Passive Treatment Alternatives for Remediating Abandoned-Mine Drainage

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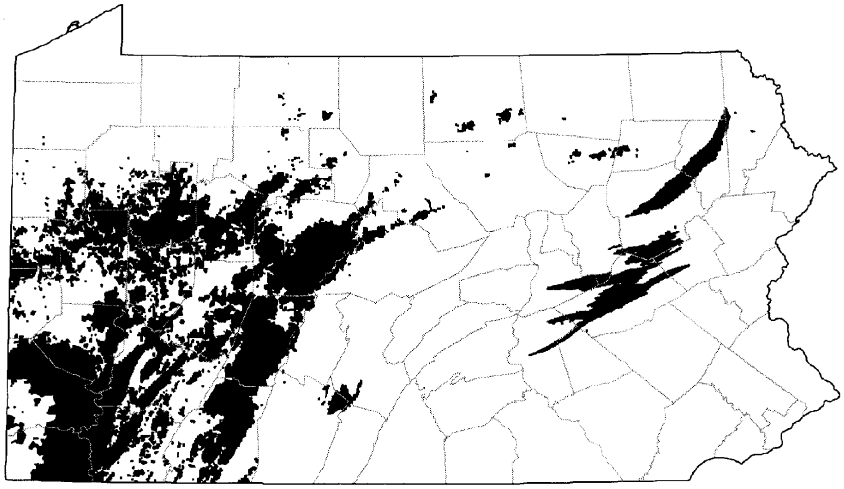
Abandoned-mine drainage (AMD) is drainage flowing from or caused by surface mining, deep mining, or coal refuse piles that is typically highly acidic with elevated levels of dissolved metals. AMD results from the interactions of certain sulfide minerals with oxygen, water, and bacteria. Passive treatment systems have been used to remediate AMD at numerous sites throughout the United States. The theory behind passive treatment is to allow naturally occurring chemical, biological, and physical reactions that aid in AMD treatment to occur in the controlled environment of the system, not in the receiving water body. The advantages of passive treatment over active treatment include lower operation and maintenance costs, virtually no use of chemicals, and minimal energy consumption. The disadvantages are that smaller volumes of water are treated than with active systems, and discharges with high concentrations of dissolved metals and extremes of pH may have to be treated several times within one system to treat the discharge. AMD passive treatment systems include aerobic treatment systems and anaerobic treatment systems. It is estimated that it will take 50 years and between \$5 billion and \$15 billion to remediate all AMD problems in Pennsylvania. © 2001 John Wiley & Sons, Inc.

INTRODUCTION

Abandoned-mine drainage (AMD), once referred to as acid mine drainage, is drainage flowing from or caused by surface mining, deep mining, or coal refuse piles that are typically highly acidic, with elevated levels of dissolved metals. Treatment technologies for AMD abound; however, passive treatment strategies provide numerous alternatives that are cost-effective and relatively maintenance-free. During the past 15 years, passive treatment systems have been implemented on full-scale sites throughout the United States. The theory behind passive treatment is to allow naturally occurring chemical, biological, and physical reactions that aid in AMD treatment to occur in the controlled environment of the system,

Exhibit 1. Study Area and Locations of Coal Mines within Pennsylvania.



not in the receiving water body (Helfrich, 1999). The advantages of passive treatment over active treatment include lower operation and maintenance costs, virtually no use of chemicals, and very minimal amounts of energy consumption. The primary disadvantages of passive treatment are that passive systems treat smaller volumes of water than active systems, and discharges with high concentrations of dissolved metals and extremes of pH may have to be treated several times within one system to effectively treat the discharge.

STUDY AREA

Exhibit 1 depicts the locations of coal mines in Pennsylvania, both operational and closed, and also depicts the study area for this article.

Pennsylvania has a long history of coal production and a legacy of environmental problems left behind by abandoned coal mines. Coal mining began in Pennsylvania in the 1800s, and coal from the state fueled the industrial growth of country and provided much of the energy to fight both world wars. Today, coal supplies 60 percent of the fuel for Pennsylvania's electric power generation, and Pennsylvania is the fourth largest coal producer in the U.S., following Wyoming, West Virginia, and Kentucky (PADEP, 1997).

Impacts of AMD in Pennsylvania

AMD has been called Pennsylvania's single biggest water-quality problem by the presidents of the Western and Eastern Pennsylvania Coalitions for Abandoned Mine Reclamation (Rossman et al., 1997). Pennsylvania has abandoned-mine issues in 45 of 67 counties (PADEP, 2001), over 250,000 acres of abandoned surface mines (PADEP, 1998), and approximately 2,400 miles of streams that do not meet water-quality standards because of AMD (PADEP, 1997). Current estimates put the cost of remediating Pennsylvania's abandoned-mine problem at $5 billion to $15 billion, involving projects over the next 50 years (PADEP, 1998).

COAL MINING AND THE LAW

Federal Law

The federal Surface Mine Control and Reclamation Act (SMCRA) of 1977 was the first attempt by the federal government to address the impacts of coal mining. Title IV of the Act initially authorized federal funds to address Priority 1 and 2 health and safety problems rather than general welfare problems, such as AMD abatement. Revisions to Title IV now consider AMD sites occurring in the vicinity of populated areas potential Priority 2 problems, thereby funding some AMD and abandoned-mine land (AML) reclamation projects.

