Acid Mine Drainage: Innovative Treatment Technologies

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NOTICE

FOREWORD

About the National Network for Environmental Management Studies (NNEMS) Program

The U.S. Environmental Protection Agency (EPA) established the NNEMS program in 1986 to foster a growing interest among higher education students in environmental careers. The NNEMS program is a comprehensive fellowship program that provides undergraduate and graduate students an opportunity to participate in a fellowship project that is directly related to their field of study. The NNEMS program is sponsored by EPA's Office of Environmental Education.

Students who are awarded NNEMS fellowships are offered a unique opportunity to gain research and training experience directly linked to their undergraduate or graduate studies. NNEMS fellows conduct research projects to augment their academic studies, which EPA supports with financial assistance.

Each year, the NNEMS program offers approximately 50 to 60 research projects, developed and sponsored by EPA Headquarters in Washington, D.C. and EPA's ten regional offices throughout the U.S. The projects allow students to conduct research while working full-time at EPA during the summer or part-time during the school year.

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Currently there is no comprehensive survey about the types of remediation technologies being used to treat abandoned mines. The purpose of this paper is to provide information about this topic with a particular focus on hard rock mining sites. Hard rock mines can be loosely defined as non-coal, metal mines, in the United States these mines are located in the Mid-West and Western states. This paper provides an overview of treatment technologies being used to remedy environmental problems at abandoned mine sites, with a focus on innovative treatment techniques.

1.0 Introduction

This report aims to identify abandoned mine sites that utilize innovative technologies to treat mine drainage or contaminated soils and to put that information into a database. Therefore, this paper is not a highly detailed description of a single technology, but rather an introduction to a variety of technologies currently used to treat mine sites in the country. A database was created to compliment this paper. It contains all of the case studies highlighted in this paper and quite a few other. It is available through the Technology Innovation Program website www.cluin.org. The goal of this database is to allow parties interested in implementing innovative treatments at AMD sites to learn from past successes and failures to advance these technologies.

A variety of sources were consulted to identify sites. Government agencies were the main targets as they are the most likely group to be addressing abandoned mines that presumably do not have a linked responsible party. Also, unlike consulting firms and private industry, i.e. the companies themselves, the government will generally disclose most technical information. The internet was used to look up information about the following agencies:

- Environmental Protection Agency - specifically the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, a.k.a. Superfund) and the Clean Water Act (CWA) programs;
- Department of the Interior - specifically the Office of Surface Mining, Bureau of Land Management (BLM), and United States Geological Survey (USGS);
- State environmental departments;
- Local environmental committees and community groups.

Another research avenue was grant distributions from CWA programs to local organizations. For example, Pennsylvania's Growing Greener grant program funds many Abandoned Mine Land (AML) reclamation efforts in the name of improving local watersheds. This did not prove beneficial for every state. Where possible individuals were contacted through email and telephone for more specific information about programs and sites. As with any project an extensive literature review was done. Science Direct was searched, the Library of Congress catalog and on-line databases were also utilized and numerous conference proceedings were perused.

Due to the universe of abandoned mines, constantly evolving programs and projects this report does not imply a complete picture of all projects and programs in the nation. The report is, however, a start toward understanding what technologies are being used and some of the barriers

to remediation, especially for non-traditional treatments. Appendix A includes brief summaries on the efforts being taken at the state level to address AML sites for selected states.

1.1 Background

Mining practices, present and past, cause environmental problems that can damage ecosystems and human health. Mining disturbs geologic formations that took millions of years to form; likewise, related natural systems and processes are disturbed, e.g. hydrology. Once disruption has taken place a variety of problems may arise, from physical hazards to pollution of water and soil. The most severe and widespread environmental problems almost always have to do with water, indeed all of the treatment technologies that will be discussed in this paper are designed for water or the prevention of water contact with solids.

There has been a lot of effort to quantify the universe of abandoned mines, the results vary. Some of the problem lies in definition. While some agencies define a site as a particular opening; others define a site as all of the openings at a particular location as one mine site. The Bureau of Land Management claims that estimates from Federal land management agencies, state and privately owned lands have ranged from about 80,000 to hundreds of thousands of small to medium-sized sites (U.S. Dept. of the Interior, 2003b). The Office of Surface Mining describes the problem in terms of money, "of the $8.2 billion of high priority [physical hazards] coal related AML problems in the AML inventory, $6.6 billion, 80%, have yet to be reclaimed; furthermore, "almost ninety percent of the $2.0 billion of coal related environmental problems in the AML inventory are not reclaimed. And this represents only a small part of the total problem as no systematic effort has been made to inventory these problems" (U.S. Dept. of the Interior, 2002a). To give one last perspective, the Mineral Policy Center, a non-profit organization, claims that there are 557,000 abandoned mines - mostly in the western United States (2003). Although it is difficult to say exactly how many sites exist, the number of abandoned mine sites in the US is enormous.

For roughly 25 years there have been efforts to address the dangers created by the past 250 - 300 years of large-scale mining in this country. The Surface Mining Coal and Reclamation Act (SMCRA), passed in 1977, requires a tax on coal production to be set aside in a fund for remediation efforts at abandoned coal mines. However, many abandoned mines are hard rock mines and are typically not eligible for SMCRA funding, though there are some exceptions. Other sources of funding may come from CWA grants, CERCLA grants or State funding. While there has been significant progress, there are still many sites without adequate funding. For example, California has no abandoned coal mines, therefore ineligible for SMCRA funding. A multi-stakeholder task force in California identified lack of funding as a key impediment to cleanup of abandoned mines in the state (see Appendix A). Some states have started to lobby for funding, for example, Colorado House Representative Mark Udall is seeking legislation that would create a fund for hard rock sites similar to that created by SMCRA.

Many states and agencies have only recently finished inventorying the number of sites and begun to evaluate sites to determine priorities for cleanup. States and other agencies that are doing remediation under SMCRA must address Priority 1 & 2 problems - those dealing with physical dangers - before they are able to use funding to address Priority 3 problems - environmental

problems and/or high priority non-coal sites. The priority number system was defined by the U.S. Department of the Interior.

Due to limited resources, especially in the case of hard rock mines, innovative technologies can offer a plausible solution to the environmental threats created by abandoned mines. Traditional water treatments are modeled after wastewater treatment plants, which are machine intensive, chemical dependant, and require continuous operations and maintenance (O & M) staff. Traditional solid mine waste remediation tactics involve covering of piles and water diversion tactics which do not treat wastes but rather mitigate their impacts. The innovative technologies that will be discussed in this paper are largely passive treatment systems. Passive treatment systems are described as having little O & M costs, require little chemical application, and few if any mechanical devices (Hedin et al., 1994). Passive treatment systems can be a good solution for small drainage sites that might otherwise have few treatment options.

1.2 Chemistry

1.2.1 Acid Generation and Metals Leaching

Acid generation and metals dissolution are the primary problems associated with pollution from mining activities. The chemistry of these processes appears fairly straightforward, but becomes complicated quickly as geochemistry and physical characteristics can vary greatly from site to site. This paper will not describe these variables and their affects on chemistry, it will give an overview of the most common scenario found at coal and hard-rock sites with environmental concerns.

Pyrite (FeS_2) is responsible for starting acid generation and metals dissolution in coal and hard rock sites alike. When pyrite is exposed to oxygen and water it will be oxidized, resulting in hydrogen ion release - acidity, sulfate ions, and soluble metal cations, equation 1. This oxidation process occurs in undisturbed rock but at a slow rate and the water is able to buffer the acid generated. Mining increases the exposed surface area of these sulfur-bearing rocks allowing for excess acid generation beyond the water's natural buffering capabilities.

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

Further oxidation of Fe^{+2} (ferrous iron) to Fe^{+3} (ferric iron) occurs when sufficient oxygen is dissolved in the water or when the water is exposed to sufficient atmospheric oxygen.

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

Some acidity is consumed in this process, however, the stage is set for further hydrogen ion release that will surpass these benefits. Ferric iron can either precipitate as ochre ($Fe(OH)_3$ the red-orange precipitate seen in waters affected by acid mine drainage) or it can react directly with pyrite to produce more ferrous iron and acidity.

$$2Fe^{+3} + 6H_2O \leftrightarrow 2Fe(OH)_3\,(s) + 6H^+ \qquad (3)$$

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

When ferrous iron is produced as a result of equation 4 and sufficient dissolved oxygen is present the cycle of equations 2 & 3 is perpetuated (Younger, et al, 2002). Without dissolved oxygen equation 4 will continue to completion and water will show elevated levels of ferrous iron (Younger, et al, 2002).

Once the waters are sufficiently acidic, acidophilic bacteria - bacteria that thrive in low pH - are able to establish themselves. Microorganisms can play a significant role in accelerating the chemical reactions taking place in mine drainage situations. *Thiobacillus Ferroxidans*, a bacteria, is commonly referenced in this case. These bacteria catalyze the oxidation of ferrous iron, further perpetuating equations 2 through 4. Another microbe belonging to the Archaea kingdom, named *Ferroplasma Acidarmanus*, has recently been discovered to also play a significant role in the production of acidity in mine waters (Lauzon, 2000).

Though not a major source of acidity, the generation of hydrogen ions when certain metals form precipitates, must be taken into account when considering treatment options.

$Al^{+3} + 3H_2O \leftrightarrow Al(OH)_3 + 3H^+$ (5)
$Fe^{+3} + 3H_2O \leftrightarrow Fe(OH)_3 + 3H^+$ (see equation 3) (6)
$Fe^{+2} + 0.25\ O_2(aq) + 2.5\ H_2O \leftrightarrow Fe(OH)_3 + 2H^+$ (7)
$Mn^{+2} + 0.25\ O_2(aq) + 2.5\ H_2O \leftrightarrow Mn(OH)_3 + 2H^+$ (8)

Other metals commonly found in mine drainage waters exist because they are present in the rocks, similar to pyrite. For example, there are a variety of other metal sulfides that may release metal ions into solution, but may not generate acidity (Younger et al., 2002) the reasons for this are not clear. Including:

Sphalerite	$ZnS(s) + 2O_2(aq) \rightarrow Zn^{+2} + SO_4^{-2}$	(9)
Galena	$PbS(s) + 2O_2(aq) \rightarrow Pb^{+2} + SO_4^{-2}$	(10)
Millerite	$NiS(s) + 2O_2(aq) \rightarrow Ni^{+2} + SO_4^{-2}$	(11)
Greenockite	$CdS(s) + 2O_2(aq) \rightarrow Cd^{+2} + SO_4^{-2}$	(12)
Covellite	$CuS(s) + 2O_2(aq) \rightarrow Cu^{+2} + SO_4^{-2}$	(13)
Chalcopyrite	$CuFeS_2(s) + 4O_2(aq) \rightarrow Cu^{+2} + Fe^{+2} + SO_4^{-2}$	(14)

Metals are naturally dissolved from weathering slowly over time. The dissolution process is sped up when the pH of the water strays from near-neutral, that is at either high or low pH - in the case of mine drainage low pH is the more plausible scenario (Younger et al., 2002; Blowes et al., 2000). For more information see Chapter 2 of Mine Water: Hydrology, Pollution, Remediation by Younger et al., 2002.

1.2.2 Neutralization and Metals Removal

The ways by which metals precipitate have seemingly endless possibilities and are not always well understood. By far the most common application for reducing acidity and adding alkalinity is lime. There are many ways to treat mine drainage through enhanced natural processes which form the basis for passive treatments. There are many aerobic and anaerobic process that lead to metals precipitation that are commonly practiced. Though not complete the following information should provide some insight about the technologies that will be discussed shortly.

