIS treatment system to address both the Upper and Lower Saxman Run AMD discharges.

Saxman Run AIS Treatment System

Based on the results of the various pilot studies, the AIS treatment system for the Saxman Run AMD discharge will consist of: 1) a storage silo and powder feed system for the pulverized limestone; 2) a two-stage reactor system; 3) a clarification system including a polymer feed, circular clarifiers with a flocculation zone and hopper bottoms equipped with solids collection and recirculation; and 4) a solids handling system to concentrate and store solids from the AIS treatment system. Table SX-6 summarizes the design information and influent water quality. A schematic flow path of the AIS treatment system is depicted in Figure SX-5. Figure SX-6 shows a conceptual AIS treatment system layout at the proposed Saxman Run AMD treatment system site. The proposed location is near the Latrobe Wastewater Treatment Plant.

Table SX-6: Summary of design information for the Saxman Run AMD AIS treatment system.

	Estimated Flow (gpm)		**Influent Water Quality**			
Source	**Average**	**Maximum**	**pH**	**Total Al mg/L**	**Ferrous Fe mg/L**	**Alkalinity mg/L**
Upper	1,820	4,700	5.7	~0.5	36.0	45
Lower	1,710	2,400	6.0	<0.5	33.0	58
Total	**3,530**	**7,100**	**5.8**	**<0.5**	**34.5**	**51.3**

The design criteria and effluent water quality for the Saxman Run AIS treatment system were determined based on the heterogeneous ferrous iron oxidation model kinetic rates. Table SX-7 summarizes the design criteria for the Saxman Run AIS treatment system and the anticipated effluent water quality. The expected performance of the Saxman Run AIS treatment system is near complete removal under average flow conditions (> 99% iron removal) and maximum flow conditions (> 98% iron removal). This effluent quality should eliminate the impacts of the Saxman Run AMD discharge on Saxman Run and the Loyalhanna River as well as produce water that may have beneficial reuse. Water reuse applications may include a geothermal source for heating and cooling. To augment flexibility in treatment, as well as improve operation and maintenance, a dual train system is recommended. This dual train design would also result in cost savings during low flow periods where both trains are not needed.

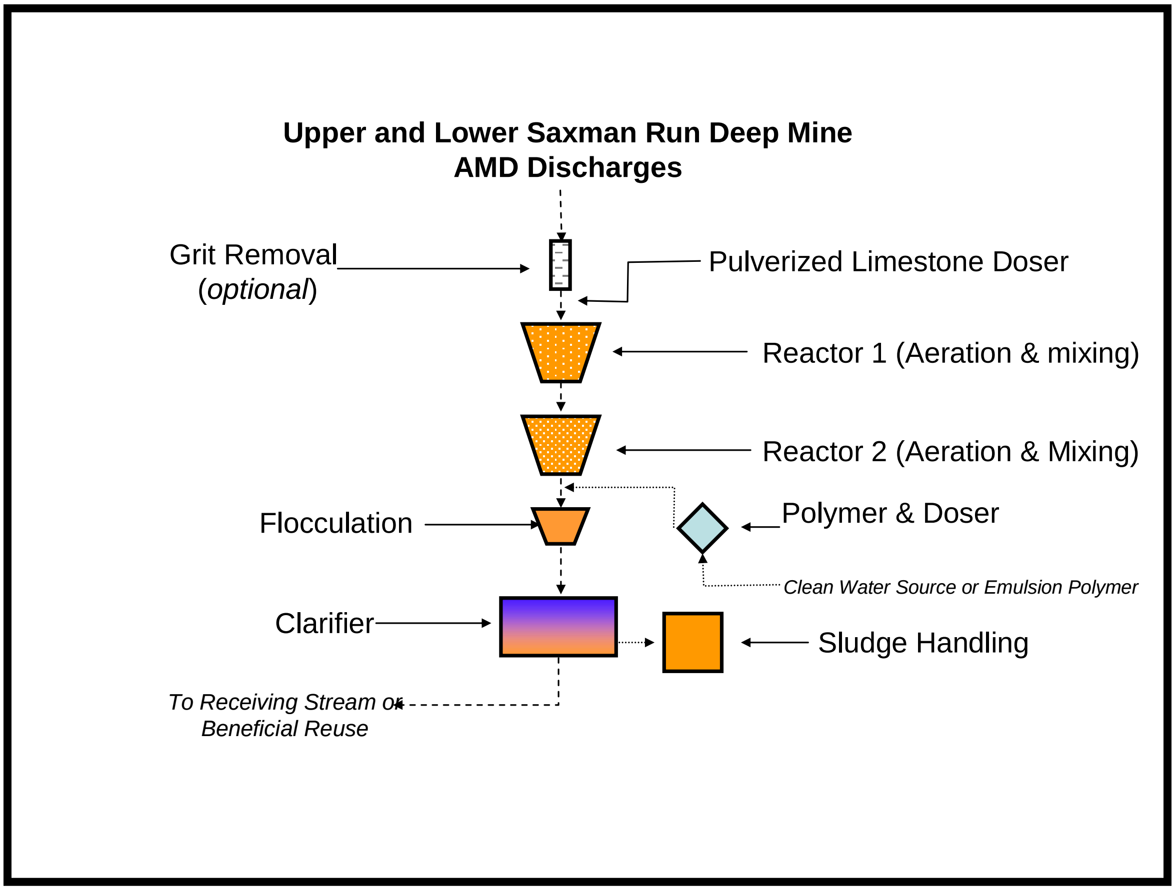
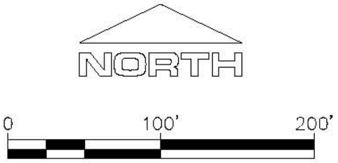