Current estimates put the cost of remediating Pennsylvania's abandoned-mine problem at $5 billion to $15 billion, involving projects over the next 50 years.

The SMCRA requires operators to reclaim land to the approximate original contour once mining has ended; sets stringent penalties for those that do not; and established the AML Trust Fund (AMLTF). For each ton of surface-mined coal, active operators pay a 35-cents-per-ton fee, which contributes to the AMLTF. While the AMLTF accumulates approximately $200 million to $250 million per year, Congress only appropriates approximately $170 million, leaving nearly $1 billion unappropriated over the years ("Paying the price," 1996). Pennsylvania receives approximately $20 million per year from this fund (PADEP, 2001).

A 1990 amendment to the SMCRA created the 10 percent set-aside program. This program applies to sites where mining ended prior to August 3, 1977, and where no continuing reclamation responsibility can be determined (PADEP, 1996). The set-aside program allows up to 10 percent of the AMLTF to address AMD issues. Under federal authority, the Pennsylvania Department of Environmental Protection (PADEP) manages these monies as a separate interest-bearing fund for AMD abatement and treatment.

Other federal funding sources for AMD abatement include forfeited mine-reclamation bonds and a relatively new program called the Appalachian Clean Streams Initiative (ACSI). The federal Office of Surface Mining created the ACSI in 1997 to give additional funds to states in the Appalachian region to address AMD abatement.

State Law

The Clean Streams Law of 1965 was the first state law in Pennsylvania to indirectly address AMD. The Clean Streams Law prohibited the unpermitted discharge of pollutants, including AMD effluent, to waterways of the Commonwealth of Pennsylvania, and established penalties for such unlawful discharges. In 1967 the Commonwealth of Pennsylvania enacted the Land and Water Conservation and Reclamation Fund. The fund authorized $120 million to reclaim AML within the state (PADEP, 1998). Operation Scarlift, as the program was called, completed over 500 projects for stream-pollution abatement at a cost of approximately $75 million (PADEP, 1998).

The Environmental Stewardship and Watershed Protection Act of 1999, better known in Pennsylvania as the Growing Greener program, set aside $650 million over five years to address various water-quality problems, including AMD abatement. Growing Greener is unique in that it encourages grassroots involvement by providing funds for watershed group start-up and implementation projects, as well as technical support and guidance.

GEOCHEMISTRY OF COAL-MINE DRAINAGE

The formation of AMD is primarily a function of the geology, hydrology, and mining technology employed for the mine site. AMD in which mineral acidity exceeds alkalinity typically contains elevated concentrations of SO_4, Fe, Mn, Al, and other ions. AMD may or may not have a low pH, since the presence of dissolved Fe, Al, and Mn can generate hydrogen ions by hydrolysis (Rose and Cravotta, 1998). The major source of acidity is the oxidation of pyrite (FeS_2) in rock that is exposed by mining. Pyrite oxidation can be rapid upon exposure to humid air or aerated water, particularly above the water table.

AMD results from the interactions of certain sulfide minerals with oxygen, water, and bacteria.

In contrast, neutral or alkaline mine drainage (NAMD) has alkalinity that equals or exceeds acidity but can still have elevated concentrations of SO_4, Fe, Mn, and other solutes. NAMD can originate as AMD that has been neutralized by reactions with carbonate minerals, such as calcite and dolomite, or can form from rock that contains little pyrite. Dissolution of carbonate minerals produces alkalinity, which promotes the removal of Fe, Al, and other metal ions from solution, and neutralizes acidity.

The geochemistry of AMD has been the subject of numerous investigations (Rose and Cravotta, 1998). AMD results from the interactions of certain sulfide minerals with oxygen, water, and bacteria. The iron disulfide minerals, pyrite (FeS_2) and marcasite (FeS_2), are the principal sulfide-bearing minerals that occur in bituminous coal (Davis, 1981; Hawkins, 1984). Pyrrhotite (FeS), arsenopyrite (FeAsS), calcopyrite ($CuFeS_2$), and other sulfide minerals containing Fe, Cu, As, Sb, Bi, Se, and Mo can also produce acidic solutions upon oxidation, but these minerals are not common in coal beds. Pyrite is recognized as the major source of AMD in Pennsylvania (Rose and Cravotta, 1998).

There are generally four chemical reactions that describe the weathering of pyrite and marcasite to form AMD. The overall reaction is given as:

$$4FeS_2 + 15\,O_2 + 14H_2O \rightarrow 4Fe(OH)_3 \downarrow + 8H_2SO_4$$

Pyrite + Oxygen + Water → "Yellowboy" + Sulfuric Acid

The first reaction in the weathering of pyrite includes the oxidation of solid pyrite by oxygen (O_2). Sulfur is oxidized to sulfate (SO_4^{2-}) and ferrous iron (Fe^{2+}) is released. Two moles of acidity (H^+) are generated for each mole of pyrite oxidized.

$$2FeS_2 + 7\ O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \qquad (1)$$

In most samples of coal-mine drainage, an abundance of dissolved ferrous iron (Fe^{2+}) indicates that the chemical reactions are at an intermediate stage in pyrite oxidation.

The second reaction involves the conversion of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}). The conversion of ferrous iron to ferric iron consumes one mole of acidity. Various species of sulfur and iron-oxidizing bacteria can increase the rate of oxidation from ferrous to ferric iron. The rate of this reaction is pH-dependent, with the reaction proceeding slowly under acidic conditions (pH= 2–3) with no bacteria present and several orders of magnitude faster at pH values near 5.