It is very important to gain control of the pH of the drainage because pH effects many things including the solubility of metals and the kinetics of the oxidation and hydrolysis processes (EPA, Vol.4). In addition, the relationship between pH and metal removal processes varies among metals and also between biotic and abiotic processes (EPA, Vol. 4)

Limestone (calcium carbonate), rich in calcite, increases the pH of water by consuming hydrogen ions and adding alkalinity through bicarbonate ions (Younger et al., 2002).

$$CaCO_3 + 2H^+ = Ca^{+2} + H_2O + CO_2 \quad (15)$$
$$CaCO_3 + H_2CO_3 = Ca^{+2} + 2HCO_3^- \quad (16)$$

Once the pH of the acidic water has been raised metals can precipitate more easily to form hydroxides and oxyhydroxides, in some cases the pH alone will change the metal ion to an insoluble form, this is true in the case of aluminum.

Other commonly used alkaline agents are hydrated lime (calcium hydroxide), soda ash (sodium carbonate), caustic soda (sodium hydroxide), and in some cases ammonia (U.S. Dept. of the Interior, 2002b).

The processes involving metals more common to coal mining regions (iron, aluminum, and manganese) are fairly well understood. The removal of iron is better understood than other metals common to drainage sites, which may be one of the reasons why passive treatments are more common in the East. Iron can form oxyhyroxides (FeOOH) or hydroxides ($Fe(OH)_3$) under aerobic conditions or a sulfide solid under anaerobic conditions. Iron and manganese (Mn) precipitation processes are related in that the precipitations are sequential in aerobic conditions (EPA, Vol. 4). Iron oxidizes and precipitates more quickly than Mn because oxidized Mn solids are unstable in the presence of Fe^{+2} therefore the levels must be reduced significantly before Mn can be converted to stable solid precipitates (EPA, Vol. 4). Manganese under aerobic conditions can form an oxyhydroxide (MnOOH) and oxides (Mn_3O_4 and MnO_2) and in alkaline environments a carbonate ($MnCO_3$) (EPA, Vol. 4). Manganese sulfide is highly soluble and therefore highly unlikely to remain precipitated if it should form under anaerobic conditions (EPA, Vol. 4).

Aluminum is removed from waters by maintaining the pH between 5 and 8, where $Al(OH)_3$ is highly insoluble; the passage of mine water through highly oxidized or reduced environments has no effect on Al concentrations (EPA, Vol. 4).

Technologies designed to remove metals common to hard rock mining almost always involve the establishment of sulfate reducing bacteria (SRB), which can be difficult in cold climates. Sulfate reducing bacteria remove metals from solution as precipitates as a result of their survival (Zaluski et al., 2000). SRB reduce sulfate to soluble sulfide when provided with an organic carbon source, i.e. compost; as a result of this process acetate and bicarbonate ion are also produced. The soluble sulfide reacts with the dissolved metals to form insoluble metal sulfides, equation 18; the bicarbonate ions increase the pH and alkalinity of the water, equation 17 (Zaluski et al., 2000). Bicarbonate also allows for the possible production of Zn, Cu, or Mn carbonates (Macalady, 1998). Metals likely to form insoluble sulfide precipitates include: Cu, Zn, Cd, Pb, Ag, and Fe(II) (Macalady, 1998). These processes are summarized by the following reactions:

$$SO_4^{2-} + 2CH_2O \longrightarrow H_2S + 2HCO_3^- \quad (17)$$

$$H_2S + M^{+2} \longrightarrow MS + 2H^+ \quad (18)$$

In addition to precipitation processes, metals can be removed from water through a variety of methods common to wetlands, and seen in technologies utilizing organic matter and/or vegetation:

- filtering suspended and colloidal material from the water
- uptake of contaminants into the roots and leaves of live plants
- adsorption or exchange of contaminants onto inorganic soil constituents, organic solids, dead plant material or algal material
- neutralization and precipitation of contaminants through the generation of HCO_3^- and NH_3 by bacterial decay of organic matter.
- destruction or precipitation of chemicals in the anaerobic zone catalyzed by the activity of bacteria
- destruction or precipitation of contaminants in the aerobic zone catalyzed by the activity of bacteria (EPA, 1993b).

It is not in the scope of this paper to describe all of the potential considerations related to each metal of concern; a few examples have been mentioned to illustrate the necessity of carefully analyzing all of the metal contaminants and the surrounding hydrologic, geologic, chemical, and biologic situation in order to properly design for removal.

1.3 Environmental Concerns

Environmental damage or pollution associated with mines nearly always has to do with a decrease in pH and/or elevated concentrations of heavy metals in nearby waters and soils. There are instances were one problem occurs without the other, for example circum-neutral pH and elevated metals concentrations or vice versa. Debris from waste piles may be blown and contaminate surrounding areas with metals. Silt and sediments may run-off into nearby streams and obstruct water flow. Other sources of pollution that may not initially come to mind are abandoned buildings and industrial equipment that contribute to pollution, including waste drums, heavy equipment, batteries, etcetera.

While all of these problems are serious, the main focus will be on polluted water resulting from mine drainage. Indeed, with the exception of a few new means of revegetation, most of the innovative technologies in the literature address water treatment.

Figure 1. Air compressor at an abandoned mine site in Leadville, CO.

Younger et al., provide information about the impacts that mining has on the water environment, they have defined six distinct impacts (2002). Not all of these impacts deal with pollution, but it is useful to consider all of the potential problems for a holistic view useful for designing an effective remediation plan.

1) "*The mining process itself*"(pp. 55) Which is associated with the disruption of groundwater hydrology. It has been pointed out that, "the miner and the water resource manager share a common interest in avoiding the ingress of fresh water into a mine void; the water manager's loss of resource is the miner's increase in nuisance" (pp. 57).

2) "*Mineral processing operations*" (pp. 57). For example, cyanide leaching operations, gold-mercury amalgamation. Contaminated abandoned leach pads can contribute to polluted runoff from the mine site. Active mines today, at least in the U.S., have regulatory obligations to prevent this type of contamination.

3) *The dewatering which is undertaken to make mining possible*. Some of the problems that can arise from pumping water out of mining shafts include: water table depression resulting in reduction in water availability for residents and the surrounding hyrdologic system, i.e. wetlands, streams, lakes; land subsidence or collapse; and, surface or groundwater pollution if mine water is of poor quality and runs to nearby waterways. However, mining industry today takes some measures to reduce these impacts through: compensation flows, in which water is added to sensitive surface waters, and may even be treated and pumped to specific locations; local re-injection of groundwater; alternate water supplies might be provided for affected residents; and/or waters that are unaffected by the mining operation itself, but are not of good quality might be treated before discharge.

4) *Seepage of contaminated leachate from waste rock piles and tailings dams*. For example, waste rock piles may not have had enough metal present to be economical to recover; however, the rock material might have sufficient pyrite present to generate acidity and mobilize metals.

5) *"The flooding of abandoned mine workings after mining has ended" or, "water table rebound"* (pp.59). While the water table is recessed and pyrite is able to oxidize causing a build-up of "acid-generating salts," when the water table rises these salts are dissolved causing an increase in pH and dissolved metals (pp. 60). There are other possible hazards like erosion of support columns in the mine tunnels leading to subsidence and also, the converse rising ground levels due to rehydration of soils, especially clays.

6) *Discharge of untreated mine water after flooding of workings* can lead to: surface water pollution, pollution of overlying aquifers, localized flooding and overloading and clogging of sewers.

For more information about environmental concerns associated with abandoned mines see EPA, 2001, chapters 2 & 3 and Younger et al., 2002.

2.0 Treatment

Treatment of mine sites generally requires pH adjustment, oxidizing or reducing (redox) conditions, and/or stabilization of wastes. Treatment technologies will be broken up into this categories: traditional and innovative. It is difficult to assign absolute definitions, the following distinctions will help to clarify the meanings.

2.1 Traditional

Traditional treatments rely on conventional, well-recognized technology to raise pH or create redox conditions. The types of technologies considered traditional in this paper include: water treatment plants, relocation of wastes, covering of waste piles, water diversion tactics, and in some cases revegetation.

Traditional or conventional treatments for mine waters are those that follow the pattern of an ordinary wastewater treatment plant often referred to as active treatment. Younger et al. define "active" treatment as "...the improvement of water quality by methods which require ongoing inputs of artificial energy and/or (bio)chemical reagents" (2002, pp. 271). There are a variety of methods that are considered "active," the most predominate one is "ODAS" - oxidation, dosing with alkali, and sedimentation (Younger, et al., 2002). The process is similar to that of traditional wastewater treatment plants. Others traditional or "active" treatments common to wastewater treatment plants include: sulfidization, biosedimentation, sorption and ion exchange, and membrane processes like filtration and reverse osmosis (Younger, et al, 2002). The waters are removed from their course, treated and then discharged.

Depending on the situation it may be advantageous to install a traditional water treatment system as described above, in some cases it might even be the only option. One of the advantages is precision. For the most part an engineered system can be altered to obtain desired discharge regardless of the changes in the incoming water characteristics. This can be useful for active mining sites with frequently changing water characteristics (Younger, et al., 2002). For instance, Russ Forba who works on the Berkeley Pit Superfund site in Montana, stated that after evaluation of the options they did not feel comfortable with the reliability and contaminant removal efficiencies associated with innovative treatments due to the seven million gallon-per-day flow and complex characteristics of the wastewater (R. Forba, personal communication, 6/20/2003). Another benefit is that the land required to establish a plant for large flows is much smaller than the space required for comparable passive treatment systems (Younger et al., 2002). Finally, traditional wastewater treatment plants are accompanied by a large body of experience and information, making the expertise easier to find and with a higher confidence level in performance.

Traditional treatment approaches to handling solid mine wastes include a variety of excavation, landscape adjustment, and stabilization techniques. Again, in most cases the main concern is to avoid water infiltration of the solid wastes. Solid wastes can be contained on-site in a variety of ways: lined pits, un-lined pits, clay or plastic caps, etc. Similarly, wastes can be shipped off-site to landfills, treatment plants, or recovery operations; however, this option may be costly as prices are by the ton. Covering or "capping" wastes is a fairly common choice, the cover can be multiple layers of plastic, cement, soil, compost, rock, vegetation, etc. The idea behind these methods is that the solid materials high in metals and/or acid-producing materials will not be exposed to the elements and will not cause typical problems associated with mine wastes. While these solutions may be a reasonable option for reducing potential harm to humans and the environments they generally do not reduce the toxicity or volume of the metals present in the soils (Pioneer Technical Services, 2002).

Re-grading is a common term used in describing remediation efforts. Re-grading is simply reducing the slope of a waste rock or tailings pile to prevent erosion by reducing water runoff and to provide a more stable surface to enhance revegetation efforts. Another tactic to control water flow near a waste pile is to attempt to divert water from the pile by installing trenches and culverts.

Whether revegetation is traditional or innovative is somewhat obscure. It is not a new idea and has been done for many years. However, some new methods have made it possible to revegetate areas that were previously thought to be a lost cause. For example, biosolids and lime applications have been proven to be a viable method for establishing self-sufficient vegetative cover. The distinction between innovative and traditional lies between the goal and outcomes of establishing vegetation. If the goal or outcome is to reduce toxicity or to recover metals then it would probably be considered an innovative treatment; if the goal is to prevent metals contaminated soils from being blown into nearby yards, but the metals are still present in the same quantities it would probably be considered traditional.

For more information about available treatment technologies please see: EPA's Abandoned Mine Site Characterization and Cleanup Handbook, Chapter 10.