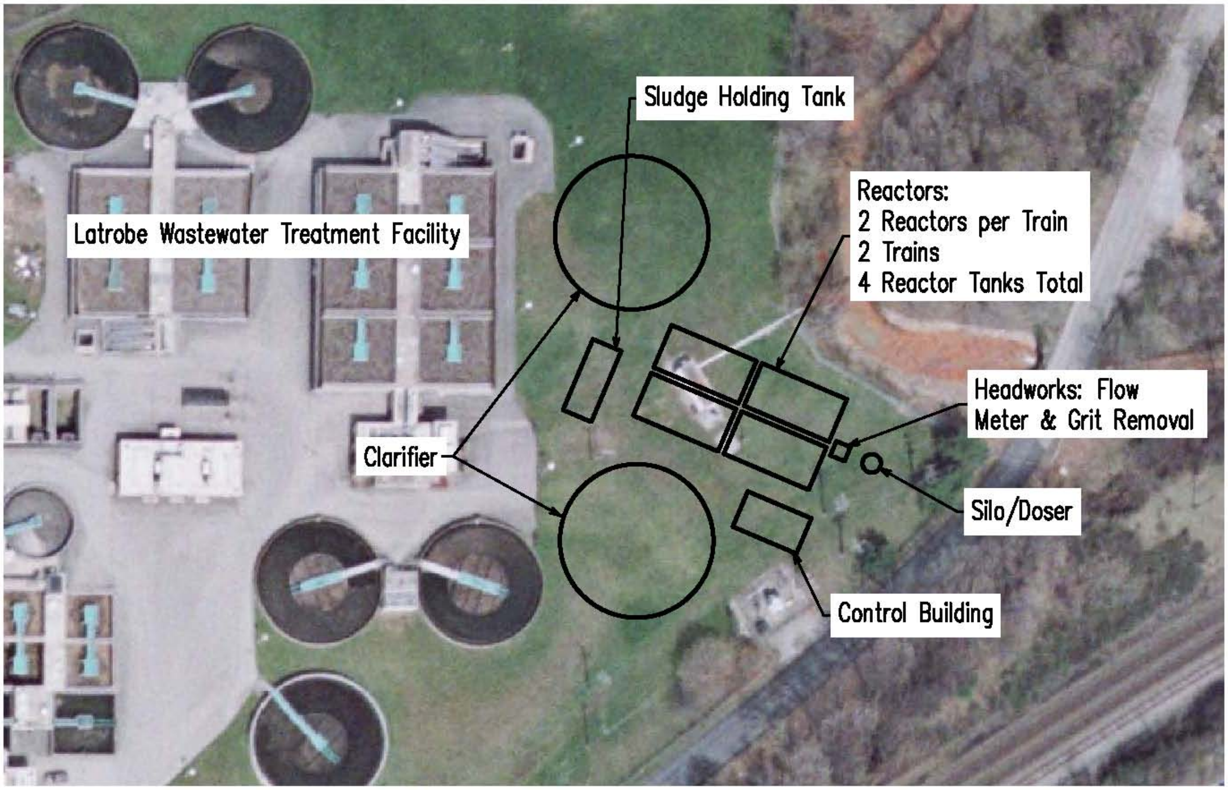
Figure SX-5. Saxman Run AMD AIS Treatment System Flow Path