This reaction generally determines the rate of the overall acid-generating sequence.

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

In well-established acid-generating environments, the typical sequence is pyrite oxidation by reaction 1 to produce Fe^{2+}, which is then oxidized to Fe^{3+} by bacteria via reaction 2; the Fe^{3+} is then available for further pyrite oxidation.

The third reaction that may occur is the hydrolysis of iron. Hydrolysis is a reaction that splits the water molecule. Three moles of acidity are generated as a by-product of this reaction. Part or all of the iron may precipitate as $Fe(OH)_3$ ("yellow boy") or related minerals. The formation of ferric hydroxide precipitate ($Fe(OH)_3$) is pH-dependent. Solids will form if the pH is above or about 3.5, whereas if the pH is below 3.5, little or no solids will precipitate. Because of the relative insolubility of Fe^{3+}, most dissolved Fe in solutions with pH greater than about 3.5 occurs as Fe^{2+}.

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

In the fourth reaction, dissolved ferric iron (Fe^{3+}), which was generated in reaction 1 and 2, is the oxidizing agent for pyrite. This portion of the overall reaction is cyclic and self-propagating, takes place very rapidly, and continues until either ferric iron or pyrite is depleted (Rose and Cravotta, 1998).

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15\ Fe^{2+} + 2SO_4^{2-} + 16\ H+ \qquad (4)$$

At acidic pH levels, rates of pyrite oxidation by Fe^{3+} are much faster than oxidation by O_2 (Garrels and Thompson, 1960; McKibben and Barnes, 1986; Moses et al., 1987, Moses and Herman, 1991; Williams and Rimstadt, 1994). Therefore in well-established acid-generating environments, the typical sequence is pyrite oxidation by reaction 1 to produce Fe^{2+}, which is then oxidized to Fe^{3+} by bacteria via reaction 2; the Fe^{3+} is then available for further pyrite oxidation. Although O_2 is not directly consumed in the pyrite-oxidizing step, it is necessary for the regeneration of Fe^{3+} to continue the pyrite-oxidation cycle.

Many factors determine the rate of AMD generation from pyrite oxidation, including the activity of bacteria, pH, pyrite chemistry and surface areas, temperature, and O_2 concentration.

In many situations, the most important control on rate of AMD generation is bacterial oxidation of Fe^{2+} to Fe^{3+} by reaction 2. The resultant Fe^{3+} can oxidize pyrite by reaction 4. In the absence of bacteria, Fe^{3+} is either not produced at a significant rate (pH<4) or is so insoluble that its dissolved form is relatively unimportant as an oxidant of pyrite (pH>4).

As previously indicated, at pH values of 4 to 7, the rate of pyrite oxidation by O_2 is slow, and Fe^{3+} concentration is limited by the low solubility of $Fe(OH)_3$. In increasingly acidic environments, Fe^{3+} is increasingly soluble. Since Fe^{3+} can rapidly oxidize pyrite, the oxidation of pyrite can be greatly accelerated at low pH (Rose and Cravotta, 1998).

Kinetic studies indicate that the rate of acid generation also depends on the surface area of pyrite exposed to solution, and on the crystallinity and chemical properties of the pyrite surface (McKibben and Barnes, 1986). In general, rock with a high percentage of pyrite will produce acidity faster than rock with a low percentage of pyrite. Also, pyrite in small particles with high surface areas will tend to oxidize more rapidly than the same mass composed of coarse smooth-surfaced grains. (Caruccio, 1975). Defects within the crystal structure of the pyrite have also been found to be important in determining the reaction rate (McKibben and Barnes, 1986).

Many factors determine the rate of AMD generation from pyrite oxidation, including the activity of bacteria, pH, pyrite chemistry and surface areas, temperature, and O_2 concentration.

Atmospheric O_2 is required for the direct oxidation of pyrite and for regeneration of Fe^{3+}. Thus, if air and oxygenated or Fe^{3+}-rich waters can be excluded from pyretic material, pyrite oxidation can be inhibited, and little or no acid will be generated.

Limestone and other materials that produce alkalinity can have an impact on the generation of AMD. If water flowing into pyretic materials is alkaline, or if alkaline conditions can be maintained in the pyretic material, the acid-generating reactions described previously may be inhibited so that little or no AMD is produced. Conversely, once AMD has formed, its interaction with alkaline materials may neutralize the acidity and promote the removal of Fe, Al, and other metals. Therefore, water with high SO_4 and low Fe may be indicative of earlier AMD generation.

The carbonate minerals calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are the main minerals which provide alkalinity to surface water and groundwater. The carbonate minerals occur as layers of limestone or dolostone in the vicinity of the coal, as cement in sandstone or shale, or as small veins cutting through rock. The initial reaction with an acidic solution is generally:

$$CaCO_3 + 2H^+ = Ca^{2+} + H_2CO_3$$

If a gas phase is present, the H_2CO_3 may partially decompose and exsolve into the gas phase:

$$H_2CO_3 = CO_2 + H_2O$$

Based on the above referenced reactions, the use of carbonate-containing materials have been found to be effective in passively treating AMD.