Case Study: California Gulch, Leadville, Colorado

The California Gulch Superfund site located in Leadville, Colorado utilizes nearly every traditional treatment option described above and even some innovative applications. Some of the treatments include: two water treatment plants, consolidation and stabilization of piles, water diversion, capping, revegetation, and biosolids application. Mining for gold, silver, copper, zinc, manganese, and lead began in 1859. The site is approximately 16.5 square miles, divided into twelve Operable Units (OUs) (EPA, 2003). Each OUs is managed by a different party including EPA, the U.S. Bureau of Reclamation, the State of Colorado, and ASARCO, the Resurrection Mining Company, a subsidiary of Newmont Gold Company, and the ASARCO-Resurrection joint venture (EPA, 2003).

Figure 2. Capped waste pile in Leadville, CO. Photo taken by author.

The two water treatment plants are located at the outfall of abandoned mine tunnels: the Yak Tunnel and the Leadville Mine Drainage Tunnel. Tunnels were built to transport ores out of mines and sometimes drain groundwater to allow access to the underground. Rock in these tunnels is highly disturbed and exposed to water and oxygen therefore, pyrite oxidation and metals leaching is likely and effluent from the tunnels is highly problematic. The treatment plant at Yak Tunnel is managed by the ASARCO-Resurrection joint venture. The flow to the plant is highly dependent on season, during summer months there can be little more than a trickle of water but in the spring during snowmelt the flow increases dramatically. Before the plant was in operation nearly 210 tons of metals entered the Arkansas River annually (EPA, 2003). The second treatment plant is at the end of the ten mile long Leadville Mine Drainage Tunnel. This plant is managed by the Bureau of Reclamation. In addition to treating water that has made its way into the tunnel, it receives runoff from tailings piles located near the origin of the tunnel from tailings & waste rock piles. Furthermore, it is believed that nearly two-thirds of the water reaching the tunnel is runoff and groundwater that is uncontaminated before entering the tunnel (M. Holmes, personal communication, 7/22/2003). If this groundwater could be diverted from the tunnel the treatment plant would be more efficient in treating the drainage. However, this is easier said than done given the depth of the tunnel and the complexity of the hydrology at the site. The current thought is to install a plug to block flow of clean water into the tunnel; but, in order to do this a shaft would have to intersect the tunnel at a depth of 500 feet below ground level (M. Holmes, personal communication, 7/22/2003). Aside from being expensive it is difficult to drill accurately enough to intersect the tunnel at an appropriate location (M. Holmes, personal communication, 7/22/2003). Further complications would arise with the construction and performance of the plug.

Given the highly variable flow patterns and difficult climate at the elevation of 10,162 feet water treatment plants are a good option for treatment at the California Gulch site. In addition, when passive treatment was considered using wetlands it was determined that the space needed for construction would consume the entire town of Leadville (M. Holmes, personal communication, 7/22/2003).

Consolidation of waste piles is another large effort taken at the site to reduce water quality impacts. More than 350,000 yards of contaminated soils, sediments, and mine processing wastes have been consolidated on site (EPA, 2003). Once consolidated, a variety of measures have been taken including diversion trenches and culverts, evaporation ponds, and capping to minimize contaminated runoff leaving the site. Diversion trenches attempt to catch runoff before it comes into contact with the waste pile thereby avoiding contamination of the water so that it might reach the river or other water body in a “clean” state. Evaporation ponds collect runoff from piles and

allow water to evaporate leaving metal precipitates, mostly iron, to stay in the pond. A couple of piles have been capped to prevent water infiltration and runoff. Revegetation efforts are also underway at many locations on the site, some of the locations have used the application of biosolids which will be describe in the Innovative Technologies section of this paper. All of these efforts have helped to reduce water quality issues in the Arkansas River.

2.2 Innovative

What is considered innovative? The Encarta English Word Dictionary provides some insight, the technology should be attempting to change the properties or form of a chemical, here the hydrogen ion and metal ions, in a way that has not been attempted in recent years:

> *innovative* is defined as: "new and original: new and original or taking a new and original approach"
> *treatment* is defined as: "technology: treating something with agent: an act of subjecting something to a physical, chemical or biological process or agent" (2003).

Though "innovative treatment" could surely describe a wide range of technologies, for example chemical encapsulation of wastes, the discussion here is limited to full-scale implementation of new technologies that have been installed at multiple abandoned mine sites. A variety of "passive treatments" have become the most predominate innovative treatments applied aside from traditional choices. Passive treatments are considered to be those that treat waters or solids using enhanced natural processes, in-situ and require minimal upkeep (Hedin et al., 1994; Younger et al., 2002). Research into these techniques began as early as thirty years ago and has been growing ever since.

The beginning of this movement developed out of the observation that wetlands naturally remove metals from contaminated water (Gusek, 1998). Through trial and error it was discovered that in many instances plants were not necessary to treat the waters, rather other biochemical and geochemical reactions were responsible for water quality improvements (Gusek, 1998). For metals common to hard rock mining (Zn, Pb, Cd, As, Mo, Au, Ag, to name a few) sulfate reduction by bacteria is usually the premise behind the design of passive treatment with the goal of inducing metal precipitation as sulfides. For metals common to coal mining (Fe, Al, and Mn) aerobic processes, with or without an alkaline agent are the most commonly applied applications. Another major player in passive treatment are alkaline agents, most commonly lime, although the application of lime to reduce acidity it not particularly innovative, some of the ways to expose the acidic waters to the alkaline agent are innovative.

Many of the innovative technologies in operation are based on the same principles. Permeable Reactive Barriers (PRBs), bio-reactors, and constructed wetland technologies can all utilize alkaline agents and sulfate reducing bacteria to treat mine drainage. The majority are in-situ applications that manipulate natural processes to treat acidic and/or metals contaminated water, the exception is the use of iron in PRBs to treat uranium, see pages 25-26. Their differences lie in construction and water source. PRBs have a subsurface reactive section that groundwater flows through following its natural course to be treated, in some cases there are impermeable walls to direct the flow of the water to the reactive section. The reactive media is usually compost

material that hosts sulfate reducing bacteria, though there are a few others. Bioreactors are somewhere between a PRB and a wetland, water - ground or surface - flows through and natural reactions work to remove metals. Whether subsurface or exposed to the atmosphere, bioreactors are generally lined, filled with composted materials and/or alkaline agents, and in some cases include vegetation. Constructed wetlands are very similar to both PRBs and bioreactors, they are often lined ponds filled with organic matter and/or alkaline agents and sometimes vegetation. Organic matter and vegetation allow an opportunity for metals to absorb and/or adsorb to organic surfaces, this is true for bioreactors and PRBs as well. Anaerobic wetlands aim to promote the growth of sulfate-reducing bacteria and raise pH. Aerobic wetlands are most often used for net alkaline waters, oxygen infiltration is encouraged and metals precipitate as oxyhydroxides, hydroxides, and carbonates. Both bioreactors and wetlands almost always include collection and piping systems, while PRBs are simply placed in the flow path.

Lime-based applications considered innovative in this paper, are anoxic limestone drains and Successive Alkalinity Producing Systems (SAPS). The latter is very similar in construction and theory to wetlands/bioreactors and is also an improvement to the anoxic limestone drain technology.

2.2.1 Limestone Drains

Anoxic Limestone Drains (ALDs) treat acidic and potentially metals-laden waters by sending them through an underground pathway that is packed with crushed limestone. ALDs typically outlet into a settling pond or wetland to allow metals an opportunity to precipitate and settle (Cravotta, 2002).
The problem with ALDs is that they often experience armoring - described as strong adhesion and complete pacification by encrustation - causing the limestone to become inactivated and potentially cause clogging of the drain (Cravotta, 2002; Sasowsky, 2000). To effectively install an ALD many suggest that dissolved oxygen, Fe^{+3}, and Al^{+3} concentrations be less than 1 mg/L; some authors have suggested that Fe^{+3} and Al^{+3} concentrations can be higher, between 1 and 5 mg/L (Cravotta, 2002). In either case this is a very low threshold when dealing with mine drainage.

A study by Sasowsky et al., suggests that the armoring of limestone can be substantially offset by incorporating sandstone into the drain (2000). Sasowsky et al., observed that when acidic and metals contaminated drainage at Big Laurel Creek at the East Fork Obey River in Tennessee discharged onto both exposed limestone and sandstone the majority of metallic oxides precipitated onto sandstone rocks (2000). This suggested a preferred precipitation media. In order to validate that the observed precipitation was not merely coincidence or mechanical, laboratory and field test at another mine drainage location in Silver Creek, Ohio were conducted. Similar results were recorded, and sandstone had an order of magnitude higher iron precipitation than limestone (Sasowsky et al., 2000). If this preference is fairly consistent, the addition of crushed sandstone to limestone drains could reduce armoring of limestone. It might also be noted that these studies were not conducted at oxygen deficit locations, and so behavior in anoxic conditions should be investigated.

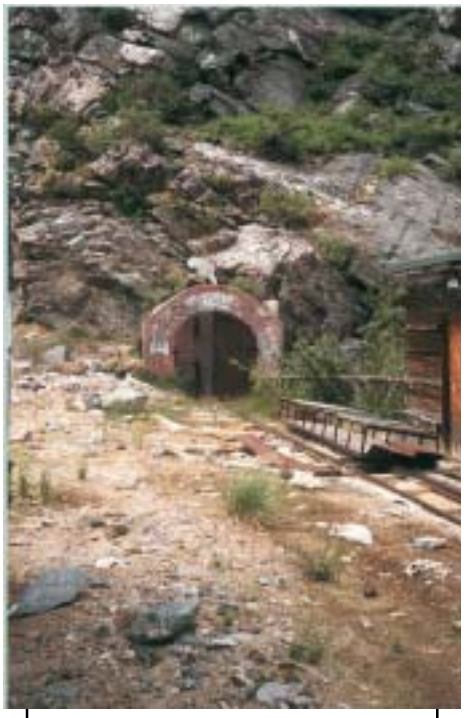

Figure 3. Burleigh Tunnel, 7/2003, photo taken by the author

Case Study: North Pennine Orefield, UK

An emerging potential use for ALDs is for zinc removal. Nuttall & Younger (2000) conducted a field-scale test to use an ALD to remove zinc from net alkaline waters. The pilot scale ALD was place in the Nent Valley within the North Pennine Orefield, United Kingdom, the area had been mined for over two centuries for lead and zinc (Nuttall & Younger, 2000).

Metals leach from spoil heaps and tailing dams; contaminated land drainage and five abandoned mine adits also discharge metals into the River Nent. The waters have high hardness values, high alkalinity, and pH in the range of 7.4 to 8.0. The dissolution of sphalerite, ZnS (see equation 5), results in zinc concentrations in the range of 3 to 8 mg/L; there are also concentrations of lead, cadmium (both well below 1 mg/L), and arsenic (Nuttall & Younger, 2000). Geochemical modeling and laboratory tests revealed that raising the pH from approximately 7.5 to 8.2 would result in the optimal reduction of zinc in solution (Nuttall & Younger, 2000).

Aerobic processes that aim to result in hydroxide or sulfite solids have not been successful in this case because in hard, net-alkaline waters zinc is predominantly present as carbonate complex ($ZnCO_3^0$) and will not readily form non-carbonate solids (Nuttall & Younger, 2000). Therefore, an anoxic limestone drain was chosen as a possible way to raise the pH to roughly 8.2 for optimal removal (Nuttal & Younger, 2000). The results of the pilot test show 22-percent reduction in zinc concentrations after passing through the anoxic limestone conditions, with a retention time of 14 hours (Nuttall & Younger, 2000).

This is not the typical example, most ALD installations have been at coal drainage sites. It is particularly interesting because it does not rely on microorganisms which tend to be more temperature dependent, so the application might be possible at colder temperature sites.