Table SX-7: Summary of design information and anticipated effluent water quality of the Saxman Run AIS treatment system.

					Anticipated Effluent Quality			
Condition	**Flow gpm**	**Reactor 1 DT Hrs**	**Reactor 2 DT Hrs**	**Clarifier ft/d**	**pH**	**Total Fe mg/L**	**Dissolved Fe mg/L**	**Alkalinity mg/L**
Average	3,500	1.50	1.50	40	6.8	<0.5	<0.03	50
Maximum	7,000	0.75	0.75	80	6.6	<1.0	<0.1	40



Treatment System Notes:
1. Treatment Capacity: 10.0 MGD
2. Reactor Tanks: 160,000 gallons (each)
   Water Depth=12' Width=30' Length=60'
3. Clarifier: 100' diameter
4. Sludge Holding Tank – 90,000 gallon
   Depth=12' Width=20' Length=50'



Date: 2/3/09 Rev No: 0	PROJECT: AIS Pilot Study - Saxman Run Iron Oxide Technologies, LLC Latrobe, Westmoreland County, Pennsylvania	D·G DIETZ-GOURLEY CONSULTING, LLC 1215 Deerfield Drive State College, PA 16803 P: 814 278 7596 F: 814 278 7795 www.DGengr.com	PROJECT NO.: 08-008 DRAWING NO.: 08-013 DRAWN BY: TSG 2/3/09 CHKD BY: JMD 2/3/09
Figure SX-6	TITLE: Conceptual AIS Treatment System		

Figure SX-6. Saxman Run Conceptual AIS Treatment System Layout

Flow Measurement & Grit Removal

Flow measurement will be included in the design of the system. This flow will be used in the control panel for automated process control. Process control is required to optimize reactor conditions through aeration and polymer dose for flocculation. Both controls will have cost benefits in electricity demand and chemical dose. Grit removal will be incorporated in flow measurement system prior to the reactors to collect solid material that is likely contained in the discharge flow. The coarse material to be removed is from erosion of materials from the deep mine and precipitated solids from the AMD in the collection pipes. The flow measurement will also split the AMD flow to the two AIS treatment system trains.

Pulverized Limestone Dosing

The Saxman Run discharges will need added alkalinity to complete the oxidation of the ferrous iron as well as maintain an adequate reactor pH for rapid oxidation in the AIS process. A storage silo and pulverized limestone doser (GYRO Vibratory Doser) will be placed on the inflow to Reactor 1. The dose rate will be varied based on the measured AMD flow with an average dose of 1.2 tons per day. The added pulverized limestone will dissolve in the reactors producing alkalinity to sustain the AIS treatment. An average effluent alkalinity of 50 mg/L is anticipated.

Reactors

The two-stage AIS reactor system follows the flow measurement and pulverized limestone dosing. The AIS reactors are sized based on the heterogeneous ferrous iron oxidation model, reactor equations, and the pilot study results. The Stage 1 and Stage 2 Reactors will each contain 90 minutes (1.5 hours) of detention time at average flow and 45 minutes (0.75 hours) of detention time at maximum flow, the design flow. The reactors will contain top mounted high performance axial flow mixers to suspend the AIS. The reactors will also have aeration provided by fine bubble diffusers using positive displacement blowers. The aeration is needed to remove excess carbon dioxide in the AMD and formed from the reaction of ferrous iron with the AIS. Aeration volume delivered is based on the pilot study results and will be adjusted with AMD flow in order to maintain the pH and dissolved oxygen required for the AIS process.