PASSIVE TREATMENT OF AMD

In 1968 Pennsylvania instituted strict effluent-discharge limitations on mine operations. Many mining companies used chemical treatment methods to meet these new effluent limits. In chemical treatment systems, the acidity is buffered by the addition of alkaline chemicals such as calcium carbonate, sodium bicarbonate, or anhydrous ammonia. These chemicals were used to raise the pH to acceptable levels and decrease the solubility of dissolved metals in the mine effluent, thus causing precipitates to form and settle out of the solution. However, these chemicals are expensive and the treatment system requires additional costs associated with operation and maintenance, as well as the disposal of metals-containing sludges.

In response to the relatively high costs associated with chemical treatment of AMD, many variations of passive treatment systems began to be studied as early as 1978 by numerous organizations conducting laboratory bench tests. During the last 15 years, passive treatment systems have been implemented on full-scale sites throughout the United States. The concept behind passive treatment of AMD is to allow the naturally occurring chemical and biological reactions that aid in AMD treatment to occur in the controlled environment of the treatment system, and not in the receiving water body.

Passive treatment in theory offers many advantages over the chemical treatment (active) systems conventionally used for treating AMD.

Passive treatment in theory offers many advantages over the chemical treatment (active) systems conventionally used for treating AMD. The use of chemical addition and energy-consuming treatment processes are virtually eliminated with passive treatment systems. In addition, the operation and maintenance requirements of passive systems are considerably less than with active treatment systems.

Designing a passive treatment system for AMD generally requires the understanding of:

- mine water chemistry,
- available treatment techniques, and
- experience.

Analytical sampling of the AMD is extremely important in the selection of appropriate treatment technologies. It is very important to understand that not all technologies work on all AMD discharges.

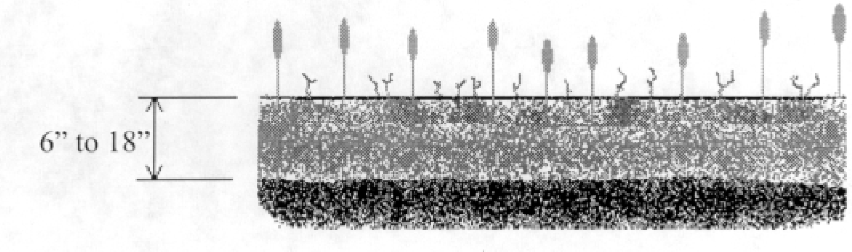
Passive treatment systems for AMD are generally grouped into two broad categories: aerobic treatment of AMD and anaerobic treatment of AMD. Aerobic passive-treatment technologies include:

- Aerobic Wetlands (**Exhibit 2**)
- Open Limestone Channels (**Exhibit 3**)
- Diversion Wells (**Exhibit 4**)
- Oxic Limestone Drains (**Exhibit 5**)
- Pyrolusite® Treatment Beds (**Exhibit 6**)

Anaerobic passive-treatment technologies include:

- Compost or Anaerobic Wetlands (**Exhibit 7**)

Exhibit 2. Typical Section of an Aerobic Wetland.



(Helfrich, 1999)

- Anoxic Limestone Drains (**Exhibit 8**)
- Vertical Flow Reactors (**Exhibit 9**)

Aerobic Passive-Treatment Technologies

Aerobic Wetland

An aerobic wetland consists of a large surface-area pond with horizontal surface flow (Exhibit 2). The pond may be planted with cattails and other wetland flora. Aerobic wetlands can only effectively treat water that is net alkaline. In aerobic-wetland systems, metals are precipitated through oxidation reactions to form oxides and hydroxides. This process is more efficient when the influent pH is at least 5.5. Aeration prior to the wetland, via riffles and falls in the impacted water body, increases the efficiency of the oxidation process and, subsequently, the precipitation process. Iron concentrations are efficiently reduced in this system; however, the pH is further lowered by the oxidation reactions.

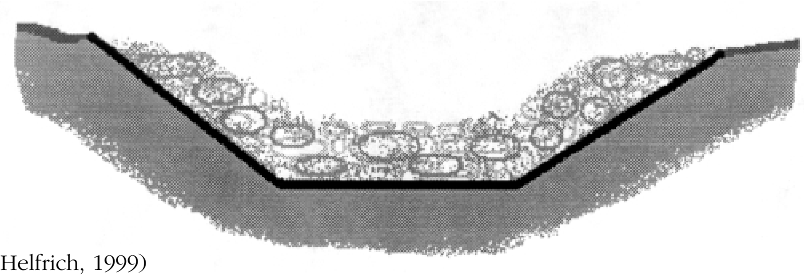
A typical aerobic wetland will have a water depth of approximately 6 to 18 inches. Variations in water depth within the wetland may be beneficial for performance and longevity of the treatment system. Shallow water zones freeze more quickly in the winter, however, they also enhance the oxygenation and oxidizing reactions and precipitation. Deeper water zones provide storage areas for precipitates but generally decrease the vegetative diversity in the wetland.

Aerobic wetlands are sized based on the following criteria originally developed by the U.S. Bureau of Mines for AML and Compliance:

Minimum wetland size (in acres) = [Fe loading (lbs/day) ÷ 180 (lbs/acre/day)] + [Mn loading (lbs/day) ÷ 9 (lbs/acre/day)] + [Acidity (lbs/day) ÷ 60 (lbs/day/acre)]

The loading rates (lbs/day) are calculated by multiplying the flow rate (gallons per minute [gpm]), the concentration (mg/L), and a constant (0.012). The constant 0.012 converts gallons per minute and milligrams per liter to pounds per day (i.e., lbs/day = (gals/min)(mg/L)(3.81/gal)(g/1000 mg)(lb/454 g)(60 min/hr)(24 hrs/day)). Compliance criteria are suggested for wetlands, which must meet a specific effluent limitation from the National

Exhibit 3.Typical Section of an Open Limestone Channel.



