

# **Guidelines for the Design of Abandoned Mine Land Remediation and Water Treatment**

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## Forward

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# 1 INTRODUCTION

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## **Purpose**

This manual was originally written to assist Corps of Engineers planners and other members of project design teams in assessing, prioritizing, designing and costing environmental restoration projects in watersheds damaged by historic mining and mine drainage. Such efforts require expertise from a variety of disciplines and people with reclamation and remediation experience. These projects generally have multiple hazards and problems that must be addressed. Besides the scientific and technical issues, management must also be considered and may influence the procedures and practices applied at sites. Management includes addressing the needs of many stakeholders: landowners, citizen watershed groups, local and state governments, tribes and other Federal agencies. This manual focuses on technical evaluation and design of remediation projects, but managerial issues will be addressed throughout the manual.

Remediation includes both on-site and off-site issues. On-site issues tend to be complex including underlying geology and groundwater, landscaping, geotechnical stability, stream form and function, surface water quality, soil quality and development, revegetation, wildlife and endangered species, health and safety hazards, and intended land use. Off-site issues may include discharges of contaminated water and dust and debris flows. The Corps has significant and long-time experience with on-site issues through its Environmental Restoration/Waste Management work with USDOE, USDOD and others. On-site restoration manuals are available which address many of these issues.

This manual focuses on both off-site and on-site issues relevant to the ecosystem restoration mission. Among these issues, contaminated water discharges from abandoned mines generate, by far, the greatest off-site impacts, and often a single mining complex will contaminate dozens of miles of otherwise productive streams and rivers. Mine drainage presents a wide variety of technical challenges including soluble toxic ions, acidity, low pH, suspended metal flocs and variable flows. In addition, it may be difficult to locate the sources and flow paths of a particular mine drainage discharge because of where the discharge might emanate from a mine, whether a surface or underground mining complex. A discharge's location, along with its quality and quantity, greatly affects the design of remediation actions. Treatment of abandoned discharges is a relatively new science which is evolving, and this manual aims to bring the engineer and planner up to date with current knowledge, mindful that much remains to be learned and new strategies and technologies are being developed continually.

## **Applicability**

This manual deals with the development of ecosystem restoration projects on abandoned hard rock and coal mines. The focus is on control and remediation of water quality impacts, particularly contaminated mine drainage.

# 2 ABANDONED MINE LAND SITES

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## Introduction

Abandoned Mined Lands (AML) are defined as lands mined for coal or minerals that were abandoned, inadequately reclaimed and where no individual or company is responsible for the site's reclamation. For coal mined sites, these lands were disturbed, inadequately reclaimed, and abandoned before August 3, 1977. Those sites inadequately reclaimed after 1977 remain as reclamation liabilities to the mining company or the sites have reverted to state government control and reclamation. For hard rock sites, AMLs have no date for when the site was abandoned and the liability for most of these sites remains with the landowner and state/federal governments. However, in many cases, AMLs are attached or near to large mines currently operating mines, which had large capital investment (such as deep open pit operations), have exchanged hands over the years, and current ownership is responsible for all liabilities on the site, new and old. Therefore, AMLs can be old or young, are as varied as the landscapes on which they are found and reflect a plethora of mining methods to extract the particular mineral resource and the reclamation efforts of engineers and mine operators that created them. Although many similarities may exist among sites, each is unique and must be approached with an open approach and attitude, keeping in mind the potential opportunities for the land being reclaimed and its future use.

Numerous problems may be present on a single site. Abandoned structures and surface features may be present including buildings, mine openings, highwalls, or impoundments. Sections of underground mines, coal stockpiles and waste rock piles may be on fire. The occurrence of unstable slopes associated with impoundments, waste rock piles, product stockpiles or highwalls can cause excessive erosion and the potential for sliding material and mass slumping. Underground mines may accumulate gases such as methane, carbon dioxide, carbon monoxide or oxygen-deficient atmospheres, and may release them at distinct locations with associated hazards. Underground mines may impound water, which, under the right circumstances, can be released catastrophically. Chemicals and other hazardous materials may have been left in buildings or exist in or on machinery, or may have been disposed by operators or others in pits on the surface or deposited in underground facilities. Water emanating from structures, the mine, the waste rock piles or impoundments may contain pollutants that can contaminate streams and nearby water supplies.

This chapter will discuss the fundamental types of mines, their physical environment and hazards.

# Hazards on Abandoned Mine Land Sites

## Structures

**Tipple.** A tipple is a structure for loading coal from the mine into a truck, rail car, or barge for transport to market. Tipples were originally wooden structures but gave way to steel frame construction in the 1940's and 1950's. Old wooden tipples found at AML sites are frequently fully or partially collapsed and are often structurally unsafe. Metal tipples often have rusted and weakened structural members that can result in the unanticipated collapse of the structure during demolition. Transite sheeting was frequently used on the exteriors of metal tipples and cleaning plants. This material may contain asbestos that will require special handling during removal and disposal.

**Head frame.** A Head Frame is a wood or framed structure located over a mine shaft for the purpose of hoisting workers, ore and equipment. The head frame must be removed from the site prior to filling and sealing the shaft. This situation poses the risk of falls into the shaft and the risk of explosion from methane gas that may be emanating from the shaft (see section 2). The use of cutting torches, arc welding or smoking in or near shafts has been known to result in explosions, some of which have been fatal. While precautions should be taken at all sites, the risk is particularly great at coal mine sites. Materials containing asbestos may be present in the structure. Oil and grease may also be present.

**Hoist house.** The hoist house is a building that contains lifting equipment which lowers or brings out materials from the mine. The hoist house structure can be made from either masonry, wood or steel and is mounted to a massive concrete foundation. Most hoists are electrically powered and may be either AC or DC in operation. If the hoist is DC powered, a motor-generator system or a rectifier may be present in an adjacent room or building. In either case, transformers are often located in close proximity to the hoist house that must be removed with caution. At very old sites, steam driven hoists may be found.

**Cleaning plants/beneficiation plants/mills.** Coal or metal-bearing minerals do not come from the ground in a pure state. The desired mineral is often finely disseminated in the ore and requires beneficiation in order to recover the metal. In this section, the general process will be described to familiarize the reader with the methods and potential risks found at these sites.

Coal-cleaning plants, also known as preparation plants or wash plants, are designed to separate rock from coal. This waste rock is variously referred to as Refuse, Gob or Slate. At combustion temperatures in a power plant boiler, the rock melts to form ash. The costs of transporting non-combustible material and handling ash at power plants create incentives for removing much of the rock prior to shipment and burning. Raw coal is the run of mine mixture of coal and rock upstream of the preparation plant. The final product for shipment to the customer is termed clean coal.



Prior to the 1950s, the separation of rock from coal was largely accomplished by hand. Structures were often constructed of wood with chutes known as picking tables where the rock would be manually removed from the moving coal. In later years, this process was mechanized to perform separation based on the specific gravity difference between the waste rock and the coal. Various methods were utilized including shaking tables, heavy media floatation, launders, cyclones, heavy media cyclones froth flotation, and air tables. These methods also had the advantage of removing some of the pyrite from the coal (the iron sulfide materials being heavier than coal) and concentrating it in the waste rock. The heavy media liquid is created by suspending finely powdered magnetite in water thus increasing its apparent specific gravity. The magnetite used in this process is recovered for reuse by passing the liquid over a magnet.

The interaction between pyrite and water in the wash circuits will often generate acidic water that will accelerate corrosion of structural members and create the potential for collapse. Silos and bins may yet contain coal or waste rock that may lead to unanticipated structural failure. On ground storage piles with below grade reclaimers can create large voids that can collapse without warning.

Metal-bearing ores frequently have low concentrations of valuable minerals and high concentrations of waste rock or gangue. The beneficiation plant or mill is designed to make the necessary separation. The ore typically goes through a crushing stage and then through a milling stage. Finally, the ore is fine enough to send to froth flotation cells where final separation is performed. Froth flotation cells use chemical additives that promote attachment of the desired minerals to air bubbles. The air bubbles float the concentrated ore to the surface where it is skimmed off and collected.

These preparation structures are large steel frame buildings with substantial foundations for the crushing and milling equipment. Froth flotation chemicals may be present in tanks within or adjacent to the building. The particular chemical used at the site will be specific to the mineralogy of the ore deposit.

**Shops and supply yards.** Equipment repair shops use oils, greases and degreasing solvents. Many mine related chemicals may be found or have been used at these facilities (see common mine chemicals). Waste oils along with stocks of unused product may be found at these sites. These materials may be stored in drums within above- and below-ground tanks, or they may have been released into the ground or into shallow pits.

Supply yards serve as the central storage areas for materials used at the mine. Used and spilled lubricants, oils, surfactants and transformer insulator fluids may all be found in the supply yards deposited in barrels that may be corroding. Unopened barrels of new material may also be found in corroding barrels or containers. In addition, mine supplies such as resin roof bolt cartridges, treated and untreated timbers, and polyurethane and Portland cement-based grouts may be found at these sites.

**Explosives and powder magazines.** Modern regulations require secure storage of explosives on the mine site. The most common modern explosive is a blend of ammonium nitrate and fuel oil (ANFO). Dynamite was also used historically but is seldom found on more modern mining operations due to its dangerous handling and detonation properties. Explosives storage facilities are known as powder magazines or powder shacks. These are often below grade or partially below grade masonry or concrete structures that allow the explosives to be stored separately from detonators such as blasting caps. It is unlikely that any explosives remain at abandoned mine sites, but if explosives are present, they may be in an extremely deteriorated and unstable condition. If explosives are found, an explosives expert should be contacted for their removal.

**Rail and river loadouts.** High volume products such as coal are shipped via truck, rail and barge. Most of the loading facilities are covered under the discussion of tipples. However, there are some issues associated with rail and river loadouts that are different than tipples.

Rail yards may yet have rails that can be salvaged. Track switches are usually lubricated by pouring oil or waste oil on the switch. This lubrication method may result in soil or ground water contamination. In the winter, coal shipments may be coated with a product to prevent freezing in the rail car. This material may be present in tanks or may have been spilled on the ground.

River loadouts are similar to tipples except larger. In addition, there may be piers or cells in the river to secure the barges during loading operations. These piers and cells may have commercial value to either remain in place or to be removed and reconstructed elsewhere. Their removal and disposal also may be required if no potential use can be found.

**Substations/power boreholes.** Electrical substations may be present on the site's surface or within underground mine works. Transformers and capacitors may contain PCBs as a dielectric fluid (see Polychlorinated biphenyl). Even if the electrical equipment has been removed, dielectric fluid spills at the substation site may be present and may require cleanup.

### **Shafts, slopes and drifts**

Shafts are vertical openings to the coal seam or ore body. Slopes provide access via an inclined opening, while drifts are horizontal openings to the coal seam or ore body. In coal mines, drifts are often found where the coal seam intersects the land surface also known as the outcrop or cropline. Shafts may be solely for ventilation purposes or they may contain stairs, elevators, vertical conveyors, water or compressed air pipelines, sand backfilling pipelines or hoisting skips. Slopes are driven for rubber-tired vehicles, conveyor belts, rail haulage systems, and secondarily for ventilation. Drifts are driven for ventilation, haulage, and occasionally for mine drainage.

Shafts, slopes and drifts pose the risks of an oxygen deficient, carbon dioxide rich atmosphere known as black damp. These structures should not be entered. Methane may also be present in amounts ranging from trace quantities to

explosive concentrations (see section 2.2.7). Abandoned shafts, slopes, and drifts pose a danger of roof or wall collapse

In all cases, these openings must be sealed for public safety and potentially to improve mine water quality by cutting off a source of oxygen. Sealing methods should meet the standards prescribed by the state or federal authority with jurisdiction at the site. In the case of shafts, sealing often includes the placement of crushed rock in the shaft bottom to prevent migration of the fill material into the mine. Then a hydraulic seal is placed above the crushed rock to prevent migration of mine water up the shaft. Once the hydraulic seal is placed, then the rest of the shaft can be filled with any available suitable material. Examples include: soil, non-reactive rock, fly ash, and cement slurries. Frequently, the fill material settles over time resulting in surface subsidence at the shaft surface or cracking thereby compromising the seal's integrity. Methods to deal with this problem begin by over filling the shaft so that a mound of earth, ten feet or more in thickness, is left over the shaft or by adding rebar to help bind and secure the fill material. The area is then fenced to prevent public access. Periodically, over the next several years, the site is inspected to see if additional fill material is required as settlement occurs or cracking occurs. Once the seal of material is secure, the fence can be removed.

Slopes and drifts are frequently sealed by pushing soil and rock into the opening. Methods for pneumatic placement of fill materials may be utilized if it is necessary to provide a more substantial seal into the mine or where the seal is part of a water treatment method.

If the mine opening is or is likely to produce water, then a hydraulic seal may be required. Hydraulic seals can either impound water or allow it to pass through the seal in a controlled manner so that outside air cannot pass into the mine. These seals must be designed to resist the anticipated hydraulic head and provide an adequate margin of safety so that pressure of the water does not "blow out" the seal. In addition, the seal should be designed with a fail-safe pressure relief system so that the design head is not exceeded (see section 2.2.8 Blowouts). This is often accomplished by drilling a hole into the mine at a surface elevation that will allow the free discharge of water at the maximum design head.

### **Highwalls**

Abandoned surface mines and face-up areas for underground mines may have highwalls. Highwalls are vertical rock faces that pose hazards to the public due to actual falling from the top of the highwall or from debris falling from the face. If highwalls are present at an abandoned mine site, they should be eliminated. If sufficient material is present, the site can be regraded and the highwall eliminated. If sufficient material is not present, the highwall can be drilled and blasted to reduce the vertical feature to a suitable grade. Some highwalls are so large that neither option is practical. These sites may require fencing or to limit access to protect the public from injury.

## **Impoundments**

Impoundments are created at mining sites for several reasons. They are used to provide fresh water to the mining facility. They are used to contain the fine waste rock slurry from the coal cleaning plant or ore beneficiation plant. Or they may be built for mine water treatment.

Terminology differs for wastes generated by hard rock and coal mines. In hard rock mines, that portion of the waste stream separated during mining from ore is called waste rock. In coal mining it is spoil. Rock rejected from the beneficiation mill in hard rock mining is called tailings. Tailings are nearly always hydraulically handled and placed in impoundments. Rejects from the coal washing process are generally called refuse and may vary in size from coarse to fine. Coarse refuse is truck hauled often to construct the dam for the impoundment, while fine refuse or slurry is hydraulically placed in the impoundment.

Tailings impoundments resulting from metal mining often contain large volumes of very fine material. The mineral beneficiation process usually requires that the ore be ground to minus 100 to 200 mesh to liberate the desired metal. Metal-bearing minerals usually constitute less than five percent and in the case of highly valuable minerals less than 0.05 percent of the ore. Consequently, 95 to 99.9 percent of the mined ore is sent to the tailings impoundment. These fine materials may be highly erodible by both wind and water, and they may be potentially thixotropic. In addition, the fine materials may contain potentially toxic heavy metals such as arsenic or mercury.

Impoundments on coal mining sites that are greater than 20 feet in height are, since 1972, governed by regulations promulgated by the Mine Safety and Health Administration for impoundment design and safety. These regulations were made necessary by slurry impoundment failures, such as the Buffalo Creek failure, which resulted in the loss of human life. Since the implementation of these regulations no active impoundments have failed due to dam failure. However, at least two incidences have occurred where impounded slurry has broken into underlying underground mine works and discharged to the surface.

Tailings or refuse often contain the highest pyrite concentrations on the site. While impoundments are flooded, they will generally be anaerobic, thereby reducing or eliminating acid generation (which requires oxygen) to produce neutral or alkaline water. When drained, however, oxygen will enter resulting in production of acid drainage.

If the abandoned mine has impoundments (in the case of a coal mining site prior to the MSHA regulations or a non-coal mining site), then the stability of the impoundment should be ascertained by site inspection and if necessary, stability analysis. All impoundments should be investigated to establish the potential for impoundment failure into an adjacent or underlying mining operation.

## **Burning mines or refuse piles**

**Burning mines.** Mine fires, while not unheard of in metal mines, are principally associated with coal mines. Coal seam fires can be natural in origin resulting from lightning strikes or forest fires; they can be the result of mine accidents such as grounded trolley wires or welding sparks; or they can be deliberately set by vandalism or as a result of a labor dispute.

Mine fires generate toxic gases that can infiltrate buildings; they can lead to land subsidence; and they cause vents where the hot gases vent to the surface creating a safety hazard and the risk of surface fires.

Mine fires are particularly difficult to control. If the fire cannot be contained within a few hours of its initiation, it is often necessary to seal the mine in an effort to deprive the fire of oxygen. Once sealed, the seals must remain in place until the coal has cooled to a point that reignition or spontaneous combustion is not possible.

Shallow coal seams are a particular problem because the subsidence of the overlying strata provides a pathway for oxygen to enter the mine and sustain combustion. In these circumstances it may be necessary to excavate a trench in advance of the fire, remove the coal, and backfill the trench with noncombustible material. Frequently the cost of putting out the fire exceeds all potential benefits. In these circumstances letting the fire burn has been the accepted course of action.

A trash fire started in an abandoned Pennsylvania surface mine in 1961 ignited the coal seam which is still burning. Over the years attempts to extinguish the fire have failed and the town of Centralia has been abandoned. The cost of efforts to extinguish the fire was \$40 million.

**Burning refuse piles.** Old coal mining refuse piles have often burned. Prior to modern coal washing plants, waste rock piles contained a higher percentage of coal than is typically found today. In addition, the refuse piles were not compacted, which allowed entry of oxygen. A fire initiated by spontaneous combustion or an outside source would then be free to burn the entire refuse pile. These smoldering fires can burn for years at temperatures sufficient to bake the cinder or even vitrify shale. This brick like material is known as red dog, scoria or clinker.

Burning coal piles generate toxic fumes including carbon monoxide and have the potential to collapse creating a potential risk to humans. The burned refuse, red dog, has been excavated and used for roadbed material. These piles frequently have very steep slopes on the landscape that pose a risk of failing.

Refuse pile fires are seldom controlled by surface application of water to the burning pile. Water injection through drill holes can lead to steam explosions. The most effective fire-fighting technique on refuse pile fires is to excavate the burning material and quench it with water. This is a particularly dangerous activity due to the extremely hot material and the potential for the fire to flare up

when exposed. Extra precautions should be taken and burning refuse should be approached with an adequate safety plan.

## **Methane**

Methane is a common risk at most coal mines but is rarely a risk at hard rock mines. Methane is found in coal seams and, in some areas, it is sufficiently abundant that commercial grade natural gas is extracted from the coal in advance of mining. In so doing, the safety of the miners is increased.

Methane is a colorless, odorless gas that is explosive in concentrations between 5 and 15 percent in air. One of the main functions of a coal mine ventilation system is to “dilute and render harmless” any methane present. Concentration less than one percent are considered safe.

Methane can accumulate at mine shafts, slopes, drifts, and boreholes. Even boreholes into flooded mines have been known to produce methane. Methane should be assumed to be present until it is proven to be absent. This testing can be performed with a methanometer or an LEL meter. However, concentrations of methane above 15% are possible and any device that is used must be able to read the full range of concentrations. At high methane concentrations, it displaces oxygen that may reduce oxygen to levels that do not support life.

Particularly hazardous locations are those places where a mine entry or borehole has been capped and work is to proceed adjacent to the cap or the cap is to be removed. Smoking or any other open flame should be avoided around a coal mine entry. Many ignitions or detonations have occurred under these circumstances.

If it is necessary to enter a confined space, such as a mine structure, it is also necessary to test for sufficient levels of oxygen. It is quite common for oxygen to be depleted in the coal mine environment.

## **Blowouts**

A blowout is the sudden and sometimes catastrophic release of water from a flooded underground mine to the surface due to a failure of an outcrop barrier, pillars, or a hydraulic seal. This is not to be confused with a release of water from a mine due solely to an increase in precipitation. Blowouts are limited to mines that are able to impound water at elevations above the local surface drainage system.

Prior to 1977, most above drainage underground coal mines were mined in an up-dip direction. This allowed for the water that infiltrated or accumulated in the mine to the drain downdip to the entry and hence little water was impounded. Unfortunately, mining in an up-dip direction promotes acid mine drainage because free draining mines are filled with oxygen, thereby promoting acid generation. In an effort to reduce the impact of acid mine drainage from coal mines, regulations were promulgated by the Office of Surface Mining that required mine operators to mine in a down-dip direction so that mine flooding

would exclude oxygen and thereby hinder acid generation which generally improved water quality. Outcrop barriers are required to ensure that the water is contained in the mine. Occasionally, one of these barriers fails resulting in the sudden release of the impounded water from the mine.

Remedial work at mine sites can initiate a blowout if the barrier or hydraulic seals are weakened or removed by the remedial activity. Similarly, remedial action can create the circumstance for a future blowout by changing the mine hydrology so that additional and excessive head is placed against the outcrop barriers or mine seals. There are a variety of hydraulic mine seal designs composed of rock aggregate, concrete blocks or soil/rock material. But those installed as wet seals almost always have either clay or plastic piping that conveys water from the mine to reduce hydraulic pressure on the seal. It is wise to look for evidence that a seal may be in place, impounding mine water, prior to construction particularly since they may be buried by surface sloughing and vegetation.

If changes in the mine hydrology are contemplated by sealing of mine entries or other activities, a study of the mine hydrology should be undertaken to ensure against future blowouts. Any activities that would affect the integrity of the barrier or seals should not be undertaken without knowledge of the level of any impounded water in the mine.

### **Hazardous, Toxic, Radioactive Wastes**

Most mines are minor users of hazardous, toxic, or radioactive waste or chemicals. Nonetheless, a number of compounds known to be hazardous or toxic are common to mining sites and some of the chemicals are associated with specific activities. For example, perchloroethylene is associated with coal laboratories but would not be expected elsewhere on the property. In this section, common chemicals used at mine sites are identified. This is not an exhaustive list. If these or other chemical products are encountered at mine sites, their identity must be confirmed and precautions taken for their safe removal and disposal. Material safety data sheets (MSDS) should be obtained for each chemical encountered. MSDS sheets may be obtained from the chemical manufacturer or on the internet at sites such as:

<http://www.msdssearch.com/DBLinksN.htm>.

**Common mine chemicals.** Cyanide (CASRN 57-12-5) usually in the form of sodium cyanide, is used in beneficiation plants and heap leach piles for the extraction of low-grade gold, silver, or copper ores. Piles of low-grade ore are built upon an impermeable pad. Dilute sodium cyanide solutions are added to the pile and the pregnant solution is recovered from the bottom of the pile.

Cyanide is extremely poisonous in either the solid or liquid (sodium cyanide) form or the gas (hydrogen cyanide) form. Sodium cyanide is toxic if it is ingested or absorbed through the skin, and hydrogen cyanide is toxic if it is inhaled. It is essential to store Sodium cyanide so that it does not come into contact with any acid. Contact with water and especially acid will cause sodium cyanide to be converted to hydrogen cyanide.

Ethylene glycol (CASRN 107-21-1) may be present in significant quantities. Ethylene glycol is the principal component of antifreeze and is poisonous to animals and humans. Spills of ethylene glycol are biodegradable. The half-life of ethylene glycol in either soil or water is between one and ten days. Consequently, spills at long abandoned sites are not likely to pose a contamination risk. Any product found on the site should be tested and either sent to a recycler or disposed at an approved facility.

Lead (CASRN 7439-92-1) is found in lead acid batteries (see sulfuric acid) and it may be a constituent of the ore that was mined at the site. As with waste rock piles and tailings disposal sites, lead can be disseminated in the environment through the action of wind or water.

Mercury (CASRN 7439-97-6) was used at old gold mining operations to separate the gold particles from the waste rock. The gold or silver would form an amalgam that would be recovered. The amalgam would then be separated, and the mercury recovered for reuse. Mercury contamination may be associated with this recovery operation. Some waste rock piles or tailings ponds may contain mercury as an unrecovered constituent of the ore. If the waste rock or tailings should be mobilized by wind or water, mercury contamination can be distributed in the environment. Very old rectifiers were based on a technology that utilized gallon quantities of Mercury. If these rectifiers are encountered, special care must be taken to see that the mercury is not released into the environment. Mercury toxicity can result in hand tremor, memory disturbances and possibly autonomic dysfunction.

Methyl Isobutyl Carbinol (MIBC) (CASRN 108-11-2), also known as methyl amyl alcohol, is used in froth flotation cells in both coal and mineral beneficiation plants. Its use may be associated with the use of diesel fuel in the same process. MIBC is flammable and should not be exposed to open flame or sparks. It is explosive at temperatures above 41°C and should not be allowed to form mists. MIBC is heavier than air and can travel along the ground to a distant ignition source. MIBC should be kept away from strong oxidants. Inhalation can cause a cough, sore throat or unconsciousness. Exposure to the skin can cause dry skin, redness or pain. Similarly exposure to the eyes can cause redness and pain.

Perchloroethylene (Perc) (CASRN 127-18-4) is also known as tetrachloroethylene (PCE) and is commonly referred to as PERC. PERC is non-flammable but may yield hydrogen chloride gas, or traces of phosgene when exposed to heat or flame.

Small laboratories are often associated with coal cleaning plants. These laboratories test the “floatability” of the coal as well as the BTU content and sulfur content. A dense liquid such as Perchloroethylene is frequently used at these facilities in the floatability test. Perchloroethylene may be present either in the test vessels or in drums on site. In addition, spills of this chemical may have occurred which may require cleanup.



Perchloroethylene is a Dense Non-Aqueous Phase Liquid (DNAPL) that can sink through the soil and ground water forming a plume at the base of the aquifer. The direction of flow of this plume will be governed by density rather than hydrodynamic gradient. Consequently, if a DNAPL is present on site, hydrogeologic testing will be required before cleanup can begin.

Polychlorinated Biphenyls (PCB) (CASRN 1336-36-3) are listed as a probable human carcinogen. PCBs were distributed under many trade names. The most common trade names are Aroclor, Inerteen, and Pyranol. In order to avoid the potential for fire, mine transformers and capacitors frequently used polychlorinated biphenyls (PCBs) as their dielectric fluid. PCBs were produced in the United States from 1929 to 1977. Consequently, equipment that was in service during these years should be scrutinized for potential PCB contamination. Mining operations have been removing PCB contaminated equipment for many years and each transformer should be labeled as to its PCB status. Older equipment or equipment that is not labeled must be sampled for PCB contamination prior to removal and disposal. Any PCBs found must be removed and disposed in accordance with Federal law contained in 40 CFR 761.

Oil and grease are used in significant quantities, particularly at surface mines. Truck fleets and excavation equipment necessitate tank farms for diesel fuel, gasoline, hydraulic oil and numerous lubrication products. There may still be product in the old tanks, or the tanks may contain water with some waste product. Product spills and leaks may be present at these sites. Any product present should be recovered and sent to a recycler. Waste products should be tested and disposed of appropriately.

In addition to the oil and grease that may be present from the abandoned operation, there may be additional product on site as part of the reclamation activity. This product should be stored or disposed of in such a way that no releases to the ground surface or surface water such as lakes and rivers occurs.

Sulfuric Acid (CASRN 7664-93-9) is found in lead acid batteries and is used in heap leaching operations for low-grade copper or uranium ores. Sulfuric acid is also the form of acid found in acid drainage from mines. Sulfuric acid is corrosive and if it has been in contact with earth materials may also contain heavy metals associated with the local geology.

Some mines use battery-powered equipment utilizing very large batteries. These batteries may be found in supply yards, maintenance facilities or onsite disposal sites. Disposal of these batteries should include recovery of any acid present and the recycling of the lead in the battery.

Trichloroethylene (TCE) (CASRN 79-01-6) has historically been associated with parts-washing operations at repair shops. It is a powerful degreasing agent that can cause severe skin irritation, irritation to the eyes and respiratory tract, and it is a suspected carcinogen. TCE is flammable but normally requires a strong ignition source such as an acetylene torch. Use of TCE for degreasing has been largely discontinued in active operations in favor of less problematic solvents.

Due to TCE's high evaporation rate, surface spills at abandoned sites should not be an issue. However, TCE can leach into the ground water and result in a contamination plume. The possibility is enhanced if routine disposal into the ground occurred at the same disposal site over an extended period of time.

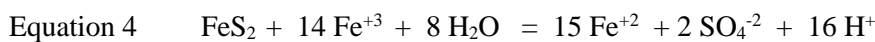
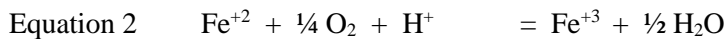
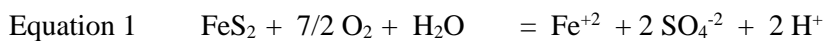
## Hazards from Water Quality

### Acid formation

Acid Mine Drainage (AMD) and Acid Rock Drainage (ARD) are two names for the same process. For the purpose of this section, AMD will be used. AMD forms when sulfide minerals are oxidized. The most significant mineral contributing to acid formation is pyrite, FeS<sub>2</sub>, however, other minerals are also known to generate AMD. Table 1, after Skousen and Ziemkiewicz (1996), identifies ten AMD-forming minerals. When these minerals are exposed to oxygen and water, the oxidation process can begin. The cause of the exposure, whether from mining or from any other earth moving activity, is irrelevant to the chemical process. Hence any earth moving activity that disturbs pyrite-containing materials can result in AMD formation. Mining, by its nature moves large quantities of rock thus exposing it to the oxidation process. In addition, sulfide materials are often the ore that is being mined.

FeS <sub>2</sub>	- pyrite	MoS <sub>2</sub>	- molybdenite
FeS <sub>2</sub>	- marcasite	NiS	- millerite
Fe <sub>x</sub> S <sub>x</sub>	- pyrrhotite	PbS	- galena
Cu <sub>2</sub> S	- chalcocite	ZnS	- sphalerite
CuS	- covellite		
CuFeS <sub>2</sub>	- chalcocopyrite		

The following equations, after Skousen and Ziemkiewicz (1996), describe the oxidation process using pyrite as an example.



As can be seen in equations 1 and 4 pyrite can be oxidized in one of two ways, either directly by reaction with oxygen and water or through the attack of

ferric iron in solution. However, ferric iron can only be generated through reaction with oxygen as shown in equation 2. Equation 2 is known to be the rate-limiting step in the oxidation process. This is due to the fact that ferrous oxidation to the ferric state slows as the pH of the solution is lowered.

The rate of ferrous oxidation can be greatly accelerated through the action of iron-oxidizing bacteria. Thiobacillus ferrooxidans has been shown to accelerate the acid formation process by up to a million times (Leathen et al. 1953).

As with any oxidation process if any of the reactants are removed, the chemical reaction will cease. This concept is the basis for all of the source reduction methods that are applied to reduce or eliminate AMD generation. Notable among these approaches is the “High and Dry” method of placing acid-forming rock above the water table and below a cap that limits or eliminates water infiltration; and the inundation approach in which acid-forming rock is placed permanently below water level.

### **AMD impacts**

Water emanating from abandoned mining sites can be a source of significant pollution loads to the surface and ground water resources, at the mine site itself and downstream of the mine site. The nature of these loads is a function of the geochemistry of the mining site as well as the physical arrangement of the mining with respect to water and air infiltration to these geochemically active materials.

Thousands of miles of streams have been impaired due to AMD. Impacts can range from barely detectable in small watersheds to complete destruction of major rivers as was the case for the Monongahela River in the 1960's.

Discharge water quality can be broken to major and minor constituents. These constituents may be present at either coal or metal mining sites, but it is frequently the case that coal mining sites are dominated by the major constituents while metal mining sites may have both major and minor constituents that require remediation.

The major pollutional constituents include pH, acidity, iron, aluminum, and manganese. The minor pollutional constituents can include antimony, arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, thallium, and zinc. In addition to these AMD-related constituents, asbestos and cyanide may also be present in some mine drainages.