2.2.2 Constructed Wetlands

There are two types of wetlands used to treat mine drainage, aerobic and anaerobic/compost. As mentioned previously, observations by ecologists that wetlands are capable of treating water and/or retaining toxics forms the basis of most passive treatment technologies.

It is possible for mine drainage to be net alkaline. If the metal of concern is iron an aerobic wetland is the best treatment option; aerobic treatment alone is rarely successful with other types of metals. Net alkaline waters are able to buffer the additional hydrogen ions released during metal hydrolysis reactions, for example: $Fe^{+3} + 2H_2O \rightarrow FeOOH + 3H^+$ (EPA, Vol. 4). The

precipitation of metals is a purely chemical reaction and is not as temperature dependent as sulfate precipitation common to anaerobic wetlands (EPA, Vol. 4). The main limiting factor for these systems is metal precipitate build-up, these deposits may need to be removed to allow for continued wetland operation. Robert Hedin has started a company that dredges this build-up and sells it for use as pigment in dyes and paints.

When waters are net acidic, the pH must be raised and ideally the waters will be bought to net alkaline conditions. When iron and aluminum are the main contaminants then alkaline addition followed by an aerobic settling pond is often used to precipitate metals and raise pH. The most common wetland application for hard rock mines aims to establish sulfate-reducing bacteria under anaerobic conditions and, as a result of the bacteria's metabolic needs, metals are precipitated as sulfides, see equations 17 &18. Anaerobic wetlands generally consist of organic substrate, often compost, and can be mixed with lime to increase alkalinity (EPA, Vol. 4).

There are a variety of considerations when designing a constructed wetland, more information can be obtained in EPA's Volume 4: Coal Mine Drainage; Younger et al., 2002; and, Macalady, 1998.

Case Study: Burleigh Tunnel, part of the Clear Creek/Central City Superfund Site, Colorado

This site is located in Idaho Springs, Colorado in a narrow valley with very harsh cold winters and limited sunlight year-round. This project was in operation for about 3 years before treatment failed for a variety of reasons and was decommissioned.

The water exiting the Tunnel is roughly neutral with a pH of 6.5, with discharge averaging 60 gallons per minute, elevated concentrations of bicarbonate buffer the mine water, and zinc is the metal of most concern (J. Lewis, personal communication, 7/7/2003). The pilot system installed is described as two "anaerobic compost wetlands in both upflow and downflow configurations," they were not designed to treat the entire flow, but only one-fourth, or 15 gpm - approximately 7.5 gpm in each cell (EPA, 2002b).

Each wetland was a 0.05-acre (2178 ft^2) cell (a.k.a. "pit") filled four feet deep with a mixture of an organic-rich compost (96 percent) and alfalfa hay (4 percent). The cells were installed below grade to reduce freezing and the earthen side walls were bermed.

The base of each cell was made up of a gravel subgrade, a 16 ounce geofabric, a sand layer, a clay liner, and a high-density polyethylene liner (EPA, 2002b). Geonets and geofabrics were applied in order to: separate influent and effluent piping; hold compost in place in the upflow cell; separate perforated PVC piping from the compost (EPA, 2002b). The geonet and perforated piping ensured even distribution of the influent water into treatment cells and prevented short-circuiting of water through the cells. For more details consult the EPA "SITE Technology" publication listed in the bibliography as EPA 2002b.

The hydraulic system for the cell involved concrete v-notch weirs, one for influent and effluent for each cell. At some point the valves in the downflow cell became locked-up and could no longer

be operated; the time and reason are unknown (J. Lewis, personal communication, 7/16/2003). Water entered the upflow cell under pressure at the bottom of the compost and exited from the top; water entered the downflow cell at the top and flowed down by gravity, exiting at the bottom (EPA, 2002b). A drainage collection structure was built within the Tunnel to build sufficient hydraulic head to drive flow through the two cells (EPA, 2002b). A bypass system was also constructed, though was not always effective (J. Lewis, personal communication, 7/16/2003).

During its three years in operation the upflow wetland removed an average of 93 percent of zinc the first year and 49 and 43 percent during the second and third years (EPA, 2002b). The downflow wetland removed a mean of 77 percent of the zinc during the first year and 70 percent the second year; flow was discontinued in the third year (EPA, 2002b). Based on aqueous geochemical modeling, observations of cell compost, results of the sulfate-reducing bacteria count, and acid volatile sulfide data, biological sulfate reduction was not the main removal mechanism. Primary removal is thought to have occurred due to precipitation of zinc oxides, hydroxides, and carbonates in aerobic portions of the cell. The upflow cell during the first six months of operation had effluent levels of less than 1mg/L; concentrations began to increase near the end of 1994 into 1995, by May 1997 concentrations had reached 60.1 mg/L (EPA, 2002b). The cell suffered a significant blow in the spring of 1995. Heavy runoff increased the flow through the cell to 20 gpm of aerobic water, and the increased flow also apparently mobilized more zinc and substantially increased the zinc concentrations. After the increased flow, removal efficiencies were around 43 to 49 percent, whereas before removal efficiency were more than 90 percent. In 1997 a visibly obvious preferential flow path developed and was eliminated. The upflow cell was decommissioned in June of 1999. It is believed that the initial high removal rates in the upflow cell are the result of adsorption and absorption along with biological sulfate reduction; decline in removal rates is speculated be related to the decline in SRBs.

Currently there is no treatment being done at the Tunnel. The water seems to be entering the subsurface, it is unclear whether it is building up on the site, draining from the site, or traveling as groundwater; however, sampling of water is indicating that zinc concentrations are within regulatory standards of less than 200 micrograms/liter, the reason is undefined (J. Lewis, personal communication, 7/16/2003).

This example is interesting because the design was to precipitate metal sulfides under anaerobic conditions, yet the predominate form of precipitate was that common to aerobic conditions. It would be useful to gather information on the potential precipitates under aerobic conditions, especially abiotic reactions.

2.2.3 Bioreactors

Passive bioreactors are lined trenches or pits that can contain a variety of materials, most commonly a mixture of cobbles, compost, other organic matter, and/or an alkaline agent. Sometimes above ground tanks containing any variety of materials including those described above and other trickling filter types of materials - common in bio-treatment of municipal waste-

water treatment used to establish appropriate microorganisms to precipitate metals and adjust pH - are referred to as “bioreactors.” The tank type of bioreactor will not be discussed in this paper, though they are used to treat acid mine drainage. They are both legitimate in using the term, “bioreactor” as they are using biological reactions to treat the waters. Arguably, the term "bioreactor" would in fact include PRBs, SAPS, and wetlands. The distinction between them has been made because the literature does so.

A. Case Study: Silver Bow County, Montana

Sulfate Reducing Bacteria (SRB) are the key to these bioreactors installed at the Calliope abandoned mine site in Silver Bow County, Montana in the Fall of 1998 (Zaluski et al., 2000). This project was funded by the EPA and jointly administered by the EPA and the Department of Energy; the project was implemented by MSE Technology Applications in Butte, MT. Water that flows through a collapsed adit discharges onto a large waste rock pile, upon exiting the pile the water has an average pH of 2.6 and elevated metals concentrations; this water then flows into a pond resulting in a pH of 3 to 5.5 depending on mixing ratios largely determined by the season. In order to treat the mine drainage and conduct research to obtain knowledge about optimal design characteristics three SRB reactors (II, III, and IV) with different attributes were designed. Two of the three reactors were placed below grade (ground) to minimize temperature changes and one above to study the effects of freezing. The reactors were filled with a combination of organic carbon, cobbles, and/or crushed limestone . Each reactor had a fifty foot section of cobble preceded by organic matter and/or limestone. Two of the three reactors had “pretreatment” sections, which consisted of an additional five foot section of organic carbon and a five foot section of crushed limestone; while the third one had only a five foot section of organic matter.

The most notable obstacle to the success was when the flow through reactor II ceased due to biofouling and consequent plugging. The problem was quickly addressed within a month.

The reactors were monitored monthly for sulfate, alkalinity, SRB count, heterotrophic bacteria count, dissolved oxygen, Eh (a measure of redox potential), and metals including: aluminum, zinc, cadmium, copper, iron, and manganese.

Overall, the results were positive, pH was increased and metals concentrations were reduced. Comparison of reactors shows that “initial increase of pH can largely be attributed to alkalinity present within the organic substrate rather than to limestone” (Zalusk, et al., 2000). Once SRB were established their metabolic reactions also contributed to pH increase.

Some of the more interesting findings when comparing the bioreactors included (Zalusk, et al., 2000):

- More organic matter leads to more organic matter fermentation reactions resulting in an increase in temperature; this could be critical in cold climates.

- Increased temperature leads to greater microbial activity.
- Prior to SRB activity, adsorption of metals to organic substrate seems to be the cause of concentration reductions.

B. Case Study: Champagne Creek - Butte, Idaho

The mine drainage from Moran Tunnel contributes low pH, metals-laden water discharging to Champagne Creek. The project is being handled through the Bureau of Land Management's Abandoned Mine Lands Program in the State of Idaho. The watershed is 9.2 square miles, moderately steep, at an elevation of 6060 feet, mostly covered by semi-arid rangeland. The stream itself is only 4.5 miles long, it is consumed by alfalfa hay irrigation and does not reach a receiving stream. The annual average precipitation is about 16 inches, the majority of runoff is due to snowmelt; in times of extreme drought the stream will run dry (Moore & Kotansky, 2002).

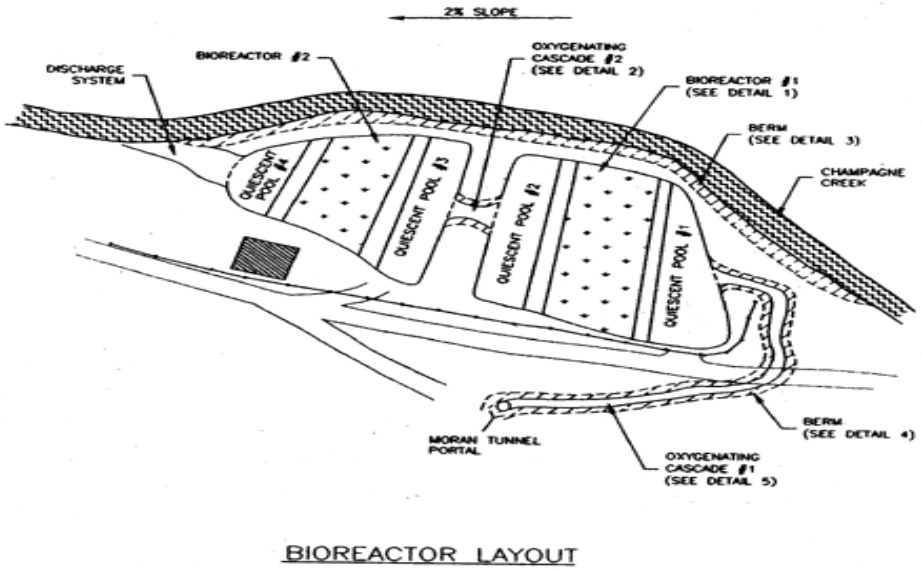

Figure 4. Schematic of Champagne Creek Bioreactor (Moore & Kotansky, 2002)

Mining around Champagne Creek began around 1883 with the discovery of silver ores, this first mine operation ended around 1887. In the late 1920s deeper base-metal sulfide ores were mined for lead and zinc. Around this same time the Moran Tunnel was constructed with the hope of intersecting the Last Chance vein at around 450 feet below the surface; the vein was never found. The area was last mined in 1946.

The site underwent a Preliminary Assessment in 1985 and a Site Investigation in 1988. The Bureau of Land Management completed its own study in 1989. It was this report that required

additional water quality monitoring and a review of which passive treatment wetland system might be able to be used (Moore & Kotansky, 2002).