(Helfrich, 1999)

Pollution Discharge Elimination System. Compliance criteria are more conservative than the AML criteria and generally require wetlands that are approximately two times as large as that required by the AML criteria.

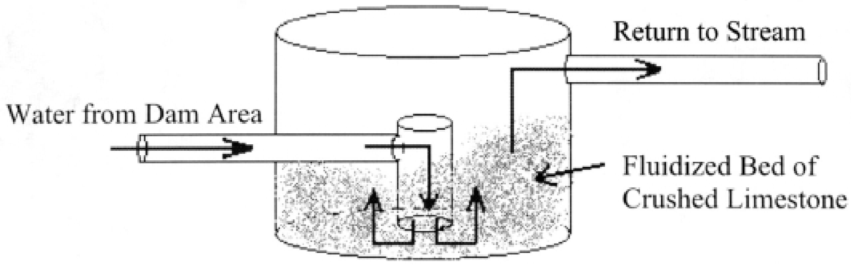
Open Limestone Channels

Open limestone channels are generally the simplest passive treatment method. Open limestone channels are constructed in two ways. In the first method, a drainage ditch is constructed of limestone and AMD-impacted water is directed to the ditch. The second method involves placing limestone fragments directly into an AMD-impacted stream. Dissolution of the limestone adds alkalinity to the water and raises the pH. Coating (or armoring) of the limestone by $Fe(CO)_3$ and $Fe(OH)_3$ produced by neutralization reduces the generation of alkalinity, so large quantities of limestone are needed to ensure long-term success of treatment. High flow velocity and turbulence enhance the performance by keeping precipitates in suspension thereby reducing the armoring of the limestone. Impervious liners are sometimes used beneath the limestone to prevent infiltration of the AMD into the groundwater table.

Diversion Wells

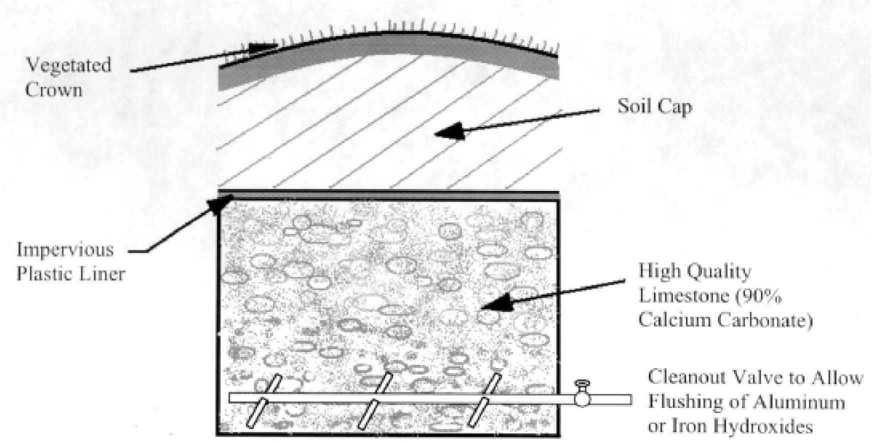
Diversion wells are another simple way of adding alkalinity to AMD-impacted waters. Acidic water is conveyed by a pipe to a downstream "well" that contains crushed limestone aggregate. The hydraulic force of the pipe flow causes the limestone to turbulently mix and abrade into fine

Exhibit 4. Schematic View of a Diversion Well.



(Helfrich, 1999)

Exhibit 5. Cross Section of an Oxic Limestone Drain.



(Adapted from Helfrich, 1999)

particles, which prevents armoring. The water flows upward and overflows the "well" and is then redirected back into the stream. Diversion wells require frequent refilling of the "well" with clean limestone to assure continued effective treatment of the AMD.

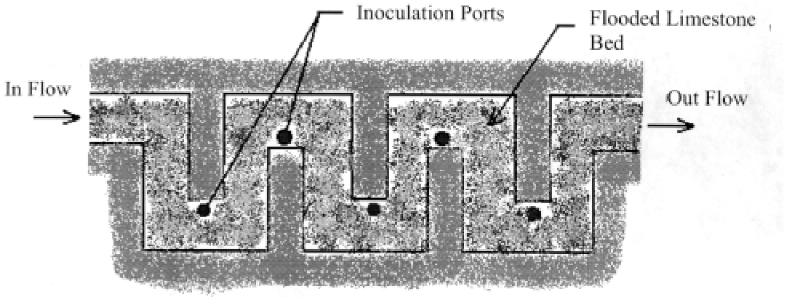
Oxic Limestone Drains

An oxic limestone drain (OLD) is a buried bed of limestone constructed to intercept subsurface flows of mine water in which the influent AMD contains oxygen (Milavec, 2000). The process of limestone dissolution generates alkalinity. The sole purpose of OLD is to provide alkalinity, thereby changing net acid water into net alkaline water. The one disadvantage of an OLD is that dissolved metals tend to oxidize in the oxygenated environment, thereby armoring the limestone. This armoring diminishes the efficiency of the system by decreasing the amount of contact between the influent AMD and the limestone. To minimize armoring of the limestone, periodic flushing of the system is required to remove iron and aluminum hydroxides. An anoxic limestone drain (ALD) solves this problem by isolating oxygen from the water to prevent oxidation of metals and armoring of the limestone. ALDs are discussed in more detail below.