## **Hard Rock Mines**

This section presents the typical characteristics of features associated with abandoned hard rock mines. With mining activities spanning at least a century, the features may have a wide range of characteristics. In many instances, wildlife habitat might have been established at these sites including bat colonies. Specific

surveys will be necessary to address these issues. Snakes may be present at these sites, especially during the summer and all visitors to abandoned mine sites must be vigilant.

### **Surface workings**

**Shallow and deep pits.** Shallow pits were often the result of prospecting work or small-scale surface mining and may have been hand dug or excavated with mechanical equipment such as bulldozers or backhoes. Their depth might only be a few feet. The prospector would often dig a shallow pit on an outcrop of a mineralized body to get a large sample for testing, or sometimes to dig through barren cover to get to bedrock for sampling, if the depth to bedrock wasn't too great. If shallow pits have gently sloping sides, then they pose little hazard since a person or animal could walk into and then out of them. If the sides are steep, such as in a trench, they are more hazardous. People or animals could be injured by inadvertently falling into them, even if they are only a few feet deep.

Deep pits usually resulted from mining activity and not just prospecting work. They can be quite large in area, such as in open pit mines. They might also be the result of underground workings opening up to the surface. They will generally have steep slopes and unstable banks and present a risk to people or animals falling into them. Deep pits might also have water in the bottom, either seasonally or permanently, which presents a drowning hazard. The water also might be of poor quality as a result of dissolved minerals or other contaminants.

**Structures and chemicals.** Abandoned mine sites might have man-made structures such as buildings, shaft head frames, ore bins, portals, mine cars, and rail tracks. Old structures can be unstable and might collapse causing very dangerous conditions for people and animals. Old wooden floors might also collapse under the weight of a person. People might also be tempted to climb into or on old structures and risk injury from falling. Structures that are more than 50 years old are considered historic and before removal or destruction a plan will usually have to be approved by the State Historical Preservation Office.

There might be chemicals left over from mining operations at an abandoned mine site. There could be liquid fuels such as diesel fuel, gasoline, or heating oil. Explosives in the form of paper or plastic cartridges, electric or non-electric detonators, or ANFO (ammonium nitrate + fuel oil) might also be present.

If the mining operations also included a mill to process the ore, then chemicals used in the milling process might be present. These could include various flotation reagents, acids, and cyanide chemicals if the mill processed gold ores.

In the last 25 years, cyanide heap leaching for gold ores has become common. An abandoned heap leach mine might have cyanide chemicals in solid or liquid form, and cyanide-bearing solutions draining from the heap leach pads or in solution holding ponds.

**Tailings and waste rock.** Tailings are the finely ground material left behind after milling and processing has extracted the valuable minerals from the ore. Waste rock is the rock of lower (too low to economically process at the time of mining) or no grade in and around an ore body that must be removed to mine the ore. Waste rock is not processed by crushing and grinding, and thus is much coarser than tailings. In some instances, waste rock may contain high enough grades so that it can be economically processed using modern extraction technology.

Not all abandoned mine sites will have tailings. Only mine sites that had a mill to process the ore had tailings, and in the case of old mines the tailings were often discharged into the nearest stream and are irretrievably dispersed. However, efforts to remove ores or tailings from streams downstream of the mine can be done and can help restore the quality and function of the stream. If the tailings were discharged on the ground and not into a stream, they can still be widely dispersed and eroded by wind and water.

Waste rock is much coarser than tailings although there can be a relatively small proportion of fine material. Through weathering, large fractions may break down over time and result in much of the waste rock containing fine material. The waste rock at old mine sites was usually dumped directly from mine cars running on tracks near the tippie and allowed to fall at its natural angle of repose, commonly near 40 degrees. These types of waste dumps were often long and narrow, like fingers radiating out from the mine portal or shaft. Remnants of iron tracks and wood ties may still be on top of the waste dumps.

More modern mines may have had the waste rock hauled by trucks. It was also usually dumped at the natural angle of repose but along a wider front.

## **Underground workings**

**Stability of workings.** Old underground workings that are still accessible are quite hazardous for many reasons, one of which is stability. There is a risk of falling rock slabs large enough to cause serious injury. The most accessible types of underground workings are adits or tunnels. These are horizontal openings into the side of a hill that a person can walk into. Often the weathered rock and soil at the portal of an adit or tunnel has sloughed in and blocked the opening, but there may also be a small opening that a person could be tempted to squeeze through.

Shafts, whether vertical or inclined, are not as easily accessible as adits or tunnels, but are more hazardous because of the danger of falling into them and dropping to a considerable depth. The support timbers around the collar of a shaft may have decayed and the rock and soil may have sloughed causing a funnel shaped opening at the surface that a person could easily stumble into, get wedged into the hole or fall through to the bottom. Even if the shaft collar is still intact there may be old wooden ladders in the shaft that could tempt a person to climb down into it.

The stability of underground workings will be determined by the rock characteristics and the size of the excavations. Some rock types, such as massive

limestone, or unaltered and unfractured igneous rock, are quite stable over large spans. But usually in hard rock metal mines, the ores are in rocks that have been fractured and hydrothermally altered, which tends to reduce the rock's strength. Sedimentary rocks such as shales are quite weak and easily break up into narrow slabs.

Another hazard from unstable underground workings is surface subsidence. Large stopes that were not filled in may eventually cave to the surface, leaving an opening like a deep pit with steep sides.

**Air quality.** Abandoned underground workings can have bad air quality. Some types of mines had high concentrations of sulfide minerals in the rock and as these materials oxidize oxygen is consumed. The air in the underground workings could then be oxygen deficient, especially if the underground workings are extensive and there is little chance for fresh air exchange with the outside. This is especially true if the underground workings have only one opening to the surface.

If the underground workings have two or more openings to the surface and they are at different elevations, then there is more of a chance for fresh airflow through the workings.

Underground hard rock mines rarely have explosive gasses in them. But if the underground workings are in carbonaceous sedimentary rocks and the workings are not well ventilated, then there is a chance of methane gas build-up. Methane gas has been found in some sandstone formations and carbonaceous shales and slates.

Although not an immediate health or safety risk, underground workings could also contain radon gas. This is a radioactive gas formed by the decay of radium in the surrounding rock. Some granitic rocks have small amounts of radium and old underground workings in such formations can have surprisingly high levels of radon gas that has accumulated over time. Radon is colorless and odorless and non-explosive, and the main health issue is from long-term exposure.

**Water.** Underground mine workings can contain pools of water and deeper areas can be entirely flooded. Underground workings that penetrated the naturally occurring ground water table will eventually fill back up to the pre-mining water table.

Underground workings that are accessed by adits or tunnels might have water flowing that can pool in low spots on the floor of the adit or tunnel. This presents an especially hazardous situation because a winze, which is a vertical or near vertical opening, was often excavated in the floor of adits or tunnels to prospect for the downward continuation of ore. These winzes could be flooded and quite deep, but they could be hidden by what appears to be shallow water.

If the underground workings penetrated rock with reactive sulfide minerals, AMD could form. Old adits or tunnels could have acidic water flowing from

them into nearby streams. The acidic water can be discolored by dissolved or suspended minerals.

## Coal Mines

Coal mining has been conducted since the mid to late 1700's in Pennsylvania and West Virginia. These early mines were underground pick and shovel operations, and the coal was utilized locally. As transportation and demand grew, the size of the mines expanded. Surface mining became prevalent as equipment became available to remove the overlying rock from the coal seam. Further expansion occurred as equipment size increased thereby increasing the amount material to be moved. Extensive surface mining in the last 50 years has led to the depletion of most of the surface mineable coal east of the Mississippi River. Today, coal mining is dominated by Eastern underground mines utilizing continuous miners and longwall equipment, and Western surface mines utilizing area mining techniques.

### Surface mines

**Area mines.** Area mines are feasible where the coal lies horizontal to the land surface and is located in a flat to gently rolling terrain. The maximum depth of the mine is a function of the seam thickness, the cost of overburden removal and the value of the coal being mined.

Area mining begins with a box cut to access the coal seam. The soil and the excavated material from the box cut are stockpiled for future reclamation. After the coal has been removed from the box cut, the overburden from the next cut is placed into the hole created by the initial box cut. This process continues until the reserve is exhausted or until the maximum economical depth has been reached. The final cut can be filled in with material from the initial box cut or it can be left to form what is called a final cut lake.

The primary excavating equipment utilized at these mines is either a drag line or a stripping shovel. Blast casting or a bucket wheel excavator may be used to augment the prime earth movers. The coal is removed via trucks loaded by front end loaders or coal shovels. Bulldozers are used to regrade the spoil ridges and replace the soil. Prior to reclamation regulations, spoil ridges were left unreclaimed.

**Contour mines.** Contour mines are utilized where the terrain is steeper. Prior to reclamation regulations, the "Shoot and Shove" method was extensively utilized in the Appalachian coal region. In this method, the overburden is drilled and fractured with explosives and then the broken material is pushed downslope in an uncontrolled fashion with bulldozers. The use of this method created environmental damage on the mining bench and on the downslope edge of the hill, and in the receiving streams. This left a potentially unstable highwall, and unreclaimed bench, and a highly erodible out slope. This practice left all of the overburden exposed to weathering and potential acid formation.

This practice was ended nationwide with the passage of the Surface Mining Control and Reclamation Act in 1977. Contour mining is allowed under the law, but it must be conducted so that the excavated material is placed on the mining bench, the highwall is eliminated, and the topsoil is replaced and the site vegetated.

As the cost of overburden removal became lower, it was possible for coal operators to revisit old contour mines and take a second cut with a higher overburden ratio. This frequently occurred after the advent of mining reclamation standards and many of these old abandoned contour mines (shoot and shove) were enlarged to remove additional coal and the entire site was reclaimed to current standards (see Remining).

**Mountain top mines.** Mountain top mining is a relatively recent mining practice. It involves the application of area mining equipment in steep terrain settings. Draglines are used in conjunction with truck - loader combinations to excavate from one side of the hill to the other removing multiple coal seams in the process. This technique is often economical where mining of any one of the seams would not be economical. This technique generates large quantities of excess broken rock called spoil. Due to the increases in volume of the broken rock, it not possible to replace all of the spoil back on top of the mountain, which would elevate the height of the mountain contrary to regulations, and consequently the excess spoil is placed in valley fills.

Debate about this technique has centered on the loss of first order streams and about downstream flooding potential. USGS open file report 03-133 is entitled "Comparison of Peak Discharges among Sites with and without Valley Fills for the July 8-9, 2001, Flood in the Headwaters of the Clear Fork, Coal River Basin, Mountaintop Coal-mining Region, Southern West Virginia." Although this study is limited to just three streams with valley fills, it suggests that fully reclaimed valley fills have less storm runoff than streams that are unaffected by mining.

Because this mining method is quite recent, these operations have been designed and permitted under current mining regulations and are designed to prevent or substantially minimize the generation of AMD.

Another consequence of this mining technique in this region is the increase of constituent elements in discharge waters from valley fills. Procedures to limit the exposure of reactive rock materials and the generation of total dissolved solids (TDS) is being conducted. The decline of coal production since 2010 has reduced the number of mountaintop mines operating in Appalachia.

**Auger.** Auger mining is a method of extracting coal once the maximum overburden thickness has been reached. An auger machine is set up on the mining bench facing the highwall. Dual augers with a diameter similar to the coal seam thickness bore into the coal and the coal is extracted on the flights of the auger. Augers may bore in excess of 500 feet into the hill thereby removing up to 50% of additional coal from the seam.



Once completed, the auger holes are to be packed with clay and sealed. On occasion, auger mining may intersect with underground mining works or visa versa. This can create a hydraulic connection between the two mines that may result in a sudden release of mine water or the failure of a mine to flood.

**Remining.** Remining is the application of any of the surface mining techniques for the purpose of profitably reducing or eliminating existing AMD or other hazardous conditions left by prior mining. Remining has been successfully employed to remove coal pillars from shallow underground mines that were generating AMD thus removing the source of the AMD. Remining has also been utilized to eliminate hazardous highwall conditions and to apply current materials handling techniques to reduce AMD production on abandoned sites. This process can reclaim an abandoned mine site to current regulatory standards without cost to the AML fund.

## **Underground mines**

### **Room and pillar.**

#### a. Development

Room and pillar mining is a technique in which interconnecting tunnels called rooms or entries are driven on a grid pattern and pillars of unmined coal are left to support the overlying rock. These tunnels are typically 16 to 22 feet wide and the pillars vary from 30 to 70 feet in width and 50 to 120 feet in length. Pillar size and shape are designed to accommodate necessary roof support as well as the mining equipment, the haulage, and the ventilation systems.

A system of mains, faces and butts are established in the coal reserve. Mains are the set of entries that are designed to remain open for the life of the mine. Faces are primary entries that split off from the mains at 90-degree angles. These entries provide access to the coal reserve. Butts or sometimes called flats are driven at 90-degrees to the faces. Development mining typically extracts only 30 to 40 percent of the coal, although this can be increased to 50 to 60 percent if needed.

#### b. Retreat

Retreat mining is a variant of the room and pillar method in which the coal pillars in the butts of flats are systematically removed as machinery is pulled back out of the mine, and as pillars are removed the roof collapses. This method has been extensively practiced in the Pittsburgh Coal seam prior to the advent of Longwall mining. Retreat mining can result in the extraction of up to 80 percent of the coal. Once all of the butts on a face have been retreated, then the face itself can be retreat mined.

**Longwall.** Longwall mining is similar to room and pillar mining in that continuous miner are used to drive main and face entries. However, the butts are used to get access to a block of coal that is 1000 to 3000 feet wide and 5000 to 10000 feet long. This block of coal is called a panel. A longwall machine is assembled at the back of the panel. The machine consists of hydraulic roof

supports called shields, a ranging shearer or plow, and a chain conveyor. The shields support the overlying rock and provide a safe working area for the operators and the shearer/conveyor. The shearer or plow is mounted on the chain conveyor and traverses the coal face removing 30 inches of coal with each pass. As the coal is removed, the shields advance by 30 inches, and the chain conveyor is pushed forward by the same distance. As the shield advances, the roof collapses in the area where the shields were, which can lead to surface subsidence.

Coal extraction within the panel is 100 percent. However, the coal in the development pillars is not recoverable and this reduces the overall extraction ratio to about 80 percent, the same as room and pillar retreat mining.

### **Surface facilities**

**Coal cleaning.** Not all coal is cleaned. Some mines ship their product directly without a beneficiation process. The purpose of coal cleaning or coal washing is the removal of non-coal components from the run of mine product. Non-coal components are referred to as ash, which is defined as the non-combustible materials such as clays, shales and other rocks). Ash is detrimental to coal-fired boilers and maximum ash limits are often specified in coal sales contracts. Coal cleaning plants use the difference in specific gravity between rock and coal to cause a separation. Heavy media baths, heavy media cyclones and froth flotation are commonly used for this purpose depending on the size of the coal to be washed. In heavy media units, the apparent specific gravity of water is increased by the addition of finely ground magnetite. The specific gravity is increased to 1.3 to 1.4 and the coal is allowed to float while the ash components sink. It is the waste rock generated by this process that is referred to as refuse. Fine coal, typically minus 48 mesh, is cleaned using froth flotation. Diesel fuel and Methyl Isobutyl Carbinol are used to promote the attachment of coal particles to air bubbles. The coal is collected at the top of the cell and the ash component is sent for disposal. This fine coal and water mixture is called slurry.

**Loading.** Coal that is ready for shipment is placed into a stockpile or a concrete silo. Shipment can take place from the mine / cleaning plant by either truck, rail, conveyor or barge. Some operations use a combination of these modes of transportation. All, except for the conveyor, require some type of loading facility. At small operations, a simple stockpile and front end loader are used to fill trucks for shipment. At larger mines, silos are used to fill unit trains as they pass under the facility. When coal is located near a navigable river, barges can be filled via belt transfer directly from a mine or from a centralized terminal facility where the incoming coal arrives by truck or train.

**Refuse.** Refuse is the coarse fraction of the non-coal waste produced when coal is cleaned. Coal may contain 10 to 40 percent reject as it comes from the mine. This material may be roof or floor rock that is taken in the mining process or it may be from shale and claystone layers found in the coal seam itself. Depending on the production capacity of the mine and the reject rate, large volumes of refuse may be generated for disposal. Refuse is usually placed in valley fill settings in first order streams. Placement of this refuse is regulated

under SMCRA, MSHA, and the Army Corps of Engineers.

Refuse disposal can be separated into three types. In its simplest form, coarse refuse is placed into a mono fill. In the second case, coarse coal refuse is combined with dewatered slurry and these are placed into a mono fill, which is called combined refuse disposal. The third disposal method is to construct an earthen starter dam and use the coarse refuse to extend the dam's height, width and length. The slurry is then disposed in the impoundment formed by the dam.

Each of the disposal options involving slurry can be problematic. Combined disposal facilities are difficult to operate in high rainfall areas. The movement of heavy equipment necessary for pile construction is impeded by the sloppy conditions created when the slurry is combined with the coarse fraction. On the other hand, slurry lagoons have also had a checkered history. Slurry dam failures led to regulation of dam construction under the Mining Safety and Health Administration. Since the advent of this regulation, dam failures are no longer the threat they once were. However, recent failures at slurry lagoons have not involved the failure of the dam but rather a breach between the lagoon and underlying or adjacent underground mining. These events prompted a study by the National Research Council. In October 2001, it issued a report entitled "Coal Waste Impoundments: Risks, Responses, and Alternatives."

**Slurry.** Slurry is generated in the fine coal circuit in the coal cleaning plant as previously described. Although it is not a goal of the coal cleaning process, coal reject, particularly fine coal reject, can be enriched with pyrite as the coal is cleaned. The finer the coal is ground, the greater the number of pyrite grains that are released and exposed to weathering reactions. As this fine coal is processed in the cleaning plant, pyrite being denser than coal is preferentially sent to the reject and hence to the slurry disposal facility.

**Spoil.** Spoil is the term given to broken overburden (rock) materials at a surface mine, and it should not be confused with refuse. These materials are most often replaced in the area from which they were excavated. Occasionally, as with mountain top mining, excess spoil is created due to the volume increase or swell. As a result, spoil must be placed at an alternative location. Due to the large volumes and steep terrain in some settings, first order stream valleys are used for this purpose.

**AMD.** Acid mine drainage formation has been previously described. It can be found emanating from flooded underground mines, from free draining underground mines, from refuse piles, coal storage stockpiles, surface mines, and final cut lakes. The flows can range from a trickle to thousands of gallons per minute. The water quality can range from being suitable for discharge without treatment to pH readings in the 2 – 3 range and acidities in excess of 10,000 mg/L.

The water quality from a given mine has been shown to change with time. This is particularly true of flooded underground mines. These mines generate a poor water quality when initially flooded. However, this water quality improves

over time. A mine in the Pittsburgh seam has been found to evolve from an acidity of 2,000 mg/L to an alkalinity of 400 mg/L over the course of seven years. Over a period of 15 years, the iron level in this mine fell from 1,100 mg/L to 60 mg/L and it continues to improve. Other mines in the basin which have been flooded for more than 20 years are discharging water that complies with standards at flows up to 2,000 gpm. Even non-flooded mines have been shown to improve with time but far less dramatically. This suggests that flooding of acid-producing coal mines should be encouraged provided that there is little or no risk of catastrophic failure (blowouts) resulting from the impounded water.

# 3 HEALTH AND SAFETY

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There are significant health and safety issues related to abandoned mines. The material in this section is currently focused on hard rock mining issues and will be extended to include coal mining.

## Regulatory Requirements

### Federal requirements

Abandoned mines will not usually fall under the jurisdiction of the Federal Mine Safety and Health Administration (MSHA). MSHA has health and safety jurisdiction over active mines and mines that are listed as temporarily inactive, but not abandoned. Any work done at an abandoned mine site will still have to comply with Federal Occupational Safety and Health (OSHA) regulations.

### State and local regulations

The individual states may have their own Occupational Safety and Health departments. Before starting any activities at an abandoned mine site in any particular state, the safety and health regulations for that state should be consulted to see if any are more restrictive than Federal OSHA regulations.

### Tribal lands

When working on Tribal Lands, the local Tribal authority should be contacted to see if they have any special health and safety regulatory requirements. For example, The Navajo Nation's Abandoned Mine Land Reclamation Department, in coordination with the Office of Surface Mining Reclamation and Enforcement (OSMRE), US Department of the Interior, has the authority and responsibility to reclaim mine lands left abandoned or inadequately reclaimed on the Navajo Reservation prior to August 3, 1977. They have developed a Health Physics and Instrumentation Monitoring Plan that describes the methods to be employed for Health Physics monitoring and protection at abandoned uranium mine land sites. The Plan is intended as a guideline document, summarizing techniques and instrumentation to be applied at all Non-coal AML Reclamation Projects. The table of contents of the Plan is included below.

**THE NAVAJO NATION  
AML RECLAMATION DEPARTMENT  
DIVISION OF NATURAL RESOURCES  
WINDOW ROCK, ARIZONA**

**HEALTH PHYSICS AND INSTRUMENTATION MONITORING PLAN**

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Other tribes also have health and safety programs. -The Hopi Tribe's Health and Human Services Department is part of the Executive Branch. |

## Documentation

### Health and safety plans

Before remediation work begins at an abandoned mine site, a Health and Safety Plan (HASP) will generally be required. The Health and Safety Plan should be site specific. A Health and Safety Plan should also have a means to evaluate its effectiveness. Inspections should be done by the site safety and health supervisor or another qualified person to determine the plans effectiveness, and any deficiencies should be corrected. The following sections show what a Health and Safety Plan should consider. Not all of the sections or parts of a section may be applicable to a specific AML site remedial activity, but an explanation of what sections are not applicable should be included. A number of issues must be considered about the health and safety at an abandoned mine site. This section describes several of these issues.

The abandoned mine site should be surveyed for physical hazards as the first step in drawing up health and safety plans for remediation work. Physical hazards would include open shafts or pits that people could fall into, unstable structures, steep slopes on waste rock dumps, and soft and wet areas in tailings impoundments.



Safety regulations require that where a person is working around an open hole such as a shaft or deep pit, then that person shall have fall protection. This usually means a safety belt or harness and attached safety line. If part of the remediation work includes erecting a fence around a shaft or deep pit, a person must be protected from falling into the hole while putting up the fence.

Old explosives are dangerous, and plans must be formulated for their proper handling and disposal. In most cases it will be best to detonate or burn the old explosives at the abandoned mine site rather than transport them elsewhere for disposal. Only a properly trained person should do this, which will generally be the person to have a blaster's license or certification from the state agency.

There may be chemicals on the site that can present an immediate health risk if not properly handled. The health and safety plan should include identifying all chemicals on site and obtaining Material Safety Data Sheets (MSDS) for each of them. The MSDS sheets will indicate the health risks associated with the chemical and the proper protective clothing and equipment. Some chemicals will no longer be in their marked containers and they may be difficult if not impossible to identify. In this case, appropriate measures should be taken such as handling the chemicals only by people in protective clothing and equipment that will protect them from skin contact, eye contact, inhalation, and ingestion of the chemical.

Abandoned mine sites are often in remote areas. This makes it even more important that the people doing the remediation work have proper safety and first aid training since immediate medical help will not be available. The location of the nearest phone or other means of communication, and how to use it, should be known by all people on the site. All workers should have communication devices on their person fully charged and operational such as cell phones or other means of communication. The location of the nearest medical facility should also be part of the health and safety plan. Remediation work should always be done by at least two people so that one person can obtain help if another person is injured or is in danger.

An outline of a typical health and safety plan for abandoned mines is shown below and each part is described in more detail in the sections that follow.

### **Outline of a Typical Health and Safety Plan for Abandoned Mines**

- 1.0 Introduction
- 2.0 Key Personnel and Project Team Organization
- 3.0 Hazard Assessment, or Safety and Health Risk
- 4.0 Emergency Response Plan or Action Plan
- 5.0 Personal Protective Equipment (PPE)
- 6.0 Site Monitoring and Air Sampling
- 7.0 Site Control
- 8.0 Decontamination Procedures

- 9.0 Employee Training
- 10.0 Chain of Custody

## **Introduction**

The introduction describes the site. This should include background information and site history, any prior activities, known contamination and site characterization, and the operations to be performed.

## **Key personnel and project team organization**

The number of key personnel should be kept to a minimum, but their responsibilities should be assigned and their qualifications listed. A large remediation project may have the following key personnel:

- Project Manager
- Site Safety and Health Officer
- Additional Safety and Health Personnel
- Field Team Leaders
- Emergency Response Coordinator
- Security Coordinator
- Specialty Team Personnel

## **Hazard assessment, or safety and health risk assessment**

This section should address the following items:

- Known chemical hazards and exposure.
- Physical hazards
- Problems due to temperature extremes
  - Heat related problems, effects, and prevention
  - Cold exposure, effects, and prevention
- Identification of the hazards associated with each task of the project, and the safe operating procedures for each task.

## **Emergency response or action plan**

This section describes what everyone is to do in case of an injury or other emergency. At a minimum it should include:

- Pre-emergency planning and training
- Emergency recognition and prevention
- Escape procedures and routes
- Emergency medical treatment and first aid
- Location of on-site medical materials for quick access

- Location of the nearest medical assistance and methods of alerting them
- Other emergency contacts

### **Personal protective equipment (PPE)**

The need for personal protective equipment should be determined during the Hazard or Safety and Health Risk Assessment. Personal protective equipment could be as simple as eye and foot protection, or it could be special clothing and respirators to protect against chemical or radiological hazards.

The Health and Safety Plan should address the following items concerning personal protective equipment:

- Equipment selection based on site hazards
- Use and limitations of personal protective equipment
- Training in the use of personal protective equipment
- Proper fitting and wearing of respirators
- Decontamination and disposal of personal protective equipment
- Maintenance and storage of personal protective equipment

### **Site monitoring and air sampling**

Some remediation sites may require site monitoring and air sampling for chemical, physical, or radiological hazards. The site monitoring and air sampling component of the Health and Safety Plan should address the following:

- Sampling methods and schedule for personal (breathing zone) air monitoring
- Air monitoring and environmental sampling for possible offsite migration
- Instruments and equipment to be used for monitoring, and their calibration and maintenance
- Quality Assurance/Quality Control procedures and analytical methods

### **Site control**

The purpose of the site control component of the Health and Safety Plan is to minimize worker's exposure to hazardous substances. It does this by controlling the movement of people and equipment. The site control component should include the following:

- A site map
- Site work zones

- The use of a “buddy system” where any worker can be observed by another for safety reasons
- Site communications procedures during normal and emergency situations
- Safe Work Practices or Standard Operating Procedures
- Locations of nearest medical assistance

### **Decontamination procedures**

If there is a possibility of people or equipment becoming contaminated by hazardous material, then a decontamination procedure must be adopted in the Health and Safety Plan and communicated to workers before they may enter these sites. It should include the following components:

- Training and standard operating procedures shall be developed to minimize contact with hazardous substances
- A procedure to monitor and decontaminate workers leaving a contaminated area
- A procedure to collect and decontaminate or dispose of contaminated clothing and equipment
- Location of decontamination stations that will minimize the exposure of uncontaminated workers and equipment to contaminated workers and equipment
- Required decontamination equipment

### **Employee training**

All workers going onto an AML site must be adequately trained and briefed on anticipated physical, chemical, or radiological hazards. In addition, if hazardous materials are present at an AML site, then 40-hour HAZWOPER training will be required. An Employee Training component of a Health and Safety Plan will typically include the following:

- Names of personnel responsible for site health and safety
- Safety, health, and other hazards present on the site
- Use of Personal Protective Equipment
- Safe work practices and safe use of equipment
- Decontamination procedures
- Familiarity with the Emergency Response Plan
- Confined Space entry procedures
- Spill containment

In addition, documentation and certification of training must be maintained.

## Chain of custody

Chain of Custody is defined as a set of procedures used to provide an accurate written record that can be used to trace the possession of a sample from the moment of its collection through its introduction into a data set and perhaps its disposal or destruction. Written procedures for sample handling should be available and followed whenever samples are collected, transferred, stored, analyzed or destroyed.

Custody of a sample means:

1. It is in one's actual physical possession
2. It is in one's view, after being in one's physical possession
3. It is in one's physical possession and then locked up or sealed to prevent tampering
4. It is kept in a secured area, restricted to authorized personnel only

A minimum number of people should be involved in sample collection, handling, and transportation to reduce the chances of mishandling and tampering. Even if no mishandling or tampering takes place, the sample's validity may be called into question if its location, who had responsibility for it, and its security cannot be accurately documented until all tests have been performed on the sample.

When a sample is first collected, a field record should be completed and signed or initialed by the sample collector. Field records should include the following information:

1. Sample or log number
2. Date and time
3. Source of sample (name, location, and sample type)
4. Preservative used (if any)
5. Analyses required
6. Name of collector
7. Pertinent field data (temperature, pH, DO, etc.)
8. Serial numbers on seals and transportation cases
9. Comments

In addition to the written field record, each sample container should have a label or standardized tag. This label or tag should have the sample number, source of sample, preservative used, and the collector's initials. If a label or tag is not available, then the information should be written with an indelible marker on the sample container. A seal should be placed on the cap or opening of the sample container to indicate if tampering takes place. The seal should have a unique number that is recorded on the field record form and the chain-of-custody form.

If possible, a better method is to place the individual sample containers in a transportation case along with the field record form, chain-of-custody form, and analysis request forms. The transportation case should then be locked and sealed. This will eliminate the need to have close control over individual samples.

When transferring possession of the samples, the person receiving the samples must record the date and time and sign their name on the chain-of-custody form. Custody transfers must account for each individual sample although samples can be transferred as a group.

When the samples are delivered to a laboratory for analysis, custody may be relinquished to laboratory personnel. If appropriate laboratory personnel are not present to receive the samples, then the samples should be locked in a designated area to prevent tampering. The person delivering the samples should make a log entry stating where and how the sample(s) were delivered and secured. Laboratory personnel may then receive custody by unlocking the secured area, noting in a logbook the absence of evidence of tampering, and signing the chain-of-custody form.

The laboratory performing the analyses should also have its own sample control procedures from the time the samples are received to the time they are discarded.

## **AML Site Health and Safety Implementation**

### **Underground mines**

Examining or entering abandoned underground mines can have several risks that abandoned surface mines won't have. These risks will usually be from bad ground, bad air, and water in parts of the mine that might be covering deep holes.

#### **Bad ground**

By their very nature, underground mines have rock overhead and often this rock is loose or fractured. The underground openings were made by blasting which not only breaks the rock that was intended to be excavated but also induces small fractures in the surrounding rock. This is one of the differences between abandoned underground mines and natural caves.

Natural caves were most often created by water dissolving some rocks or minerals, or the gradual cooling of lava flows where some of the lava solidified, while still molten lava continued flowing out, leaving behind hollow tubes that are sometimes quite large. None of these natural openings will have blast-induced fractures in the wall rock.

The blast-induced fractures can make otherwise strong, or competent rock, into incompetent and unstable rock that can break apart. In active underground mines, the miners would test the back and ribs after a blast, usually with a steel bar, and pry down any loose pieces of rock still remaining. This process of “barring down” might be repeated a number of times as the fractured rock continued to loosen, until that particular part of an underground mine, or the entire mine itself, was abandoned.

When entering an abandoned underground mine, the back and ribs have to be tested for loose rock with a pry bar and any loose rock must be barred down.

## **Bad air**

**Oxygen deficient air.** Oxygen deficient air has an oxygen content equal to or less than 19.5%. The oxygen deficiency can be caused by the displacement of oxygen by another gas, such as methane or carbon dioxide, or the consumption of oxygen by a chemical reaction between the air and minerals in the rock.

