Acid Mine Drainage Treatment

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Complexity	Environmental Value	Cost
Low Moderate High	Low Moderate High	Low Moderate High

OVERVIEW

Contaminated water flowing from abandoned coal mines is one of the most significant contributors to water pollution in former and current coal-producing areas. Acid mine drainage (AMD) can have severe impacts to aquatic resources, can stunt terrestrial plant growth and harm wetlands, contaminate groundwater, raise water treatment costs, and damage concrete and metal structures. In the Appalachian Mountains of the eastern United States alone, more than 7,500 miles of streams are impacted. The Pennsylvania Fish and Boat Commission estimates that the economic losses on fisheries and recreational uses are approximately $67 million annually (ref). While most modern coal-mining operations (Figure 1) must meet strict environmental regulations concerning mining techniques and treatment practices, there are thousands of abandoned mine sites in the United States (Figure 2). Treatment of a single site can result in the restoration of several miles of impacted streams.

The purpose of this document is to briefly summarize key issues related to AMD treatment. This document is intended as a brief overview; thus, it is neither inclusive nor exhaustive. The technical note presents the preliminary planning issues associated with AMD – determination of the problem and identification of potential alternatives.

Figure 1. Modern coal mine operation, West Virginia

Figure 2. Abandoned mine site and AMD source, Maryland

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SOURCES OF AMD

Mining activities can expose a significant amount of geologic material. While in situ, the interaction of the geologic material with the surface environment is minimal. However, surface and deep mines can accelerate oxidizing conditions. Acid mine drainage occurs when groundwater comes into contact with remnant coal and rock rich in sulfide. Iron sulfides that are common in coal regions are predominantly pyrite and marcasite (FeS_2), but other metals may be complexed with sulfides (*Green Lands* 1998). These sulfide minerals oxidize in the presence of water and oxygen, the by- product being a highly acidic, sulfate-rich drainage. In general, contaminated water enters the surface environment via the following:

- Diffuse surface discharges such as seeps (Figure 3).
- Discharges from underground mine portals (Figure 4).
- Existing surface drainage ditches.

The AMD can then travel either below or above ground, eventually making its way into nearby streams.

Figure 3. Seep, West Virginia

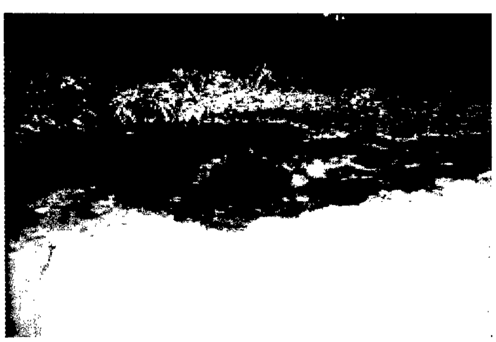

Figure 4. Mine portal, Maryland

PLANNING

Preliminary planning efforts are targeted at defining the nature of the AMD problem and potential remedial measures. This is best accomplished using an interdisciplinary team. Team members should include hydraulic, civil, and geotechnical engineers, chemists, and others who have an understanding of mining, chemistry, AMD treatments, and stream restoration. The team should also include biologists and ecologists knowledgeable about the local stream and riparian conditions and habitat requirements for the targeted species. Questions that should be addressed by the team include the following:

1. Is AMD a limiting factor for the stream ecology? Significant biological and water quality sampling is typically available to give a preliminary answer to this question but the watershed should be examined for other sources of pollutants. If a target species has been selected, limiting habitat conditions should also be investigated.
2. What is the source of the AMD?
3. What length of stream will benefit from the reduction of the AMD?
4. Will site conditions permit construction?
5. Are the costs acceptable?

Costs for AMD treatments vary by several orders of magnitude depending on site conditions, volume of the AMD, and the chemical nature of the AMD.

AMD SAMPLING

Assessing the nature and volume of the mine discharge is necessary to select the proper treatment. Typically, a minimum of 1 year of water quality sampling is required. Samples should include pH, flow, dissolved oxygen (DO), sulfates, and metal (Fe^{+2},Fe^{+3}, Al, Mn, Mg) concentrations. Samples should be obtained under high, medium, and low flow conditions.