Pyrolusite® Process

Pyrolusite® process is a patented process, which utilizes site-specific, laboratory-cultured microbes to remove iron, manganese, and aluminum from AMD. The treatment process consists of a shallow bed of limestone aggregate inundated with AMD. After laboratory testing determines the proper combinations, the microorganisms are introduced into the limestone beds via inoculation ports located throughout the bed. The microorganisms grow on the surface of the limestone chips and oxidize the metal contaminants while removing limestone, which increases the alkalinity and raises the pH of the water.

Exhibit 6. Plan View of a Pyrolusite® Bed.



(Helfrich, 1999)

Anaerobic Passive-Treatment Technologies

Anaerobic Wetlands

Anaerobic (or compost) wetlands consist of a large pond with a lower substrate of organic material. The flow is horizontal within the organic layer of the basin. Piling the compost a little higher than the free-water surface can encourage the flow within the substrate. Typically, the compost layer is made from spent mushroom compost that contains approximately 10 percent calcium carbonate. Other compost materials include peat moss, wood chips, sawdust, or hay. A typical compost wetland will have 12 to 24 inches of organic material and be planted with cattails or other emergent vegetation. The vegetation helps stabilize the organic material and provides additional material to perpetuate the sulfate reduction reactions.

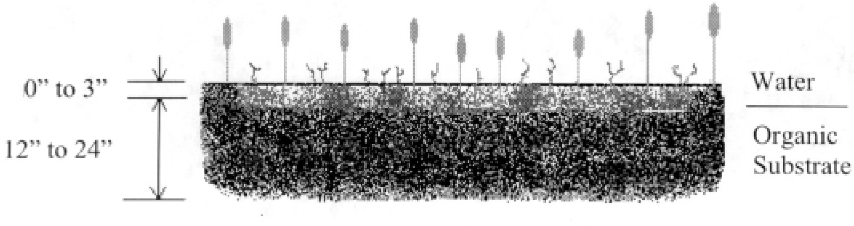
Anaerobic wetlands are used to treat AMD from active-mine discharges to meet established effluent requirements. Generally, the design of these wetlands is conservative and can treat discharges that contain dissolved oxygen, Fe^{3+}, Al^{3+}, or acidity of less than 300 mg/L.

The anaerobic wetland acts as a reducing wetland where the organic substrate promotes chemical and microbial processes that generate alkalinity and increase the pH. The compost removes any oxygen in the system. This allows sulfate to be reduced and also keeps the metals from oxidizing and armoring or coating the limestone present in the compost, thereby preventing its dissolution. Microbial respiration within the organic layer reduces sulfates to water and hydrogen sulfide. The anoxic environment within the substrate also increases the dissolution of limestone.

Anoxic Limestone Drain

ALD is a buried bed of limestone constructed to intercept subsurface flows of mine water and prevent contact with atmospheric oxygen. Isolating oxygen from the water prevents oxidation of metals and armoring of the limestone. The process of limestone dissolution generates alkalinity. The sole purpose of ALD is to provide alkalinity, thereby changing net acid water into net alkaline water. Retaining carbon dioxide in the drain can improve limestone dissolution and alkalinity generation.

Exhibit 7. Typical Section of an Anaerobic or Compost Wetland.



Helfrich, 1999

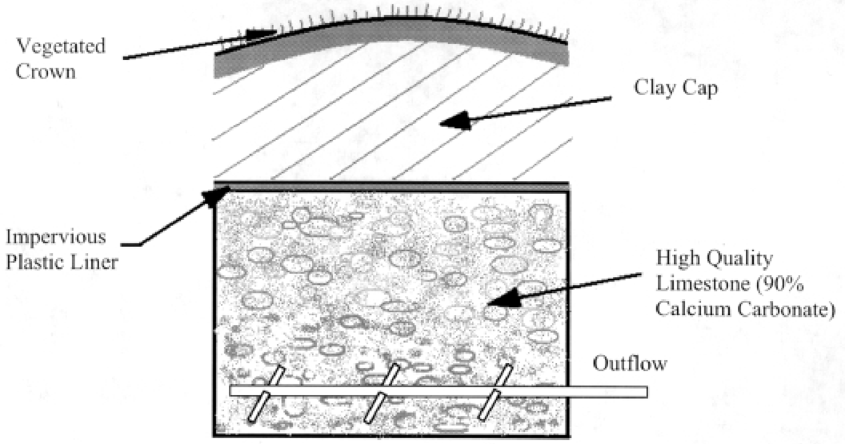
An ALD can be considered a pretreatment step to increase alkalinity and raise pH before the water enters a constructed aerobic wetland. In the aerobic wetland, metals can be oxidized and precipitated. ALDs are limited to the amount of alkalinity they can generate based on solubility equilibrium reactions. Also, the effectiveness and longevity of an ALD can be substantially reduced if the AMD has high concentrations of ferric iron, dissolved oxygen, or aluminum.