Oxygen deficient air can cause increased breathing and heart rates, impaired attention, unconsciousness, and death. When an underground mine was active, it may have had a mechanical means of ventilation, such as a fan, but after being abandoned this means of ventilation would no longer be available.

Some early mines relied on “natural ventilation” which requires at least two openings for air to enter and then exit the mine workings. However, an abandoned underground mine that relied on “natural ventilation” when it was active cannot be counted on to have good air after being abandoned. An abandoned mine with only one opening should be approached with special caution until the air can be tested to ensure sufficient oxygen content. There are several instruments that can test the oxygen content of air. Among them are the following.

- Draeger microPac
- Draeger microPac Plus
- Draeger Pac III
- Draeger Mini Warn

- MSA A-Mini-OX-1-10-00
- MSA Oxygen Indicator 476260 Model 246RA
- MSA Microgard Portable Alarm #1LN 1000000 OXY/LEL
- MSA 804625 Cricket O2 Monitor

**Radon gas.** Radon gas is a colorless, odorless, radioactive gas. It will be present in abandoned uranium mines, but it could also be present in other types of abandoned underground mines. Radon gas is a decay product of radium, and rocks types such as granite, shale, and phosphate can contain small amounts of radium.

While high levels of radon gas will not cause immediate health effects such as oxygen deficient air or other air contaminants, prolonged exposure to elevated levels of radon gas will increase a person's risk of getting lung cancer. Active underground mines that have radon gas problems control it by using good ventilation practices, but abandoned underground mines are likely to have poor ventilation. The radon gas concentration in an abandoned mine could be many times greater than what it was when the mine was active.

If the geology of the abandoned mine suggests the possibility of radon gas, then the air should be sampled for radon if extensive underground work or surveys are planned.



## 4 REGULATORY AGENCY OVERSIGHT OF AML

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This chapter provides information about the regulatory oversight that occurs at abandoned mine lands. The material currently reflects the situation for hard rock mines in Nevada and Utah but forms a framework for regulatory oversight of these abandoned sites in other western states.

### Land Ownership

Land ownership can be private (including patented mining claims), State lands, public lands administered by the Bureau of Land Management and Forest Service and other Federal agencies such as Department of Defense, National Park Service, and Fish and Wildlife. Tribal lands are under separate jurisdiction. It is often difficult to identify land ownership because abandoned mine sites don't usually have fences or other property boundary markings. If the section, township, and range of the abandoned mine site is known, then the owner of record can usually be determined from the County courthouse records. If the abandoned mine site is on unpatented claims, this means that the land owner is still the Federal Government, but the claimant of record can be determined from Bureau of Land Management records. If the last claimant hasn't paid the required claim maintenance fees to the Federal Government, then the claim will be considered abandoned.

### Federal Agency Oversight

Federal oversight of Abandoned Mine Land reclamation is mostly through the Office of Surface Mining Reclamation and Enforcement (OSMRE), although other Federal agencies, such as the Bureau of Land Management, the US Forest Service, and the National Park Service also have AML programs. The Office of Surface Mining Reclamation and Enforcement was established as a result of the Surface Mining Control and Reclamation Act of 1977 (SMCRA). This act, among other things, assesses a reclamation fee on all coal producers. The fee was initially 35 cents per ton for surface mined coal and 15 cents per ton for underground mined coal, but was lowered slightly in 2007 and again in 2021. This reclamation fee is the primary funding source for most AML programs in the Nation.

The SMCRA reclamation fee is collected in states that have active coal mining operations. A SMCRA state can receive 50% of that money back to fund an OSM approved Abandoned Mine Land program. In that case the state would manage its own AML program. If a SMCRA state doesn't establish an OSM approved AML program, then the OSM will manage the AML program in that state. Several Indian tribes have approved AML programs and manage the AML program on their lands. Table 2 shows who manages the AML program in SMCRA states and Indian tribes.

<b>Table 2</b>					
<b>Who Manages the OSM Abandoned Mine Land Program?</b>					
<b>State/Indian Tribe</b>	<b>AML Program</b>	<b>State/Indian Tribe</b>	<b>AML Program</b>	<b>State/Indian Tribe</b>	<b>AML Program</b>
Alabama	Yes*	Kentucky	Yes	Oregon	OSM
Alaska	Yes	Louisiana	Yes	Pennsylvania	Yes
Arkansas	Yes	Maryland	Yes	Rhode Island	OSM
California	OSM	Michigan	OSM	South Dakota	OSM
Colorado	Yes	Missouri	Yes	Tennessee	OSM
Crow	Yes	Montana	Yes	Texas	Yes
Georgia	OSM	Navajo	Yes	Utah	OSM
Hopi	Yes	New Mexico	Yes	Virginia	Yes
Illinois	Yes	North Carolina	OSM	Washington	OSM
Indiana	Yes	North Dakota	Yes	West Virginia	Yes
Iowa	Yes	Ohio	Yes	Wyoming	Yes
Kansas	Yes	Oklahoma	Yes		

\*If "Yes" is in the AML Program column next to a state or Indian tribe's name, then that state or Indian tribe manages their AML program. Otherwise, the OSM manages the AML program in that state.

Non-coal states don't receive any SMCRA funds for AML reclamation (Table 3). However, some of these states do have their own state funded AML program, such as Nevada, Arizona, and South Dakota.

<b>Table 3</b>		
<b>Non-Coal States</b>		
Arizona	Maine	New Hampshire
Connecticut	Massachusetts	New Jersey
Delaware	Minnesota	New York
Florida	Mississippi	South Carolina
Hawaii	Nebraska	Vermont
Idaho	Nevada	Wisconsin

The SMCRA program was set up primarily to address reclamation of coal mines abandoned before 1977, or to complete or redo reclamation work that was

done inadequately. The SMCRA set up priorities for remediation work at abandoned mine sites. The priorities are in the order stated below.

- (1) The protection of public health, safety, general welfare, and property from extreme danger of adverse effects of coal mining practices.
- (2) The protection of public health, safety, and general welfare from adverse effects of coal mining practices.
- (3) The restoration of land and water resources and the environment previously degraded by adverse effects of coal mining practices including measures for the conservation and development of soil, water (excluding channelization), woodland, fish and wildlife, recreation resources, and agricultural productivity.
- (4) The protection, repair, replacement, construction, or enhancement of public facilities such as utilities, roads, recreation, and conservation facilities adversely affected by coal mining practices.
- (5) The development of publicly owned land adversely affected by coal mining practices including land acquired ... for recreation and historic purposes, conservation, and reclamation purposes and open space benefits.

In certain circumstances, SMCRA funds can be used by a state's or Indian tribe's AML program for reclamation and remediation at abandoned hard rock mines, but only after priority 1 and priority 2 sites have been remediated. SMCRA funds can also be used for priority 4 projects, otherwise known as Public Facilities Projects, but again only after priority 1 and priority 2 sites have been remediated.

## **Bureau of Land Management**

The BLM has an Abandoned Mine Lands program for the western states of Washington, Oregon, California, Idaho, Nevada, Utah, Arizona, Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas. The BLM has concentrated its inventory of abandoned mines to areas near population centers and areas of high visitation and has identified over 9400 AML sites. Approximately 25 percent of the AML sites have physical hazards, such as open shafts, adits, or unstable structures, and approximately 5 percent have the potential to cause environmental damage primarily in the form of water pollution.

These 9400 AML sites pose the most immediate threat to physical safety, or the greatest risk of watershed pollution. Because of this the BLM is not planning any more general inventories of AML sites on its lands, but it will continue to add AML sites that are identified as a part of routine business. If there are any expanded or new recreation areas established on BLM lands, then specialized AML inventories may be conducted.

The BLM's emphasis is on the environmental effects of abandoned mine lands. The BLM relies on the states to identify watersheds polluted by AML sites that they want cleaned up. Then the BLM joins with other government and private landowners to clean up those sites. Since the BLM's efforts are focused

on repairing environmental damage to watersheds, the securing of physical hazards at AML sites has mostly been the responsibility of state AML programs.

### **Forest Service**

The US Forest Service's lead agency for restoring and reclaiming lands and watersheds affected by mining practices on Forest Service administered lands is Minerals and Geology Management. The Minerals and Geology Management agency of the US Forest Service approaches restoration on a watershed basis, and often collaborates with other Federal and State AML programs and private industry. A 1995 Forest Service report estimated that there were an estimated 13,500 former mines on National Forest lands, and that 1,500 of these mining sites had already been identified as having significant mine drainage problems.

### **National Park Service**

The National Park Service's (NPS) Geological Resources Division established an Abandoned Mineral Lands program in 1984. The AML program is now part of the National Park Service's Disturbed Land Restoration Program, whose goal is the restoration of all human caused landscape disturbances on NPS lands.

An inventory of NPS lands identified 3,200 abandoned mine sites. Since NPS lands attract many visitors, the closure of abandoned underground mine openings that present a hazard to park visitors and staff is a major priority. These closures have most often been contracted and funded through the Office of Surface Mining Reclamation and Enforcement and various state AML programs. Before closure of an abandoned mine opening takes place, the NPS, as with any other land management agency, must ensure compliance with the National Environmental Policy Act and the Endangered Species Act. This may involve writing an Environmental Impact Assessment which addresses potential adverse impacts on resources and wildlife.

## **State Agency Oversight**

Some states have an AML program while other states don't have any AML program. The states that do have an AML program can be divided into two groups, SMCRA states and Non-SMCRA states.

### **SMCRA States**

SMCRA states are ones that have coal mining operations that pay into the SMCRA reclamation fund. SMCRA states with an approved state regulatory AML program are allocated up to 50 percent of the reclamation fees collected in that state to manage their AML programs. Other SMCRA states without an approved state AML program have their AML program managed by the Federal Office of Surface Mining (OSM).

The contacts for each state that manage their own SMCRA Abandoned Mine Land Program are listed in Appendix B.

### **Non-SMCRA states**

Non-SMCRA states in the Western US are Arizona (except on tribal land), California, Idaho, Nevada, and South Dakota. None of these states have qualifying coal mining operations and therefore get no SMCRA funds from the Federal government. Several of these states have started their own state AML programs. Examples of some state funded AML programs are discussed below. Get rid of contact list, too many years ago.

**Arizona.** Arizona's Abandoned Mine Unit is part of the Arizona State Mine Inspectors Office. The Arizona Legislature appropriated money for an abandoned mine inventory in 1990. In 1992, the Arizona State Mine Inspector entered into an agreement with the Bureau of Land Management to inventory abandoned and inactive mines on federally managed lands. In 1999, the focus changed from inventory to mine remediation.

In 1996, the State Mine Inspector began assisting the National Park Service in closures of abandoned mines in national parks, monuments, and recreation areas in Arizona.

In 1998, Arizona established an Abandoned Mine Safety Fund that encourages private contributions that can be used along with legislative appropriations to safety risks from abandoned mines on State lands.

Arizona has an abandoned mine fencing program and has made it a felony to vandalize fences and signs around hazardous mine openings.

Through January 1999, Arizona had inventoried 8,787 abandoned mines and determined that 3.3% of them had some type of environmental hazard, and 13.1% had significant public hazards associated with them.

**Nevada.** Nevada has an Abandoned Mine Land program that is part of the Division of Minerals. The State will identify and rank hazards relating to physical dangers associated with abandoned mines. The ranking system assigns one to five points for the location of dangerous conditions, taking into account how far it is from a public road, town, or occupied structure. An additional one to five points are assigned depending on the degree of danger associated with the condition. The rating points for location and degree of danger are added up, and a dangerous condition with a total of at least 8 points is a high hazard, 6 or 7 points is moderate hazard, and points 5 or less is a low hazard.

The State will then determine ownership of the land, if it is a patented claim or it is a claimant of record for unpatented claims, and notify the responsible person that the hazard must be secured. The time allowed to secure the hazardous condition depends on its ranking. High hazards are supposed to be secured within 60 days of notification, moderate hazards with 120 days, and low hazards within

180 days. If no landowner or claimant exists, the State will secure the hazard as soon as possible based on the hazard's ranking.

In Nevada, the BLM has delegated AML remediation on BLM lands to the state. Before the state can do any remediation work on BLM land, however, the appropriate BLM field office must approve an "Authorization to Secure" form.

If work on BLM lands involves backfilling mine openings, then cultural and biological issues must be addressed. This involves the State Historic Preservation Office (SHPO), and wildlife specialists to study such topics as bat habitat in underground workings.

**South Dakota.** South Dakota levied a fee on active gold mines in the state to fund an inventory of abandoned mines conducted by the Department of Environment and Natural Resources (DENR). This inventory focused on the Black Hills region, specifically, within Meade, Lawrence, Pennington, and Custer counties. The US Forest Service also inventoried abandoned mines on Forest Service land. The inventories located approximately 700 sites on private land and 200 sites on Forest Service land.

The South Dakota DENR has identified three sites in Lawrence County that should be reclaimed: the Minnesota Ridge Mine, the Belle Eldridge Mine, and the Eagle Bird Mine. These three sites are characterized by draining mine tunnels and acid mine drainage, sulfide waste rock piles, and eroding stream side tailings. The DENR has worked with the Forest Service and the EPA on assessment work and cleanup at the Minnesota Ridge Mine, and with the BLM to assess and reclaim the Belle Eldridge Mine.

While the AML inventory has been completed, South Dakota has not yet established a state AML program, nor does it have adequate funds to reclaim the remaining AML sites that warrant further cleanup work.

**California.** California has an Abandoned Mine Lands Program that is part of the state Office of Mine Reclamation. The Abandoned Mine Lands Unit was created in 1997 to prepare a report on the scope and magnitude of abandoned mine lands in California. The report estimated that there were approximately 39,000 historic and inactive mine sites in the state. Further work such as scanning and digitizing mining features from USGS 7.5-minute topographical maps led the Abandoned Mine Lands Program to estimate that there are more than 154,800 mine features in the state. California also compiled a data set of 2,422 mining operations and their potential water quality problems. This data set is known as the Principal Areas of Mine Pollution (PAMP).

Once a probable mine site is located, program staff visit to perform a preliminary assessment. A Preliminary Assessment Ranking (PAR) score, based on observed physical and chemical hazards, is assigned to the mine site.

The sites that present the greatest hazards receive a full site characterization. This involves extensive soil and water sampling, in-depth study of the geology, hydrology, and biology, as well as investigations of wildlife habitat issues. The

full site characterization helps to determine the need and the most suitable approach for abandoned mine site remediation.

Once a decision to remediate an abandoned mine site is made, there are still many questions to be answered such as ownership, responsibility, and liability. A lead agency must coordinate all the remediation work and secure permits and necessary approvals, prepare the California Environmental Quality Act (CEQA) documents, obtain access and right-of-way, and handle all other contingencies. Adequate funding must also be secured.

When an abandoned mine site has been identified, inventoried, and characterized; when ownership, responsibility, and liability issues have been resolved; when a lead agency has been identified; when the necessary permits and approvals have been obtained, and the appropriate CEQA documents have been prepared; and when funding has been secured, actual abandoned mine site remediation can begin. CEQA also requires consultation with appropriate state agencies. These are usually the State or Regional Water Quality Control Boards, the Department of Toxic Substances Control, and the County Public Health Department. For most abandoned mines in the state, the steps described in this section, which may take years to complete, must be followed.

If hazardous substances known to cause cancer are involved in an abandoned mine cleanup, then California's Proposition 65 would require the appropriate notices to be filed.

**Pacific northwest.** Washington has a small coal mining industry and receives limited SMCRA funds. Oregon and Idaho don't have active coal mining operations and therefore don't receive any SMCRA funds. These three states formed a three-way partnership and entered into a compact with the EPA known as the Tri-State Agreement. This allows the three states to accomplish cost effective priority reclamation projects and inventory abandoned mine sites.

**Idaho.** Idaho passed an Abandoned Mine Reclamation Act in 1994 in anticipation of reform of the Federal Mining Law of 1872. It was anticipated that reform of the mining law would, among other things, establish a royalty on production of hard rock minerals from federal lands and that part of those royalties would be put into a new abandoned hard rock mine reclamation fund that would be distributed to the states. Idaho's Abandoned Mine Reclamation Act created a place for those anticipated funds to go and guidelines on how the money would be spent. Reform of the Federal Mining Law never occurred, however.

To put some money in its Abandoned Mine Land fund, Idaho modified its Mine License Tax in 1999. This modification earmarked 1/3 of the state's Mine License Tax for its Abandoned Mine Land program. The State Board of Land Commissioners is responsible for administering the Abandoned Mine Reclamation Act. The agency that carries out the land board's work is the Idaho Department of Lands, Bureau of Minerals.

The Reclamation Act allows the land board to do the following:

- Reclaim abandoned surface, placer and underground mines including milling and processing areas.
- Seal deep mine entries.
- Revegetate affected land to prevent erosion and sedimentation.
- Prevent, abate, treat, and control water pollution created by abandoned mine drainage.
- Control of surface subsidence due to underground mines.
- Enter into contracts and make grants to conduct and promote research, surveys, or training needed to carry out the provisions of the act.
- Prioritize public health and safety over the restoration of land and water resources.
- Coordinate with other state and federal agencies.
- Reasonably compensate other agencies.

Idaho's Abandoned Mine Reclamation Act is a voluntary program. An abandoned mine is defined as "A mine deserted by the operator, having no regular maintenance, and not covered by a valid mining claim." A mining operation eligible for reclamation is an abandoned mine on state or federal land, or an abandoned mine on private land when the owner has requested designation as an eligible mine. Trespassing without the landowner's consent is not authorized, and the Abandoned Mine Reclamation Act also does not require compensation by Potentially Responsible Parties (PRP's). In addition, if an abandoned mine site is over 50 years old, the land board will try to avoid impacts to its historical integrity or to mitigate any impacts.

**Utah.** Utah is a SMCRA state and receives some funding for abandoned mine land remediation from fees on mined coal. Priorities have been set. The priorities for abandoned coalmines are:

- 1<sup>st</sup> Priority – Abandoned mine sites that present a hazard of immediate death.
- 2<sup>nd</sup> Priority – Sites with hazards that could cause death or injury.
- 3<sup>rd</sup> Priority – Sites with environmental hazards.

Under SMCRA Utah can only address 1<sup>st</sup> Priority issues at abandoned hard rock mines.

## **Minnesota**

Minnesota has a unique state agency called the Iron Range Resources and Rehabilitation Agency (IRRR). It was created in 1941 and its mandate is to strengthen and diversify the economy of northeastern Minnesota, specifically, in the Taconite Tax Relief Area. IRRR programs are funded entirely by a tax on the region's taconite mines. The IRRR's Mineland Reclamation Division was established in 1977 and works to reclaim and restore publicly owned lands that have been affected by mining. Its activities in the past have included shaping, sloping, and planting seedlings on mined areas. To support this effort, the division has its own facilities to grow approximately 300,000 seedlings each year. It also has developed recreational areas and lakes with boat docks and



landings in abandoned mine pits and created campsites and built trails for hiking and skiing. The division also ensures the safety of abandoned mine lands by capping mine shafts and stabilizing pit walls. The division accepts applications annually for mineland reclamation projects.

**Interstate Mining Compact Commission**

While not a regulatory agency, the Interstate Mining Compact Commission (IMCC) is of interest because it is a multi-state governmental agency concerned with abandoned mined lands reclamation. The Commission currently consists of 17 member states with three associate member states. The states are officially represented by their Governors who serve as commissioners. The Commission operates through several committees, including an Abandoned Mined Lands Committee, with representatives appointed by each member state Governor.

Among the IMCC’s purposes is the protection and restoration of land, water and other resources affected by mining. It does this through studies, providing grant funds, gathering and dissemination of information, making recommendations, and cooperating with Federal, public, or private entities.

The member states and associated member states are listed in Table 4.

<b>Table 4 Interstate Mining Compact Commission</b>			
<b>Member States</b>			<b>Associate Member States</b>
Alabama	Maryland	South Carolina	New Mexico
Arkansas	Missouri	Tennessee	New York
Illinois	North Carolina	Texas	North Dakota
Indiana	Ohio	Virginia	
Kentucky	Oklahoma	West Virginia	
Louisiana	Pennsylvania		

**Tribal Oversight**

Indian tribes are considered as states by SMCRA and ordinarily a state must have an approved regulatory program for surface coal mining and reclamation before it can manage its own SMCRA Abandoned Mine Land Program. Public Law 100-71, however, authorized the Crow, Hopi, and Navajo tribes to obtain approval from the Secretary of the Interior to manage the AML program on their lands without prior approval of a surface mining regulatory program as ordinarily required by Section 405 of SMCRA. The Crow, Hopi, and Navajo are the only Indian tribes that manage their own AML programs. Table 5 lists other Indian tribes where AML reclamation has been done but who do not manage their own AML programs.

Cheyenne River	Northern Cheyenne	Ute Mountain Ute
Fort Peck	Rocky Boys	Wind River
Fort Berthod	Southern Ute	Zuni
Jicarilla Apache	Uintah and Ouray	

### **Crow Indians**

The Crow Reservation is in south-central Montana adjacent to the Wyoming border. It totals 2,226,000 acres. In addition, the Crow Ceded Area, 1,100,000 acres in size, adjoins the Crow reservation on the north. The Crow Ceded Area was part of the Crow reservation before 1904 but then the Federal Government took the surface rights back and they were eventually acquired by non-Indians. The Crow Tribe retained ownership of the minerals, however, and jurisdiction of Abandoned Mine Land Reclamation Program for the Ceded Area.

All of the funds to support the Crow Tribe's AML program are generated by one active coal mine in the Ceded Area. All accessible high priority areas on the Crow Reservation have been reclaimed. The few remaining high priority sites are on private land in the Ceded Area and the Tribe has been unable to obtain access. The Tribe is concentrating its AML reclamation efforts on low priority areas where it has access. The AML program is a major employer on the Crow reservation. All construction and reclamation work is been done with manual labor and hand tools.

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### **Hopi Indians**

The Hopi Abandoned Mine Land Program has completed its entire coal reclamation inventory and is able to work on Public Facility Projects or Community Impact Projects with its SMCRA funds. Public Facility Projects are priority 4 projects under SMCRA and are a way to mitigate mining related impacts from past and ongoing activity.

The Hopi Tribe consists of thirteen villages on the reservation, located on three mesas called First Mesa, Second Mesa, and Third Mesa. Twelve of the thirteen villages were elected to participate in the Public Facilities Project.

Coal production on the Hopi Reservation is small compared to the Navajo Nation. The Hopi Tribe and the Navajo Nation share equally in the ownership of

all minerals underlying a 1.8-million-acre former “Joint Use Area” and the Hopi AML program is currently funded from its share of proceeds from active mining in the “Joint Use Area.”

The Hopi AML program is currently only considering Public Facilities Projects that qualify for funding under the AML program. The Hopi government determines the project priorities, however, for the Tribe and the individual villages.

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### **Navajo nation**

The Navajo Nation Abandoned Mine Land Reclamation Program is part of the Navajo Division of Natural Resources. In 1994, the Navajo AML Program completed reclamation work on all known priority 1 and priority 2 abandoned coal mines. This cleared the way for the Navajo AML Program to begin reclamation work on non-coal abandoned mines, as well as include Public Facilities Projects. There are quite a few abandoned uranium mines on Navajo Nation lands and the Navajo AML Program finished its entire inventory of non-coal uranium hazards by the end of 2002.

Much of the Navajo AML Program’s work is now concentrated on abandoned uranium mines. In addition to the normal work associated with abandoned mine reclamation, the Navajo AML Program also includes a detailed Health Physics and Instrumentation Monitoring Plan to protect its employees, the public, and the environment from unnecessary exposure to low levels of radiation. More information on the Navajo AML program’s Health Physics and Instrumentation Monitoring Plan can be found in Chapter 3, Health and Safety.

The Navajo AML Program also cooperates with the Navajo Nation’s Uranium Mill Tailings Remedial Action (UMTRA) program.

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# 5 SITE INVESTIGATIONS

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## Background

The objective of site investigation is to locate the source of AMD and to characterize it sufficiently to develop a successful restoration plan. This is not a simple task particularly with underground mines. Towns and mine structures burn down, scrap metal is removed and, particularly in the eastern U.S., vegetation masks the old workings. With underground mines, seeps on a hillside may be the only clue that a mine existed. It is important to understand whether those seeps express an isolated, freely draining 10-acre mine or a 10,000-acre mine complex with a pool of AMD measuring in the hundreds of millions of gallons. There have been cases where excavation of such seeps has resulted in catastrophic release of AMD and contamination of surface waters. Since underground mines are well connected to regional groundwater, they reflect recharge rates over the previous several years. Thus, sampling after a dry period may reveal a very different picture than after 3 years of above normal precipitation. And, of course, there are significant seasonal variations in groundwater levels. Failure to understand the hydrologic regime within the mine may result in AMD control structures that are “high and dry” during dry periods or “swamped” during wet periods.

## Surface history

The distribution of AMD sources has a major bearing on project cost and feasibility. Perhaps the most difficult treatment settings involve numerous, small discharges. In the site investigation, it is important to characterize the distribution of AMD discharges. In general, concentrated discharges are more easily treated due to simplicity of access, ownership, mobilization and logistical issues during construction. Figure 1 indicates typical sources and flow paths of AMD.

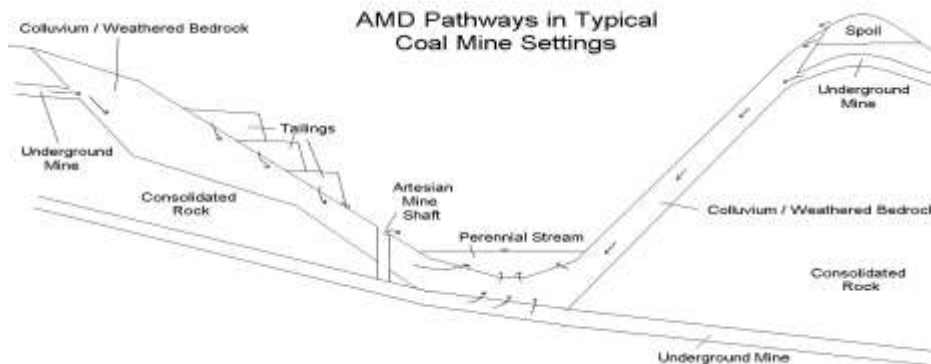


Figure 1. Pathways for AMD to reach streams including shafts, underground mine discharges, surface runoff from tailings or spoils, or seepage upwards into regional water tables.

**Design parameters.** For design purposes, the key AMD parameter is acid load, which is the mass of acidity to be treated. It can be expressed in two ways: 1) dynamically in tons per year as in a flowing stream or 2) statically in tons as in a stagnant underground mine pool or a surface pond. Acid load indicates how much alkalinity would be needed to treat a given volume of AMD. In a flowing stream, volume is given per unit time and therefore the acid load is given over a period of time. In static situations such as pools, it is expressed per unit volume. It is estimated using the formulae:

**Dynamic**

$$\text{Acid load (tons/year)} = \text{flow (gpm)} \times \text{acidity (mg/L)} \times 0.0022$$

$$\text{Acid load (tons/year)} = \text{flow (cfs)} \times \text{acidity (mg/L)} \times 0.9856$$

**Static**

$$\text{Acid load (tons)} = \text{volume (gal)} \times \text{acidity (mg/L)} \times 4.16383 \times 10^{-9}$$

$$\text{Acid load (tons)} = \text{volume (ft}^3\text{)} \times \text{acidity (mg/L)} \times 3.11485 \times 10^{-8}$$

The same formulas can be used to estimate alkaline or metal loadings.

Acid load determines how many tons of limestone or other alkaline agent must be purchased for the project and how long it will last until acid neutralization consumes it. Therefore, while other parameters are important, the site investigations must focus on AMD flow and acidity.

One of the goal of ecosystem restoration is improvement of stream habitat. The primary objective of AMD treatment is to treat the maximum amount of acid at the lowest cost. Secondly, it is necessary to ensure the removal of metal and other soluble contaminants from the water. So, it is fundamental to the project's success that AMD treatments be suitable to treat the bulk of contaminant reaching the target stream. Many AMD projects failed because they focused on obvious discharges which were, nevertheless, minor contributors to the stream's AMD load, when other discharges not seen introduced the largest contaminant loads to the stream. Figure 1 shows the pathways by which AMD can enter a stream. Many, such as bank seepage and upwellings in stream channels, are not obvious yet they may constitute 80% of the AMD reaching the stream. Failure to recognize their importance will result in a failed project because the designer did not account for the extra contaminant load.

In the following section we will discuss how a good site investigation will allow planners to maximize the potential for success.

### **Mining history**

Mines are complex structures and a single property might have been mined by several operators using different methods under a variety of regulatory and reporting requirements. Underground mining properties that began as low

volume, hand-mining operations in 1900 might have evolved into large, highly mechanized mines by the 1950's. Or, several previously isolated underground mines might have become connected after pillar or barrier failures. In some cases, active mining operations have established "cut throughs" to channel water away from the working faces via older mines. Generally illegal now, this practice was common in the recent past. As a result, vast underground mining complexes are frequently interconnected, allowing formation of "pools" which rise and fall as a single unit.

Therefore, it is useful to not only understand the history of the mine with the target discharge but surrounding mines that may be hydraulically connected. Due to their enormous volume, underground mine complexes and deep open pits can take years to reach equilibrium flooding levels and some may not reach equilibrium because of frequent and dynamic inputs and outgoes of water.

The following historical data are useful in characterizing a mine property:

**Mine maps.** Maps are perhaps the most useful and most difficult pre-mining information to access. Late stage production maps are best but any maps can be useful and informative. Often mapped at 1:100 or 1:200 scale, they show structure contours, main haulage corridors, pillars, openings (portals), shafts and void spaces. Mine maps are sometimes found in state offices, company offices or within abandoned buildings on the property. They are extremely useful for guiding the pre-project drilling for mine water quality sampling. They also help guide survey teams toward down gradient openings where AMD discharges are most likely to be found. Mine maps also indicate where workings pass under streams and where upwellings may occur.

**Type of mineral deposit.** Coal, lead, zinc, copper etc.

**Geological information.** Often available from USGS, may include ore body maps, descriptions, geologic columns, and a discussion of associated rock.

**Processing wastes.** If refuse or tailings are present on site, are they pyritic? Are cyanide heap leach pads present on the property?

**Ore body or seam extracted.** Nearly all mineral deposits are named. Often mines within the same seam/ore body share many common characteristics.

**Host rock/overburden.** What types of rock are or would be expected to be found in the spoil piles and surrounding the mined-out ore bodies?

**Mining method.** Was this a surface or underground mine? Was it mined by room and pillar, longwall, stope, shaft methods, etc.? In the absence of mine maps, this may be the only way to understand the direction of groundwater flow within the mine.

**Volumes extracted.** This will indicate how much void is likely to be in the mine that can be correlated with the mine maps and area of the mine.

**Dates of operation.** While coal mines are rarely reopened, hard rock mines are frequently opened, closed, and reopened in response to market conditions.

**Post-mining history.** This should indicate the nature of any post-closure work done at the mine. It should describe reclamation work, shaft and portal sealing, and locations of seals. This sort of information should be on file in state land management offices.

### **Photographs**

Photos can be very useful in developing presentations and in locating structures such as tailings ponds, portals and shafts, which may have been obliterated by later work. Securing photos of the mine can almost be as important as mine maps.

## **Initial Evaluation**

The objective of the initial site evaluation is to identify the potential for a successful project on the site, treatment locations, treatment options and approximate costs. To address these issues, it is necessary to locate the sources of AMD, measure their volumes, flows and chemistry.