Clarification

The clarification system will consist of a polymer dosing system, flocculation and clarification. A polymer was identified during subsequent pilot studies that will be applicable to this discharge. The polymer reacts with the AIS during flocculation to form large rapidly settling particles. The powder polymer identified is a medium molecular weight, low charge anionic acrylamide polymer. The polymer will be dosed into the effluent from the Stage 2 Reactors or prior to the flocculation zone of the clarifier. The polymer dosed water will flow into a flocculation zone of the clarifier where high performance variable speed mixers equipped with low shear impellors will promote flocculation of the AIS. Flocculated solids will flow from the flocculation zone into hopper bottom clarifiers where the AIS (i.e., particulate iron) will be settled and collected. The collected AIS will be returned to the reactors or removed to an AIS holding tank using positive displacement cavity pumps.

Solids Handling

An AIS holding tank will receive excess solids from the clarifiers where the solids will be allowed to further thicken with additional settling time. The Saxman Run AIS treatment system will produce an average volume of AIS to be wasted daily between 4,000 and 9,000 gallons per day (4-8% solids), based on RAIS from pilot study. However, the solids handling facility will concentrate the solids to a final average volume of 1,000 to 2,000 gallons per day (20-30% solids). A solids handling option consists of a holding tank with storage capacity between 10 and 15 days. The holding tank will be equipped with a decant pump to remove clarified water from the top of the solids holding tank and return it to the treatment system. Solids will accumulate in the bottom of the tank until the tank is full which corresponds to approximately 50% of the total volume of solids. A jet mixer placed in the bottom of the tank will be used to periodically and at the time for transport to the disposal or reuse option re-suspend the thickened solids to slurry. A sludge pump will be used to remove the iron oxide slurry from the tank for transport to a disposal or processing site. Alternative solids handling will be evaluated depending on the final disposal and/or reuse of the iron oxides produced by the AIS process.

ESTIMATED AIS TREATMENT SYSTEM COSTS – CAPITAL & OPERATIONAL

The Saxman Run AIS Treatment System capital costs will include plant headworks, silo system, reactor tanks, flocculation clarifiers, water piping, air lines, drop-outs, diffusers, blowers, mixers, pumps polymer makeup and dosing systems, control panels, buildings for housing the control panel, blowers and polymer units, solids handling tanks, and perimeter fence. Backup electrical generators should also be considered to prevent loss of treatment in case of power failure.

Table SX-8 provides an estimate of the capital costs associated for the 10.8 MGD (7,500 gpm) Saxman Run AIS Treatment System. Actual costs of an AIS Treatment System may vary depending on a number of factors related to final effluent quality goals and the site conditions. In addition to the treatment system costs, there will be costs associated with site development, treatment system installation, control/polymer building installation, and perimeter fencing. The estimated cost for these items is $400,000 which results in a total estimated cost for the treatment system and installation of $3,350,000.

Table SX-9 provides an estimate of O&M Costs for the Saxman Run AIS Treatment system and includes labor, operating and maintenance costs. Also provided is the value of the iron oxide solids produced and the direct effect this beneficial reuse will have on the O&M costs by removing disposal costs and offsetting other operating costs. Depending on a number of factors (primarily solids handling/reuse), the annual O&M costs at the Saxman Run treatment system will be between $140,000 and $370,000.