ALDs are sized based on the assumption that the drain will produce water between 275 and 300 mg/L of alkalinity. The amount of alkalinity generated is based on the solubility of the calcite within the limestone and the retention time within the ALD. Retention times of 14 to 15 hours are used as standard practice to balance construction costs and efficiency of alkalinity generation.

Vertical Flow Reactors

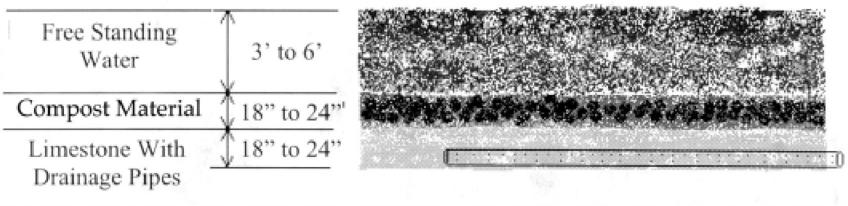
Vertical flow reactors (VFR) were conceived as a way to overcome the alkalinity-producing limitations of ALDs and the large area requirements for compost wetlands. The VFRs consist of a treatment cell with an

Exhibit 8. Cross Section of an Anoxic Limestone Drain.



(Adapted from Helfrich, 1999)

Exhibit 9. Typical Season of a Vertical Flow Reactor.



(Adapted from Helfrich,1999)

underdrained limestone base topped with a layer of organic substrate and standing water. The water flows vertically through the compost and limestone, and is collected and discharged through a system of pipes. The VFR increases alkalinity by limestone dissolution and bacterial sulfate reduction. Highly acidic waters can be treated by discharging the AMD through a series of VFRs. A settling pond and an aerobic wetland where metals are oxidized and precipitated typically follow a VFR plan.

VFRs are sized based on retention times required to produce the necessary alkalinity. Retention times of 12 to 15 hours are typically used for sizing VFRs.

CASE STUDIES

Pyrolusite® Process Systems – Laurel Run and Squatter Falls

As of the summer of 2000, PADEP has constructed two Pyrolusite® beds, and two more are in construction (Milavec, 2000). The systems consist of limestone-filled beds, which are inoculated with aerobic microorganisms, preceded by small aerobic wetlands. The wetlands serve a dual purpose—they provide some pretreatment of the AMD influent as well as a nutrient source for the microorganisms in the system. PADEP has experienced a high rate of treatment with minimal maintenance at the first site, while experiencing a number of difficulties at the other site.

The first site is known as Laurel Run, and is in the upper reaches of the Loyalhanna Creek watershed, in Westmoreland County (**Exhibit 10**). A bed measuring 40 feet by 120 feet by 5 feet deep is successfully treating a discharge of 30 gpm with low iron and aluminum concentrations (average concentrations of 5.22 mg/L and 7.94 mg/L) and moderate concentrations of acidity and manganese (average concentrations of 94.22 mg/L and 12.27 mg/L) (Milavec, 2000). Some plugging and ponding were observed at the head of the system shortly following initiation of treatment; however, these problems were easily fixed by using larger diameter stone (AASHTO No. 57 was replaced with AASHTO No. 3) (Milavec, 2000). A shallow trench was also dug at the head of the system to allow better flow distribution. This project was completed during early fall 1997, with the above-mentioned maintenance performed during spring 1998. Since then, the system has not required any further maintenance, and recent biological surveys have shown that this system is having a beneficial impact on the macroinvertebrate community of Laurel Run (Milavec, 2000).

The second site, known as Squatter Falls, is located on Glenwhite Run, in Blair County (Exhibit 10). The system was completed in the summer of 1999, consists of a bed measuring 80 feet by 212 feet by 6 feet deep, and receives flows of up to 100 gpm. Concentrations of iron and acidity are also much higher than the Laurel Run site (average concentrations of 78.89 mg/L and 194.57 mg/L versus 5.22 mg/L and 94.22 mg/L at Laurel Run) (Milavec, 2000). This system has not been as successful as the Laurel Run site, and has been plagued by maintenance difficulties nearly from the beginning.

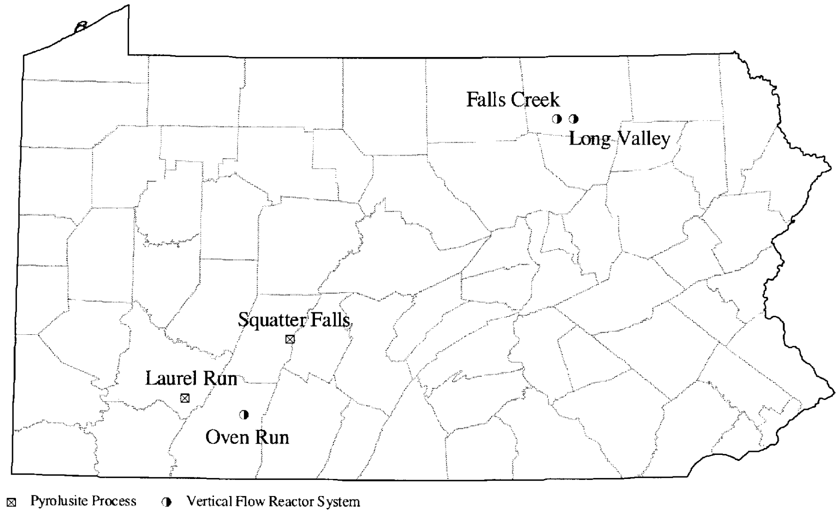
As with the Laurel Run site, plugging with iron precipitate occurred at the entrance to the system. A trench was constructed across the width of the bed and inoculated with microorganisms (Milavec, 2000). Depressed dissolved oxygen (DO) concentrations in the wetland effluent led to a concern that the microorganisms would be killed. An 8-inch pipe was then cut in half, notched, and laid into the trench at the head of the system. The pipe was connected to the pipe leaving the wetland, allowing water to cascade over the notches and become aerated. While this cooled water temperatures, allowing for higher concentrations of DO, this solution led to more plugging (Milavec, 2000). The system continued to fill with water, and at one point the bed overflowed its embankment (Milavec, 2000).