### **Phase I watershed evaluation: Locating the sources of AMD**

Finding and characterizing every potential source of AMD in a watershed can be time consuming and the effort and cost constraints may hinder the identification of every source. Sampling and chemical analysis are the major costs. Locating and sampling the sources of water involves significant labor and the analysis of those samples can incur significant laboratory charges. Steps can be taken, however, to improve the efficiency of the process. This process relies on clues that enable the samplers to focus on stream segments that have the highest probability of contributing to AMD pollution. Neither clue requires laboratory analysis.

A two-phase sampling approach is recommended. In Phase I, a crew walks the mainstem with a hand-held pH/conductivity meter. Readings are taken above and below each tributary or major seep enters the mainstem. The intersections of the tributary or seep with the stream can be called nodes. At intersections (nodes), readings are taken 100 feet downstream of the node (D or downstream) and 25 feet upstream in the mainstem (U or upstream), and reading should be taken in the tributary or seep (T or S) before they enter the mainstem. If the mainstem readings change dramatically between two sampling points, an AMD source has been discovered.

**Clue 1. Metal Staining.** Most AMD metals precipitate to form characteristically colored sediments. Table 6 gives the color and pH at which precipitation occurs. The field reconnaissance team will look for turbidity or streambed precipitates of the colors given to indicate where acid water (where the

metals are soluble) meets more alkaline water. If ferric iron ( $\text{Fe}^{3+}$ ) is present, it often will mask or obliterate colors of the other precipitates, particularly if stream pH rises quickly. If stream pH rises gradually, then a zone of white aluminum precipitation may be miles downstream of the orange iron precipitation zone. The presence of these colors is an important indicator for acid or metal inputs into mainstems from tributaries or seeps.

<b>Table 6</b>			
<b>Precipitation behavior of common metal ions in AMD treatment. The flocs are expressed as hydroxides for simplicity, though they may be a mixture of various oxyhydroxide forms.</b>			
<b>Metal Ion</b>		<b>pH and Chemistry of Flocc Formation</b>	<b>Floc Color</b>
$\text{Al}^{3+}$	>4.2	$\text{Al}(\text{OH})_3$	white
$\text{Cu}^{2+}$	>6.0	$\text{Cu}(\text{OH})_2$	blue
$\text{Fe}^{2+}$	>9.0	$\text{Fe}(\text{OH})_2$	green
$\text{Fe}^{3+}$	>3.0	$\text{Fe}(\text{OH})_3$	orange
$\text{Mn}^{2+}$	>9.5	$\text{Mn}(\text{OH})_2$	white
$\text{Mn}^{4+}$	>5.5	$\text{Mn}(\text{OH})_4$	Black

\* oxidation to  $\text{Mn}^{4+}$  requires either microbial mediation (a slow process) or high pH (>9.5).

$\text{Fe}^{2+}$  and  $\text{Mn}^{2+}$  only precipitate at pH ranges which rarely occur under natural conditions, so their precipitates are generally only seen at chemical treatment facilities. AMD rich in  $\text{Fe}^{2+}$  is often seen discharging from underground mines. This water may come out of the mine clear and with pH of 6.2. On exposure to the atmosphere, precipitates will form and the water will quickly turn orange. Depending on how much alkalinity is present, the color change may be accompanied by a drop in water pH.

**Clue 2.** pH and conductivity readings. Metal concentrations will not always be sufficient to cause visible staining. So, the use of a combined pH/electrical conductivity meter will indicate chemical changes across this boundary and, as pH decreases, conductivity will increase. However, as AMD is neutralized by alkalinity in the receiving stream, the pH will increase back to the neutral range while leaving elevated electrical conductivities. A change in field pH of 1 unit would be considered significant as would an electrical conductivity reading of 500 micro S/cm above background levels (typical clean water in the region).

Where clues 1 and 2 indicate AMD input, take a water sample upstream, downstream and in the tributary or seep. These sampling stations are flagged or marked and a GPS reading is taken and recorded. The GPS location will facilitate developing the watershed map and properly identifying the location of all sampling stations. Following acid tributaries upstream will lead to AMD sources.

This procedure focuses the sampling effort on the most significant AMD sources, which can save time and considerable money. Phase I sampling should



be completed within one week. At the end of phase 1, the project design team should have the following:

- Mapping
- Stream quality
- pH, acidity, alkalinity,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ , Al, Mn, sulfate, electrical conductivity
- As needed: Sb, As, Ba, Be, Cd,  $\text{Cr}^{6+}$ , pH, Hg, Ni, Se, Ag, Tl.
- AMD sources and polluted stream segments
- Watershed map displaying AMD sources and contaminated stream segments

### **Phase II: Identifying treatment sites**

The objective of phase II is to identify, characterize, and prioritize treatment sites. Using the sampling stations established in phase I, a more detailed sampling regime is initiated which includes monthly sampling for a year. Phase I analysis will indicate, based on the project's water quality objectives, which chemical parameters should be included in further sampling. In phase II sampling, it is necessary to estimate the flows at each sampling station at each sampling date. Flow measurements are needed to estimate pollutant loading rates, which are needed to select and size treatment units.

Proportional loading rates are calculated by using the load formula given herein for any analyte expressed in mg/L. It is useful to express the contribution of a given AMD source or at any point in the stream as a proportion of the load that discharges from the watershed. Figure 2 is an example of a watershed analysis that indicates the sampling node, sampling station and an acid load mass balance. In this idealized representation, all of the acid load is accounted for in tributaries and seeps. It is clear that the bulk of acid load enters at stations D1 and D2. A similar analysis would be undertaken upstream in tributary D1 and D2 to locate individual discharges.

In a different analysis, a significant addition of acid load is indicated in Figure 2. Further field work would be needed to identify the source of this AMD. Treatment of the other AMD sources, in this case, will not significantly improve water quality at the mouth of the stream. The remediation plan can then target those sources of AMD and treat or control the water before reaching the main stem.

Simple, arithmetic analyses only work with acidity and alkalinity (alkalinity is expressed as negative acid load). Metal ion concentrations and pH require much more elaborate modeling techniques.

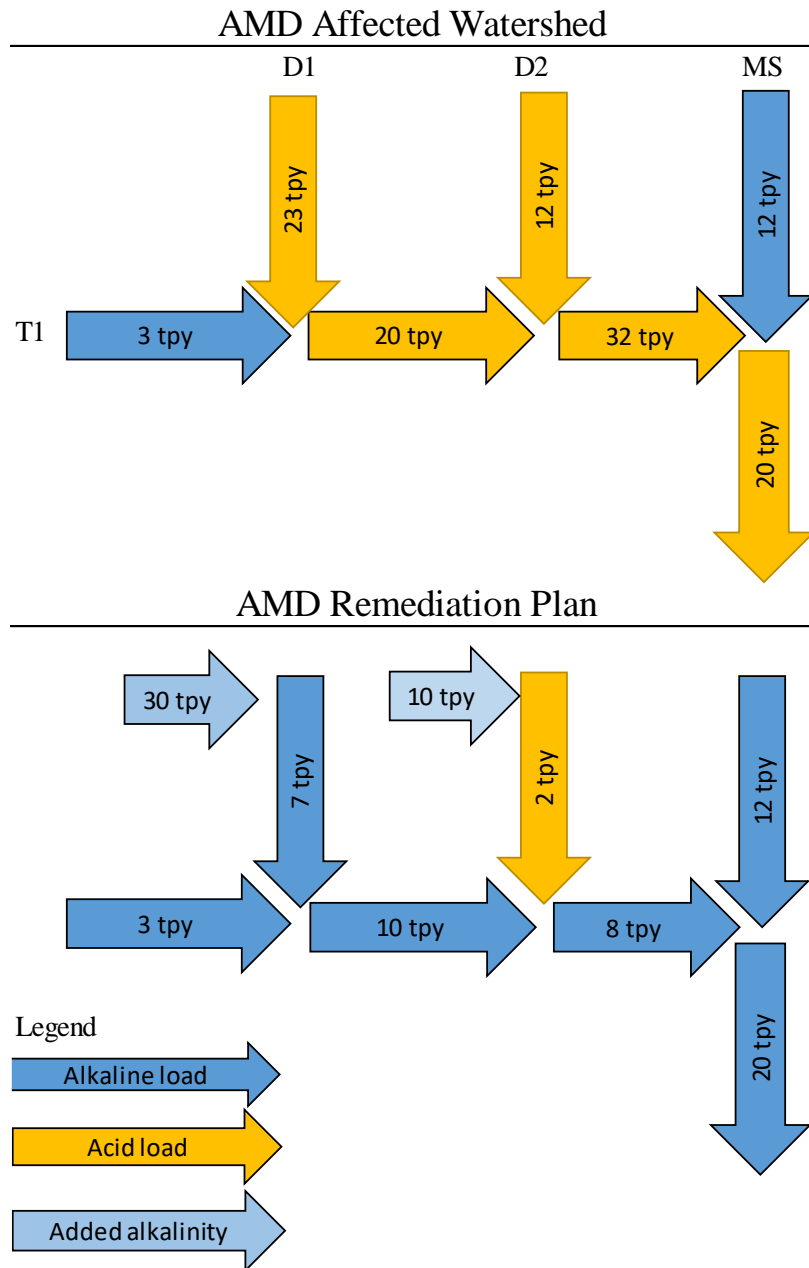


Figure 2. Acid-alkaline loading (tons/year) in an AMD-affected watershed. The upper diagram shows the pre-remediation load balances on the polluted tributary (T1) and the mainstem (MS). The lower diagram shows the effect of adding alkalinity at the two discharges (D1 and D2).

At the end of phase II, planners should have available an analysis which includes:

- Treatment site quality
- pH, acidity, alkalinity, Fe<sup>2+</sup>, Fe<sup>3+</sup>, Al, Mn, sulfate, electrical conductivity
- As needed: Sb, As, Ba, Be, Cd, Cr<sup>6+</sup>, Hg, Ni, Se, Ag, Tl
- Hydrologic survey: Flow, annual cycle, acid-base mass balance
- Prioritization of treatment sites
- Identification of treatment needs

### **HTRW concerns**

(to be filled in at a later date)

### **Geology**

**Lithology.** AMD may be emanating from a varied number of sources within a mine site. These sources often have different AMD-producing characteristics. Some may even be alkaline-producing. AMD may discharge from the mine proper, from waste rock piles, from slurry lagoons, and from heap leach facilities. The site investigator must assess the physical and geochemical potential of each AMD-generating source as well as any potential AMD source that will be disturbed during the reclamation process.

The mine itself, particularly underground mines, are often the most difficult to assess because much of the useful information is largely inaccessible. Key information includes the excavated volume of the mine, volume of water stored in the mine, mine discharge chemistry, pumping rates and discharge outlets, the spatial distribution of the mining, and details of the mining method(s) utilized. In some cases, surface mines are used as access points for underground mines. This situation may not be readily apparent from an on-site survey but may be revealed in mine mapping or mine permitting data.

Unreclaimed surface coal mines may have a number of sources of AMD within the backfill. Particular attention should be paid to rock materials with a dark color, particularly black shales. Pyrite is often associated with these dark materials. Sandstones have been known to produce acid but as a generalization they tend to have low pyrite content. Weathered materials, often identified by the colors red yellow or orange, have little to no pyrite left in them as it has all been oxidized prior to the mining operation. Particular attention should be paid to rock layers just below the coal seam. This layer is called the under clay, pavement, bench, or alternatively the seat earth. This layer has frequently been the source of AMD at coal mines and should be evaluated with chemical analysis.

Coal cleaning plant reject material (course or fine refuse) is occasionally placed into the mine backfill. This reject material is often enriched in pyrite and can cause an otherwise benign backfill to produce AMD. It is important to

identify weather coal-cleaning plant reject was placed in the backfill, how much, and at what locations.

Open cast mines for ore minerals are usually not backfilled because the ore body is not a flat lying seam that can be extracted and have the overburden replaced on the underlying material. Rather, the mine must continually enlarge the pit diameter in order to mine at greater depths and widths.

Many metal ores occur as sulfides or are associated with sulfide mineralization. The near surface portions of these ore deposits may have undergone weathering prior to being mined. This oxidized portion of the ore deposit is unlikely to produce AMD because all of the sulfide minerals have already been oxidized. As the mining continues deeper into the ore body, the ore will transition from an oxide-mineral phase to a sulfide-mineral phase. It is at this point that the AMD potential increases. The site investigation should try to identify if these two phases are present and if so how they were handled. For example, was the oxidized rock used to form a base for placement of the potentially acid-forming material? This practice would help keep the acid-forming material above the level of ground water, which would be very useful in designing a remedial action.

## Hydrology

**Surface runoff.** The potential to divert uncontaminated surface runoff from the site should be identified. At surface mines and around surface facility areas, diversion ditches may be non-existent or breached. All locations where surface runoff can be diverted from contacting acid-forming materials should be identified. This applies to underground mines as well. Surface collapse features can divert surface water into the mine, which will increase mine water treatment volume. Similarly, the loss of stream water flow may be a source of infiltration into the mine. The extent of vegetative cover of the upstream slopes should be noted. Good plant ground cover can limit water inflow to the acid-forming materials.

Surface water exiting the facility may be causing excessive erosion and potential flooding. The site investigator should note these conditions for inclusion in the reclamation plan. If possible, high water marks, and approximate channel roughness coefficients should be determined so that stream flow can be estimated.

The most frequent cause of error in determining annual pollution loads, and hence, errors in reclamation design, is the poor estimation of flow at mine sites. In order to improve this estimate and to measure seasonal flow variations, it may be advantageous to deploy more sophisticated surface water measurement techniques. Stream flow measurements can be made using the area velocity method or a primary flow-measuring device, such as a weir or a flume. On smaller streams, weirs and flumes are inexpensive to construct and can provide greater accuracy than the area velocity method. Weirs can be made of easily accessible materials but suffer from blockage by sediment and debris. H-flumes are quite useful because they are capable of reading 1 / 1000 of their peak flow

rating while more effectively passing sediment and debris. Both structures can be instrumented for continuous recording of water level so that complete hydrographs can be obtained. A recording rain gauge may also be needed if the site is not close to an existing station.

The United States Geological Survey (USGS) maintains a nationwide stream gauging network. Most of these sites are on larger streams but some are located in headwater areas. Flow records for USGS sites can be obtained online at <http://www.usgs.gov>. Data from existing stations can be useful for comparative purposes and for projections of what a normal surface water flow would have been at a disturbed site.

Weather records are also available online at <http://www1.ncdc.noaa.gov>. These data include precipitation, temperature, and deviations from the 30-year averages. There is usually a small fee for accessing data at this site.

**Ground water.** Ground water contamination can be a significant problem at abandoned mining sites. One way to tell if ground water is contaminating a stream is to see an increasing contaminate load without direct surface water load contributions. Springs may also be observed near water courses. Contaminated spring discharges often exhibit colorful staining. Sometimes, the water is sufficiently acidic that the discharge appears clear, therefore field pH testing and sample collection are needed.

Ground water contamination may not be apparent at the surface. Ground water can travel underground through alluvial sediments or through fractures for significant distances before emerging.

Ground water monitoring wells are often the only method of identifying ground water contamination. The location and number of monitoring wells required to evaluate a site will depend on the site geology as well as the nature of the contaminant.

Conceptual ground water flow models are very useful in designing a monitoring well network. In many sedimentary geological settings where there is vertical topographic relief, stress relief fractures are often present. These fractures are usually the principal aquifers in the system. This flow system is dominated by vertical fractures in the valley side walls that are oriented parallel with the valley axis, along with horizontal bedding plane separations under the valley floor. The flow in this system is from the valley walls to the valley bottom and then downstream beneath the valley floor. Monitoring wells can be placed in this flow path to intercept potential ground water contamination. Because the ground water flow is essentially funneled into the stream bottom, the number of monitoring wells needed in a reconnaissance survey can be reduced.

Most contaminants move with the flow of ground water and this flow direction can be estimated based on topographic and geologic considerations. AMD contaminates are generally expected to flow with the groundwater. However, non-aqueous phase liquids may exhibit significantly different flow

behavior. Non-aqueous phase liquids are divided into two categories, dense non-aqueous phase liquids (DNAPL) and light non-aqueous phase liquids (LNAPL). Examples of these potential mine site contaminants are Perchloroethylene (Perc) (DNAPL) and gasoline and diesel fuel (LNAPL). DNAPLs percolate vertically down through the unsaturated zone because their density is greater than water and continue moving vertically down through the saturated zone. When an impermeable layer is reached, the plume will begin to spread laterally following fractures or the dip of the impermeable layer even if this is different from the ground water flow direction. DNAPLs are particularly difficult to remediate and efforts to develop monitoring wells to identify DNAPL contamination should only be undertaken after evidence of potential contamination is identified.

LNAPLs are more frequent at mining sites. Gasoline and diesel fuel are stored and used in great quantities at some mining sites. Spills can occur at refueling stations, from over filling storage tanks, and from corrosion of underground storage tanks. Oil from large earthmoving equipment is often changed in the field and disposed at that location. Prior to the 1990s, little concern was paid to the fate of this oil. Small spills located well above the water table are often absorbed on rock and soil particles and thus prevented from reaching the water table. Over time, these spills can be degraded by naturally occurring soil bacteria. However, if the spill is larger or it reaches the water table, contamination can persist for many years. Excavation of underground storage tanks and removal of surface tanks will often reveal whether a serious spill has occurred. Once this potential has been identified, a monitoring program can be designed to identify the extent of the plume.

**Impoundments.** Impoundments at mine sites are quite common. Impoundments are used as fresh-water reservoirs, as slurry or slime disposal facilities, as water treatment facilities, and in some cases the mine itself can be considered an impoundment if it contains water above the elevation of local streams. Impoundment failures at mine sites have resulted in the loss of life, property, and environmental values.

Site investigations on mine properties should include dam safety inspections for all mine impoundments with particular emphasis on structures with greater than 20 feet of head. Field investigation should include the location of springs seeps and boils; identification of land slips in the dam itself or in the slopes above the impoundment; and the integrity and availability of the primary and emergency spillways. Standard dam inspection techniques should be employed.

Unlike modern earth fill dams, mining impoundments may have hidden design problems that can lead to failure of the structure. These include mining underneath or adjacent to the impoundment, up-stream construction, and construction with materials that have low cohesive strength. If records are available, then the construction design should be evaluated to determine if an acceptable factor of safety has been achieved. In the absence of records, a stability analysis may be required in order to assure impoundment stability.

Elimination of impoundments is frequently a goal of a site reclamation strategy. However, impoundment elimination may not be the best course of

action. If the impoundment contains acid-forming materials, dewatering of the structure may cause a significant increase in acid formation resulting from the exposure of the acid-forming materials to oxygen. Alternatively, if a stable impoundment is available, it could be used for the underwater disposal of acid-producing materials. Extensive work by the MEND program in Canada has shown that sub-aqueous disposal is the preferred alternative for preventing acid formation. This is particularly true when there is little alkaline-producing material in the vicinity of the reclamation site.

### **Water quality targets**

**Receiving stream standards.** Point source discharges from mining sites are regulated under the Clean Water Act (CWA) and its various amendments. Best Available Technology Economically Achievable (BAT) and the New Source Performance Standards (NSPS) are the technology-based standards established by the CWA as the most appropriate means available on a national basis for controlling the direct discharge of toxic and non-conventional pollutants to navigable waters. BAT and NSPS effluent limitations, in general, represent the best existing performance of treatment technologies that are economically achievable within an industrial point source category or subcategory. BAT and NSPS have been developed for coal, mineral, and ore mining sub-categories and these standards have been adopted by the various state agencies as they implement the federal program. Coal mining standards can be found at 40 CFR part 434. Mineral mining standards can be found at 40 CFR Part 436 and Ore mining and Dressing can be found at 40 CFR 440. These regulations can be downloaded at <http://www.epa.gov/docs/epacfr40/chapt-I.info/subch-N.htm>.

### **PART 434--COAL MINING POINT SOURCE CATEGORY BPT, BAT, BCT LIMITATIONS AND NEW SOURCE PERFORMANCE STANDARDS**

### **PART 436--MINERAL MINING AND PROCESSING POINT SOURCE CATEGORY**

<b>436.20</b>	<b>Crushed Stone</b>
<b>436.30</b>	<b>Sand and Gravel</b>
<b>436.40</b>	<b>Industrial Sand</b>
<b>436.50</b>	<b>Gypsum</b>
<b>436.60</b>	<b>Asphaltic Mineral</b>
<b>436.70</b>	<b>Asbestos &amp; Wollastonite</b>
<b>436.100</b>	<b>Barite</b>
<b>436.110</b>	<b>Fluorspar</b>
<b>436.120</b>	<b>Brine Lakes</b>
<b>436.130</b>	<b>Borax</b>
<b>436.140</b>	<b>Potash</b>
<b>436.150</b>	<b>Sodium Sulfate</b>
<b>436.180</b>	<b>Phosphate Rock</b>
<b>436.190</b>	<b>Frasch Sulpher</b>
<b>436.220</b>	<b>Bentonite</b>

<b>436.230</b>	<b>Magnesite</b>
<b>436.240</b>	<b>Diatomite</b>
<b>436.250</b>	<b>Jade</b>
<b>436.260</b>	<b>Novaculite</b>
<b>436.310</b>	<b>Tripoli</b>
<b>436.380</b>	<b>Graphite</b>

**PART 440--ORE MINING AND DRESSING POINT SOURCE  
CATEGORY**

<b>440.10</b>	<b>Iron Ore</b>
<b>440.20</b>	<b>Aluminum</b>
<b>440.30</b>	<b>Uranium, Radium, Vanadium</b>
<b>440.40</b>	<b>Mercury</b>
<b>440.50</b>	<b>Titanium</b>
<b>440.60</b>	<b>Tungsten</b>
<b>440.70</b>	<b>Nickel</b>
<b>440.80</b>	<b>Vanadium</b>
<b>440.90</b>	<b>Antimony</b>
<b>440.100</b>	<b>Copper, Lead, Zinc, Gold, Silver, &amp; Molybdenum</b>
<b>440.110</b>	<b>Platinum</b>
<b>440.140</b>	<b>Gold Placer Mine</b>

The CWA also requires the states to adopt use-based water-quality standards for all of the streams, rivers, and lakes within their jurisdiction. These “in-stream standards” are designed to support and maintain the use for which the water body has been designated. Examples include warm-water fishery, cold-water fishery, etc. A state water-quality board establishes standards based on federal guidelines for these designated waters. A separate provision of the CWA provides that point source discharges may not cause a receiving water body to exceed its water-quality standard. This circumstance arises when the mine discharge volume is large in comparison to the stream flow. Consequently, mine discharge locations in headwater streams frequently will cause the stream to exceed water-quality standards. In these circumstances, the NPDES permit will be issued with the in-stream water-quality standards as the discharge limit.

**303(d) listing.** The CWA requires states to periodically evaluate the water bodies in their jurisdiction in order to determine if the water body complies with the applicable in-stream water-quality standards. If the water-quality standard is exceeded (generally greater than 10% of the time, this varies by state) then the state is required to report these water bodies to EPA on the “303(d) list.” Based on this list, the state is then required to generate a Total Maximum Daily Load (TMDL). 303(d) status can be determined from the state’s water-quality agency.

**Total maximum daily load (TMDL).** Total maximum daily loads are developed by the regulatory authority for those water bodies that are listed on the 303(d) list. The purpose of the TMDL process is to identify those pollutant loads that are coming from point sources, non-point sources and from natural sources. These loads are then scheduled for reduction with the goal of achieving



compliance with the in-stream water-quality standards. Natural sources of pollutant loading are grouped with non-point sources under the phrase “Load Allocation” and all point sources are grouped under the term “Waste Load Allocation.” The various contributions to the watershed pollution load are then scheduled for reduction. The load allocations are reduced using non-permitting techniques such as Best Management Practices (BMP) or through AML reclamation. Waste load allocations are achieved through the use of more stringent permit limits. These new lower limits are applied at the time the NPDES permit is renewed.

If the site that is to be reclaimed is located on a stream that has an existing TMDL, the discharge limits for that site will be determined within the context of the TMDL process. Similarly, if the receiving stream is on the 303(d) list, the future discharge limits from the site may not be fully established until the TMDL is developed.

### **Establishing the ground water sampling network**

**Parameters.** Ground water samples at mining sites are often analyzed for only the common AMD parameters of pH, specific conductivity, acidity / alkalinity, iron, aluminum, manganese, and sulfate. However, based on ore that was mined, additional parameters may be added to the list. For example, at a massive sulfide mine, arsenic, copper, lead, nickel, and zinc may be needed to complete the chemical characterization of the ground water.

The appropriate parameter list can be determined through evaluation of any existing records, consultation with any regulatory authorities, and if needed a analysis of the initial water samples collected at the site. This list may include the inorganic priority pollutants plus any organic contaminants that are suspected of being present. Parameter lists may be found in the Code of Federal Regulations (CFR 122 Appendix D Tables II, III, IV, V).

It is often important to determine the amount of dissolved oxygen (DO) present in the ground water, particularly from underground mines. This can give the investigator insight into the availability of oxygen in the mine environment. DO is a sensitive parameter to measure because any sample taken will quickly absorb oxygen from the air while the DO measurement is being made. This means that DO samples must be collected prior to contact with the atmosphere and analyzed without air contact. This can be accomplished by pumping the sample through a cell that contains the DO probe.

The state of iron oxidation is frequently important in designing a treatment system. Both total and dissolved iron should be determined. This requires field filtration of the dissolved sample with a 0.45 µm filter. Both samples should be field acidified with hydrochloric acid to prevent oxidation in transit to the lab.

**Methods.** There are two methods of obtaining ground water samples. The first is through the sampling of springs or mine discharges, and the second is through ground water extraction through wells or other openings such as mine shafts or abandoned boreholes. Mine discharge samples are particularly

important in understanding the hydro-geochemistry of the mine. These samples can be used to determine the acid load that will require treatment.

Samples from wells should be pumped so that a representative sample can be obtained. Mine water that is stagnant can undergo a process called stratification. In this process, the dissolved metals and acid sink to the bottom of the shaft or borehole or mine pool. Samples that are bailed from the surface appear to be better than the actual concentration. Borehole and shafts should be pumped until the specific conductivity of the water stabilizes. If specific conductivity is not available, then at least three well volumes should be pumped before the sample is collected.

**Locations.** Choosing locations for monitoring wells is largely dependent on the purpose of the monitoring well. Well location can also be dependent on the target pollutant. For example, dissolved pollutants are expected to flow with the ground water, however, DNAPLs may flow with the dip of the rock or the presence of fractures at the base of the aquifer. Will the well be used as part of a reconnaissance survey, will it be used to facilitate a remediation strategy, or will it be used for permit compliance? The construction and location of monitoring wells is often dependent on its intended purpose. That said, there are a number of typical settings where monitoring wells are often used.

Mine discharges are the first priority in understanding the hydrology of the mine. Both flow and water quality data are necessary to understand the scope of the problem. The discharge may be occurring as an identifiable flow from an old mine opening or it may be discharging directly to a ground water flow system that is only known from contaminated wells or streams. If a mine discharge is present, it is often the easiest point of ground water data acquisition.

In long abandoned underground mining operations, there is a high probability that the mine is currently discharging somewhere. This discharge may be to surface water, ground water, or to an adjacent mining operation. These mine discharges represent an inflow-weighted average water quality that is a function of the location of the dominant recharge flow paths. In large underground coal mines, the high inflow areas tend to be in shallow cover areas that are often close to the discharge resulting in localized dilution of the AMD in situ. Large open pit mines can serve as funnels directing rainfall into any underground mines that may be present. These high inflow areas can establish an identifiable flow path through the mine, and they can also dominate the discharge water quality. Wells and boreholes that are not located in the primary flow path(s) can, and frequently do, generate water quality data that are not representative of the present or future discharge water quality. Consequently, predicting discharge water quality, while the mine is still flooding is highly questionable.

Anticipating the ground water flow direction is a significant advantage in locating monitoring wells. Ground water flow frequently, but not always, mimics the surface topography; consequently, if the land slopes downhill the ground water will often flow in the same direction. While this is frequently the case, mining is one of the circumstances that can cause ground water flow to deviate from the norm.

Stress Relief fractures can exert a significant influence on ground water flow when they are present. These fractures occur when erosion has removed the weight of overlying rock as in valley settings. The removal of this stress results in vertical fractures in the valley walls that are oriented parallel to the valley axis. This stress removal also results in horizontal bedding plan separations beneath the valley floor. In the eastern coal fields, stress relief fractures are the dominant control on the flow of ground water.

Surface mine spoils and waste rock piles may contain contaminated ground water. Drilling within these materials is often difficult due to well collapse. Drilling techniques such as mud rotary or reverse circulation may be needed in order to complete the hole. Discharge from these facilities is often at the point of lowest elevation where the waste material meets the original land surface. However, ground water contamination can extend down-gradient of the disposal site within the alluvium, or the primary or secondary porosity of the local rock units.

If direct ground water contamination is suspected, then a preliminary geophysical survey may be indicated. Acidic mine drainage is often more conductive than the local ground water. This conductivity difference can be used to map the extent of the ground water plume. Terrain conductivity surveys can be used to generate a conductivity profile map. Resistivity surveys may also be used but these are often more time consuming than the conductivity survey. Once completed, these surveys may be used to optimize the placement of monitoring wells.

**Duration.** Monitoring wells vary in the length of time that they are needed. Reconnaissance monitoring may be short term while compliance monitoring may last for decades. Similarly, wells used in various treatment strategies will vary in length of operation based on the treatment methodology employed.

# 6 DEVELOPING THE REMEDIAL STRATEGY

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## Remedial Action Objectives

Assessments of project success or failure will be based on achieving the remedial action objectives. Therefore, objectives must be carefully formulated and presented to the public and project partners. Objectives should be:

### Realistic

Objectives must be well within the range of the achievable.

### Risk control

This includes minimizing uncontrollable risk. Since AMD control systems are expected to perform for 10 to 20 years, they will be subject to extraordinary events at various times. It is important to design systems so that they are less vulnerable to such events. Systems that are designed for optimal conditions will quickly fail. Risk, is controlled by the following factors:

**Complexity.** In AMD treatment, simplicity reduces risk. Simplicity means replacing things that can fail or plug up: e.g. replace pipes with things that are less failure prone such as ditches.

**Maintenance.** Any component of the system that requires regular attention induces additional risk. Power requirements, chemical resupply, valve adjustments, and pond cleanout are factors that increase the potential for failure due to inattention or poor access due to weather.

**Location.** Given a choice, it is less risky to build an AMD treatment structure at the source of discharge rather than in a stream channel or flood plain. Washout or debris can destroy a system or require costly repairs. On the other hand, it is less expensive to build few, large treatment units where AMD can be collected rather than many, isolated units.

**Vandalism and theft.** Most AMD treatment systems are placed in remote, unsecured settings. Simple and robust designs will suffer less than complex, fragile systems with valuable components.

**Power.** Power is often problematic in remote locations. Systems requiring permanent pumps, aerators and electrical-powered chemical dosers should only be set in locations where year around access is assured and security can be maintained.

**Access.** Siting a treatment unit is often a compromise between optimal benefits and optimal costs. Access costs will be a significant portion of the total project budget and every attempt should be made to locate treatment units near existing roads and in locations having adequate working space. Year-round access is more important for chemical dosing systems that require regular charging and maintenance.

### **Evaluation criteria**

Ecosystem restoration projects are fundamentally construction projects. Construction project management includes well-established evaluation criteria: schedule, costs, equipment, personnel, and quality control, etc. In addition, these projects will be evaluated by the local sponsors in the context of meeting community goals. For example, the treatment plan may involve a series of units that are designed to remove only a portion of the acid load from several AMD sources. While they may discharge low pH water, the cumulative acid load reduction may permit re-establishment of a fishery at a point well downstream. This 'control point,' not the discharge from each treatment unit, needs to be accepted and understood by the community as the site where ecosystem restoration benefits are to be realized. It is critical to achieve consensus on evaluation criteria and to re-enforce those criteria in project related communications. One should consider the following when developing project evaluation criteria.