At an early reconnaissance study phase, a visual examination of rocks and the effluent can give qualitative information on the nature of the AMD. Orange stains and cloudy water indicate the presence of iron with a pH above 3.5. Wine-colored stains but clear water indicate the presence of iron with a pH below 3.5. White stains can indicate the presence of aluminum with a pH above 4.5. Chocolate brown to black stains indicate the presence of manganese at a pH level greater than 7. In pools, a blue color can indicate aluminum in the water and reddish brown can indicate iron. The presence or absence of macroinvertebrates can also be a good indication of impact; however, there are non-AMD processes that can result in similar colorings. Therefore water quality sampling is highly recommended before proceeding too far into a study.

TREATMENT AND CONTAINMENT MECHANISMS

Acid mine drainage treatment falls under two broad categories, active and passive. Active treatment involves physically adding a neutralizing agent to the source of the AMD or directly to the stream that has been impacted. Active treatment can be very successful; however, it necessitates a long-term and continuous commitment to treatment. Weather, equipment failure, and budget reductions can result in lapses in treatment, which, in turn, can result in fish kills. In addition, active treatment does not significantly reduce the metal contamination to streams. Passive treatment encompasses a variety of techniques to raise the pH and reduce metal loadings through a constructed treatment or containment project. While initial costs for passive treatment techniques can be higher than active treatment, passive treatment is more uniform and uses processes that are not operation-intensive. However, passive treatment can involve some periodic maintenance.

The concentration of metals in AMD can impact the selection of treatment mechanisms because metal precipitation can clog passive systems. At a pH greater than 3.5 with oxygen present, ferrous (Fe^{+2}) will precipitate as ferric (Fe^{+3}). If oxygen is low, this precipitation will not occur until the pH reaches 8.5. Similarly, aluminum precipitates at a pH greater than 5 and manganese precipitates at a pH greater than 7. Aluminum flocs are significantly lighter than iron or manganese and can be more readily flushed from a treatment system. The concentration of metals that is allowed to leave the site is also a concern, in that their precipitation on a streambed can have not only an aesthetic impact but an ecological impact. The deposits can cause cementing of the substrate as well as imbeddedness, which can adversely affect macroinvertibrates and fish.

Treatment processes for AMD can also be divided into two broad categories, chemical and biological. Chemical treatment is typically implemented through the addition of lime to raise the pH. In passive systems, this is accomplished with limestone (calcium carbonate - $CaCO_3$). The lime content is normally 90 percent, with a dissolution of 75 percent and a maximum of 5-percent Mg_2CO_3. Quicklime (often used in active treatments) is about twice as effective, but more expensive and difficult to handle as it can react violently with water. Bacterial treatment is usually by a bacterial sulfate reduction, which occurs in the presence of sulfate, organic matter, and a reducing (anaerobic) environment. This process reduces metal concentrations, raises the pH, and can be part of a passive treatment.

Some of the most common treatment and containment mechanisms are listed and briefly described below:

Grout Injection: This treatment involves the injection of a grout (typically a mixture involving fly ash) into a mine to control acid mine drainage and mine subsidence. The grout must be designed for proper flowability, chemical stability, and compressive strength and is typically injected through holes drilled on 50-ft to 200-ft centers, depending on the mine condition.

Sealing of Mine Portals: In addition to improving public safety, sealing mine portals can minimize AMD production by reducing water and air infiltration. The portals are typically sealed with a plug of expansive grout with steel reinforcement. A "wet seal" includes pipe drains through the grout to collect AMD from the mine, which can then be treated. The analysis required involves extensive examination of subsurface conditions and mine maps. Failure can occur via sudden and dangerous 'blow-outs' of the seal or mine walls. In addition, a seal can cause the water table in the mine to rise and form additional seeps at a higher elevation. Implementation of seals in older mines that have partially collapsed or have insufficient mapping may be a problem.

Mine Capping: Capping can prevent or reduce rainfall from reaching acid-forming units in a backfilled mine. Capping is generally used for surface mines. The cap is typically fly ash covered with topsoil and seeded. For capping to be effective, horizontal components of groundwater must be negligible.

Limestone Dumping: Limestone fines can be placed in an acidic stream for direct water treatment. Benefits from this treatment are temporary, and the approach shocks the system. A variation of this technique involves lining a channel with a steel slag product or soda briquettes. Streams thus treated should flow through a settling pond to collect the metal sludge. The limestone must be periodically replaced. The dosing and replacement rate depends upon the acidity loading.