Table SX-8: Saxman Run AMD Discharge AIS Treatment System Preliminary Equipment List & System Cost[1]

Item No.	Item Description	Number
1	**Control System**	
	a. PLC Unit	1
	b. pH/Turbidity/Flow Monitors	2
	c. Control Building	1
2	**Pulverized Limestone System**	
	a. 45 ton Storage Silo	1
	b. GYRO Doser	1
3	**AIS Treatment System – IOT, Inc.**	
	a. 80,000 gallon Reactor Tanks (mix & aeration)	4
	b. 20 H.P Top Mounted Mixers (incl. mounts)	8
	c. 35 H.P. Blower/& Aeration Equipment	3
	f. 8,500 sq. ft. Flocculation Clarifiers	2
	g. 25 H.P. AIS Recirculation and WAIS Pumps	4
	h. 12 L/min (max.) Polymer System	1
4	**Sludge Handling System – IOT, Inc.**	
	a. 80,000 gallon AIS Holding Tank	1
	b. 100 H.P. Jet Mixer	1
	c. 1 H.P. Rail Mounted Decant Pump	1
	d. 15 H.P. Sludge Discharge Pump	1
Estimated System Cost		**$2,750,000**
Estimated Freight		**$200,000**
Estimated Total Equipment Cost		**$2,950,000**

[1] Costs reflect 2008 pricing for equipment and freight. Installation not included.

Table SX-9: Saxman Run AIS Treatment System Operating Cost Estimate

Item	**Cost $/yr**
O&M Electricity ($/yr)	$118,000
Pulverized Limestone Use ($/yr)	$16,000
Polymer Use ($/yr)	$18,000
Solids Disposal ($/yr)	$80,000
Equipment Maintenance ($/yr)	$15,000
Personnel O&M Costs ($/yr)	*$30,000-$50,000*
Total O&M Costs ($/yr)	**$287,000**[1]
Non-Personnel O&M Costs ($/yr)	**$247,000**
Potential Iron Oxide Reuse (@ $0.05/lb)	***+$54,000***
BALANCE of O&M Costs	***$113,000***

[1] using personnel O&M cost of $40,000/yr

The treatment costs will vary depending on inclusion of the various Saxman Run system capital and operating costs. Using the annual operating cost (labor not included) of $247,000 for the Saxman Run system equates to a cost of $0.14 per 1,000 gallons of treated water. If sludge disposal costs are removed and an iron oxide revenue option is identified, the treatment costs decrease to treatment costs to $0.06 per 1,000 gallons. The total treatment cost for the Saxman Run AMD discharge using the AIS treatment process, includes annualized capital costs (25-year basis) and all O&M costs ($287,000 per year), is $0.23 per 1,000 gallons of treated AMD.

SUMMARY

The Saxman Run AIS pilot study results, data fro the other pilot studies, and this summary report provide considerable information regarding the AIS Treatment process. The results indicate:

- AIS Treatment effectively oxidizes ferrous iron in short detention times needed to meet effluent objectives for the Saxman Run AMD.
- AIS ferrous iron oxidation rates are not affected by polymer dosing.
- Observed oxidation rates by the AIS solids are slightly slower, but consistent with the heterogeneous ferrous iron oxidation model.
- Pulverized limestone can be used as an alkalinity source to address the slightly net acidic Saxman Run AMD discharges.

Based on the results of the pilot study and the (modified) heterogeneous ferrous iron oxidation model, a conceptual AIS treatment system was developed that included:

- A new complete AIS treatment system for the Saxman Run AMD discharge that will produce an effluent iron less than 0.5 mg/L at average flows and 1 mg/L at maximum flows.
- An alternative clarification system to improve removal of particulate iron solids produced by the AIS process that includes:
  - Polymer make-up and feed system
  - Flocculation horizontal flow clarifiers.

The Saxman Run treatment system will have a capital cost of $3,350,000 with an annual operating cost between $110,000 and $290,000 depending on inclusion of labor and solids reuse. The treatment costs for the Saxman Run discharge range between of $0.06 and $0.23 per 1,000 gallons of treated water depending on inclusion of various operating costs and reflection of capital costs in the estimate.

The AIS Treatment approach produces iron oxide solids with characteristics that offer a significant potential for beneficial reuse. Investigations indicate there is substantial potential for the solids to be used in the pigment industry. This investigation is ongoing. Water reuse is also significant potential for the treated water due to the treated water characteristics which may be used as a geothermal heating/cooling source and/or a commercial fishery.

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