In 1999 cleanup at the Moran Tunnel began. The first actions were removal of waste rock piles, a 17,500 cubic yard pile was placed in a repository above the flood plain; additional waste rock totaling 2700 cubic yards from surrounding areas was also placed in this repository (Moore & Kotansky, 2002). A four-cell passive bioreactor system was constructed based on SRB and lime treatment. The cells consisted of organic material (manure and hay) to encourage SRB establishment and limestone to neutralized acidic discharges (Moore & Kotansky, 2002). Berms were also put into
place leading to the passive system; they were made up of lime and materials to encourage SRB growth.

The system was effective in improving water quality for the first few months of operation (S. Moore, personal communication, 7/30/2003). The pH from pond 1 to pond 2 increased from 3.3 to 6.4. The first winter (1999-2000) after installation revealed lower metal discharges and a decrease in SRB activity common during cold weather (Moore & Kotansky, 2002). The first berm, made of "limestone and SRBs," initially led to a decrease in aluminum and copper of nearly 100-percent, 92-percent of cadmium, 77-percent of zinc, and 65-percent of iron (Moore & Kotansky, 2002). By May 0f 2000 the removal rates were nearly 100-percent aluminum and copper, 91-percent iron, and 56-percent zinc (Moore & Kotansky, 2002).

In 2001 the passive treatment system was enhanced with the addition of an anaerobic treatment tank. It was added between the discharge from the Moran Tunnel and the first treatment pond. The tank was put into place because water quality data indicated that the high concentration of iron on the first pond was interfering with the effectiveness of the bioreactor berms in removing zinc, copper, and buffering pH (Moore & Kotansky, 2002). Eventually, the tank also clogged and performance of the system declined (S. Moore, personal communication, 7/30/2003).

The system has required recharge of the berms with "SRBs and limestone" and the addition of the anaerobic tank (Moore & Kotansky, 2002). This system has not yet proved to be a walk-away solution, but BLM-Idaho are working on improving the system and carefully documenting efforts so that lessons may be learned for future projects (S. Moore, personal communication, 7/30/2003).

2.2.4 Successive Alkalinity Producing Systems

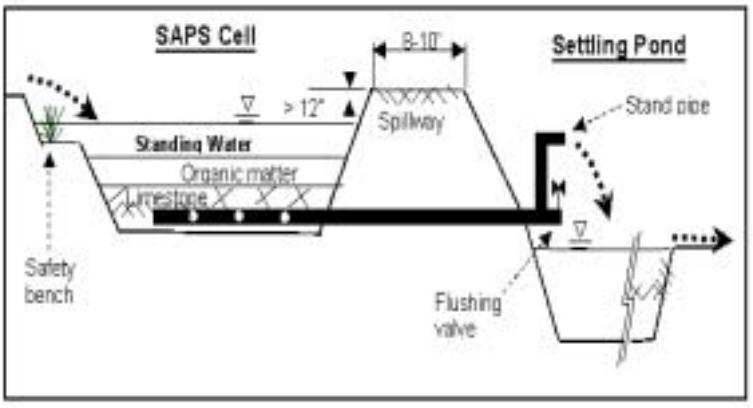

Figure 5. General Schematic of a SAPS Available at: http://sudan.cses.vt.edu/prp/Research_Results/SAPS.html

Successive Alkalinity Producing Systems have the following basic elements: organic mulch layer, limestone layer, and a drainage system - most include a flushing system as well. This technology was created in the early 1990's by Kepler and McCleary (Younger et al., 2002). The idea is that mine drainage flows into the tops of the cell creating a top layer of water which prevents the infiltration of oxygen into the bottom layers (water is also used in this way in tailings holding dams). The organic layer serves to remove dissolved oxygen from the water, farther down anaerobic conditions support the establishment of sulfate-reducing bacteria. The anaerobic environment is a reducing environment that changes Fe^{+3} to $Fe,^{+2}$ thereby reducing the likelihood of iron hydroxide precipitation, see equation 3. Since these units encourage reducing conditions and establishment of SRB, a major contribution to the treatment of the water, these units are sometimes referred to as RAPS - Reducing and Alkalinity Producing Systems (Younger et al, 2002). Finally, the water enters the limestone region, essentially devoid of oxygen preventing the armoring of limestone. Upon leaving the SAPS the water is usually directed to an aerobic settling pond or wetland to allow metals to form precipitates and further water polishing (Kepler & McCleary, 2003).

Many SAPS include flushing systems because as one would imagine oxidation and reduction of Fe and Al leads to precipitates that can clog the cell (Rees et al., 2001). The flushing systems generally operate by generating head differences that move water rapidly through the system (Kepler & McCleary, 2003).

SAPS tend to be more efficient than anaerobic wetlands and require less space to provide the same level of treatment (Younger et al., 2002). SAPS require some maintenance, not only for periodic flushing, but also to prevent or correct the development of preferential flow paths, possible in any of these passive systems (Kepler & McCleary, 2003; Rees et al., 2001). If preferential flow paths develop the water short circuits the system. They also require driving head and freeboard resulting in topographic relief requirements of greater than five meters (Younger et al., 2002).

A. Case Study: Oven Run, Pennsylvania

The watershed protection group Stoneycreek - Conemaugh River Improvement Project (SCRIP) located in western Pennsylvania, has initiated and completed multiple projects to improve their watershed. During a phone conversation with Dave , who is directly involved in this project, it was revealed that many of their remediation projects utilize SAPS (personal communication, 6/18/2003). Oven Run is one of the larger sites handled by SCRIP, it has six sources of highly acidic, metals-laden drainage totaling 720,000 gallons a day (Oven Run). Projected costs were $5 million, actual costs were $4.1 million (D. Steel, personal communication, 6/18/2003). Five of the six sources are treated using SAPS, the sixth has been backfilled. The first SAPS was installed in 1995, the last in 2003.

Figure 6. Oven Run, SAPS, Available at: http://www.ctcnet.net/scrip/stoven.htm

So far treatment has been successful in removing metals and acidity, while generating alkalinity. Not including the most recently installed SAPS, pH at downstream monitoring points have increased from the 3 to 4 range to the 5 to 6 range and 200 tons of iron and 200 tons of aluminum are removed each year. In addition, the samples showed some alkalinity, which is particularly impressive because other acidic waters drain into the creek after Oven Run, so the treated waters are able to buffer some of the additional pollution.

B. Case Study: #40 Gowen, Gaines Watershed. Oklahoma

This is a former coal mining site experiencing the typical aliments, acidity and elevated metals concentrations, mostly iron. This project was commissioned in 1998 with the help of an EPA Region 8 Section 319 grant and the Oklahoma Conservation Commission, by the University of Oklahoma (EPA, 2002c). This site, amongst other AMD sites, was designated as having the greatest impact on Pitt Creek, a

Figure 7. SAPS cell ("Section 319 Success Stories" Available at: http://www.epa.gov/owow/nps/Section319III/OK.htm

tributary to Gaines Creek which drains into Lake Eufaula (EPA 2002c). The Gaines Creek Watershed is located in Pittsburg and Latimer counties. The treatment design is a four-cell system with alternating vertical flow wetland (though figure shows little more than ornamental plant-life) and surface flow aerobic ponds. The project budget was $125,000 and was installed in 1998. To avoid confusion, the vertical flow cell is what would typically be defined as a SAPS though some define the entire alternating system as a SAPS as well. The vertical flow cell consists of a layer of water on top, followed by 1 meter of compost mixed with limestone and flyash and a cobble-fill pipe drainage system (EPA, 2002c).

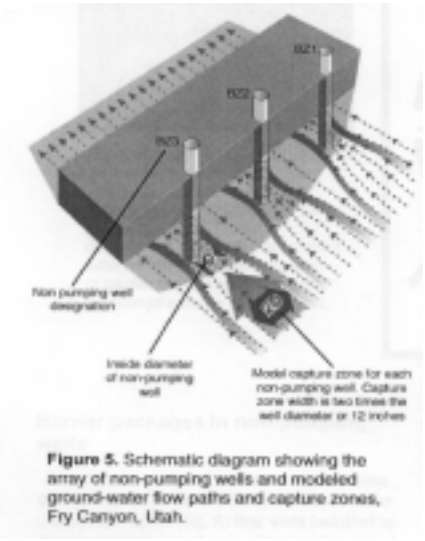

Figure 8. Schematic of Non-pumping well PRB.

There was not enough space at this site to construct a system that would be able to treat the entire flow; the system treats approximately 7600 gallons per day (EPA, 2002c). The design was based on "contaminant loadings of about 18,000 and 7,000 grams per day of acidity and iron" (EPA, 2002c). Removal rates for acidity are estimated to be 30 - 40 gram/meter^2 - day; the total surface area is approximately 750 meter^2.

The system has been in operation for two years and monitored every two weeks. Though actual data could not be obtained, the report about the project on EPA's website indicates that "concentrations of iron, aluminum, and manganese have decreased significantly," pH of the final effluent is at 6 and alkalinity is above 150 milligram/liter (EPA, 2002c). Trace metals - barium, cadmium, chromium, copper, nickel, zinc, and lead - were reduced to near or below detection levels. A recent biological survey counted 2000 healthy populations of fish and macroinvertebrates in three of four cells.

This project is of particular interest because it is the first successful passive treatment AMD treatment project carried out in Oklahoma (EPA, 2002c). The success of this project has spurred the state to use this wetland design at the Tar Creek Superfund site in Ottawa county, Oklahoma, and is being investigated for application in several watershed nationwide (EPA, 2002c).

2.2.5 Permeable Reactive Barriers

Permeable Reactive Barriers (PRBs) are exactly what they sound like: barriers that react with specific chemicals of concern that are placed in the path of groundwater flow allowing the water to flow through easily (Blowes et. al, 2000). In PRBs designed to treat acid mine drainage (AMD) with metals contamination the barrier is generally composed of solid organic matter, like municipal compost, leaf compost, and wood chips/sawdust (Blowes, et. al., 2000). Organic matter encourages the proliferation of sulfate-reducing bacteria that will reduce sulfate to sulfide

and will result in the subsequent formation of insoluble metal sulfides which has been described with regards to bioreactors, please see equations 17 & 18. Research has been done to evaluate the efficiency of using PRBs to remove uranium contamination at abandoned mine sites; possible reactive materials are zero-valent iron, bone char phosphate, and amorphous ferric oxyhyroxide (Naftz, et al., 1999).

One important consideration in the design of a PRB to treat AMD is the stability of the metal sulfides (Blowes, et. al., 2000). Sulfides have low solubility in anaerobic conditions, if oxidation were to occur, metals could be released from their metal sulfide form into the environment (Blowes, et. al., 2000). An example of designing to prevent oxidation is illustrated by a project at Nickel Rim Mine, Sudbury, Ontario. The designers considered the implications of an oxidizing agent in the flow of groundwater and the PRB was covered by a 20cm saturated clay cap to prevent oxygen infiltration (Blowes, et. al., 2000).

Although not discussed much in this paper, former uranium mines are also a serious concern Naftz et al. conducted a field demonstration using six different PRBs to study the removal efficiencies of uranium at a site in southeastern Utah (1999). There were four different reactive media and two design types. Three of the PRBs were "funnel and gate" types, the gate is where the reactive media is located and the funnel is two impermeable walls directing groundwater to the gate. Each gate was consisted of a different material: (1) bone char phosphate (PO_4) pellets, the phosphate source facilitates the formation of insoluble uranyl phosphate compounds; (2) zero valent iron (ZVI) pellets which induce the reduction of uranium (VI) to the less soluble uranium (IV); and (3) pelletized amorphous ferric oxyhydroxides (AFO) which remove uranium by adsorption to the ferric oxide surface (Naftz et al., 1999). The other three PRBs were six-inch diameter non-pumping wells consisting of different proportions of bone char phosphate and foamed iron oxide pellets; the phosphate will adsorb to the iron pellets to allow access for formation of uranyl phosphate compounds (Naftz, et al., 1999). The hypothesis is that wells will allow for contact with deeper plumes and will be more suitable for remote locations (Naftz et al., 1999).