Limestone Dosing: Limestone fines can be introduced into an acidic stream to buffer acidity in regular increments from a large hopper or a plant-type operation. The doser can be electric or water-driven. Significant white to yellow deposits can be observed below dosers at low or base stream flows.

Anoxic Limestone Drain (ALD): An ALD is an adequately sized buried channel containing limestone that is designed to limit diffusion of atmospheric oxygen with the mine discharge. It requires relatively low metal concentrations (less than 10 to 25 ppm iron and aluminum) and low dissolved oxygen (less than 1 to 2 ppm). Aeration and a wetland system and/or settling pond to allow for metal precipitation reactions typically follow an ALD. If the dissolved oxygen is greater than 2 ppm, pretreatment may be provided by a wetland. If sulfates are higher than 2,000 ppm, gypsum precipitation may be a concern.
Anaerobic Wetland: A wetland generates alkalinity through bacterial activity and the use of Fe^{+3} as a terminal electron acceptor. Limestone can be added to the organic substrate for additional treatment through limestone dissolution. The wetlands are usually 1 to 6 acres in size for seeps, and are sized according to flow rate. In some cases an aerobic settling pond may be needed for metal precipitation reactions before the wetland. These treatments are limited to cases where the discharge has a pH greater than 4.

Aerobic Wetland: Aerobic wetlands are typically designed to promote precipitation of iron hydroxide. Limestone can be added to the organic substrate for additional treatment through limestone dissolution. The wetlands are usually 1 to 6 acres in size, but depend upon the flow rate and may require periodic dredging. These treatments are limited to cases where the discharge has a pH greater than 4 and are often used as a final polishing treatment.

Successive Alkalinity Producing Systems (SAPS): An SAPS is a combination of an ALD with an anaerobic wetland/pond. The AMD flows through a pool of water, an organic substrate, and a limestone bed before discharging from the bottom. The organic substrate and the depth of water create the anaerobic conditions necessary to reduce the likelihood of metals precipitating and clogging the limestone. The SAPS should empty into an aerobic wetland and/or settling pond for metal removal. The typical maximum treatment is 300 ppm acidity, so SAPS are often implemented in succession. This treatment is suited for AMD with high dissolved oxygen and metal concentrations. If sulfates are higher than 2,000 ppm, gypsum precipitation may be a concern. Since the SAPS is designed for vertical flow, sufficient head can be a significant design issue.

Open Limestone Channel (OLC): An OLC is an adequately sized open channel containing large limestone that carries and treats the AMD. It is sized to take into account expected armoring by metal precipitates. However, it is limited to fairly steep slopes (greater than 10 percent). On milder slopes, there is a strong likelihood that metal sludge precipitation may cover the limestone. A settling basin may be necessary at the end depending on the metal concentrations and dissolved oxygen in the AMD. An OLC is suited for AMD with high O_2 and metal concentrations.

Modified Open Limestone Channel (MOLC): An MOLC resembles a limestone French drain. It is basically an OLC with a perforated pipe to carry large flows. It provides pretreatment before a doser and is suitable for areas with limited construction. It must have slopes equivalent to an OLC and is suited for AMD with high dissolved oxygen and metals.

Leach Bed: This treatment mechanism involves passing surface water through a bed lined with alkaline material into acidic mine spoil. For leach beds to be effective, horizontal components of groundwater must be negligible.

Oxic Limestone Drain (OLD): An OLD resembles an ALD that has provisions for periodic flushing of sludge. It can operate with relatively high dissolved oxygen but has only been tested for low metal concentration. If sulfates are higher than 2,000 ppm, gypsum precipitation may be a concern. An OLD would probably not be suitable for AMD with high iron concentrations.

EXAMPLE DESIGN CALCULATIONS:

Designs of each of the treatment mechanisms mentioned above require specific calculations. The design of a hypothetical SAP is provided in this document as an example. Many of the calculations required are also applicable in part for other treatments.

Given:
Life of project = 20 years
$CaCO_3$ content of limestone = 90 %
Dissolution of limestone = 75 %
Bulk density (ρ) = 100 lb/ft^3
Residence time (T_d)= 15 hr
V_v = 40 %
From sampling data
Q = $\sum$ flow = 11.5 gpm
x 3.78 liter/gal = 43.53 liter/min
Weighted average of acidity = 200 ppm
Weighted average Fe = 1.0 ppm
Weighted average Al = 10.3 ppm
Weighted average Mn = 26.4 ppm
pH = 3.3 to 3.8
DO = 7 ppm
Maximum sulfate = 850 ppm

The DO is too high for an ALD and the pH is too low for a treatment wetland. Metal concentrations in the AMD are too high for an OLD. For this example, it is assumed that site conditions do not permit capping, sealing, or grout injection. It is also assumed that there are environmental reasons to reduce the metal precipitation in the streams. Therefore, an SAPS is the logical choice.