**Popular.** Chemical stream water quality criteria rarely capture the public imagination. While treatment unit design is based on flow and water quality, many of the watershed stakeholders will be interested in establishing a fishery. So, it is important to establish, early in the planning process, the criteria by which the community will judge the success of the project by visible and easy discernable results.

**Measurable.** Evaluation criteria should be easily measured and understood by the community. They can range from the biological to the chemical. Most commonly, the stakeholders are convinced of the project's success when a fishery is established downstream of the control point or the color of the stream is clear rather than contaminated.

**Finite.** Projects have a finite service life. The service life of passive treatment systems is poorly understood but generally range from 10 to 20 years. Nonetheless, it is important to identify the rate at which servicing, rebuilds, or rehabilitation are expected. This will allow the local sponsors to evaluate their ongoing maintenance and operating responsibilities prior to signing the project cooperation agreement.

# General Response Actions

## Treatment alternatives

Watershed remediation has many stakeholders each with a vision of the project outcome. It is critical to meet early and often with local sponsors and stakeholders to achieve a very clear understanding of their expectations and to articulate a project outcome that satisfies those needs within the constraints of budget, time and technology. It is also important to recognize that AMD treatment under field conditions is not an exact science. Flows vary seasonally and over multiple-year cycles. Pollutant concentrations also vary. Where possible, it is useful to phase in treatments until water quality targets are achieved. Otherwise, the tendency is to over build the systems. The following checklist will help in rationalizing the sampling process to focus effort on maximum information gain while simplifying the process of selecting treatment options. The first two phases of this process were discussed in greater detail in the previous chapter.

Phase I Watershed Evaluation: This represents the initial watershed sampling. Often, the local sponsors invest considerable effort toward water sampling prior to Corps involvement. Collation of this information, along with data QA/QC is an important initial step. Phase I identifies the total pollutant loads in the watershed and the proportion contributed by each source. This highlights the ‘hot spots’ in the watershed and helps to focus more intensive follow-on sampling in Phase II.

- Mapping
- Stream quality
  - \*pH, acidity, alkalinity,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ , Al, Mn, sulfate, conductivity
  - \*As needed: Sb, As, Ba, Be, Cd,  $\text{Cr}^{6+}$ , Pb, Hg, Ni, Se, Ag, Tl
- Hydrologic survey:
  - \*Flow, annual cycle, mass balance
- Identify high load stream segments:
  - \*Display high load stream segments on watershed map

Phase II Site Evaluation: While Phase I sampling indicates the priority pollutant sources in the watershed, Phase II sampling characterizes them to allow for treatment system design.

- Treatment site water quality
  - \*pH, acidity, alkalinity,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ , Al, Mn, sulfate, conductivity
  - \*As needed: Sb, As, Ba, Be, Cd,  $\text{Cr}^{6+}$ , Pb, Hg, Ni, Se, Ag, Tl
- Hydrologic survey:
  - \*Flow, annual cycle, mass balance impact
- Prioritize treatment sites
- Identify treatment needs
  - \*Alkalinity, oxidation, metal floc handling

Phase III Identify Treatment needs. Evaluation of Phase II data allows development of initial designs and costs. This will be the first opportunity to present project alternatives to the local sponsors. The following questions will be addressed during Phase III:

- Is alkalinity required?
  - \*Quantity needed (tons/year)
  - \*Alkalinity options
    - Limestone
    - Steel slag
    - Kiln dust
- Is oxidation required?
  - \*Fe<sup>2+</sup> load (tons/year)
- Is floc removal needed?
- Amount of floc handling needed (tons/solid/year)

Phase IV Treatment technology selection. -The following decision table will help to identify treatment needs and their cost implications.

<b>Table 7 Decision Table</b>						
Decision	Site Criteria		Treatment Options	Residence Time	Max. Output	Cost
Add alk.	Fresh Water?	Yes	Limestone Leachbed	11 hrs.	70mg/L alkalinity	\$50-\$100 /ton/yr*
		Yes	Steel Slag Leachbed	1-3 hrs.	2,000mg/L alk	\$50-\$100 /ton/yr*
		No	ALD	11 hrs.	~100mg/L alk	\$50-\$300 /ton/yr*
		No	OLC	5-10 hrs.	50-95% acid load removal	\$50-\$150 /ton/yr*
		No	Flushable Limestone Leachbed	1.5 hrs. max	50% acid load removal	\$50-\$300 /ton/yr*
Oxidize	Slope > 10%	Yes	OLC	.25 hrs.	Oxidation	\$40-150 per/ft
(Continued)						
*dollars per ton of acid load removed per year						

<b>Table 7 (Concluded)</b>						
<b>Decision</b>	<b>Site Criteria</b>		<b>Treatment Options</b>	<b>Residence Time</b>	<b>Max. Output</b>	<b>Cost</b>
		No	Aerobic Wetland	1-2 hrs.	Oxidation	\$5000 /ac.ft.
Settle Floccs	Slope > 10%	Yes	OLC	4-6 hrs.	99% removal	\$40-150 per/ft
		No	Aerobic Wetland	35-80 days 500t Fe/ac/yr	99% removal	\$5000 /ac.ft.
*dollars per ton of acid load removed per year						

If one year after construction and commissioning, the system meets water treatment expectations then the design and construction process is complete. Otherwise, return to Phase II above.

## Critical Parameters in Watershed Planning and Remediation

The following parameters are critical in assessing design needs of an AMD remediation project:

### pH

- Hydrogen ion concentration

### Acidity (mg/L)

- Concentration of base needed to neutralize a volume of water
- $50 \times ((V_o \times ([Me_1]/A_1)) + (V_o \times ([Me_2]/A_2 + \dots + (1000 \times 10^{-pH}))$
- Where:  $V_o$  = valence at treatment oxidation state  
 $[Me]_{1 \text{ to } n}$  = metal ion concentration (mg/L)  
 $A_{1 \text{ to } n}$  = atomic weight of metal ion
- Acidity is given in mg/L (Calcium Carbonate Equivalent)
- Flow: gallons per minute (gpm)/449 = cubic feet/second (cfs)

### Acid load

- Mass of base needed to neutralize a given mass of acid
- Based on concentration (mg/L) and flow (gallons per minute (gpm)/449 = cubic feet/second (cfs)



\*Dynamic:

$$\text{flow (gpm)} \times \text{acidity (mg/L)} \times 0.0022 = \text{tons/year}$$

$$\text{flow (gpm)} \times \text{acidity (mg/L)} \times 0.012 = \text{lbs/day}$$

\*Static

$$\text{volume (ft}^3\text{)} \times \text{acidity (mg/L)} \times 3.11485 \times 10^{-10} = \text{tons}$$

$$\text{volume (gal)} \times \text{acidity (mg/L)} \times 4.16383 \times 10^{-11} = \text{tons}$$

- The same formulas can be used to estimate the mass of alkalinity.

### Mass of chemical

- To calculate the mass of treatment chemical, multiply the acid load by:

CaCO <sub>3</sub>	100%
Ca(OH) <sub>2</sub>	74%
CaO	56%
NaOH	40%
Na <sub>2</sub> CO <sub>3</sub>	106%
NH <sub>3</sub>	17%

### Acid/base mass balance

- Tons of acid – tons of alkalinity = net acid load

### Residence time (T)

- $T_{\text{hours}} = \text{cross-sectional area (ft}^2\text{)} \times \text{length (ft)} \times \% \text{ voids/flow (cfs)} \times 3600$
- Where: Voids = 40 to 50% for rip-rap sized limestone

### Hydraulic considerations

- Many passive treatment systems put AMD in direct contact with limestone.
- Most passive systems fail due to filling of the void spaces with metal flocs.
- Ferric hydroxide flocs will form above pH 3.0 and aluminum flocs above pH 4.2.
- When treating AMD, it is critical to minimize opportunities for floc accumulation to occur in the system. Rather, capture these flocs in settling basins after treatment.

- It is always better to use large dimension limestone (> 6 in.).
- Place a six-inch bed of 0" to 1" crusher run limestone or steel slag below sized limestone.
- Only use crusher run limestone as a bedding material.
- Ensure that there is a good hydraulic connection between the source of AMD and the treatment structure.
- If the AMD can find a way around the treatment structure, it generally will, generally as a result of eventual clogging or plugging.
- With ALDs, avoid discharges with widely varied flows. Low flow periods will create an air space in the ALD, encouraging ferric hydroxide formation. Steady flows work best.
- OLCs operate over a wide variety of flows and chemical conditions.
- Make sure ponds do not LEAK!

### Cost estimation

- Excavation  
\*Cross-sectional area x length /27 x \$3.00 / cubic yard.
- Limestone  
\*Should be between \$15 and \$30 / ton delivered.
- Organics  
\*Vary widely in availability and cost. Straw bales, manure and peat can be used. Where permeability is critical as in a vertical flow wetland, avoid peat.
- Other costs  
\*Access, clearing, reclamation and other items are too difficult to estimate without specific information. Generalizations are not possible.

### Fe sludge formation

- $\text{Fe}^3 + 3\text{H}_2\text{O} = \text{Fe}(\text{OH})_3 + 3\text{H}^+$   
\*56 g/g mole => 107 g/g mole
- Inflow Fe = 1.0 mg/L x 43.53 L/min x (1/1000)g/mg x (1/1000)kg/g x 2/205 lb/kg x 60 min/hr x 24 hr/day = 0.138 lb/day x 107/56 = 0.264 lb/day
- Sludge volume (sludge weight = water weight)
- 0.264 lb/day x (1/62.4) ft<sup>3</sup>/lb = 0.00423 ft<sup>3</sup>/day

### Mn and Al sludge formation

- Use same equation as Fe but correct for molecular weight of Al, Mn, etc.
- Al = 27 g/g mole
- Al(OH)<sub>3</sub> = 78 g/g mole
- Mn = 55 g/g mole
- Mn(OH)<sub>2</sub> = 89 g/g mole

### Alkaline amendment

- Where: A = required amendment (tons)  
W = amount of waste rock: spoil or refuse (tons)  
%S = % sulfur in waste rock  
%NNP = % Net Neutralization Potential  
1.1 = Safety factor

$$A = \frac{W \times \%S \times 3.125}{\%NNP} \times 1.1$$

- Example:
- Where: W = 1,000,000 tons  
%S = 2  
%NNP = 30

$$A = \frac{1,000,000 \times 2 \times 3.125}{30} \times 1.1 = 229,167 \text{ tons}$$

<b>Table 8 Common Alkaline Amendments</b>	
<b>Amendment</b>	<b>Typical % NNP</b>
Limestone fines <1/4"	70-95
Waste lime	70-95
Kiln dust	70-80
Steel Slag <1/4"	60-70
Class C coal ash	10 to 30
Alkaline spoil	1 to 30

### AMD treatment cost vs. change in pH

Many AMD impaired streams have a pH in the range of 2.7 to 5.0. Improvement of stream pH to the neutral range (6.0-7.5) is often seen as the target for remediation projects. Since the relationship between pH and acidity is not linear, neither is the relationship between acid load reductions and pH. It is useful to think in terms of titration of a highly buffered solution. The primary buffers in AMD treatment are ferric iron

and aluminum. Figure 3 (below) illustrates the change in stream pH with increasing investments in acid load reduction. The curve illustrates a flattening of the line between pH 3 and 4 reflecting the consumption of hydroxide ions by  $\text{Fe}(\text{OH})_3$  formation. The slope of the curve also decreases between pH 4 and 5 accounting for the precipitation of  $\text{Al}(\text{OH})_3$ . This has serious implications when dealing with public expectations. In highly impaired watersheds, a great deal of money is normally required before the stream pH will rise into the neutral range. Thereafter, with metal buffering gone, pH will rise with very modest alkalinity inputs.

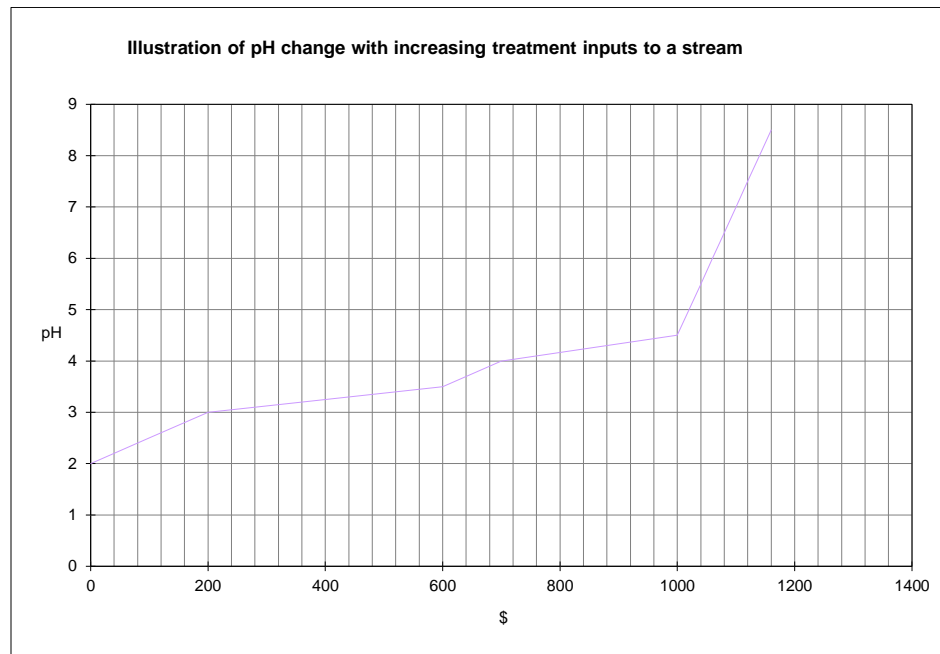


Figure 3

### Source control

The best possible remedial action is one that eliminates the source of AMD entirely. If that is not possible, then the goal should be to design into the reclamation plan as much reduction as possible so that the long term treatment loads, and the long term treatment expense, is minimized.

**Sub-aqueous placement.** By far the most effective method of source control is the permanent sub-aqueous placement of acid generating materials. Studies in the United States and Canada have shown that acid-forming materials that are placed under water generate AMD at such low levels as to not require treatment. In the United States, flooded underground coal mines that once produced metal concentrations hundreds of times the effluent limits are now discharging water that is in compliance with those same limits. In Canada, underwater disposal of

mill tailings has proven to be the most effective method of preventing AMD formation that has been found.

Sub-aqueous disposal is effective because, by generating an anoxic environment, it eliminates the contact of pyrite with oxygen. However, the inundation of the acid-producing material must be complete *and* permanent. Studies conducted at surface coal mines have shown that the most significant acid formation occurred in a zone bounded by the maximum and minimum water table levels. This zone is alternately exposed to oxygen and then rinsed and rewetted by the fluctuating water table.

**Land reclamation.** The simple act of regarding and revegetating a surface mine spoil or refuse pile has been shown to reduce acid loads by up to 90%. A good vegetative cover reduces water infiltration into the fill material thus reducing contact between pyrite and water. In addition, the organic decay of the vegetative cover materials may increase carbon dioxide while at the same time reducing oxygen. This effect, however, is counteracted by the barometric and convective flow of air through the fill material. If oxygen reduction is designed into a reclamation plan, it must be remembered that oxygen does not become rate limiting until the oxygen concentration in the pore gas is reduced to less than one percent.

In designing a dry disposal facility, care must be taken in the use of under drains and spring collector systems. While useful and necessary in maintaining stability of the fill, these systems can also be significant sources of air entrance into the fill material under both convective and barometric influence.

**Mine sealing.** Abandoned underground mines often have openings to the surface. These shafts, drifts, fractures, and boreholes provide an easy access for air to enter the mine. Air flow is driven primarily by convection. The mine maintains a relatively constant temperature. In the summer, air is expelled from the mine at low elevation and it is drawn in at higher elevation. In winter, the flow direction reverses. If the mine cannot be flooded, then it should be sealed to minimize or eliminate this air movement. Mine sealing can be effective in reducing the acid load generated by the mine provided that there is some method of oxygen consumption in the mine. Oxygen consumption is necessary to reduce the O<sub>2</sub> concentration and to compensate for air exchange, such as barometric breathing, that cannot be eliminated by sealing. Coal mines usually have sufficient oxygen sinks that this is not an issue; however, non-coal mines may not have sufficient oxygen sinks.

**Alkaline addition.** Alkaline addition has been used as both a preventative measure as well as an in-situ treatment technique. In its use as a preventative agent, alkaline materials such as FBC ash and cement kiln dust have been used to create alkaline environments around known acid-producing zones. For example, alkaline materials are used to coat acid producing underclays at surface coal mines prior to the placement of the spoil. They have also been used as a backfill against the coal seam that is exposed in the highwall. In this usage, the alkaline materials create an environment that is not conducive to pyrite oxidation.

Alkaline materials have also been used to offset the acid-producing potential of refuse material. In this usage, the alkaline material is more of an in-situ treatment in that the alkaline material does not prevent the formation of the acid but rather neutralizes it after it has been formed. Discharges from these sites may be neutral pH with low metals content but they may have elevated sulfate content. By keeping the pH of the fill material in the neutral range, this method of alkaline addition prevents the biologically accelerated rate of pyrite oxidation from taking place. This is because *T. ferrooxidans* prefers low pH conditions.

**Water management.** Water management has been discussed in relation to sub-aqueous disposal, however, it is also the primary component in preventing or minimizing AMD from dry sites as well. Because of the difficulty in excluding oxygen from dry facilities, reclamation designs focus on the exclusion of water from the acid-forming materials. This is accomplished using several techniques.

Where possible, water is diverted around the entire disturbed facility. Perimeter ditches are often the method of choice. In some cases, water is conveyed through the fill in non-reactive rock drains. As previously mentioned, these rock drains can promote the influx of air into the fill material.

Acid-forming materials are placed on a pad of non-reactive rock so that they are elevated above any fluctuating water level in the pit. A drainage system may also be designed to keep the pit dewatered. Pipes or French drains have been used for this purpose. Pit dewatering is particularly important when the pit floor contains acid-forming material as does the underclay of some coal seams, and when complete flooding cannot be achieved.

Surface infiltration must also be controlled in order to prevent water contact with acid-forming materials. Caps or covers have been designed to work in one of two different ways. Designs often include an impermeable layer beneath the plant growth layer. The purpose of this layer is to prevent infiltration. Materials used can range from locally-available clay-rich soils to synthetic materials such as high-density polyethylene (HDPE). Studies at some sites have indicated that compacted soil barriers may, over time, exhibit increased permeability thus reducing the effectiveness of the barrier. While synthetic barriers do not lose permeability with time, care must be taken in designing the system so that excess saturation of the overlying soils does not lead to slippage at the soil-membrane interface.

The second design approach to caps and covers is to create a cover that is capable of absorbing all of the anticipated infiltrating precipitation. The goal of this system is that the retained water is then evaporated directly or transpired by the vegetative cover. This type of cover is easier to implement in those parts of the country that have high evaporation rates. In designing this type of cover, it is useful to have the cover underlain by a high permeability material. This promotes water retention in the cover via capillary action. If needed, these two concepts can be combined with an absorption / evaporation – transpiration layer over an impermeable layer over a permeable layer.

## Modeling the Watershed

A computer program *TAMDL* was designed to simulate the evolution of stream water quality in watersheds affected by AMD and its treatment. The watershed's *TAMDL* model and the remediation endpoints for the mainstem are used to calculate the level of treatment required in each sub-watershed affected by AMD. The level of required AMD treatment was employed to design passive and active AMD treatment structures for each affected sub-watershed. The feasibility of the designed structures is tested by incorporating them into the watershed model and comparing the simulated stream pH, aluminum and iron concentrations against the corresponding remediation endpoints. The remediation design is then adjusted until the remediation endpoints were satisfied.

### Governing equation

The following partial differential equation is the governing equation for the one-dimensional transport of a water quality constituent in a stream and is solved by *TAMDL* for each of the simulated constituents, except for proton activity.

$$\frac{\partial C_i}{\partial t} = \mu \frac{\partial^2 C_i}{\partial x^2} - V \frac{\partial C_i}{\partial x} + L_i + S_i \quad (1)$$

Where:	$C_i$	=	Simulated concentrations of the constituents.
	$L_i$	=	Model node loading terms for each of the constituents.
	$S_i$	=	Net chemical and physical reaction source (sink) terms.
	$\mu$	=	Hydrodynamic dispersion.
	$V$	=	Mean stream velocity.

Because the hydrodynamic dispersion and mean stream velocity must remain uniform throughout the computational domain, the watershed must be divided into small sub-watersheds before using the computer program. The spatial coordinate,  $x$ , proceeds from the head of the sub-watershed and follows the stream channel to the mouth.

The governing equation is solved using net acidity rather than pH. Net acidity is defined as the total acidity minus the total alkalinity. Total acidity consists of the acidity caused by metal ion hydrolysis and the acidity caused by proton activity. In typical mine drainage, metal ions, rather than protons, constitute the major component of acidity. Therefore, *TAMDL* estimates pH through its relationship with net acidity by subtracting the effect of the metal ions.

If the stream chemistry was simulated with proton activity instead of net acidity, then it would be necessary to also simulate dissolved carbon dioxide, bicarbonate ion, carbonic acid and total sulfate in addition to the other constituents. While this would be more correct theoretically, each of the

additional parameters would require the estimation of boundary and initial conditions, which would degrade overall simulation precision. When the transport of acidity by the stream is simulated with net acidity instead of proton activity, then a constitutive relationship is required to calculate the pH from the net acidity.

### **Net acidity – pH constitutive relationship**

The parameter pH must be calculated by the model because water quality standards invariably use pH instead of net acidity and the kinetic rates of ferrous iron, aluminum and manganese oxidation and/or precipitation depend heavily upon pH. Because defining the nature of the net acidity – pH constitutive relationship is a part of the modeling process, the computer program *TAMDL* allows the user to specify the relationship with paired series of net acidity and pH data.

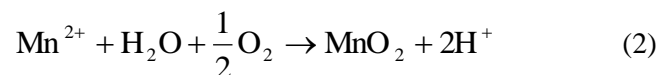
### **Ferric iron sedimentation**

*TAMDL* assumes that all ferric iron above the pH-dependent ferric iron solubility limit has combined with dissolved oxygen to form ferric hydroxide. The computer program also assumes all of the ferric hydroxide in the stream clings to sediment particles, which leave the computational domain by flowing through the downstream boundary or by sedimentation. The rate at which ferric iron leaves the model domain via sedimentation is assumed to follow Stokes Law. This assumption is valid when the particle Reynolds number is less than unity (Roberson and Crowe, 1980). Given the size of sediment particles most likely to carry ferric hydroxide, this assumption is realistic.

Because this process is not dependent upon the precise concentration of suspended solids, the simulation of the erosion, transport and deposition of sediment was not required. Since *TAMDL* is often employed to simulate watersheds, where very little information on stream hydraulics is available, sediment transport is not simulated, and the re-suspension of ferric iron-containing sediment particles must be neglected. Because the computer program can be easily modified to use the results of a sophisticated hydraulics model, the incorporation of a suspended sediment constituent and ferric iron re-suspension into the model would not be difficult.

### **Manganese oxidation and precipitation**

The formulation used by *TAMDL* to calculate the kinetic rate of manganese oxidation and precipitation was obtained from Stumm and Morgan (1981). When the stream's dissolved oxygen concentration is less than 0.01 mg/L, manganese oxidation and reduction are neglected.





The kinetic rate for the progress of manganese oxidation and precipitation is calculated by the program using the following formula.

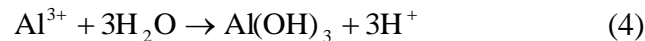
$$S'_{\text{Mn}} = \frac{-a_{\text{Mn}} C_{\text{Mn}} C_{\text{DO}} C_{\text{Fe}^{3+}}}{[H^+]^2} \exp\left(\frac{-E_{\text{Mn}}}{RT}\right) \quad (3)$$

Where:	$S'_{\text{Mn}}$	=	Manganese kinetic rate, mg/L/day.
	$E_{\text{Mn}}$	=	Empirical rate constant, kJ/mole.
		=	107.987 kJ/mole.
	$a_{\text{Mn}}$	=	Empirical rate multiplier specified by user, L <sup>4</sup> /(mg <sup>4</sup> -day).
	$R$	=	Universal gas constant, kJ/mole/K.
		=	8.314 x 10 <sup>-3</sup> kJ/mole/K.
	$T$	=	Stream water temperature, K.
	$C_{\text{Mn}}$	=	Manganese concentration, mg/L.
	$C_{\text{DO}}$	=	Dissolved oxygen concentration, mg/L.
	$C_{\text{Fe}^{3+}}$	=	Ferric iron concentration, mg/L.

The array containing the net rate of production (consumption) for each of the constituents,  $S_i$  is calculated by taking the algebraic sum of the kinetic rates for each chemical and physical reaction being modeled. Because manganese oxidation consumes oxygen, equation (2) is used to calculate the corresponding decline in dissolved oxygen concentration. The effect of this reaction's proton production on the pH and net acidity is calculated with equation (2) and the net acidity – pH constitutive relationship.

### Aluminum precipitation

The chemical reaction for aluminum precipitation is similar to the equation for manganese oxidation and precipitation except for the absence of oxidation because aluminum has only a single oxidation state.



$$S'_{\text{Al}} = \frac{-a_{\text{Al}} C_{\text{Al}} A_{\text{Al}}}{[H^+]^3} \exp\left(\frac{-E_{\text{Al}}}{RT}\right) \quad (5)$$

Where:	$S'_{\text{Al}}$	=	Aluminum precipitation kinetic rate, mg/L/day.
	$a_{\text{Al}}$	=	Empirical rate constant specified by the user, dimensionless.
	$C_{\text{Al}}$	=	Aluminum concentration, mg/L.
	$A_{\text{Al}}$	=	Empirical rate multiplier, mole <sup>3</sup> /L <sup>3</sup> /day.
		=	3160 mole <sup>3</sup> /L <sup>3</sup> /day.
	$E_{\text{Al}}$	=	Empirical rate constant, kJ/mole.
		=	58.2 kJ/mole.

Like for manganese precipitation and oxidation, the effect of this reaction's production of protons on the pH and the net acidity is calculated with the chemical equation (4) and the net acidity – pH constitutive relationship.

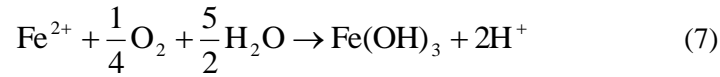
If the user specifies a negative value for the dimensionless empirical rate constant, the program does not evaluate equation (5), but does not allow the aluminum concentration to be greater than the solubility limit under equilibrium conditions, which is calculated with equation (6).

$$C_{Al-equ} = \exp(35.071 - 6.9078 \text{ pH}) \quad (6)$$

Where:  $C_{Al-equ}$  = Solubility limit for aluminum, mg/L.

### Ferrous iron oxidation

Ferrous iron oxidation can be simulated by *TAMDL* with the following chemical reaction, when the stream's dissolved oxygen concentration is greater than 0.01 mg/L.



The rate of ferrous iron oxidation is calculated by the program with the formulation presented by Kirby et al. (1998). This formulation has a biotic term as well as an abiotic term to account for the oxidation of ferrous iron by *T. ferrooxidans* bacteria.

$$S'_{\text{Fe}^{2+}} = -\frac{U_{\text{DO}} A_a C_{\text{Fe}^{2+}} C_{\text{DO}}}{[\text{H}^+]^2} \exp\left(\frac{-E_a}{RT}\right) - U_{\text{DO}} A_b C_{\text{Fe}^{2+}} C_{\text{DO}} C_{\text{TF}} [\text{H}^+] \exp\left(\frac{-E_b}{RT}\right) \quad (8)$$

Where:  $S'_{\text{Fe}^{2+}}$  = Ferrous iron oxidation kinetic rate, mg/L/day.  
 $U_{\text{DO}}$  = Unit conversion constant, g-moles  $\text{O}_2$  / mg  $\text{O}_2$ .  
=  $3.125117192 \times 10^{-5}$  g-moles  $\text{O}_2$  / mg  $\text{O}_2$ .  
 $A_a$  = Empirical abiotic oxidation rate multiplier, mole/L/day.  
=  $3.456 \times 10^{10}$  mole/L/day.  
 $E_a$  = Empirical abiotic rate constant, kJ/mole.  
= 96 kJ/mole.  
 $C_{\text{Fe}^{2+}}$  = Ferrous iron concentration, mg/L.  
 $C_{\text{TF}}$  = Dry biomass concentration of *T. ferrooxidans* bacteria, mg/L.  
 $A_b$  = Empirical biotic rate constant, mole/L/day.  
=  $8.8128 \times 10^{13}$  mole/L/day.  
 $E_b$  = Empirical biotic rate constant, kJ/mole.  
= 58.77 kJ/mole.

All of the empirical rate constants in equation (8) were determined from the analysis of field data (Kirby et al., 1998). Because the results of Kirby et al. (1998) suggest that the dry biomass concentration of *T. ferrooxidans* bacteria is difficult to measure accurately, it can be used as a model calibration parameter. Simulating ferrous oxidation requires that the user have information about the speciation of iron in the stream. Because this data may not be available for the streams being modeled, the *TAMDL* computer program allows one to assume that all of the iron is in the ferric oxidation state by specifying a zero concentration for ferrous iron.

### **Other reactions**

Because the kinetic rates of manganese oxidation and precipitation, aluminum precipitation and ferrous iron oxidation depend upon the stream temperature and the dissolved oxygen concentration, it is necessary that *TAMDL* simulate these water quality constituents as well. With dissolved oxygen, the user has the option of directing the program to assume that saturated conditions are always present or calculate the dissolved oxygen concentration from stream re-aeration and organic material decay. A zeroth order sediment oxygen demand formulation from the lake model *CE-QUAL-W2* (Cole and Buchak, 1995) was adapted for use in *TAMDL*. Stream re-aeration is calculated with the O'Conner and Dobbins (1958) formulation. Because stream temperature is not absolutely crucial to the modeling of streams affected by acid mine drainage, the simplified formulation used by the program assumes that the amount of heat transferred between the stream and the atmosphere is directly proportional to the difference in temperature and wind speed and inversely proportional to the depth of the stream.

### **Boundary and initial conditions**

Upstream of the computational domain for each simulation, the user specifies the boundary temperature and concentrations. The specified upstream boundary temperature and concentrations may vary with simulation time. Normally, the upstream boundary condition is calculated from the results of the model for the upstream sub-watershed. If there is no upstream sub-watershed, the upstream boundary condition must be implied from the results of water quality sampling.

At the downstream end of each computational domain, *TAMDL* assumes that the spatial gradient of the temperature and concentration is zero. Downstream boundary conditions are required because of the dispersion (second derivative) term in governing equations. If there is no flow through the computational domain, *TAMDL* automatically applies the downstream boundary condition to the upstream boundary, and the concentrations specified for the upstream boundary are ignored.

The program also requires that the initial temperature and concentration be specified for each node. Initial conditions are not very important when one desires a steady state solution. When one is simulating a transient problem, the

precise selection of initial conditions may have an important effect on the results calculated in the early portion of the simulation. Realistic initial conditions can be generated by simulating water quality conditions for a period prior to the desired simulation period.

### **Numerical algorithm**

In order to make efficient use of computational resources, the selection of an appropriate numerical algorithm is very important. In the planning stages of *TAMDL*, it was decided that the selected algorithm should be both explicit and at least second order accurate in both time and space. One well-tested algorithm that satisfies this requirement is the explicit MacCormack predictor – corrector method described by Anderson et al. (1984). Because this finite difference algorithm is normally applied to the solution of the advection – dispersion equation, the loading and chemical reaction terms in the governing equation must be solved analytically or with a numerical technique for first order ordinary differential equations.