In early 2000, a decision was made to take greater action to prevent the plugging from becoming more widespread. A small vertical flow wetland system has been constructed before the existing pretreatment wetland to remove a larger portion of iron prior to entering the bed (Milavec, 2000). The limestone bed will then remove manganese and any residual iron, raise the pH, and add alkalinity prior to discharging to Glenwhite Run.

Vertical Flow Reactors—Long Valley, Falls Creek, and Oven Run

The majority of systems constructed by PADEP have been VFRs. While a typical design for VFRs was discussed in an earlier section, these systems

Exhibit 10. Locations of System Case Studies.



are highly flexible and variations of the standard design abound in Pennsylvania. The first two systems constructed by PADEP addressed AMD discharges to Schrader Creek, in Bradford County (Exhibit 10). The Long Valley system has operated very well with minimal maintenance, while the Falls Creek system has had a number of problems (Milavec, 2000).

Both systems were constructed somewhat differently than typical VFRs for two reasons. Both discharges are characterized by low acidity and very low iron concentrations. Because iron oxide precipitate was not expected to be a concern, the systems were constructed without flushing devices. There were space limitations at the Falls Creek site, so the systems were constructed without sedimentation basins.

The Falls Creek site, which is the larger of the two sites, was designed to treat a maximum flow of 600 gpm, using four treatment cells. Under design flows, water moves vertically through each cell, while during high-flow events, a portion moves horizontally across the cell and overflows into the adjacent cell (Milavec, 2000). Alkalinity is generated by the portion of the flow that comes into contact with the limestone, and the net discharge will therefore be alkaline. While the Falls Creek system initially operated well when it went on-line in 1997, continued operation demonstrated problems with the system design. The system was designed so that the intake would be four feet higher than the normal elevation for a deep mine pool (Milavec, 2000). Due to this design imperfection, the water started to discharge from around and underneath the system, particularly during dry times of year when the mine-pool elevation is down (Milavec, 2000). During the spring, the pool has adequate head for some of the flow to reach the system, and this has resulted in higher-than-design flows. This in turn has resulted in inadequate treatment when AMD is flowing into the system (Milavec, 2000). Solutions to these problems are currently being developed, and will likely include installation of a subsurface clay barrier to force the discharge to develop the head needed to reach the system (Milavec, 2000). Treatment alternatives for managing the higher-than-design flows are also being evaluated.

While the Falls Creek system initially operated well when it went on-line in 1997, continued operation demonstrated problems with the system design.

A third VFR that deserves mention is the Oven Run VFR system. This system was constructed along Oven Run, a tributary of Stony Creek, in Somerset County (Exhibit 10). This is the largest system constructed by PADEP to date, and is possibly the largest such system in the state (Milavec, 2000). The first VFR in the system is 950 feet by 100 feet, and was completed during fall 1999. The system features three separate piping systems to control and direct flushes (Milavec, 2000). The Oven Run system is working very well at treating a high-flow acid discharge, and during high flows, the system is generating upwards of one ton of alkalinity per day (Milavec, 2000). The VFRs in the system are retaining iron; however, significant amounts of iron, along with aluminum, are being discharged when the system is flushed, suggesting that the compost layer may be less effective than expected in reducing ferrous iron within the system.

The Oven Run site was one of six projects constructed to abate AMD along Stony Creek. Stony Creek is now showing significant water-quality improvement as a result of these systems and active re-mining of abandoned sites within the watershed. The fishery is gradually recovering in the once degraded stream, which was documented by a survey conducted by the Pennsylvania Fish and Boat Commission.

CONCLUSIONS

AMD is one of the legacies left by Pennsylvania's long history of coal extraction. While federal and state laws that direct funds toward the abatement of AMD have existed for more than 30 years, recent legislation has led to an increase in the number and type of AMD abatement projects undertaken in Pennsylvania. Pennsylvania's Growing Greener program, now in its third year, awarded $37.5 million in its first year, leading to 55 watershed assessment and protection plans and 85 restoration and demonstration projects being implemented. The organization of 21 watershed groups has also been facilitated by the first year of Growing Greener funding.

While much work has been conducted within Pennsylvania, as well as in other states affected by abandoned-mine issues, much work remains. The estimate to fully remediate all abandoned-mine problems in Pennsylvania ranged between $5 billion and $15 billion, and is expected to take 50 years to complete. Through the use of passive AMD treatment technologies, both time-tested and innovative, PADEP and local grassroots organizations are finding low-cost and high-value solutions to AMD abatement. With three more years and approximately $450 million of Growing Greener funding remaining, a significant amount of AMD and other mine issues stand to be solved within Pennsylvania.

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