Results of the field demonstration were positive. After one year of operation and seven sampling events the funnel the ZVI barrier removed >99.9 percent consistently, the PO_4 barrier removed >90 percent on all but two of the seven sampling events, and the AFO barrier varied the most but still removed an average of 88.1 percent (Naftz, et al., 1999, Table 1). Data from the wells spans only three months and the results are not quite as impressive, but still reasonable; the average of removal rates overall was 67 percent (Naftz et al., 1999)

PRBs are a relatively new technology and work is continually being done to optimize installations. As it is often helpful to learn from past error a brief discussion of common problems of PRB performance is presented (Blowes, et. al., 2000).

1) Although barriers often have very long theoretical treatment lifetimes when only the material and the contaminants of concern are considered, actual lifetimes are considerably shorter due to the presence of other reactive substances in the environment;

2) Chemical reactions can be slowed due to depletion of reactive component of the barrier;

3) Precipitation of a secondary reactive precipitate can reduce the reactive surface area;

4) Physical clogging or preferential path flow.

2.2.6 Biosolids

Biosolids are treated municipal sewage sludge; the EPA defines biosolids as follows:

> "...the nutrient-rich organic materials resulting from the treatment of sewage sludge (the name for the solid, semisolid or liquid untreated residue generated during the treatment of domestic sewage in a treatment facility). When treated and processed, sewage sludge becomes biosolids which can be safely recycled and applied as fertilizer to sustainably improve and maintain productive soils and stimulate plant growth."

Biosolids have a growing number of useful applications and the search for more continues as population and hence sludge production increases. Biosolids are being used to reclaim mine lands (Murray et al., 1981; Sopper, 1993; Toffey, 2003) and have also been used for agricultural purposes. There are federal standards, namely Section 103C of the Clean Water Act and state standards that have to be met in order to apply biosolids to land. Over a twenty-five year period, the field experience with biosolids continues to demonstrate clear environmental benefits and negligible adverse effects (Sopper, 1993; EPA; Toffey, 2003).

When reclaiming mine sites biosolids are almost always applied with lime, either pre-mixed or in stages (R. Bastian, personal communication, 6/2/2003). Lime serves to increase the pH of the soil rapidly. Lime application alone may not be sufficient for long term improvement in the soil characteristics because the pH will eventually decline as sulfur-bearing minerals are oxidized (Sopper, 1993). However, biosolids application without lime has in some cases raised the soil pH and decreased availability of metals (Sopper, 1993).

Biosolids also show advantages over chemical fertilizers (Sopper, 1993) because they provide a source of carbon and capacity for moisture retention which are conducive to microbial and plant growth. This is important for the establishment of a long-term self-sustaining system. Sopper summarizes that biosolids application re-establishes a functioning microbial population comparable to undisturbed levels within two or three years of application, much more quickly than with traditional chemical treatment (1993).

The application of biosolids does not necessarily reduce the amount of metals present in the soil. In a draft report for the EPA, Maxemchuk explains that tailings sites treated with biosolids do not experience a reduction in total metals, rather metals availability is reduced (2001). Metals are immobilized through precipitation as carbonates, phosphates, sulfides, silicates and sorption by organic matter, and hydroxides (Sopper, 1993). In some cases vegetation may be responsible for immobilizing the metals, or might even remove the metals from the soil, also known as phyto-extraction.

There is ample evidence to support the use of biosolids in reclaiming mine lands. It is a cost-efficient method for reducing potential harm to the environment and its occupants. It is particularly attractive when the other options are removal and/or capping. Removal is generally expensive, especially when sites are very large and this approach just relocates the waste material, posing a potential problem at a new location. Capping alone can prevent further exacerbation of the problem, but will not help to re-establish a functioning ecosystem at the site unless natural soils are used. The use of natural soils as caps on large area sites is impractical, expensive and leaves "borrowed" areas highly disturbed and subject to intense erosion. Biosolids provide an apparently indefinite solution to contaminated sites because metals of concern are complexed, reducing their bioavailability, and the health of the A-horizon in the soil profile is improved. This allows vegetation to replenish itself - stabilizing and improving the health of the ecosystem in the area.

A. Case Study: Frostburg, Maryland

This project is a testament to the longevity of the use of biosolids in the reclamation of mine lands. The field plot experiments were installed in 1974 on a former strip mine. The site had been completely devoid of vegetation for four years (Griebel et al., 1979). The overburden and rock wastes resulted in a dark-colored, acidic - pH of 2.9, spoil material (Griebel et al., 1979).

A total of nine test plots 3.6m x 4.5m were installed. There were three basic applications tested: biosolid compost alone, biosolid compost with rock phosphate, and biosolid compost with dolomitic limestone (Griebel et al., 1979). For each of these three scenarios biosolids were applied in three different amounts: 56 metric tons per hectare (mt/ha), 112 mt/ha, and 224 mt/ha (Griebel et al., 1979). The biosolids were supplied by the Blue Plains Wastewater Treatment Plant in Washington, DC. They were then composted at ARS-MES Composting Facility in Beltsville, Maryland. When sewage sludge is composted the material becomes more humus-like and excess heat and water are driven off and decreases in the availability of certain metals results (Griebel et al., 1979). Both rock phosphate and dolomitic limestone were applied at the rate of 11 mt/ha. In addition, each plot received 110 kg/ha of nitrogen in the form of NH_4NO_3. A grass legume seed mixture was applied at 40 kg/ha and Empire birdsfoot trefoil, *Lotus Coniculatus L.*, was applied at 10 kg/ha (Griebel et al., 1979)

After two years the vegetation was harvested and analyzed for yield and metals uptake into the plants. Soil conditions were also analyzed.

After two years the control plot had a pH of 3.1, the test plots had pH's as seen in the table below. The plots with the maximum biosolid application had the most improved pH; interestingly the difference between compost alone and compost with alkaline amendments did not differ significantly.

pH of the Soil Two Years After Biosolids Application

	56 mt/ha of biosolid	112 mt/ha of biosolid	224 mt/ha of biosolid
compost alone	4.2	3.9	5.0
compost & rock phosphate	4.5	4.8	5.1
compost & dolomitic limestone	4.6	4.8	5.1

Adapted from Griebel et al., 1979

Plant yields, shown in figure 9, below are from a single harvest taken during the second growth season (Griebel et al., 1979). Overall the results are positive, and certainly better than the control plot with no amendments.

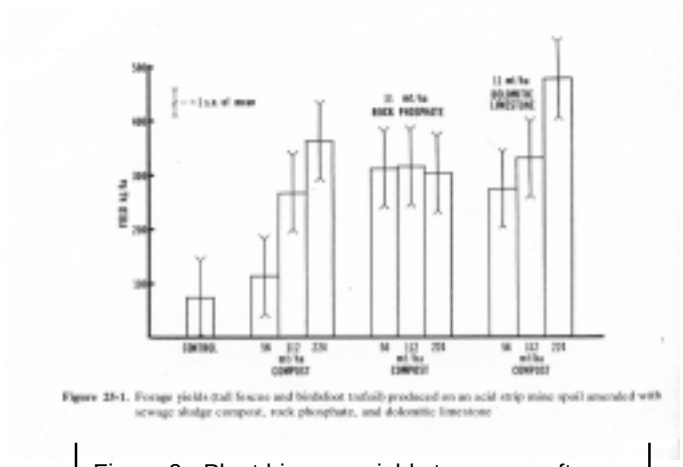

Figure 9. Plant biomass yields two years after biosolids application (Griebel et al., 1979, figure 25-1)

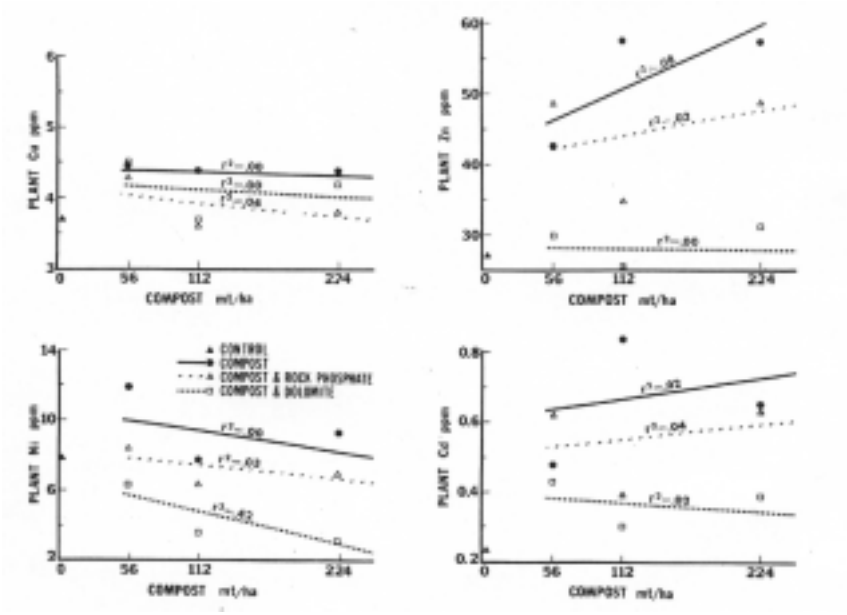

Figure 10. Relationship between total plant metals and rates of application of biosolids and other amendments (Griebel et al., 1979, figure 25.8)

One of the more interesting things to note is that the "lowest compost treatment (56 mt/ha), used in combination with either rock phosphate or dolomite, provides yields equal to those obtained with 112 mt/ha compost alone" (Griebel et al., 1979. p. 296). Furthermore, the highest rate of compost alone (224 mt/ha) was exceeded only when the same amount was applied with dolomitic limestone (Griebel et al., 1979).

A common concern when applying biosolids at metals contaminated sites with the intention of establishing vegetation is that the vegetation will accumulate high levels of metals that could potentially be a hazard to wildlife. In this study the observed metal concentrations of Cu, Zn, Ni, and Cd in vegetation were well within the range of concentrations found in vegetation produced on regular agricultural soils (Griebel et al., 1979). Figure x shows the concentrations of the metals with respect to each amendment combination. It is obvious from studying the graphs that the addition of limestone or phosphate rock reduces the amount of metals taken up by the plants, generally to around the levels found in the control plot's vegetation.

B. Case Study: Leadville, Colorado

Biosolids were applied at the Leadville site to revegetate the alluvial tailings deposits that were washed in and around the Arkansas River. The tailings have been deposited at various locations

along an 11-mile stretch of the river. This has created a variety of environmental problems including acidic soils in the range of pH 1.5-4.5, Zn and Pb salt formation on the soil surface, sedimentation in the river of up to two feet in some spots, and death of vegetation leading to erosion of river banks ("Upper Arkansas," 2000).

Figure 11. Metal salt accumulation on soils in Leadville, CO on the banks of the Arkansas River, (Upper Arkansas, 2000).

Biosolids provided by Denver Metro were applied to portions of the site at a rate of 100 dry tons/acre in August of 1998 ("Upper Arkansas," 2000). Approximately 100 tons/ac of lime were also applied; both were tilled into the soil at a depth of twelve inches ("Upper Arkansas," 2000). A variety of soil amendment combinations were also applied to test plots at the site, to determine which mix of biosolids and alkaline agent would promote the most vegetation. During a visit to the site in July of 2003 it appeared that the applications were working quite well.