Since the equations describing the kinetic rates of the aforementioned reactions are both complex and non-linear, it was decided that both the loading and reaction terms should be solved numerically. First order ordinary differential equations are commonly solved with one of the Runge-Kutta methods (Boyce and DiPrima, 1977). In order to simplify the program's source code, it was decided that intermediate time steps to solve the chemical reaction terms would not be employed. Therefore, to achieve the desirable accuracy, it was decided to use the fourth order Runge-Kutta method to solve the contributions of these terms.

### **Source loads**

The source loads applied to finite difference model nodes are represented in *TAMDL*'s governing partial differential equation, equation (1), by the array  $L_i$ . The program allows one to specify thermal, alkaline, acid, ferrous iron, ferric iron, manganese, aluminum and dissolved oxygen loads with this array. The operation of passive acid mine drainage treatment systems can also be simulated for specified model nodes. Because the production of alkalinity by passive acid mine drainage treatment systems depends upon the stream's acidity, the source load terms can be non-linear and the fourth order Runge-Kutta method is also used to calculate the contribution of these terms.

### **Hydrology**

Because the advection term in the governing partial differential equation, equation (1), contains the mean flow velocity of the stream,  $V$ , the mean velocity must be known for all portions of the computational domain throughout the simulation period. The current formulation of the explicit MacCormack predictor – corrector method requires that the stream velocity and the hydrodynamic dispersion be uniform throughout the computational domain. Therefore, to account for changes in the stream hydraulics, the watershed must be divided into many small sub-watersheds.

## Strengths and weaknesses of TAMDL

The basic strength of the *TAMDL* computer program is that it solves the differential equation governing the transport, loading and reaction of AMD-related water quality constituents, equation (1). This equation requires that the user specify the stream's discharge flow rate,  $Q$ , throughout the simulation period and rating tables for the depth,  $h$ , flow area,  $A$ , wetted perimeter,  $P$ , and top width,  $T$ . Ideally, one would use a hydrologic simulation program to determine these parameters before executing the *TAMDL* computer program.

Unfortunately, those streams affected by AMD tend to be small and the information required to run a sophisticated hydrologic simulation program is not available. In those situations, the user is required to estimate the discharge flow rate for a particular stream segment from the drainage area of the stream segment and discharge flow rate data collected at a nearby stream gage. The rating tables for the stream segment are then estimated from measurements of the stream channel geometry and educated guesses about the Manning's  $n$  value for the stream.

# 7 Remedial Design and Remedial Action

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## Introduction

### Mine settings and hazards

Abandoned mine lands can be found in all mining regions throughout the world. Some of the more common settings are the surface disturbances associated with underground mines. Portals may be exposed at the land surface and accessible, and have no flowing water. Others may be wet, draining acid mine drainage or other polluted water from the mine. The land surface over underground mines may have subsidence holes or cracks, which may allow people or animals to fall directly down into the mine, or the land surface may show depressions where underground rock materials have caved or settled into the mine. Water supplies may be impacted by underground mines, affecting both quantity and quality of water in surrounding wells. The regional water table can be influenced also as a result of underground mining.

Abandoned surface mines are generally more visible and noticeable than abandoned underground mines because they often include large scars on the land surface and barren or semi-vegetated piles of spoil or rock materials. Sometimes highwalls (sharp vertical cliffs) are left where the mining operation ceased, leaving steep, unstable slopes, and areas for water impoundment. Many of the spoil-material and flat-bench areas have acid-producing rock materials, making them difficult to be colonized by adjacent plant species through natural succession. The barren landscapes facilitate the erosion and movement of sediments into streams. Old facilities and buildings may have been left that are clearly hazardous to visitors.

### Assessment strategies

During preliminary site investigations, an assessment should be made as to the extent and degree of health and safety hazards, since these are the most important considerations to the reclamation of any abandoned mine site. These include mine portals that must be sealed, subsidence holes that must be filled, broken and falling-down facilities and buildings that must be demolished and removed, and burning debris or coal seams that must be extinguished. Once the hazards have been documented, then other correctable conditions on the site may

be evaluated. These include the amounts of spoil materials that need regrading and reclamation, the linear feet of highwall that must be backfilled, the ponds or other impoundments that must be drained and excavated/filled, and any other environmental problem that can be addressed during reclamation.

Site assessment will generally include drilling to discover the depths, amounts, and quality of geologic materials on the site. During drilling, rock samples at pre-determined depths should be taken and analyzed for their pollution potential. The most common technique for analyzing mine soil, spoil, and overburden materials is the Acid-Base Account. Acid-Base Accounting (ABA) outlines procedures that should be conducted on the rock sample to provide its acid-producing or alkaline-producing (neutralization potential) status (Sobek et al., 2000). Acid production is determined by measuring the sulfur content of the material. Neutralization potential (NP) is assessed by an NP test (ADTI, 2000). These analytical techniques, which are part of the ABA procedure, provide a simple, relatively inexpensive, and consistent procedure to evaluate disturbed rock materials. It balances potential acidity (based on total or pyritic sulfur content) against total neutralizers (primarily carbonates) in a rock or spoil sample. Samples containing more acid potential than alkaline material are shown to be deficient in neutralizing materials ("maximum needed"), while the reverse situation is shown as "excess" neutralizing materials.

Rock layers that are marginal (having about equal proportions of each type of material) can be subjected to leaching or weathering analyses (Hornberger and Brady, 1998; Skousen et al., 1987). The information can supplement information given by ABA and can often help evaluate how a particular rock may react upon leaching with water under natural conditions. Identification of the acid or base status of disturbed rock materials greatly aids in developing reclamation handling and placement plans, in determining what materials should and should not be re-disturbed or treated during reclamation, and in deciding upon the best remediation strategies.

Water sampling is also extremely important to assess the current condition of surface materials. Many sites have drainage water of low pH, high conductivity, and high dissolved metal and sulfate concentrations. Other abandoned mine sites may have neutral water containing only high suspended solids especially during or immediately after rain events. Sampling of running water or water found in ponds or impoundments on the site is very helpful to determine the current chemical status of geologic and earthen materials on the site.

### **Acid mine drainage formation**

Acid mine drainage (AMD) forms when sulfide minerals are exposed to oxidizing conditions in coal and metal mining. Iron sulfides common in coal regions are predominately pyrite and marcasite ( $\text{FeS}_2$ ), but other metals may be complexed with sulfides forming chalcopyrite ( $\text{CuFeS}_2$ ), covellite ( $\text{CuS}$ ), galena ( $\text{PbS}$ ), and sphalerite ( $\text{ZnS}$ ). Pyrite commonly occurs with these other metal sulfides thereby causing AMD where Ag, Au, Cu, Ni, Pb, and Zn are mined.

Upon exposure to water and oxygen, sulfide minerals oxidize and generate sulfate salts that can be dissolved in water. The drainage from areas containing

oxidizing sulfides is acidic, laden with sulfate, and usually has high concentrations of metals. Metal concentrations in AMD depend on the type and quantity of sulfide minerals present. The drainage quality emanating from underground mines or backfills of surface mines is dependent on the acid-producing (sulfide) and alkaline (carbonate) minerals contained in the disturbed rock. In general, sulfide-rich and carbonate-poor materials produce acidic drainage. In contrast, alkaline-rich materials, even with significant sulfide concentrations, often produce alkaline conditions in water.

### **Predominant concepts**

Accurate prediction and control of AMD on disturbed sites require an understanding of three important factors: 1) overburden geochemistry, 2) methods used in overburden handling and placement in the backfill during reclamation, and 3) the post-mining hydrology of the site.

As already mentioned, overburden geochemistry can be assessed by ABA, which gives an indication of the acid or base status of the rock. Once a sample has been analyzed by the methods of ABA, the material can be classified as acid-producing, neutral, or alkaline-producing. If questions remain as to its status, leaching tests can be conducted.

The prevailing approach to control AMD in the USA is to keep water away from acid-producing material. Recommendations have focused on segregating and placing acid-producing materials above the water table (Skousen et al., 1987). Where adequate supplies of limestone or other alkaline material occur in the overburden, these materials may be blended to neutralize the acid-producing materials. Limestone should be added to the topsoil to neutralize any residual acidity and to raise the pH for vegetation establishment.

The hydrology of a backfill and the release of water from these porous rock fills are complex. Generally, the porosity and hydraulic conductivity of blasted, disturbed rock materials are greater than those of the consolidated rock overburden that existed before mining, and changes in flow patterns and rates should be expected after mining (Caruccio and Geidel, 1989). As water moves into coarse materials in the backfill, it follows the path of least resistance. For example, water will flow through more permeable acid sandstones and around calcareous shales. The water continues downward until it encounters a barrier, the coal pavement, or other compacted or slowly permeable layer. Water does not move uniformly through the backfill by a consistent wetting front. The chemistry of the water emanating from the backfill will reflect only the rock types encountered in the water flow path, not the geochemistry of the total overburden (Ziemkiewicz and Skousen, 1992).

Diverting surface water above the site to decrease the amount of water entering the mined area is highly recommended. Alternatively, pyritic material can be placed where it will be rapidly and permanently inundated, thereby preventing oxidation of the acid-forming material. Inundation is only suggested where a water table may be permanently established to cover acid-producing materials (such as below drainage deep mines) and has not been recommended for surface mined lands or above drainage deep mines in mountainous regions. In



areas adjacent or above mined areas, water with low mineral acidity (metal-free) can flow through ditches or channels filled with limestone to improve water quality.

## **Control of Acid Mine Drainage**

Acid mine drainage control technologies are measures that can be undertaken where AMD formation has either already taken place or is anticipated to be a problem in the future. At-source control methods treat the acid-producing rock directly and stop or retard the production of acidity, whereas treatment methods add chemicals directly to acidified water exiting the rock mass. Companies mining in acid-producing areas must often treat AMD, and they face the prospect of long-term water treatment and associated liabilities. Cost-effective methods that prevent the formation of AMD at its source are preferable. Some control methods are most suitable for abandoned mines, while others are only practical on active operations or during active reclamation on abandoned mines. Other methods can be used in either setting.

Some techniques described below are partially successful and have demonstrated less than 100% control of acidity produced on-site and are considered failures by some people. Removing a significant portion of the acid or metal load in a watershed by a partially-effective control strategy may improve the health of a stream to a point of re-introducing some fish species or re-establishing some designated uses of the stream. Alternatively, the method may be combined with another partial-control scheme to achieve effluent limits. Since partial-control methods are often the least costly, their use in combination with other techniques is financially attractive.

### **Land reclamation**

Backfilling and revegetation together are two of the most effective methods for reducing acid loads from current mining operations or abandoned mine lands. In a study by Faulkner and Skousen (1995), backfilling alone reduced the acid load substantially or improved the water quality to the point of meeting effluent limits. Water flow was reduced in 12 out of 16 sites, and on sites where flow was not reduced, water quality improved significantly. Therefore, these results demonstrate that backfilling reduces total acid load either by reducing the flow, acidity, or both.

Topsoiling of abandoned mine sites has also shown improvements in drainage water. The topsoil creates a barrier against acidity that may have been present in the previous surface material, and encourages the growth of plants, which can increase water infiltration and reduce the amount of runoff. Further, additions of lime to the topsoil to neutralize soil acidity can also aid in water improvement. If heavy applications of lime are needed to neutralize soils, it is recommended that deep ripping be employed to introduce the lime to greater soil depths. On abandoned mine lands where acid-producing materials were left on the surface, heavy applications of lime (20 to 100 tons/ac) on the surface with deep incorporation is recommended before topsoiling is done.

Revegetation of abandoned sites is especially important to improve the aesthetics of a site. In the eastern USA, adjacent plants from nearby forests will colonize the site within a few years after abandonment. If there are no serious acid or toxic conditions in the soil, the ground cover may achieve 100% and be quite complete. Serious consideration should be given to the plant community that has naturally established on the abandoned site and to what degree the community needs to be disturbed during reclamation. In many cases, simply revegetating the barren patches within the site is preferred, rather than disturbing the surface of the entire site. Patch revegetation is simple and inexpensive. Sometimes, only a little mulch, fertilizer, and seed are needed to be applied to the surface for revegetation, and this can be done by small machinery or by hand, depending on the size of the patches. This technique is very useful where additional land disturbance on the surface will only expose more acid-producing materials, causing more AMD, and where a diverse and successful plant community has already become established.

Remining is returning to abandoned surface or underground mines for further coal removal. Where AMD occurs, remining reduces acid loads by: 1) decreasing infiltration rates, 2) covering acid-producing materials, and 3) removing the remaining coal which is the source of most of the pyrite. Hawkins (1994) studied 57 discharges from 24 remined sites in Pennsylvania and found contaminant loads (e.g. flows and metal concentrations) were either reduced or unchanged after remining and reclamation. Short-term loads were sometimes increased during the first six months after remining and reclamation. Reduction in loads resulted from decreased flow rather than large changes in concentrations. An evaluation of ten remining sites in Pennsylvania and West Virginia showed eight of the sites to produce a net profit from coal sales. All the sites were reclaimed to current standards, thereby eliminating highwalls, covering refuse, and revegetating the entire areas. All sites also had improved water quality and some sites were completely remediated so that no AMD came from the site (see also Skousen et al., 1997). Faulkner and Skousen (1995) found significant reductions in acid loads after land reclamation, and the acid load reductions were due both to reductions in water flow from the site and reductions in acid concentration in the water.

Diverting surface water from above the mined site to decrease the amount of water entering the mined area is highly recommended in acid-producing areas. Channeling surface waters or mine waters to control volume, direction and contact time can be used to minimize the effects of AMD on receiving streams. Surface diversion of runoff involves the construction of drainage ditches to move surface water quickly off the site before infiltration or to limit its movement into the backfill. The diversion is accomplished either by ditching on the uphill side of surface mines or by providing new channels or impervious channels for existing surface streams to convey water across the disturbed area. These diversion channels that carry water can also be lined with limestone to add alkalinity to the water. This will help the quality of receiving streams and buffer these waters from AMD that may enter at lower points in the watershed.

## Special handling and placement

Special handling includes selection, identification in the field, segregation, storage, and the placement of acid-producing and alkaline-producing rock during mining and reclamation at surface mines. Directing surface and highwall seepage water into drains and compacting materials are also included in special handling. The purpose of special handling is to minimize the contact of water and air with acid-producing materials. This is best accomplished by compacting the acid-producing material, such that water moves preferentially around these materials, or the water is encouraged to move preferentially through alkaline material. Special handling is often used in conjunction with other remediation measures, such as alkaline addition, water management and barrier techniques, and surface reclamation.

The prevailing concept of special handling in the eastern USA is to segregate acid-producing materials by placing them as quickly as possible in the backfill, high off the pit floor and away from the highwall. The material should be compacted and treated with alkaline material to neutralize the acid-producing potential. After the acid-producing rock is placed, compacted and treated, it should be capped with a layer of slowly permeable material and covered with non-acid-producing material and topsoiled to reduce water and air movement into the acid rock (Figure 4).

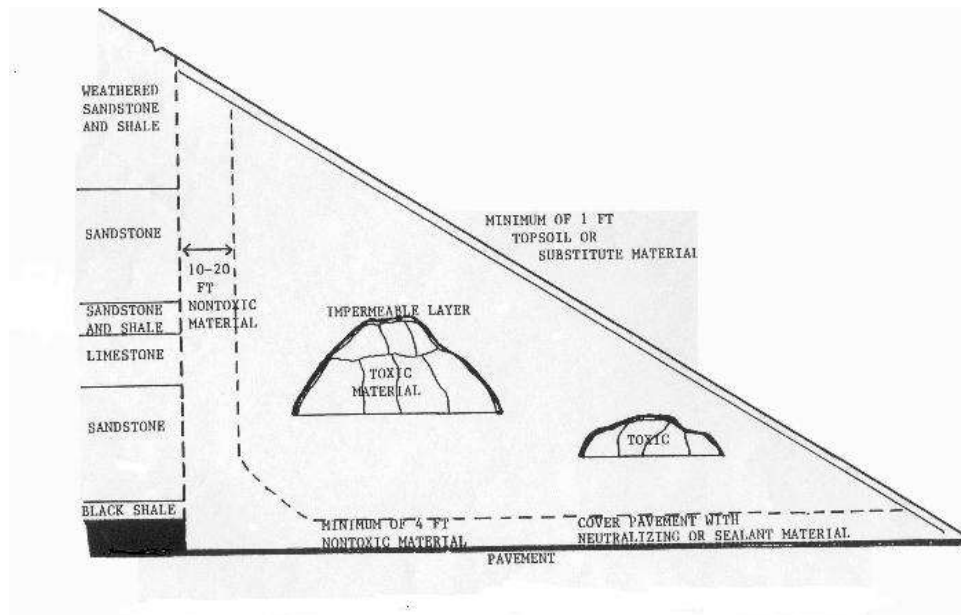


Figure 4. During construction of the backfill, toxic material should be placed off the pit floor, compacted, treated with neutralizing material, and capped with an impermeable layer to reduce air and water contact (from Skousen et al., 1987).

Selective handling seeks to blend acid-producing and alkaline-producing rock units in the mining process to develop a neutral rock mass. Selective handling may also create a post-mining hydrologic regime that minimizes the contact between acid-producing rock and groundwater, or it may isolate acid-

producing rocks from the rest of the backfill by use of barriers. In the eastern USA, the pit floor is often rich in pyrite, so isolating it from groundwater may be necessary. Isolation methods can include building highwall drains, which move incoming groundwater away from the pit floor, or placing impermeable barriers on the pit floor. For example, acid-forming material can be compacted or capped within the spoil (Meek, 1994). If insufficient alkalinity is available in the spoil, then external sources of alkalinity may be imported (Skousen and Larew, 1994; Wiram and Naumann, 1995).

Proper analysis, identification, handling, blending or treatment, and placement of acid-producing materials in the backfill are the key issues in controlling AMD. Substantial reductions in AMD are realized with correct identification and application of appropriate mining procedures.

### **Alkaline amendments**

Field studies have indicated that certain types of alkaline amendments can successfully control AMD from acid-producing spoil and refuse (Brady et al., 1990; Perry and Brady, 1995; Rich and Hutchison, 1990; Rose et al., 1995). Nearly all alkaline-amendment schemes rely on ABA to identify the required alkalinity for neutralization of acid-producing materials. Alkaline amendment methods are a modification of the concept of selective handling, where enough alkalinity is added and blended to neutralize the acid-producing rock. Limestone is often the least expensive and most readily available source of alkalinity. It has a neutralization potential (NP) of between 75 and 100% and is safe and easy to handle. On the other hand, it has no cementing properties and cannot be used as a barrier or slowly-permeable material.

Fluidized Bed Combustion (FBC) ashes generally have NPs of between 20 and 40%, and they tend to harden into a cement after wetting (Skousen et al., 1997). Other power-generation ashes, like flue gas desulfurization products and scrubber sludges, may also have significant NP, which make them suitable alkaline amendment materials (Stehouwer et al., 1995).

Kiln dust, produced by lime and cement kilns, contains similar levels of CaO (15 to 30%) as FBC ash, but it also contains 50 to 70% unreacted limestone. Kiln dust absorbs moisture and also hardens upon wetting (Rich and Hutchison, 1994). It is widely used as a stabilization and barrier material.

Steel slags, when fresh, have NPs from 45 to 90%. Steel slag can be used as an alkaline amendment as well as a medium for alkaline recharge trenches. Slags are produced by a number of processes, so care is needed to ensure that candidate slags are not prone to leaching metal ions like Cr, Mn, and Ni. Several slag materials are being used in passive treatment systems, like alkaline leach beds.

Other alkaline materials may have higher NPs than limestone, but the source of the material must be tested, and a complete analysis should be done to evaluate NP and metal content before use. Phosphate rock has been used in some studies to control AMD. It may react with Fe released during pyrite oxidation to form insoluble coatings (Evangelou, 1995), but phosphate usually costs much

more than other calcium-based amendments and is needed in about the same amounts (Ziemkiewicz and Meek, 1994).

### **Alkaline recharge trenches**

Alkaline recharge trenches (Caruccio et al., 1984) are surface ditches filled with alkaline materials. These trenches can minimize or eliminate acid seeps through an alkaline-loading process by placing alkaline material in contact with surface-infiltrating water. Early research with these trenches only used the surface water that naturally collected in trenches during precipitation events. Little effect was found since water movement into the backfill was limited by rainfall. Alkaline recharge trenches were constructed on top of an 8-ha coal refuse disposal site, which produced AMD seepage (Nawrot et al., 1994). After installing the alkaline recharge pools, acidity reductions of 25 to 90% were realized with concomitant 70 to 95% reductions in Fe and sulfate in seepage water. Recent applications of this technology are using water pumped from ponds into the alkaline trenches to greatly accelerate the movement of alkalinity into the backfill (Ziemkiewicz et al., 2000). In one study, connection between the water/lime injection point and backfill seeps was determined and acid seeps turned alkaline.

### **Biological treatment**

Anionic surfactants are used to control bacteria that catalyze the conversion of  $\text{Fe}^{2+}$  to  $\text{Fe}^{3+}$ , which thereby controls pyrite oxidation (Kleinmann et al., 1981). They are used primarily in situations where immediate control of AMD formation is important and work best on fresh, unreacted sulfide materials like fresh refuse from coal preparation plants. Bactericides are often liquid amendments, which can be applied to refuse conveyor belts or sprayed by trucks on cells of acid-producing materials in the backfill. Bactericides have also been used successfully at metal mines (Parisi et al., 1994).

Surfactants, by themselves, are not seen as a permanent solution to AMD. Eventually the compounds either leach out of the rock mass or are decomposed. However, slow-release formulations are commercially available and have been successfully used at regraded sites (Splitdorf and Rastogi, 1995). Bactericides appear to work best when used in combination with other control methods and can be useful in preventing acid conditions in acid-producing refuse or spoil piles which remain open for several years until the site is reclaimed. Bactericides were not very effective when applied to the overburden surface of an abandoned, pre-1970 mined site in Ohio. No topsoil was applied at the site, but reclamation efforts had established some surface vegetation. Controlled release surfactant pellets were applied by hydroseeder in 1982 to a predominantly sandstone overburden containing pyrite nodules. Seeps discharging from the site initially had acidities between 1000 to 3000 mg/L as  $\text{CaCO}_3$ ; however, there was only minor improvement after bactericide application (Gwen Geidel, personal communication).

## **Dry barriers**

The use of topsoil to act as a barrier was already covered in the Land Reclamation section (7.2.a). Various types of barriers are constructed from materials that retard the movement of water and oxygen into areas containing acid-producing refuse or spoil. Sometimes these techniques may be categorized as water control technologies (Skousen et al., 1998) and include impervious membranes, dry seals, hydraulic mine seals, and grout curtains/walls. Surface barriers can achieve substantial reductions in water flow through piles, but generally do not control AMD completely. Grouts can be used to separate acid-producing rock and groundwater. Injection of grout barriers or curtains may significantly reduce the volume of groundwater moving through spoil. Gabr et al. (1994) characterized the groundwater flow of an acid-producing reclaimed site where a 1.5-m thick wall was installed by pumping a mixture of class F fly ash and Portland cement grout into vertical boreholes near the highwall. After two years, the grout wall reduced groundwater inflow from the highwall to the spoil by 80%, resulting in one of two seeps completely drying up and substantially reducing the flow of the other seep.

At the Heath Steele Metal Mine in New Brunswick, a soil cover was designed to exclude oxygen and water from the pile, and its performance was evaluated for five years (Bell et al., 1994). The capillary barrier consisted of a 10-cm gravel layer for erosion control, 30-cm gravel/sand layer as an evaporation barrier, 60-cm compacted till (conductivity of  $10^{-6}$  cm/sec), 30-cm sand, and pyritic waste rock. The barrier excluded 98% of precipitation, and oxygen concentrations in the waste rock dropped from 20% initially to around 1%.

Plastic liners are seldom used in surface mining applications, because covering a large volume of waste with a liner is usually too expensive. At the Upshur Mining Complex in West Virginia, Meek (1994) reported covering a 20-ha spoil pile with a 39-mil-thick PVC liner at a cost of \$1 million in 1980. This treatment reduced acid loads by 70% initially, but the effect gradually was reduced over time. However, this method may be appropriate in settings where isolation of small pods or cells of acid-producing material is possible.

Fly ash from fluidized bed boiler power plants is also being used as a sealant or dry barrier on surface mines. Ash is placed on pit floors to isolate water from the acid-producing material in the pavement, and ash is also being placed in 15- to 30-cm layers beneath the topsoil to retard water movement into the backfill.

## **Wet covers**

Disposal of acid-producing tailings under a water cover, such as a lake or fjord, is another way to prevent acid generation by excluding oxygen to sulfides. Wet covers also include flooding of above ground refuse or tailings ponds. Deposition of acid-producing refuse or sulfide tailings under water has been used at various mines in Canada, but this technique is not often used in the USA. Fraser and Robertson (1994) studied four freshwater lakes used for subaqueous tailings disposal in Canada. They found low metal concentrations in the lake, and biological communities existed in some of the lakes.

Deep mine sealing is defined as closure of mine entries, boreholes, outcrops, subsidence holes, and other openings into underground mine complexes. Deep mine seals are constructed to achieve one or more functional design goals. These goals include elimination of potential access points to the mine, minimizing AMD production by limiting infiltration of air and water into the deep mine, maximizing the amount of inundation of the mine works, and developing staged internal mine pools to regulate maximum hydraulic head and pressure. The primary factor affecting the selection, design and construction of underground mine seals is the anticipated hydraulic pressure that the seal will have to withstand when sealing is completed.

There are many types of mine seals, with each having a specific purpose. A wet mine seal is a concrete wall across a draining mine portal with a pipe inserted through the wall, which allows water flow through the seal, but prevents air from entering the mine. A dry mine seal is a concrete wall across a mine entrance where water does not drain from the entrance. To the extent that the seal raises the water level in the mine and inundates the workings, the production of AMD can be inhibited. Although complete blockage of portals at the down-dip side of underground mines has been attempted in order to prevent drainage and raise the water level in the mine, this procedure has commonly led to breakout of the water, sometimes explosively, either at the seal or at nearby locations (mine blowout). The placement and construction of mine seals, therefore, must be carefully planned and executed. For a complete discussion of the various types of mine seals, the section on mine seals in Skousen et al. (1998) is recommended.

### **Alkaline amendment and in-situ treatment at abandoned underground and surface mines**

Abandoned mines in the eastern USA generate more than 90% of the AMD in streams and rivers, most of which comes from underground mines. Abandoned underground mines are problematic because they are often partially caved and flooded, access is restricted, and reliable mine maps are often unavailable. Abandoned surface mines comprise huge volumes of spoil of unknown composition and hydrology. Re-handling and mixing alkalinity into the backfills of acid-generating surface mines is generally prohibitively expensive and it re-exposes much of the acid-producing material that has been buried. These problems on abandoned mines were considered so intractable that they have only recently been addressed.

Limestone has been placed in entrances of underground mines to limit access and also to treat the water as it flows out of the portal. If metal concentration in the water is high, the limestone can become coated with metal hydroxides and cause plugging, thereby restricting the flow of water from the mine. Creating a pond to inundate the limestone in the portal is a good method to reduce the chance for coating and plugging.

Filling underground mine voids with non-permeable, alkaline materials is one of the best methods to prevent AMD from abandoned underground mines. Since underground mine voids are extensive (a 60-ha mine with a coal bed height of 1.5 m and a recovery rate of 55% would contain about 500,000 m<sup>3</sup> of voids), the fill material and the placement method must have very low unit costs.

Mixtures of class F fly ash and 3-5% Portland cement are pumped beneath structures to control subsidence in residential areas. The slurries are injected through vertical boreholes at between 8- and 16-m centers to support the structures. Research and demonstration projects have used both pneumatic (the use of air pressure) and slurry injection methods for placing FBC ash in abandoned underground mines (Burnett et al., 1995). Results indicate that pneumatic methods can extend the borehole spacing to about 30 m at costs substantially less than those of slurry methods. On reclaimed surface mines still producing AMD, researchers in Pennsylvania saw small improvements in water quality after injecting coal combustion residues into buried pods of pyritic materials.

Grout curtains or walls can be used to separate acid-producing rock from groundwater. Injection of grout barriers may significantly reduce the volume of groundwater moving through spoil and thereby greatly reduce the amount of AMD coming from a site. Grout curtains can be developed by drilling grout injection holes along the side or within an underground mine to contain water flow or soil slippage. In a variation of the above technique, a trench can be excavated, and a concrete grout mix can be poured into the trench to prevent leakage or water movement from an underground mine.

There have been a few instances where alkaline materials such as a mixture of fly ash, coal refuse, and AMD treatment sludge (floc) are pumped underground. This technique provides for the disposal of waste materials and the material also treats the underground acid water due to its alkaline nature. During filling, displacement of underground mine water occurs and a treatment system is needed to handle and treat the water before discharge.

## **Chemical Treatment of Acid Mine Drainage**

If AMD problems develop during mining or after reclamation, a plan to treat the discharge must be developed. Treatment of AMD includes neutralization of acidity and precipitation of metal ions to meet the relevant effluent limits. In most cases, a variety of alternative treatment methods can be employed to meet the limits specified.

In order to select an AMD treatment system, one must determine the flow rate, pH, acidity, dissolved oxygen content, metal concentrations, and sulfate concentration in the AMD. The receiving stream's designated use and seasonal fluctuations in flow rate are also important. After evaluating these variables over a period of time, the operator can consider the economics of different chemicals and alternative AMD treatment systems. Most AMD chemical treatment systems consist of an inflow pipe or ditch conveying the AMD, a storage tank or bin holding the treatment chemical, a means of controlling the chemical's application rate, a settling pond to capture precipitated metal hydroxides, and a discharge point. In some instances (although not common on abandoned sites), an effluent limit has been established for the discharge and those limits must be achieved. In other instances, the water from the abandoned site must not degrade the receiving



stream, and therefore the water quality of the discharged water must meet stream quality.

Six chemicals are used to treat AMD (Table 9). Each chemical has characteristics that make it more or less appropriate for a specific condition. The best choice among alternatives depends on both technical and economic factors. The technical factors include acidity levels, flow, and the types and concentrations of metals in the water. The economic factors include prices of reagents, labor, machinery and equipment, the number of years that treatment will be needed, and the interest rates. Enough alkalinity must be added to raise water pH so insoluble metal hydroxides will form and settle out of the water. The pH required to precipitate most metals from water ranges from pH 6 to 9 (except Fe<sup>+3</sup>, which precipitates at pH  $\geq$ 3.0). The types and amounts of metals in the water therefore heavily influence the selection of an AMD treatment system.

### Oxidation and aeration

Aeration is the process of introducing air into water. Oxidation occurs when oxygen in air combines with metals in the water. If the water is oxidized, metals generally will precipitate at lower pH values. However, only about 10 mg/L of oxygen can dissolve in water, thereby limiting the oxidizing effects of water not directly exposed to air. At any rate, aeration of water promotes oxidation and,

<b>Table 9</b>					
<b>Chemical Compounds Used in AMD Treatment</b>					
Common Name	Chemical Name	Formula	Conversion Factor <sup>1</sup>	Neutralization Efficiency <sup>2</sup>	2000 Cost <sup>3</sup> \$ per Mg or L Bulk Bulk
Limestone	Calcium carbonate	CaCO <sub>3</sub>	1.00	30%	\$ 11 \$ 16
Hydrated Lime	Calcium hydroxide	Ca(OH) <sub>2</sub>	0.74	90%	\$ 66 \$110
Pebble Quicklime	Calcium oxide	CaO	0.56	90%	\$ 88 \$264
Soda Ash	Sodium Carbonate	Na <sub>2</sub> CO <sub>3</sub>	1.06	60%	\$220 \$350
Caustic Soda	Sodium hydroxide	NaOH	0.80	100%	\$750 \$970
20% Liquid Caustic	Sodium hydroxide	NaOH	784	100%	\$.06 \$.16
50% Liquid Caustic	Sodium hydroxide	NaOH	256	100%	\$.29 \$.33
Ammonia	Anhydrous ammonia	NH <sub>3</sub>	0.34	100%	\$330 \$750

<sup>1</sup> The conversion factor may be multiplied by the estimated Mg acid/yr to get Mg of chemical needed for neutralization per year. For liquid caustic, the conversion factor gives L needed for neutralization.