Limestone requirements
The calculation for limestone is the same as for an ALD.

M = f(Q, life, $CaCO_3$ content of limestone, dissolution, residence time)

$$M = \frac{Q \times \rho \times T_d}{V_v} + \frac{Q \times \text{alkalinity added} \times \text{life}}{CaCO_3 \text{ content}}$$

Acidity < 300 ppm $\therefore$ need one SAP cell to add 200 mg/L alkalinity
M = 260 metric tons = 300 tons
Vol = 6,000 ft^3

SAP configuration: 5- to 6-ft-deep pool over organic matter 2 ft in depth, which is interred over a bed of 2-ft-deep limestone. The minimum length-to-width ratio should be 2. An SAP cross section is shown in Figure 5.

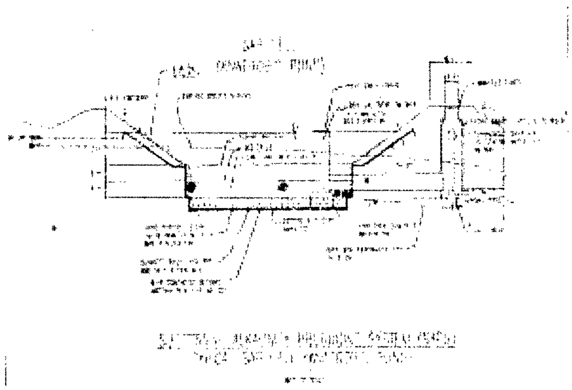

Figure 5: SAP – SAP detail

Limestone: Minimum size is No. 4. Can be as large as 2 in. Minimum of 90-percent $CaCO_3$ and a maximum of 5-percent Mg_2CO_3. Typical organic matter: should be spent mushroom compost with a minimum 10-percent $CaCO_3$ content.

Settling Pond Requirements
These calculations are the same as those required to size any settling pond.
Estimate volume of sludge production:

$$\text{iron}: Fe^{+3} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$$

$$56 \frac{g}{g.mole} \rightarrow 107 \frac{g}{g.mole}$$

$$\text{manganese}: Mn^{+2} + 2H_2O \rightarrow Mn(OH)_2 + 2H^+$$

$$55 \frac{g}{g.mole} \rightarrow 89 \frac{g}{g.mole}$$

$$\text{aluminum}: Al^{+3} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$$

$$27 \frac{g}{g.mole} \rightarrow 78 \frac{g}{g.mole}$$

Iron sludge production:

$$\text{Inflow iron} = 1.0 \text{ mg/liter} \times 43.53 \text{ liter/min} \times (1/1000) \text{ g/mg} \times (1/1000) \text{ kg/g} \times 2.205 \text{ lb/kg} \times 60 \text{ min/hr} \times 24 \text{ hr/day} = 0.138 \text{ lb/day}$$

$$\text{Inflow Fe sludge} = 0.138 \text{ lb/day} \times \frac{107}{56} = 0.264 \text{ lb/day}$$

It can be assumed that the weight of sludge is equivalent to water:

$$\gamma_w = 62.4 \text{ lb/ft}^3$$

$$\therefore \text{Inflow iron sludge volume} = 0.264 \text{ lb/day} \times (1/62.4) \text{ lb/ft}^3 = 0.00423 \text{ ft}^3\text{/day}$$

Similarly:

Inflow manganese sludge = .09463 ft^3/day
Inflow aluminum sludge = .06593481 ft^3/day
$\sum$ Sludge = 0.1648 ft^3/day

Volume of sludge (20 years) = 20 years x 365 days/year x 0.1648 ft^3/day = 1,200 ft^3

Assume 24-hr detention time
Volume = 11.5 gpm x (1/7.48)ft^3 /gal x 60 min/hr x 24 hr. = 2,213 ft^2
$\sum$ volume = 3,413 ft^3 $\rightarrow$ 3,500 ft^3

The detention pond should be 4 ft deep with a minimum length-to-width ratio of 3.

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