2.2.7 Phytoremediation

Phytoremediation suggests the use of plants to treat or remove contamination. Wong defines the term as, "the use of green plants and their associated microbiota, soil amendments, and agronomic techniques to remove, contain, or render harmless environmental contaminants (2003). Though there are a wide variety of subcategories in the field of phytoremediation only four will be discussed in this paper, phytoextraction/phtyomining, phytostabilization, rhizofiltration, and phytovolatilization. For more information about other technologies, consult US EPA's Introduction to Phytoremediation.

Phytoextraction, or phytomining if metals can be recovered, is defined as:

> "the uptake of contaminants by plant roots and translocation within the plants. This concentration technology leaves a much smaller mass to be disposed of than does excavation of the soil or other media" (EPA, 2000, p. 143).

There are a limited number of plants known to be capable of this and climate determines what species can be used. Phyto-mining requires that the plants be "hyperaccumulators," i.e., they will uptake more than the average concentration of metals. According to Brooks et al., there are about 300 species that hyperaccumulate nickel, 26 cobalt, 24 copper, 19 selenium, 16 zinc, 11 manganese, one thallium and one cadmium (1998). Although these numbers are encouraging there are few field applications. An important consideration in applying phytoextraction, especially with the use of hyperaccumulators, is whether the resulting vegetation will be hazardous to local animals; this possibility varies from site to site (Wong, 2003).

Phytostabilization is fairly common with regards to mining sites, it is a common practice to revegetate spoiled mine lands to prevent soil erosion and deposition of contaminated soils in streams and nearby lands. The EPA defines it as:

> "(1) immobilization of a contaminant in soil through adsorption and accumulation by roots, adsorption onto roots, or precipitation within the root zone of plants, and (2) the use of plants and plant roots to prevent contaminant migration via wind and water erosion, leaching, and soil dispersion" (EPA, 2000, p. 21).

Ideal plants for this technique use metal-tolerant, drought-resistant, fast growing crops that can also grow in nutrient deficient soils (Wong, 2003). The advantages are that it is a relatively inexpensive technique, soils do not need to be removed, ecosystem restoration is enhanced, and disposal of hazardous materials or biomass is not required (EPA, 2000). Disadvantages are that the contaminants remain in place - care must be taken to ensure that the vegetation continues to stabilize the metals; extensive fertilization or soil modification may be necessary; plant uptake and translocation of metals must be prevented; root zones, root exudates, contaminants, and soil amendments must be monitored to prevent an increase in metal solubility and leaching; it may only be considered a temporary measure; stabilization might be due primarily to the effects of soil amendments, with plants only contributing to stabilization by decreasing the amount of water moving through the soil and by physically stabilizing the soil against erosion (EPA, 2000). The application of biosolids fits well with this phytoremediation technique as it provides necessary fertilizing agents and aids in microorganism establishment.

Rhyzofiltration involves the removal of contaminants in solution through adsorption or precipitation onto plant roots or absorption into the roots, this can also be achieved by the microorganisms associated with the rhizosphere (EPA, 2000; Wong, 2003). This technology is applied in water, that is the plants are either aquatic plants or terrestrial plants on a floating platform (EPA, 2000). Contaminants can be physically removed by removing the plants themselves. Some of the disadvantages to this technology include a need for good control over pH, and a clear understanding of the chemical speciation and interaction of all species in the influent (EPA, 2000). In addition to this, control over influent concentration and flow rate may be necessary, plants may need to be grown and then translocated to the site (especially terrestrial plants), periodic harvesting and disposal are required, and laboratory results might not be achievable in the field (EPA, 2000). Phytovolatilization has been identified as a potential treatment for mercury and selenium contaminated soils (Chaney, et al., 1997; EPA, 2000). Phytovolatilization is defined by the EPA as,

> "...uptake and transpiration of a contaminant by plant, with release of the contaminant or a modified form of the contaminant to the atmosphere from the plant through contaminant uptake, plant metabolism, and plant transportation" (EPA, 2000).

This process is beneficial if the contaminants of concern will be transformed to less-toxic forms, for example elemental mercury and dimethyl selenite gas. The disadvantages are uncertainty about

metabolites, unhealthy plant accumulation, and uncertainty about other constituents at the site, i.e., where there is one form of contamination there could be many more and one must understand how they will react with the plants as well. For more information including references and plant species appropriate for the different technologies discussed here please see the following reference: Introduction to Phytoremediation, 2000; Wong, 2003; Brooks et al., 1998; Brooks, 1998; and, Madejon et al., 2003.

3.0 Conclusion

Given the seriousness and scale of mine drainage it is important to continue to work towards affordable and effective treatment options. The passive treatments discussed in this paper are exhibiting mixed success, results are encouraging but not the "walk-away," cheap solution that they are sometimes described to be. Still the innovative treatments discussed here are showing progress and with further research and performance analysis these technologies may become more widely used in the future. While there are drawbacks to traditional treatments, there are some benefits that make them widespread and in some cases the preferred alternative.

As with almost any topic, there is need for more work, some of the more pressing areas include communication, funding, and research about fundamental processes that cause precipitation of metals. Many of the people contacted for this report expressed their desire for a better line of communication and access to information about similar projects. The database created in conjunction with this report began to create a place to access project information, though it is not a complete picture of the efforts being done. Regional communication between parties working with similar geology and climate would probably be the most useful effort as the performance of passive treatments seems to be greatly affected by these factors. Funding, or lack thereof, is a serious issue especially for hard rock sites. As previously mentioned, non-coal states are not eligible for SMCRA funds and states that are eligible must address coal-related issues before hard rock. Considering the number of hard rock sites it does not seem reasonable to rely on existing federal and state environmental funds, for example CERCLA and CWA, to sponsor remediation efforts. As mentioned earlier in this paper, some states are making efforts to identify and remedy this funding problem. Research about the precipitation of metals has been done, however, the differences from site to site in geology, hydrology, climate, and chemistry make general application of this information quite difficult. Each site must be addressed separately to account for the variations that occur in nature. As experience builds and information is shared the application of passive technologies will improve.

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Appendix A: State Mine Reclamation/Remediation Status

This section presents state programs and activities that address abandoned mines. The focus was limited to Western states dealing with hard rock mines. Note that this list is not comprehensive of all of the programs and activities occurring in each state.

Alaska
Department of Natural Resources
Division of Mining, Land & Water
http://www.dnr.state.ak.us/mlw/mining/aml.htm

Funding for this program comes from SMCRA funds. The state is only able to generate $200,000, but has $2 million in reclamation needs; therefore, the state qualifies for Minimum Program Status from the SMCRA fund, entitling them to $1.5 million plus emergency funds annually until the work remaining on the inventory drops below $2 million.

Coal and non-coal mining abandoned mines were inventoried. The coal inventory is complete, and 340 sites were identified. The non-coal inventory is incomplete with a count of 432. Each site was evaluated to determine funding eligibility. Priority 1 and 2 coal projects must be completed first, so only priority non-coal projects can be reclaimed. Priority 3 projects can be worked on in conjunction with Priority 1 and 2 projects or after all Priority 1 and 2 projects have been completed.

The state developed a variety of priorities to select sites for remediation; they came up with 224 coal projects and 32 - 123 non-coal projects. Initial inventories estimated costs at $52 million and non-coal costs at $2.7 million. To date, 36 AML projects have been completed at a cost of $8,880,980. Most of the projects involved preventing physical hazards.

U.S. Department of the Interior - Bureau of Land Management - Alaska
http://www.ak.blm.gov
http://www.ak.blm.gov/amines/amlindex.html

About 15 to 20 projects are either active or have been completed. Projects are selected using water shed approach (i.e., projects that will have the greatest impact on water quality in the watershed are chosen first). As with many of the programs, funding is an issue. The Web page states, “Because there is never enough money, the BLM must first consider watersheds damaged by abandoned mines.”

Arizona

Arizona State Mine Inspector

http://www.asmi.state.az.us

http://www.asmi.state.az.us/abandoned.html

Part of this state office's mission is to review and monitor all mine reclamation activities. This office established the Abandoned and Inactive Mine (AIM) Survey to inventory abandoned and inactive mines throughout Arizona. The majority of the funding for this program comes from the Bureau of Land Management. The program began inventorying sites in 1992 and estimates that there are at least 125,000 abandoned or inactive openings in the State of Arizona.

As of January 1999, 7,844 mines have been surveyed, with 288 mines with some type of Environmental Hazards and 1149 mines with Significant Public Hazards.

U.S. Department of the Interior - Bureau of Land Management - Arizona

http://www.az.blm.gov/

California

U.S. Department of the Interior - Bureau of Land Management - California

http://www.ca.blm.gov

http://www.ca.blm.gov/pa/aml/ - for specific AML activity

The California BLM manages 15 Resource Areas (RA's, Field Offices) comprising over 16 million acres in California and Northwest Nevada. Over 12,000 mine properties in California and Northwest Nevada are listed in the Bureau of Land Mines Mineral Industries Location System (MILS) database as on BLM land. An estimated additional 5000 sites likely to be on BLM land are not recorded in this database are. Of these 17,000 sites, an estimated 3000 significant properties contain hazardous substances or physical features and/or have environmental problems. No comprehensive AML inventory has been conducted on any RA in the state and six RA's have no recorded inventory of mine sites.

"The California State Office, (with limited staff) from mid-2000, has been conducting watershed-based projects that have and will continue to identify mine sites with environmental and/or safety issues" (http://www.ca.blm.gov/pa/aml/). To date about 40 sites have been identified as "high priority," more than 170 sites have been added to the Abandoned Mine Land Identification System - a database of AMLs on BLM lands. According to the website 7 projects have been completed as of April 21, 2003.

California Environmental Protection Agency

State Water Resources Control Board

http://www.swrcb.ca.gov/

One of the things found via this website was a document entitled, "The Abandoned Mine Technical Advisory Committee's Report on Abandoned Mines." [http://www.swrcb.ca.gov/nps/docs/tac_abandmin.doc] The document was created by the Abandoned Mines Technical Advisory Committee (TAC). TAC spent six months discussing the issues surrounding abandoned mines, past cleanup efforts, and desired future courses of action. They prioritized courses of action and identified barriers to progress. TAC identified lack of funding as a key impediment to cleanup of abandoned mines.

California is not a coal-mining state and therefore is ineligible to receive SMCRA funds.

Colorado

Colorado Department of Public Health and Environment

Hazardous Materials and Waste Division

http://www.cdphe.state.co.us/hm/hmhom.asp

This division regulates solid waste management, treatment, disposal facilities, and hazardous waste generation, storage, transportation, treatment, and disposal. The division also ensures compliance with state hazardous waste regulations and permits and oversees remediation of contamination at Federal Facilities located in the state. The division assists in the cleanup of hazardous waste sites under the Superfund Program, and encourages brownfields redevelopment through implementation of the Voluntary Cleanup and Redevelopment Act.

This state agency has dealt with the remediation of a few mine sites including Bonanza, Clear Creek, Eagle, Idarado, Leadville (California Gulch), and Summitville Mine.

U.S. Department of the Interior - Bureau of Land Management

Colorado Abandoned Mine Land Program

http://www.co.blm.gov/mines/mine.htm

There are about 2,600 abandoned mines on Colorado's public lands. The projects during 2002 are listed below. The projects are being addressed with a watershed approach.