<sup>2</sup> Neutralization Efficiency estimates the relative effectiveness of the chemical in neutralizing AMD acidity. For example, if 100 Mg of acid/yr was the amount of acid to be neutralized, then it can be estimated that 82 Mg of hydrated lime would be needed to neutralize the acidity in the water (100(0.74)/0.90).

<sup>3</sup> Price of chemical depends on the quantity being delivered. Bulk means delivery of chemical in a large truck, whereas <Bulk means purchased in small quantities. Liquid caustic prices are for L. Others in Mg.

where aeration is incorporated into treatment systems, chemical treatment efficiency is improved and costs are decreased. Air may be introduced into water by mechanical stirrers or paddle wheels. Alternatively, water can cascade down a rock-lined channel or over a dam to encourage splashing and turbulence.

Sometimes, in-line aerators can be used that incorporate spray nozzles. Water laden with carbon dioxide (common in AMD pumped from underground mines) should be aerated and the carbonic acid in the water is then released, which greatly reduces chemical consumption and treatment costs.

## **Limestone**

Limestone has been used for decades to raise pH and precipitate metals in AMD. It has the lowest material cost and is the safest and easiest to handle of the AMD chemicals. Unfortunately, its successful application is limited due to its low solubility and tendency to develop an external coating, or armor, of  $\text{Fe}(\text{OH})_3$  when added to AMD. When pH is low and mineral acidity is also low (low metal concentrations), finely-ground limestone may be dumped in streams directly (limestone sand application) or limestone gravel may be ground into powder by water-powered rotating drums (limestone drum stations) and metered into the stream. Limestone sand is also dumped in AMD streams, and the agitation of the limestone sand in the streambed helps dissolve the material and does not allow a coating to form. Sand-sized limestone has been placed in a large cylinder tank and AMD is introduced into the bottom of the tank (diversion wells). The water flow into the tank fluidizes the limestone, causing dissolution and no armoring. Limestone has also been used to treat AMD in anaerobic (anoxic limestone drains) and aerobic environments (open limestone channels).

## **Hydrated lime**

Hydrated lime is the most common chemical used for treating AMD. It is sold as a powder that tends to be hydrophobic, and extensive mechanical mixing is required to disperse it in water or the lime is mixed with water to form a slurry. Hydrated lime is particularly useful and cost effective in large-flow, high-acidity situations where a lime treatment plant with a mixer/aerator is constructed to help dispense and mix the chemical with the water (Skousen and Ziemkiewicz, 1996). Hydrated lime has limited effectiveness if a very high pH is required to remove ions such as Mn. Operators of lime treatment systems often increase lime application as Mn levels increase in the water. However, due to the kinetics of lime dissolution, increasing the lime rate increases the volume of unreacted lime that enters the metal floc-settling pond.

## **Pebble quicklime**

Pebble quicklime (CaO) has been recently used in conjunction with the Aquafix Water Treatment System utilizing a water wheel concept (Jenkins and Skousen, 2001). The amount of chemical added is dictated by the movement of the water wheel, which causes a screw feeder to dispense the chemical. The hopper and feeder can be installed in less than an hour. This system was initially used for small and/or periodic flows of high acidity because CaO reacts very quickly. Recently, water wheels have been attached to large silos for high flow/high acidity situations. Tests show an average of 75% cost savings over NaOH systems and about 20 to 40% savings over  $\text{NH}_3$  systems.

## **Soda ash**

Soda ash ( $\text{Na}_2\text{CO}_3$ ) is generally used to treat AMD in remote areas with low flow and low amounts of acidity and metals. Selection of  $\text{Na}_2\text{CO}_3$  for treating AMD is usually based on convenience rather than chemical cost. Soda ash comes as solid briquettes, and is gravity fed into water by the use of bins or barrels. The number of briquettes to be used each day is determined by the rate of flow and quality of the water being treated. One problem with the bin system is that the briquettes absorb moisture, causing them to expand and stick to the corners of the bin. This hinders the briquettes from dropping into the AMD stream. For short-term treatment at isolated sites, some operators use a much simpler system employing a wooden box or barrel with holes that allows water inflow and outflow. The operator simply fills the barrel with briquettes on a regular basis and places the barrel in the flowing water. This system offers less control of the amount of chemical used.

## **Caustic soda**

Caustic soda ( $\text{NaOH}$ ) is often used in remote locations (e.g., where electricity is unavailable), and in low flow, high acidity situations. It is commonly the chemical of choice if Mn concentrations in the AMD are high. The system can be gravity fed by dripping liquid  $\text{NaOH}$  directly into the AMD. Caustic is very soluble in water, disperses rapidly, and raises the pH of the water quickly. Caustic should be applied at the surface of ponds because the chemical is denser than water. The major drawbacks of using liquid  $\text{NaOH}$  for AMD treatment are high cost and dangers in handling.

## **Ammonia**

Ammonia or sometimes called anhydrous ( $\text{NH}_3$  or  $\text{NH}_4\text{OH}$ ) is an extremely hazardous chemical that must be handled carefully. A gas at ambient temperatures,  $\text{NH}_3$  is compressed and stored as a liquid but returns to the gaseous state when released. Ammonia is extremely soluble in water and reacts rapidly. It behaves as a strong base and can easily raise the pH of receiving water to 9.2. At pH 9.2, it buffers the solution to further pH increases, and therefore very high amounts of  $\text{NH}_3$  must be added to elevate the pH beyond 9.2. Injection of  $\text{NH}_3$  into AMD is one of the quickest ways to raise water pH. It should be injected near the bottom of the pond or water inlet because  $\text{NH}_3$  is lighter than water. The most promising aspect of using  $\text{NH}_3$  for AMD treatment is its cost and cost reduction figures of 50% to 70% are usually realized when  $\text{NH}_3$  is substituted for  $\text{NaOH}$  (Skousen et al., 1990). Major disadvantages of using  $\text{NH}_3$  include 1) the hazards associated with handling the chemical, 2) the uncertainty concerning nitrification, denitrification, and acidification downstream, and 3) the consequences of excessive application rates.

## **Costs of treating AMD**

Costs were developed for five AMD treatment chemicals under four sets of flow and acid concentration conditions (Table 2, from Skousen et al., 2000). Use of  $\text{Na}_2\text{CO}_3$  had the highest labor requirements (10 hours per week) because the dispensers must be filled by hand and inspected frequently. Caustic had the

highest reagent cost per mole of acid-neutralizing capacity and Na<sub>2</sub>CO<sub>3</sub> had the second highest. Hydrated lime treatment systems had the highest installation costs of the five technologies because of the need to construct a lime treatment plant and install a pond aerator. However, the cost of Ca(OH)<sub>2</sub> was very low. The combination of high installation costs and low reagent cost made Ca(OH)<sub>2</sub> systems particularly appropriate for long-term treatment of high-flow/high-acid situations.

For a five-year treatment period, NH<sub>3</sub> had the lowest annual cost for the low flow/low acid situation (Table 10). Pebble quicklime was only about \$160 per year more expensive than the NH<sub>3</sub> system but had lower reagent and higher installation costs. Caustic was third because of its high labor and reagent costs, and Na<sub>2</sub>CO<sub>3</sub> was fourth due to high labor costs. Hydrated lime was the most expensive because of its high installation costs. With the intermediate flow and acid cases, NH<sub>3</sub> and CaO systems were by far the most cost effective, with Ca(OH)<sub>2</sub> and Na<sub>2</sub>CO<sub>3</sub> next. Caustic was the most expensive alternative at this intermediate-flow and intermediate-acidity condition. In the high-flow/high-acidity category, the Ca(OH)<sub>2</sub> and CaO systems were clearly the least costly treatment systems, with annual costs of about \$250,000 less than NH<sub>3</sub>, the next best alternative.

<b>Flow and Acidity Conditions</b>					
<b>Flow (L/min)</b>		<b>189</b>	<b>3780</b>	<b>945</b>	<b>3780</b>
<b>Acidity (mg/L)</b>		<b>100</b>	<b>100</b>	<b>500</b>	<b>2500</b>
<b>Chemical</b>					
<b>Soda Ash</b>					
	reagent costs	\$3,731	\$44,000	\$58,300	\$1,166,000
	Repair costs	\$0	\$0	\$0	\$0
	annual labor	\$14,040	\$14,040	\$14,040	\$14,040
	Installation costs	\$229	\$229	\$229	\$229
	Salvage value	\$0	\$0	\$0	\$0
	Net present value	\$75,052	\$224,679	\$245,774	\$4,911,804
	Annual cost	<b>\$17,817</b>	<b>\$58,086</b>	<b>\$58,346</b>	<b>\$1,166,046</b>
<b>Ammonia</b>					
	Reagent costs	\$2,543	\$22,440	\$28,050	\$561,000
	Repair costs	\$495	\$495	\$495	\$495
	Tank rental	\$480	\$120	\$120	\$120
	annual labor	\$7,020	\$7,020	\$7,020	\$7,020
	electricity	\$600	\$600	\$600	\$600
	Installation costs	\$1,936	\$6,357	\$6,357	\$6,357
	Salvage value	\$0	\$0	\$0	\$0
	Net present value	\$48,547	\$139,117	\$162,749	\$2,407,752
	Annual cost	<b>\$11,525</b>	<b>\$33,026</b>	<b>\$38,636</b>	<b>\$571,586</b>

(Continued)

<b>Table 10 (Concluded)</b>				
<b>Caustic Soda (20%)</b>				
Reagent costs	\$5,174	\$79,341	\$99,176	\$1,983,520
Repair costs	\$0	\$0	\$0	\$0
annual labor	\$7,020	\$7,020	\$7,020	\$7,020
Installation costs	\$283	\$5,478	\$5,478	\$5,478
Salvage value	\$0	\$0	\$0	\$0
Net present value	\$51,601	\$368,398	\$451,950	\$8,389,433
Annual cost	<b>\$12,250</b>	<b>\$87,457</b>	<b>\$107,292</b>	<b>\$1,991,636</b>
<b>Pebble Quicklime</b>				
Reagent costs	\$1,478	\$9,856	\$12,320	\$246,400
Repair costs	\$500	\$2,500	\$2,500	\$10,000
annual labor	\$6,500	\$11,200	\$11,200	\$11,200
electricity	\$0	\$0	\$0	\$0
installation costs	\$16,000	\$80,000	\$80,000	\$120,000
salvage value	\$0	\$5,000	\$5,000	\$20,000
Net present value	\$49,192	\$162,412	\$172,790	\$1,127,200
Annual cost	<b>\$11,678</b>	<b>\$38,556</b>	<b>\$41,020</b>	<b>\$267,600</b>
<b>Hydrated Lime</b>				
reagent costs	\$814	\$3,768	\$12,210	\$244,200
repair costs	\$1,000	\$3,100	\$3,500	\$10,500
annual labor	\$6,500	\$11,232	\$11,232	\$11,232
electricity	\$3,500	\$11,000	\$11,000	\$11,000
installation costs	\$58,400	\$102,000	\$106,000	\$200,000
salvage value	\$5,750	\$6,500	\$7,500	\$25,000
Net present value	\$94,120	\$228,310	\$242,809	\$1,313,970
Annual cost	<b>\$22,344</b>	<b>\$54,200</b>	<b>\$57,642</b>	<b>\$311,932</b>
*The analysis is based on a 5-yr operation period and includes chemical reagent costs, installation and maintenance of equipment, and annual operating costs. The <Bulk chemical prices in Table 10 were used to calculate the reagent costs for only the 189 L/min flow. The Bulk prices were used for higher flows. Neutralization efficiencies were not included in the reagent cost calculation.				

### Acid mine drainage treatment flocs

After chemical treatment, the treated water flows into sedimentation ponds so metals in the water can precipitate. Dissolved metals precipitate from AMD as a loose, open-structured mass of tiny grains called "floc." All chemicals currently used in AMD treatment cause the formation of metal hydroxide sludge or floc. Sufficient residence time of the water, which is dictated by pond size and depth, is important for adequate metal precipitation. The amount of metal floc generated by AMD neutralization depends on the quality and quantity of water being treated, which in turn determines how often the ponds must be cleaned. Knowing the chemical and AMD being treated will help determine the general floc properties and will provide an estimate of the stability of the various metal compounds in the floc. Floc disposal options include: 1) leaving the floc

submerged in a pond indefinitely, 2) pumping or hauling floc from ponds to abandoned deep mines or to pits dug on surface mines, and 3) dumping floc into refuse piles. Floccs pumped onto the surface of land and allowed to age and dry is a good strategy for disposal. In its oxidized and dried condition, AMD floccs can become crystalline and become part of the soil.

Each AMD is unique and the chemical treatment of any particular AMD source is site specific. Each AMD source should be tested with various chemicals by titration tests to evaluate the most effective chemical for precipitation of the metals. The costs of each AMD treatment system based on neutralization (in terms of the reagent cost, capital investment and maintenance of the dispensing system) and floc disposal should be evaluated to determine the most cost effective system.

## **Passive Treatment of Acid Mine Drainage**

Active chemical treatment of AMD to remove metals and acidity is often an expensive, long-term proposition. In recent years, a variety of passive treatment systems have been developed that do not require continuous chemical inputs and that take advantage of naturally-occurring chemical and biological processes to cleanse contaminated mine waters. Passive technologies include constructed wetlands, anoxic limestone drains (ALD), vertical flow wetlands (VFW, formerly called successive alkalinity-producing systems (SAPS)), limestone ponds, open limestone channels (OLC), and alkaline leach beds. In low-flow and low-acidity situations, passive systems can be reliably implemented as a single permanent solution for some AMD problems to meet effluent limits.

### **Aeration**

As mentioned under chemical treatment, aeration is the process of introducing air into water. With alkaline mine water that contains metals, simple aeration and metal floc settling is all that is needed for water treatment. No chemical addition is needed and the water can be discharged safely without polluting receiving streams after metals are settled in a pond. Therefore, some treatment situations with this type of water simply require a channel for aeration and a pond for metal floc settling.

### **Constructed Wetlands**

Aerobic wetlands consist of *Typha* and other wetland vegetation planted in shallow (<30cm), relatively impermeable sediments comprised of soil, clay or mine spoil. Anaerobic wetlands consist of *Typha* and other wetland vegetation planted into deep (>30cm), permeable sediments comprised of soil, peat moss, spent mushroom compost, sawdust, straw/manure, hay bales, or a variety of other organic mixtures, which are often underlain or admixed with limestone. Mechanisms of metal retention within wetlands, listed in order of importance, include: 1) formation of metal oxides and oxyhydroxides, 2) formation of metal sulfides, 3) organic complexation reactions, 4) exchange with other cations on negatively-charged sites, and 5) direct uptake by living plants. Other mechanisms

may include physical filtration of suspended metal colloids and adsorption/exchange of metals onto algal mats. Other beneficial reactions in wetlands include generation of alkalinity due to microbial mineralization of dead organic matter, microbial dissimilatory reduction of Fe oxyhydroxides and  $\text{SO}_4$ , and dissolution of carbonates.

Aerobic wetlands promote metal oxidation and hydrolysis, thereby causing precipitation and physical retention of Fe, Al, and Mn oxyhydroxides, much like sedimentation structures. Successful metal removal depends on dissolved metal concentrations, dissolved oxygen content, pH and net acidity of the mine water, the presence of active microbial biomass, and detention time of the water in the wetland. The pH and net acidity/alkalinity of the water are particularly important because pH influences both the solubility of metal hydroxide precipitates and the kinetics of metal oxidation and hydrolysis. Therefore, aerobic wetlands are best used in conjunction with water that contains net alkalinity, and the wetland serves primarily as a metal-floc collection and retention structure.

Anaerobic wetlands promote metal oxidation and hydrolysis in aerobic surface layers, but primarily rely on chemical and microbial reduction reactions to precipitate metals and neutralize acidity. The water infiltrates through a thick, permeable organic subsurface sediment that becomes anaerobic due to high biological oxygen demand. Several other treatment mechanisms function beyond those in aerobic wetlands, including metal exchange reactions, formation and precipitation of metal sulfides, microbially-generated alkalinity due to reduction reactions, and continuous formation of carbonate alkalinity due to limestone dissolution under anoxic conditions. Since anaerobic wetlands produce alkalinity, their use can be extended to poor quality, net acidic, low pH, high Fe, and high dissolved oxygen ( $>2$  mg/L) AMD. Microbial mechanisms of alkalinity production are of critical importance to long-term AMD treatment. When wetlands receive high acid loads ( $>300$  mg/L), the pH sensitive microbial activities are eventually overwhelmed. Therefore, like their aerobic counterparts, anaerobic wetlands are most successful when used to treat small AMD flows of moderate water quality. At present, the sizing value for Fe removal in anaerobic wetlands is 10 grams per day per meter squared of wetland area (Hedin and Nairn, 1992).

Sorption onto organic materials (such as peat and sawdust) can initially remove 50 to 80% of the metals in AMD (Brodie et al., 1988), but the exchange capacity of substrates decline with time. Over the long term, metal hydroxide precipitation is the predominant form of metal retention in a wetland. Weider (1993) reported up to 70% of the Fe in a wetland to be composed of  $\text{Fe}^{+3}$  oxyhydroxides, while up to 30% of the Fe retained in wetlands may be found as reduced Fe and combined with sulfides (Weider, 1992).

### **Anoxic limestone drains**

Anoxic limestone drains (ALDs) are buried cells or trenches of limestone into which anoxic water is introduced. The limestone dissolves in the acid water, raises pH, and adds alkalinity. Under anoxic conditions, the limestone does not coat or armor with Fe hydroxides because  $\text{Fe}^{+2}$  does not precipitate as  $\text{Fe}(\text{OH})_2$  at pH 6.0. Faulkner and Skousen (1994) reported both successes and failures among

11 ALDs treating mine water in West Virginia. In all cases, water pH was raised after ALD treatment but three of the sites had pH values <5.0, indicating that the ALD was not fully functioning. When working correctly, the pH values of water in ALDs should achieve 6.0. Water acidity in these drains decreased 50 to 80%, but Fe and Al concentrations in the outflow, unfortunately, were also decreased. Ferric iron and Al will precipitate as hydroxides at this pH and, with Fe and Al decreases in outflow water, it is probable that some coating or clogging of limestone occurred inside the ALD.

Longevity of treatment is a major concern for ALDs, especially in terms of water flow through the limestone. Eventual clogging of the limestone pore spaces with precipitated Al and Fe hydroxides, and gypsum is predicted (Nairn et al., 1991). For optimum performance, no  $\text{Fe}^{+3}$ , dissolved oxygen (DO), or Al should be present in the AMD. Selection of the appropriate water and environmental conditions is critical for long-term alkalinity generation in an ALD. Like wetlands, ALDs may be a solution for AMD treatment for specific water conditions or for a finite period after which the system must be replenished or replaced.

### **Vertical Flow Wetlands**

In Vertical Flow Wetlands (VFW), acid water, from 1 to 3 m, is ponded over an organic compost of 0.2 to 0.3 m, which is underlain by 0.5 to 1 m of limestone (Kepler and McCleary, 1994). Below the limestone is a series of drainage pipes that convey the water into an aerobic pond where metals are precipitated. The hydraulic head drives ponded water through the anaerobic organic compost, where oxygen stripping as well as Fe and sulfate reduction can occur prior to water entry into the limestone. Water with high metal loads can be successively cycled through additional VFWs. Iron and Al clogging of limestone and pipes can be removed by flushing the system (Kepler and McCleary, 1997). Various results have been obtained with these passive systems, but VFW have shown successful treatment in a number of cases.

### **Open limestone channels**

Open limestone channels (OLCs) are another means of introducing alkalinity to acid water (Ziemkiewicz et al., 1994). Past assumptions have held that armored limestone (limestone covered or coated with Fe or Al hydroxides) ceases to dissolve. Ziemkiewicz et al. (1997) found armored limestone to be 50 to 90% effective in neutralizing acid compared to unarmored limestone, and seven OLCs in the field reduced acidity in AMD by 4 to 62% compared to a 2% acid reduction in a sandstone channel. Open limestone channels show promise for neutralizing AMD in watershed restoration projects and AML reclamation projects where one-time installation costs are incurred, little to no maintenance is required, and systems do not have to meet specific water quality standards. Long channels of limestone can be used to convey acid water to a stream or other discharge point. Based on flows and acidity concentrations, cross sections of stream channels (widths and heights) can be designed with calculated amounts of limestone (which will become armored) to treat the water. Open limestone channels work best where the channel is constructed on steep slopes (>20%) and where flow velocities keep metal hydroxides in suspension, thereby limiting their



precipitation and plugging of limestone pores in the channel. Utilizing OLCs with other passive systems can maximize treatment and metal removal. If constructed correctly, OLCs should be maintenance free and provide AMD treatment for decades.

### **Limestone ponds**

Limestone ponds can be constructed over an AMD upwelling, seep or underground mine discharge. Limestone is placed in the bottom of the pond and the water flows upward through the limestone. Based on the topography of the area and how the water emanates from the ground, the pond can be built to pond water from 1 to 3 m deep or deeper, containing 0.3 to 1 m of limestone immediately overlying the seep. The pond should be sized and designed to retain the water for 12 to 24 hrs for maximum limestone dissolution, and to keep the seep and limestone under water. If limestone coating occurs by Al or Fe hydroxides, the limestone in the pond could be periodically disturbed with a backhoe to either uncover the limestone or to knock or scrape off the precipitates. If the limestone is exhausted by dissolution, then a load of fresh limestone can be dumped into the pond over the seep.

### **Alkaline leach beds**

Alkaline leach beds are ponds or cells filled with limestone. In their first usage, acid water with no metals was introduced into limestone-filled ponds. The slightly acid water causes limestone dissolution, which causes small amounts of alkalinity to be added to the water (usually in the 50 to 75 mg/L as CaCO<sub>3</sub> range). The alkalinity in the water can then buffer the stream when AMD or other pollution sources enter downstream. In several cases where limestone-filled alkaline leach beds were installed, fisheries have been re-established.

In situations where large metal and acid loads enter downstream, the upstream water must be charged with greater levels of alkalinity. Steel slag, a by-product and waste from the making of steel, contains high levels of alkalinity that are released into water. Alkaline leach beds can be filled with steel slag, which can generate much higher alkalinities in water (as much as 2,000 mg/L as CaCO<sub>3</sub>). Sites where these high alkalinities are generated in water must be carefully selected, because greater damage than good can be done if water is not balanced. The amount of alkalinity delivered to the stream has much to do with the load generated, so greater water flows can introduce much greater quantities of alkalinity.

## **Design Criteria for Passive AMD Treatment Systems**

### **Open limestone channels**

#### **Application**

- Terrain: steep
- Impact: generally uses stream channels

- Water quality: strongly acidic, oxidized AMD
- Reliability: high
- Maintenance: very low
- Efficiency: low
- Unit cost: low

**Conditions**

- Grade: should exceed 10%
- Space requirement: extensive, channel lengths generally exceed 1,000 ft.
- Safety: channel and limestone rip rap sized to resist major flood
- Design factor: Increases with decreasing slope, Fe concentration

Open Limestone Channels (OLC) are placed directly in the stream to add alkalinity and provide a convenient location for metal precipitation. Figure 5 shows the general layout of an OLC.

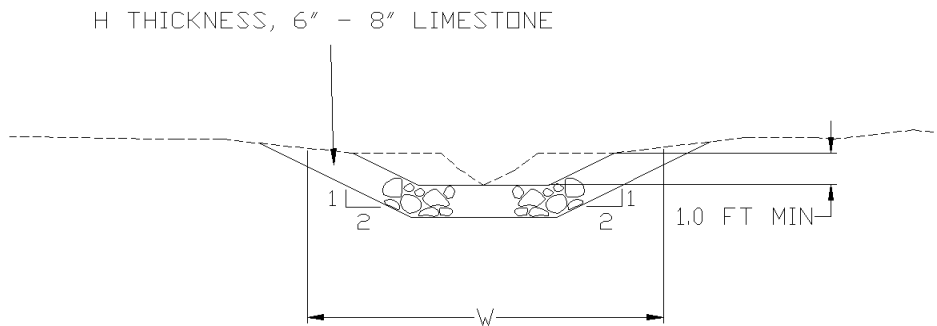


Figure 5. General cross-section layout of an open limestone channel.

The design of an OLC is based upon the limestone’s residence time. When one knows the existing and desired post-treatment total acidity, the design equations are as follows:

$$T = \frac{-S}{2.303} \ln \left( \frac{C_f}{C_o} \right) \tag{1}$$

- Where:
- $T$  = Required residence time, hours.
  - $C_o$  = Pre-treatment total acidity, mg/L  $\text{CaCO}_3$  equivalents.
  - $C_f$  = Post-treatment total acidity, mg/L  $\text{CaCO}_3$  equivalents.
  - $S$  = Design safety factor, normally between 5 and 10.

The effective cross-sectional area is calculated with the following formula. Because these design equations are intended to describe the behavior of the OLC during median flow conditions, the following formula does not take into account the geometric details of the OLC cross section or the effective depth of flow during high flow events. During high flow events, the following formula is invalid, but AMD treatment is not normally required during those conditions.

$$A_{CS} \approx HW \quad (2)$$

Where:

$H$	=	Height of the bottom to the top of the channel, ft.
$W$	=	Width of the bottom of the channel, ft.
$A_{CS}$	=	Effective cross-sectional area of channel, ft <sup>2</sup> .

The effective cross-sectional area is used to calculate the pore water velocity through the limestone channel.

$$V = \frac{Q}{n A_{CS}} \quad (3)$$

Where:

$Q$	=	Discharge flow rate of water through OLC, ft <sup>3</sup> /s.
$n$	=	Effective porosity (void ratio) of the OLC
$A_{CS}$	=	Void Volume / Total Volume $\approx$ 50%.
$V$	=	Pore water velocity, ft/s.

Because the goal of the OLC is to effectively reduce the acidity under a variety of flow conditions, the mean discharge flow rate should be used in equation (3). The required length of the channel is the required residence time, calculated with equation (1), multiplied by the pore water velocity through the limestone.

$$L = 3600TV \quad (4)$$

Where:

$L$	=	Length of the OLC, ft.
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The amount of limestone required for the OLC can then be calculated.

$$M = \gamma_{LS}(L)(A_{CS})(1 - n) \quad (5)$$

Where:

$\gamma_{LS}$	=	Particle density of the limestone, tons/ft <sup>3</sup> .
$A_{CS}$	$\approx$	0.0845 tons/ft <sup>3</sup> .
$M$	=	Amount of limestone required, tons.

The cost of the OLC can then be calculated from the placement cost of the limestone.

$$O = MU_{LS} \quad (6)$$

Where:  $U_{LS}$  = Unit cost of placing the limestone in the OLC, \$/ton.  
 $O$  = Total cost of the OLC minus site specific costs, \$.

The limestone consumption rate can be calculated from the change in total acidity and the discharge flow rate through the OLC.

$$R_{LS} = 0.98521 Q(C_o - C_f)P_{LS} \quad (7)$$

Where:  $P_{LS}$  = Purity of the limestone ( $\text{CaCO}_3$  content by wt).  
 $\geq 85\%$ .  
 $R_{LS}$  = Limestone consumption rate, tons/year.

Finally, the percent reduction in total acid load being transported by the stream is calculated with the pre-treatment and post-treatment total acidity levels.

$$P = 100\% \frac{C_o - C_f}{C_o} \quad (8)$$

Where:  $P$  = Percent reduction in the total acid load, %.

When one desires to know the post-treatment total acidity from an existing OLC, the residence time of the OLC is first calculated.

$$T = \frac{LA_{CS}n}{3600Q} \quad (9)$$

Then equation (1) is rearranged to yield the post-treatment total acidity.

$$C_f = C_o \exp\left(\frac{-2.303T}{S}\right) \quad (10)$$

The freeboard for the OLC (1.0 ft minimum in Figure 5) should be selected large enough so the OLC is not overtopped during moderately large flood events (i.e. 100-year return period). Similarly, the diameter of the limestone (6 - 8 inches in Figure 5) should be selected large enough so that the OLC is stable during similarly large flood events.

## Limestone leach beds

Limestone Leach Beds (LLB) are normally employed to add buffering capacity to a stream above AMD seeps. Figure 6 contains the general layout of a LLB.

### Application

- Terrain: variable
- Impact: low, placed immediately below AMD source
- Water quality: pH<2.8, strongly acidic, oxidized or reduced AMD
- Reliability: high
- Maintenance: very low
- Efficiency: low, designed to remove about 50% of acidity
- Unit cost: low

### Conditions

- Grade: flat
- Space requirement: small, size for about 1.5 hours of residence time
- Safety: off channel installation, few safety issues
- Design factor: none

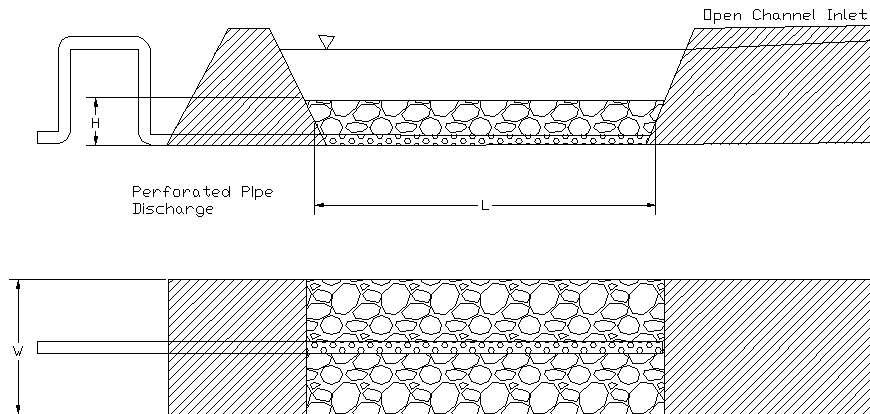


Figure 6. General layout of a limestone leach bed.

Like an OLC, the design of LLB is based upon the residence time. The residence time is calculated by dividing the void volume by the discharge flow rate.

$$T = \frac{LHWn}{3600Q} \quad (11)$$

Where:

$L$	=	Length of the LLB, ft.
$H$	=	Depth of the LLB, ft.
$W$	=	Width of the LLB, ft.

$n$	=	Effective limestone porosity (void ratio).
	=	Void Volume / Total Volume.
	$\approx$	50%.
$Q$	=	Discharge flow rate, ft <sup>3</sup> /s.
$T$	=	Residence time of the LLB, hrs.

The net alkalinity of the water leaving the LLB is calculated by the following formula.

$$C_f = C_m \left( 1 - \exp\left(\frac{-T}{5.5}\right) \right) \quad (12)$$

Where:	$C_m$	=	Maximum possible discharge net alkalinity, mg/L CaCO <sub>3</sub> equivalents.
		=	80 mg/L CaCO <sub>3</sub> for open top LLB.
		=	200 mg/L CaCO <sub>3</sub> for closed top LLB.
	$C_f$	=	Discharge net alkalinity, mg/L CaCO <sub>3</sub> .

The amount of limestone required for the LLB can be calculated from the dimensions.

$$M = \gamma_{LS}(L)(H)(W)(1 - n) \quad (13)$$

Where:	$\gamma_{LS}$	=	Particle density of the limestone, tons/ft <sup>3</sup> .
		$\approx$	0.0845 tons/ft <sup>3</sup> .
	$M$	=	Amount of limestone required, tons.

The cost of the LLB can then be calculated from the placement cost of the limestone.

$$O = MU_{LS} \quad (14)$$

Where:	$U_{LS}$	=	Unit cost of placing the limestone in the LLB, \$/ton.
	$O$	=	Total cost of the LLB minus site specific costs, \$.

The limestone consumption rate can be calculated from the change in net alkalinity and the discharge flow rate through the LLB.

$$R_{LS} = 0.98521 Q(C_f - C_o)P_{LS} \quad (15)$$

Where:	$R_{LS}$	=	Limestone consumption rate, tons/year.
	$C_o$	=	Alkalinity of the water entering LLB, mg/L CaCO <sub>3</sub> equivalents.
	$P_{LS}$	=	Limestone purity (CaCO <sub>3</sub> content by wt.).

$$\geq 85\%$$

Finally, the percent reduction in total acid load being transported by the stream is calculated with the pre-treatment and post-treatment net alkalinity levels.

$$P = 100\% \frac{C_o - C_f}{C_o} \quad (16)$$

Where:  $P$  = Percent increase in net alkalinity load, %.

### Slag leach beds

Slag Leach Beds (SLB) are also employed to add alkalinity upstream of AMD seeps. The general layout of a SLB is shown in Figure 7.

#### Application

- Terrain: flat to moderate slopes
- Impact: may be installed off channel or near heads of drainage.
- Water quality: must be free of metals
- Reliability: high
- Maintenance: moderate, short life (3-5 years)
- Efficiency: high
- Unit cost: low

#### Conditions

- Grade: <5%
- Space requirement: small
- Safety: generates strongly alkaline, pH water (10 or higher)
- Design factor: none, must keep soluble metals and sediment out of source water

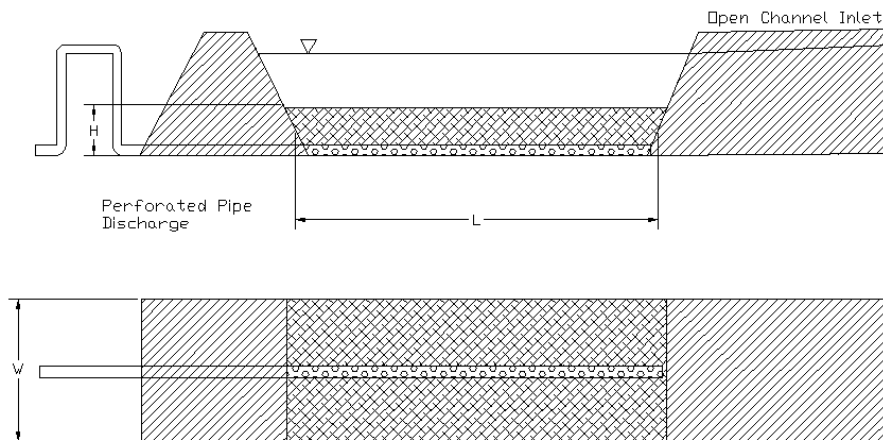


Figure 7. General layout of a slag leach bed.

The maximum infiltration rate for the SLB can be calculated with the following empirical formula, which was derived from the results of column experiments at WVU.

$$I = \frac{1}{5H^{1.4}} \quad (17)$$

Where:  $H$  = Depth of the SLB, ft.  
 $I$  = Maximum infiltration rate, gal/min/ft<sup>2</sup>.

The required surface area for the SLB can be calculated from the maximum infiltration rate.

$$A_s = \frac{QS}{I} \quad (18)$$

Where:  $Q$  = Discharge flow rate through SLB, gal/min.  
 $S$  = Design safety factor, normally between 5 and 10.  
 $A_s$  = Required surface area, ft<sup>2</sup>.  
=  $L(W)$ .

The net alkalinity load produced by the SLB can be calculated with the discharge flow rate and the discharge net alkalinity.

$$L_{ALK} = 0.0022 Q C_f \quad (19)$$

Where:  $C_f$  = Discharge net alkalinity, mg/L CaCO<sub>3</sub> equivalents.



$$L_{ALK} \approx 2000 \text{ mg/L CaCO}_3 \text{ equivalents.}$$

$$L_{ALK} = \text{Net alkalinity load produced by the SLB, tons/year.}$$

The amount of steel slag required for the SLB can be calculated from the dimensions.

$$M = \gamma_{SLB}(A_S)(H) \quad (20)$$

Where:

$$\gamma_{SLB} = \text{Bulk density of the steel slag, tons/ft}^3.$$

$$\approx 0.05 \text{ tons/ft}^3.$$

$$M = \text{Amount of steel slag required, tons.}$$

The cost of the SLB can then be calculated from the placement cost of the steel slag.

$$O = MU_{SLB} \quad (21)$$

Where:

$$U_{SLB} = \text{Unit cost of placing the steel slag in the SLB, \$/ton.}$$

$$O = \text{Total cost of the SLB minus site specific costs, \$}.$$

The expected lifetime of the SLB can be estimated from the residence time of the SLB.

$$T_{SLB} = K T = K \frac{A_S H n}{70306.1 Q} \quad (22)$$

Where:

$$T_{SLB} = \text{Expected lifetime of the SLB, yrs.}$$

$$T = \text{Residence time of the SLB, yrs.}$$

$$K = \text{Expected number of pore water volumes that can pass through before alkalinity is expended.}$$

$$\approx 1600.$$

$$n = \text{Effective porosity (void ratio) of the SLB.}$$

$$\approx 47 \pm 5\%.$$

Finally, the percent increase in net alkalinity load being transported by the stream is calculated with the pre- and post-treatment net alkalinity levels.

$$P = 100\% \frac{C_o - C_f}{C_o} \quad (23)$$

Where:

$$P = \text{Percent increase in net alkalinity load, \%}.$$

## Vertical Flow Wetlands

Vertical Flow Wetlands (VFW) are used to treat AMD in a series of steps. Figure 8 is a profile view of one step of a SAPS. Because sulfate reduction can be achieved with VFWs, VFWs are sometimes referred to as Reducing and Alkalinity Producing Systems (RAPS).

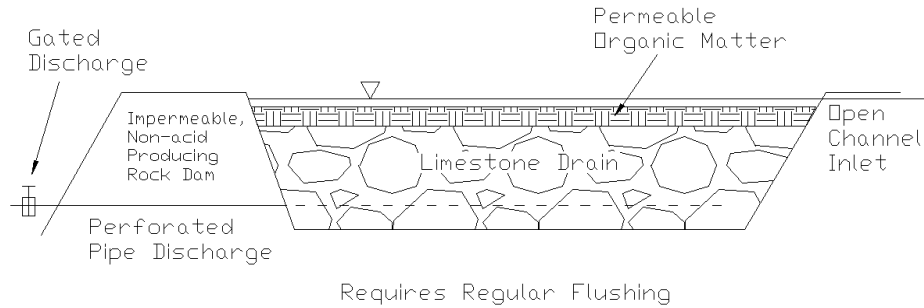


Figure 8. Profile view of one step in a successive alkalinity producing system.

## Anoxic limestone drains

Anoxic Limestone Drains (ALD) are used to add alkalinity to the water being discharged from an abandoned mine in the absence of ferric iron, aluminum and oxygen in the discharged water. The general layout of an ALD is shown in Figures 9 and 10.

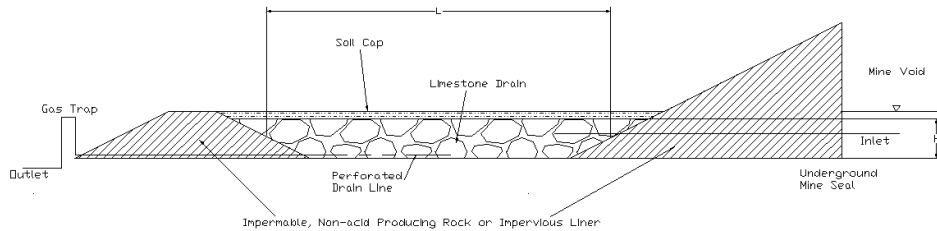


Figure 9. Profile view of an anoxic limestone drain.

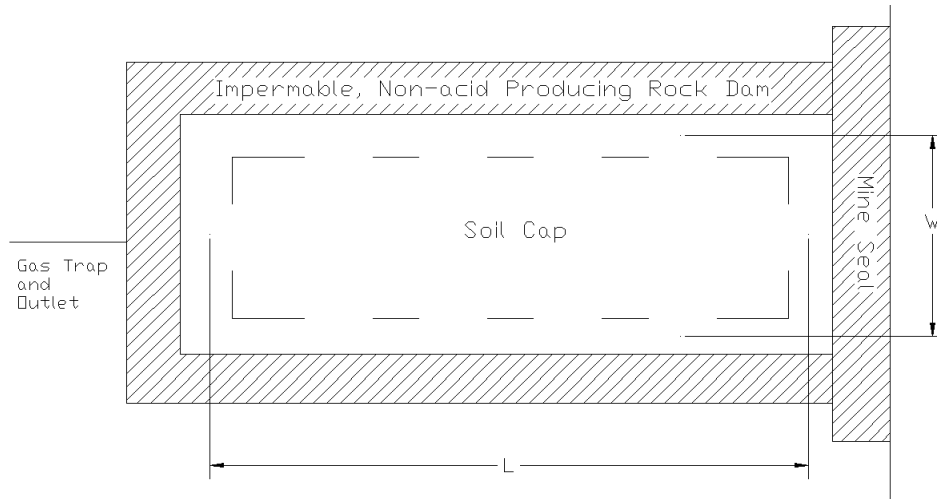


Figure 10. Plan view of an anoxic limestone drain.

### Design equations for ALD and VFWs

The basic design of ALD and VFWs are identical, and the procedure is outlined below. Like the design of other passive treatment systems that use limestone, the design of an ALD or VFWs is based upon the residence time.

For the purposes of this report, ALD and VFWs are designed to neutralize acidity only. In many cases, positive alkalinity will be generated, but the creation of positive alkalinity is not included in the design equations, because this process is not reliable. Therefore, the following formula can be used to calculate the required residence time.

$$T = \frac{-S}{2.303} \ln \left( \frac{C_f}{C_o} \right) \quad (24)$$

Where:	$T$	=	Residence time of the structure, hrs. ≥ 30 hrs.
	$S$	=	Design safety factor.
	$C_f$	=	Post-treatment net acidity, mg/L CaCO <sub>3</sub> equivalents.
	$C_o$	=	Pre-treatment net acidity, mg/L CaCO <sub>3</sub> equivalents.

The pore water velocity through the limestone in the ALD or SAPS can be calculated with the following formula.

$$V = \frac{Q}{HWn} \quad (25)$$

Where:	$V$	=	Pore water velocity, ft/s.
	$Q$	=	Discharge flow rate, ft <sup>3</sup> /s.

$H$	=	Height of the limestone in the structure, ft.
$W$	=	Average width of the limestone in the structure, ft.
$n$	=	Effective porosity (void ratio) of the limestone.
	=	Void Volume / Total Volume.
	$\approx$	50%.

The residence time and pore water velocity can then be used to calculate the required average length of the ALD or SAPS.

$$L = \frac{3600VT}{P_{LS}} \quad (26)$$

Where:	$P_{LS}$	=	Limestone purity (CaCO <sub>3</sub> content by wt).
		$\geq$	85%.
	$L$	=	Average length of limestone in treatment structure, ft.

The amount of limestone required for the ALD or SAPS can be calculated from the dimensions.

$$M = \gamma_{LS}(L)(H)(W)(1 - n) \quad (27)$$

Where:	$\gamma_{LS}$	=	Particle density of the limestone, tons/ft <sup>3</sup> .
		$\approx$	0.0845 tons/ft <sup>3</sup> .
	$M$	=	Amount of limestone required, tons.

The cost of the ALD or SAPS can then be calculated from the placement cost of the limestone.

$$O = MU_{LS} \quad (28)$$

Where:	$U_{LS}$	=	Unit cost of placing the limestone in structure, \$/ton.
	$O$	=	Total cost of structure minus site specific costs, \$.

The limestone consumption rate can be calculated from the change in net acidity and the discharge flow rate through the ALD or SAPS.

$$R_{LS} = 0.98521 Q(C_f - C_o)P_{LS} \quad (29)$$

Where:	$R_{LS}$	=	Limestone consumption rate, tons/year.
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$$P_{LS} = \begin{array}{l} \text{Limestone purity (CaCO}_3 \text{ content by} \\ \text{wt.).} \\ \geq 85\% \end{array}$$

Finally, the percent reduction in net acid load being released by the mine is calculated with the pre-treatment and post-treatment net acidity levels.

$$P = 100\% \frac{C_o - C_f}{C_o} \quad (30)$$

Where:  $P$  = Percent reduction in net acidity load, %.

Life cycle dissolution calculations were not included in these design equations because the mechanism by which the limestone dissolves, metallic ions precipitate, and bacterial colonies grow is chaotic and heavily dependent upon site specific conditions.

### Manganese oxidation beds

Manganese Oxidation Beds (MOB) are designed to facilitate the oxidation of manganese in the mine drainage. Figure 11 is a general profile view of a MOB.

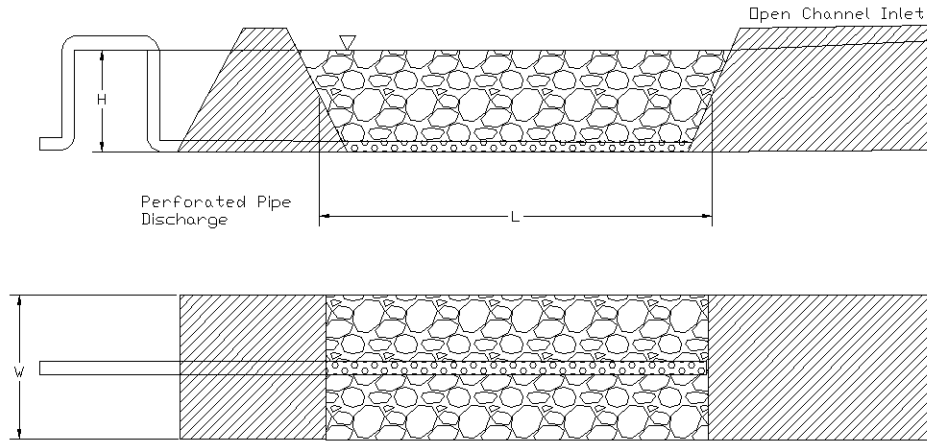


Figure 11. General profile view of a manganese oxidation bed.

Provided that the residence time of the designed MOB is greater than 5 hours, the amount of manganese removed from the mine drainage is a function of the discharge flow rate through the MOB. The pore water velocity is calculated with the following formula.

$$V = \frac{Q}{LWn} \quad (31)$$

Where:  $V$  = Pore water velocity, ft/s.

$Q$	=	Discharge flow rate through the MOB, ft <sup>3</sup> /s.
$H$	=	Height of the MOB, ft.
	≤	3 ft.
$L$	=	Length of the MOB, ft.
$W$	=	Width of the MOB, ft.
$n$	=	Effective porosity (void ratio) of the limestone.
	=	Void Volume / Total Volume.
	≈	50%.

The pore water velocity can then be employed to calculate the residence time of the MOB.

$$T = \frac{H}{3600V} \quad (32)$$

Where:	$T$	=	Residence time of the MOB, hours.
		≥	11 hours.

Provided that the residence time is sufficient, the following formula can then be used to calculate the discharge manganese concentration.

$$C_f = C_o \exp(1.1 - 0.7 \ln(Q)) \quad (33)$$

Where:	$C_o$	=	Manganese concentration of the mine drainage entering the MOB, mg/L.
	$C_f$	=	Manganese concentration of the water leaving the MOB, mg/L.

Which can then be employed to calculate the percent manganese removal by the MOB.

$$P = 100\% \frac{C_o - C_f}{C_o} \quad (34)$$

Where:	$P$	=	Percent manganese removal by MOB, %.
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The amount of limestone required for the MOB can then be calculated.

$$M = \gamma_{LS}(L)(H)(W)(1-n)(P_{LS}) \quad (35)$$

Where:	$\gamma_{LS}$	=	Particle density of the limestone, tons/ft <sup>3</sup> .
		≈	0.0845 tons/ft <sup>3</sup> .
	$M$	=	Amount of limestone required, tons.

$$\begin{aligned}
 P_{LS} &= \text{Limestone purity (CaCO}_3 \text{ content by wt.)} \\
 &\geq 85\%
 \end{aligned}$$

The cost of the MOB can then be calculated from the placement cost of the limestone.

$$O = MU_{LS} \quad (36)$$

Where:

$U_{LS}$	=	Unit cost of placing the limestone in the MOB, \$/ton.
$O$	=	Total cost of the MOB minus site specific costs, \$.

These systems rely on the colonization by manganese oxidizing organisms on the limestone. Both research and experience have indicated that these organisms are naturally occurring and will colonize the bed within six to eight weeks (Brant and Ziemkiewicz, 1997) and (Rose, Means, and Shah, 2003).

## Wetlands

Wetlands are normally classified according to the desired oxygen content of the mine drainage that passes through the wetland. Aerobic Wetlands (AW) are designed so that the water that passes through them is nearly saturated with dissolved oxygen. AW are used to facilitate the oxidation and sedimentation of any metals that may be in the discharge. Figure 12 is a general plan and profile view of an AW, and Figure 13 is a general cross-section view of an AW.

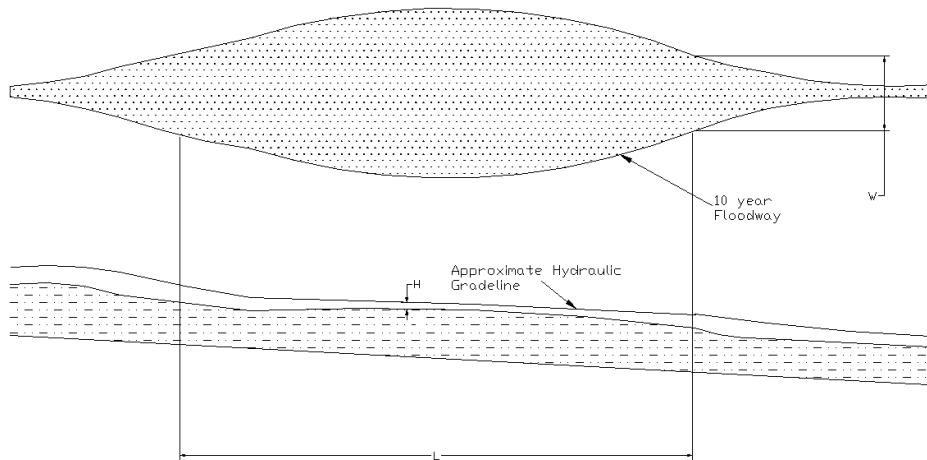


Figure 12. General plan and profile views of an aerobic wetland.

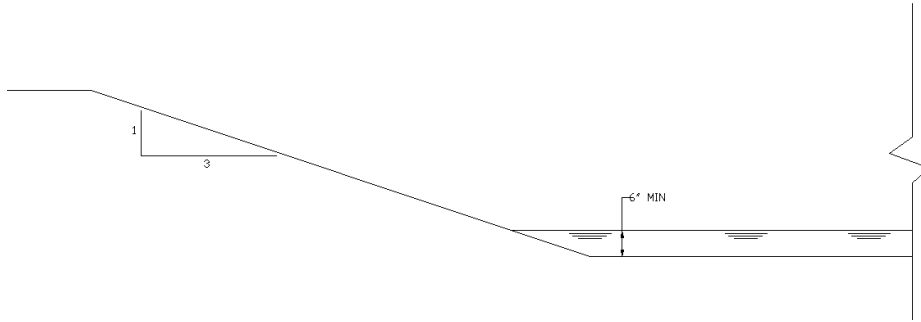


Figure 13. General cross-sectional view of an aerobic wetland.

Anaerobic Wetlands (ANW) are designed so that there is an anoxic zone in the body of water. ANW are used to facilitate the reduction of metals and to reduce the sulfate concentration of the mine drainage. ANW are characterized by the presence of decaying organic matter to maintain reducing conditions. Figures 14 and 15 are general profile and cross-sectional views of an ANW. Figure 15 contains limestone, which may or may not be present in an ANW.

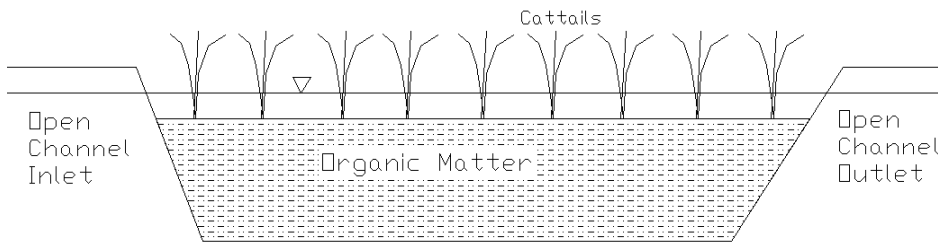


Figure 14. General profile view of an anaerobic wetland.

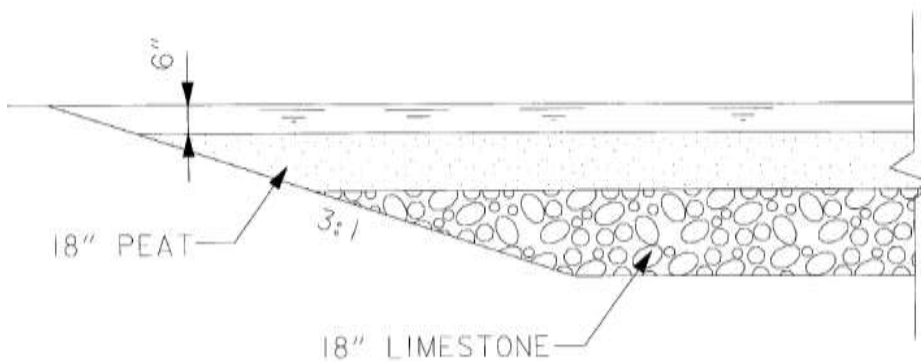


Figure 15. General cross-sectional view of an anaerobic wetland (under-drains may be present).

Both AW and ANW are sized according to the total iron load entering the wetland with the following formula.



$$A = 0.030 Q C_o \quad (37)$$

Where:	$A$	=	Required surface area of wetland, acres.
	$Q$	=	Discharge flow rate through wetland, ft <sup>3</sup> /s.
	$C_o$	=	Total iron concentration in the water entering the wetland, mg/L.

Hedin and Nairn (1992) recommend that wetlands (both aerobic and anaerobic) be sized according to 20 grams of iron removal per square meter of wetland per day. This corresponds to the coefficient 0.030 acres per cubic feet per second per mg per liter in the above equation.

## Summary

Acid mine drainage occurs when geologic materials containing metal sulfides are exposed to oxidizing conditions. Subsequent leaching of reaction products into surface waters pollute over 20,000 km of streams in the USA alone. Prediction of potential problem areas is necessary and can be done with overburden and mine soil analyses like the Acid-Base Account. On sites where a potential acid problem exists, special handling of overburden materials and quick coverage of acid-producing materials in the backfill should be practiced. Alkaline addition with materials such as kiln dust and FBC ash has shown favorable results in reducing or completely eliminating AMD problems. Placing acid-producing materials under dry barriers effectively isolates these materials from air and water. While not practiced much in the USA, placing acid-producing materials under water has shown good success in other regions where complete inundation is assured. Injection of alkaline materials into underground mines and buried pods of acid material in surface mine backfills, re-mining of abandoned areas, and alkaline recharge trenches show much promise as AMD control technologies.

Chemicals used for treating AMD are  $\text{Ca}(\text{OH})_2$ ,  $\text{CaO}$ ,  $\text{NaOH}$ ,  $\text{Na}_2\text{CO}_3$ , and  $\text{NH}_3$ . Each chemical has advantages for certain water conditions and treatment. Caustic is generally used when Mn is the primary element to be removed from the water. Under low-flow situations, all of the chemicals except  $\text{Ca}(\text{OH})_2$  are cost effective. Under high-flow situations,  $\text{Ca}(\text{OH})_2$  and  $\text{CaO}$  are clearly the most cost effective due to low reagent cost compared to the other chemicals. Floc, the metal hydroxides collected in ponds after chemical treatment, are disposed of in abandoned deep mines, refuse piles, or left in collection ponds.

Wetlands treat AMD by removing metals through formation of oxyhydroxides and sulfides, exchange and organic complexation reactions, and direct plant uptake. Aerobic wetlands are used when water contains enough alkalinity to promote metal precipitation. Anaerobic wetlands are designed when AMD contains no alkalinity, and alkalinity is generated in these systems by microbial sulfate reduction and limestone dissolution in anaerobic sediments. Anoxic limestone drains use limestone under anoxic conditions to generate

alkalinity. Under anoxia, limestone theoretically will not be coated or covered with  $\text{Fe}^{+3}$  hydroxides in the drain, decreasing the likelihood of clogging. Vertical Flow Wetlands pre-treat oxygenated AMD with organic matter to remove oxygen and  $\text{Fe}^{+3}$ . The water is then introduced into an ALD or limestone underneath the organic matter. Open limestone channels use limestone in aerobic environments to treat AMD. Coating of limestone occurs but the limestone continues to dissolve and the reduced effectiveness of limestone dissolution is designed into the AMD treatment system. Limestone ponds are built over underground AMD upwellings to treat water and precipitate metals. Alkaline leach beds can be used to treat water upstream of AMD inputs and, based on the amount of acidity introduced downstream, can be filled with limestone or slag. At present, most passive systems offer short-term treatment possibilities after which the system must be recharged or replaced. Further, few passive systems can assure specific discharge qualities and therefore are more practical for installation on abandoned sites or watershed restoration projects where effluent limits often do not apply and where some removal of acid and metals will benefit stream restoration.

# 8 Quantification Of Costs And Benefits

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## Introduction

Water issues have become increasingly popular in the United States. Since the introduction of the Clean Water Act in 1970, water quality and quantity are issues that are given considerable attention by public policy makers. With the advent of the Surface Mining Reclamation and Control Act of 1977, water quality issues from abandoned and active coal mines came to the forefront of public and industry attention. As detailed in early chapters, the field of AMD treatment has become rather robust. Many options exist for the treatment of AMD while many more technologies are still being developed. The focus of most research is on passive or indirect treatment methods. These are methods that do not require active pumping of water or chemicals to treat AMD. This chapter seeks to quantify the costs of the various treatment options while paying particular attention to passive treatment systems.

## Cost Engineering Approach

Since AMD treatment relies on engineering drawings and diagrams to detail the design of the treatment systems, the methods of cost engineering are quite useful in predicting and quantifying project costs. While other methods of cost estimation rely on accounting data, the cost engineering method uses data from the process. This eliminates the variability that may arise from varying accounting practices in an industry (Fletcher et al., 2001).

The engineering documents are key deliverables in determining the level of project definition, and thus the extent and maturity of estimate input information (AACE, 1997). The treatment systems can easily be divided into units and each unit cost determined separately. In order to complete this analysis, a complete understanding of the treatment system must exist. Various technologies are outlined in Chapter 6.

## Cost estimation and project planning

A quick estimation method that is used by the National Mine Land Reclamation Center relies on the mass balance of acidity approach. That is, the amount of alkaline material that is needed to treat the acid load in a mine discharge is calculated for one year. The acid load is simply the concentration of acidity in mg/L of Ca CO<sub>3</sub> equivalents multiplied by the flow and corrected to yield a unit of tons of acid per year. Equation 1 displays the full equation.

Once the tonnage of acidity for one year is known, the tonnage is multiplied by 10 to gain a ten-year life on the treatment system. The total tonnage of the alkalinity for ten years is then multiplied by the unit cost of the alkalinity. Table 1 gives assumed values for common alkaline sources used in passive treatment systems and the typical transportation charges. The total value of the ten-year tonnage is then multiplied by 80% to gain the estimated construction or placement cost. The alkaline material cost and the construction cost are summed to yield the estimated construction cost. This method is particularly useful when a determination can be made that passive treatment systems can be used at the site.

$$\begin{aligned} \text{Tons/year} = & \\ & \frac{[(\text{flow}(\text{gpm}) * 1440(\text{min}/\text{day}) * 3.785(\text{L}/\text{gal}) * 1000(\text{ml}/\text{L}) * \text{Acidity}(\text{mg}/\text{L}))]}{[1,000,000(\text{mg}/\text{L}) / 453.6(\text{g}/\text{lb}) / 2000(\text{lbs}/\text{ton}) * 365(\text{days}/\text{year})]} \end{aligned}$$

This equation can be simplified to Equation 2.

$$\text{Tons/year} = \text{flow}(\text{gpm}) * \text{Acidity}(\text{mg}/\text{L}) * 0.0022$$

The shipping charges in Table 1 can be highly variable due to the location of the treatment site. For instance, off-road conditions preclude the use of highway dump trailers. Highway dump trailers can haul more tonnage and are typically the most cost-effective trucking method. Tri-axle dump trucks, which can handle off-road conditions, are more expensive for long distance haul. This is usually the case when steel slag is used as the alkaline source. The steel slag originates in the Pittsburgh, PA, to Wheeling, WV, area. To overcome the high freight charges, the highway trailers will haul to a central location on or near the site and then the slag will be placed in smaller trucks or even bucket hauled to final placement. Typical delivered price for steel slag is \$20 +/- \$4. Barging is an option for steel slag delivery and will have to be priced on a case specific basis. Typical delivered price for limestone is \$15 +/- \$3.

## Scale of Management

The first step in deciding on treatment options is to determine the scale for the management of AMD in a watershed. A watershed is defined as a topographic area within which surface water runoff drains to a specific point on a stream (Fletcher et al., 2001). So, for the purpose of AMD treatment, is the objective to protect the main stem of the river, the main stem of the tributary

stream or the entire tributary to the headwater? Each of these scales (from basin, sub-basin to catchment) greatly affect the benefits that can be derived from AMD treatment and the point at where they can be measured. It should be noted that in many cases the AMD is so extreme that the headwater and tributary may not be able to be returned to a clean stream and may actually be part of the AMD treatment system. In this case, the scale of management decision has been made for the designer. As new techniques and technologies are derived, i.e., in-situ treatment schemes, the designer may have more options to return more miles of stream to a resource and not have them part of the treatment system.

## **Cost Benefit Analysis**

The broad purpose of Cost Benefit Analysis (CBA) is to assist in social decision-making. In the case of AMD treatment and the watershed approach, CBA will allow an agency to efficiently spend reclamation dollars where the greatest benefits can be realized. This approach assumes that the agency can use a performance-based standard to achieve improved water quality for a given watershed. Any combination of reclamation technologies and techniques outlined in previous chapters can be combined to treat the AMD from abandoned mine lands. Currently, water treatment from the active mining operations is managed with technology-based standards. The technologies are rather fixed (active treatment with the addition of chemicals, aeration and settling ponds). While the chemical can be altered, so that treatment is optimized, passive treatment systems which can be used on abandoned mine lands are unallowable for treatment within the active mining industry.

### **Method of cost benefit analysis, case studies**

(to be filled in at a later date)

### **Benefits**

(to be filled in at a later date)

### **Resource valuation (Dr. R. Rosenberger to assist)**

(to be filled in at a later date)

### **Overview of methods and current issues**

(to be filled in at a later date)

### **Use and nonuse values**

(to be filled in at a later date)

### **Nonmarket benefit estimation**

(to be filled in at a later date)

**Ability to place monetary values on watershed/ecosystem characteristics**

(to be filled in at a later date)

**A review of cost benefit analysis methods applicable to watersheds (attention paid to water uses described in previous chapters)**

(to be filled in at a later date)

# Appendix A

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