Arkansas Watershed:

LakeFork Project - includes Nelson and Dinero Tunnel Projects

Mill Sap Gulch Project

Mount Robinson Project/Historic Rosita Mining District

Upper Animas Watershed

Elk Tunnel

Forest Queen

Joe and John

Lackawanna and Lark

Upper Gunnison Watershed

Palmetto Mine Remediation

Roy Pray #1 Remediation

Ute Ulay Mine/Mill Remediation and Mine Waste Repository

Wyoming Mine Remediation

Many of the project involve water diversion, materials removal, and revegetation.

United States Geologic Survey (USGS)

Toxic Substances Hydrology Program

http://toxics.usgs.gov/sites/upper_ark_page.html

The USGS has a few projects in Colorado and elsewhere that attempt to characterize metal transport in streams affected by mining. Work in the Upper Arkansas Toxic-Substance Hydrology Project began in 1986. The approach is to study chemical processes within a hydrologic context, using a two-step approach. First, we have employed in-stream experimentation to provide data about the processes affecting metals. Second, they have used the resulting data sets to develop and apply solute transport models that help quantify rates and processes. See the Web page for more information about this and other projects.

Idaho

U.S. Department of the Interior - Bureau of Land Management

Idaho Abandoned Mine Lands

http://www.id.blm.gov/aml/index.htm

The program stems from a 1982 report that four dozen livestock had been poisoned by ingestion of lead tailings.

Significant effort has been put into Pine Creek, a tributary of the Coeur d'Alene River, in the Silver Belt region of northern Idaho. Between 1996 and 1998 more than 30,000 cubic yards of tailings were removed from the flood plain to prevent the deposition of the material in the river. Much of the cleanup effort was accomplished through funding by the hazardous materials program, Central Haz Mat Fund, and emergency flood funding.

Systematic AML site inventories began in mid-1990s.

Starting in the fiscal year 1999, Clean Water Action Plan funding enabled a more uniform national effort to move from inventory to cleanup of AML sites. Project summaries of completed or active projects can be found in the AML Project Notebook link at http://www.id.blm.gov/aml/notebood.htm

In FY 2002, 2 projects using passive treatment were installed: Champagne Creek and Bridge Creek.

At the beginning of fiscal year 2002, the focus was to better integrate AML with other statewide Idaho priorities. "Lack of a national source of funding dedicated to addressing physical hazards continues to be an issue. This year we are seeking a reallocation of some of Idaho's BLM program funding to better address priority sites, particularly in the proximity of recreation sites and other public lands heavily visited by the public" (http://www.id.blm.gov/aml/program.htm).

Basin Environmental Improvement Project Commission

http://www.basincommission.com/

This organization was created by the Idaho legislature under the Basin Environmental Improvement Act of 2001; the group became operation in March of 2002. It consists of representatives of the state of Idaho, the three Idaho counties in the Basin, the Coeur d'Alene Tribe, the state of Washington, and the United States of America (represented by the U.S. EPA). It is the policy of the state to provide a system for environmental remediation, natural resource restoration and related measures to address heavy metal contamination in the Coeur d'Alene Basin.

Montana / Dakotas

Department of Environmental Quality

Mine Waste Cleanup Bureau

http://www.deq.state.mt.us/rem/mwc/index.asp

The Mine Waste Cleanup Bureau (MWCB) focuses on two primary site types:

1) inactive mine sites addressed under the Surface Mining Coal and Reclamation Act (SMCRA 1977).

2) mining related sites addressed under the Federal Comprehensive Environmental Response and Liability Act (CERCLA) .

The MWCB divided its site-reclamation duties in this way because of distinctions between applicable environmental laws and associated funding mechanisms.

The DEQ-MWCB must give priority to abandoned coal mines, and Montana has completed reclamation of its abandoned coal mines and has now moved on to non-coal sites. The non-coal sites are ranked in priority order based on a scoring system developed by the state. To date, Montana's abandoned mine reclamation program has overseen the completion of more than 283 projects totaling nearly 1174 acres.

U.S. Department of the Interior - Bureau of Land Management

Montana/Dakotas Abandoned Mine Land Program

http://www.mt.blm.gov/aml/index.html

Montana BLM has been working to clean up abandoned mines located on public lands utilizing a watershed approach since 1995. An inventory of 1078 abandoned mines located on public lands resulted in 65 sites that needed further investigation and potentially reclamation.

At least 15 projects are underway or completed. More information can be obtained from the Web page cited above.

Navajo Nation

Division of Natural Resources

Navajo AML Reclamation/UMTRA [Uranium Mill Tailings Radiation Control Act] Department

http://www.navajoaml.osmre.gov

This program was certified to have reclaimed all Priority 1 and 2 abandoned coal mines by the Secretary of Interior as of May 4, 1994 . The program is now permitted to focus attention on non-coal mines. The Navajo AML Program anticipates having all known and eligible abandoned mines reclaimed by the end of 2004.

In 2000, the Navajo AML Program amended its AML Plan to incorporate the provisions of SMCRA, Sections 411(e) and (f), which provide the authority for using AML funds to construct public facilities as a means of mitigating current and past mining-related impacts to such communities. Thus, the Navajo AML Program can now also use its AML funds for the construction of Public Facility Projects (PFP's). Navajo AML funded its first PFP in EY-2002.

In 2002, four reclamation projects were completed, all of the work done "minimized the need for maintenance, promotes landscape stability, enhances re-establishment of natural vegetation, enhances wildlife, and most importantly, adequately safeguards the physical and radioactive hazards."

> - Office of Surface Mining Reclamation and Enforcement : Annual Evaluation Report - Evaluation Year 2002 (Oct. 1, 2001 through Sept. 30, 2002) - on the Navajo Abandoned Mine Lands Reclamation Program.
> http://www.navajoaml.osmre.gov/News_Rprts/AML/OSM_AER_Nav2002.pdf

Nevada

State of Nevada Commission on Mineral Resources

Division of Minerals

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http://minerals.state.nv.us/

The state's first priority is to reduce hazards such as high walls, embankments, etcetera. It is estimated that the state has 200,000 abandoned mine features. Approximately 50,000 present physical safety hazards, including 9,244 hazardous mine openings throughout the state. Seven thousand have been secured.

As for environmental problems, the State of Nevada has an Interagency Abandoned Mine Land Environmental Task Force. In their Sept. 1999 report, an estimated 1 to 3 percent of 200,000 to 500,000 abandoned mine land features have the potential to impact ground or surface waters. Even at 1 percent the numbers are very high--20,000 to 60,000 potential pollution sources. As of 1999 there were 33 sites identified for clean-up; 6 of these sites were considered high priority and site characterization had begun. The report can be reviewed at: http://minerals.state.nv.us/forms/aml/nvamlreport.pdf

U.S. Department of the Interior - Bureau of Land Management

Nevada

http://www.nv.blm.gov/AML/

In March of 1999, the Bureau of Land Management-Nevada State Office (BLM) initiated the formation of an Interagency Abandoned Mine Land Environmental Task Force (IAMLET) to begin remediation of abandoned mine land (AML) environmental problems associated with watersheds in Nevada. The task force is comprised of federal and state agencies with a role in abandoned mine lands in the state. Initial funding for the program is from the BLM through the Soil, Water, and Air Management Budget, in accordance with the Clean Water Action Plan.

> - From the report, 1999 Interagency Mined Land Environmental Task Force Report, found on the webpage above.

Their accomplishments as of March 1999 included:

- Initiation of cleanup of two AML sites (Steward and Atronics millsites) in priority watershed;

- Establishment of site selection criteria for potential AML reclamation projects;

- Compilation of an initial list of 33 AML sites based on proximity and potential impacts to watersheds and assignment of a priority rank to each site;

- Initiation of data compilation, including location and land status maps, existing site characterizations, and photographs for the 33 sites.

The groups involved with this Interagency are:

Bureau of Land Management, BLM

United States Forest Service, USFS

United States Fish and Wildlife Service, USFWS

United States Geological Survey, USGS

Environmental Protection Agency, EPA

Nevada Division of Minerals, NDOM

Nevada Division of Environmental Protection, NDEP

Nevada Division of Wildlife, NDOW

Nevada Bureau of Mines and Geology, NBMG

Desert Research Institute, DRI

New Mexico

New Mexico Energy, Minerals and Natural Resources Department

Mining and Minerals Division

Abandoned Mine Land Program

http://www.emnrd.state.nm.us/Mining/aml/default.htm

The program was formed when SMCRA was passed in 1977. The description of this program states: "the fund is used to reclaim coal mines abandoned prior to the enactment of SMCRA. Under certain conditions, abandoned noncoal mines may also be reclaimed." The most common mine hazards in NM are open adits and shafts. There are other concerns, including burning gob piles and acid mine drainage.

New Mexico Energy, Minerals and Natural Resources Department

Mining and Minerals Division

Mining Act Reclamation Program

http://www.emnrd.state.nm.us/Mining/marp/default.htm

This program was created under the New Mexico Mining Act of 1993 to regulate hard rock mining reclamation activities for all minerals except potash, sand, gravel, quarry rock used as aggregate in construction, flagstone, calcite, clay, adobe, borrow dirt, activities regulated by the Nuclear Regulatory Commission, and waste regulated under Subtitle C of the Federal Resource Conservation and Recovery Act.

New Mexico Energy, Minerals and Natural Resources Department

Ground Water Quality Bureau

Mining Environmental Compliance Section

Active mines are handled through this office when water quality is an issue. Upon speaking with Mark Phillip of this office, it became clear that most of their work involves water diversion and water treatment plants.

Wyoming

Department of Environmental Quality (DEQ)

Abandoned Mine Land

http://deq.state.wy.us/aml

AML's mission is to eliminate safety hazards and repair environmental damage from past mining activities and to assist communities impacted by mining. AML pursues this mission in two ways:

1. The Traditional Reclamation Program which has reclaimed thousands of acres of abandoned coal, bentonite, and uranium open pit mines, and new projects are initiated each year. AML has also closed several hundred hazardous gold and copper mine openings, and has an ongoing program to mitigate subsidence risks. AML also makes subsidence insurance available to property owners in affected communities.

2. The Public Facility Program, operating in conjunction with the State Loan and Investment Board, provides financial assistance for projects in communities with current or past impact from mining. Applicants must first establish eligibility, then projects are ranked and funded based on human health and safety issues.

U.S. Department of the Interior - Bureau of Land Management

Abandoned Mine Land Reclamation

http://www.wy.blm.gov/whatwedo/aml/aml_home.html

Wyoming BLM works closely with DEQ to share resources and pool funding. The projects listed on the Web page did not use any innovative treatments.

Inventory of the sites and the work needed at each was expected to be done by the end of 2001.

Appendix B: Brief Case Description of Case Studies Found in This Report

Site	Location	Mine Information	Pollution (media)	Treatment	Page
North Pennine Orefield	Nent Valley, UK	Metal/Hardrock	Zn (water)	Anoxic Limestone Drain	12
Burleigh Tunnel	Silver Plume, CO	Metal/Hardrock	Zn (water)	Constructed Wetland	14
Calliope Mine	Silver Bow, MT	Metal/Hardrock	Al, As, Cd, Cu, Fe, Mn, Zn, low pH (water)	Bioreactor	15
Champagne Creek	Butte, ID	Metal/Hardrock	Al, Cd, Cu, Fe, Zn, low pH (water)	Bioreactor	16
Oven Run	Pennsylvania	Coal	Fe, Al, low pH (water)	Successive Alkalinity Producing System	18
Gowen Run	Gowen, OK	Coal	Fe, other metals, low pH (water)	Successive Alkalinity Producing System	18
	Frostburg, MD	Coal - strip mine	metals, low pH (soil)	Biosolids	21
	Leadville, CO	Metal/Hardrock	Zn, Pb, low pH (soil)	Biosolids	23