

ACID MINE DRAINAGE (AMD) MANAGEMENT

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ABSTRACT

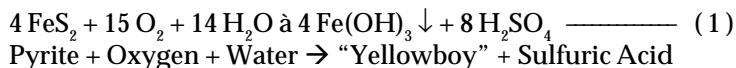
AMD is recognized as one of the most serious environmental problem in the mining industry. The problem of acid mine drainage (AMD) has been present since mining activity began thousands of years ago. Mining activity has disrupted the hydrology of mining areas so badly that it is extremely difficult to predict where water would eventually re-emerge. Its causes, treatment have become the focus of number of researchers. This paper describes Acid Mine Drainage (AMD) generation and its associated pollution.

INTRODUCTION

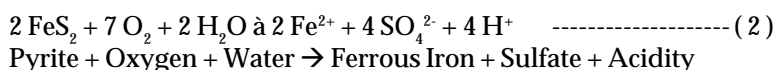
Acid mine drainage (AMD), also is a natural occurrence resulting from the exposure of sulfur and iron bearing materials to erosion and weather. Percolation of water through these materials results in a discharge with low pH and high metals concentration. Although AMD is naturally occurring, mining activities may greatly accelerate its production. AMD production is accelerated since mining exposes new iron and sulfide surfaces (e.g, underground mine walls, open pit walls, and overburden and mine waste piles) to oxygen. As such, AMD is one of the primary environmental threats at mining sites. To efficiently remediate mining sites, project managers must understand the formation of AMD and those factors that influence its quality and quantity, such as the interaction of sulfide minerals, air, water, and micro-organisms. This section has been added to introduce the project manager to these issues. AMD results from the oxidation of sulfide minerals inherent in some ore bodies and

the surrounding rocks. Iron sulfide minerals, especially pyrite (FeS_2) and also pyrrhotite (FeS) contribute the most to formation of AMD. Oxygen (from air or dissolved oxygen) and water (as vapor or liquid) which contact the sulfide minerals directly cause chemical oxidation reactions which result in the production of sulfuric acid. The primary reactions associated with pyrite are described below (APHA, 1992).

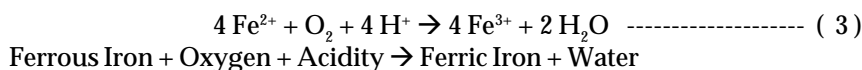
The general chemical reactions explaining the oxidation of pyrite and the production of acidity are given by the following equations. There are four commonly accepted chemical reactions that represent the chemistry of pyrite weathering to form AMD. An overall summary reaction is as follows:



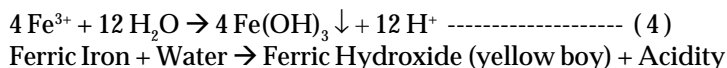
The first reaction in the weathering of pyrite includes the oxidation of pyrite by oxygen. Sulfur is oxidized to sulfate and ferrous iron is released. This reaction generates two moles of acidity for each mole of pyrite oxidized.



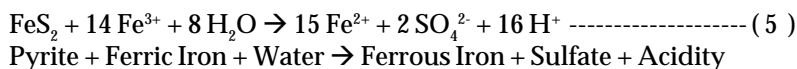
The second reaction involves the conversion of ferrous iron to ferric iron. The conversion of ferrous iron to ferric iron consumes one mole of acidity. Certain bacteria increase the rate of oxidation from ferrous to ferric iron. This reaction rate is pH dependant with the reaction proceeding slowly under acidic conditions (pH 2-3) with no bacteria present and several orders of magnitude faster at pH values near 5. This reaction is referred to as the "rate determining step" in the overall acid-generating sequence.



The third reaction which may occur is the hydrolysis of iron. Hydrolysis is a reaction which splits the water molecule. Three moles of acidity are generated as a byproduct. Many metals are capable of undergoing hydrolysis. The formation of ferric hydroxide precipitate (solid) is pH dependant. Solids form if the pH is above about 3.5 but below pH 3.5 little or no solids will precipitate.



The fourth reaction is the oxidation of additional pyrite by ferric iron. The ferric iron is generated in reaction steps 1 and 2. This is the cyclic and self propagating part of the overall reaction and takes place very rapidly and continues until either ferric iron or pyrite is depleted. Note that in this reaction iron is the oxidizing agent, not oxygen.



The presence of iron-oxidizing microorganisms as catalysts affects the rate of AMD forming reactions. These bacteria are indigenous to many environments including sulfide ore bodies. As discussed above, the iron oxidizing

autotrophic bacteria, *T. ferrooxidans*, greatly increases the oxidation of ferrous to ferric iron, which causes reaction 4 to quickly proceed. Reaction 4 produces 16 equivalents of hydrogen ions further lowering pH and causing more ferric iron to be oxidized. At low pH levels (pH 2 to 4) these bacteria thrive and multiply, further increasing reaction rates. Sulfide-oxidizing bacteria, such as *T. thiooxidans* may also increase AMD formation, although to what extent is less well-known.

Mineral sulfides vary in their reactivity. This is due to the physical and chemical characteristics of the various sulfide minerals. For example some metal sulfides (i.e., copper, lead, and zinc) have a tendency to form low solubility minerals which encapsulate them and prevent further oxidation. The crystal structure of the sulfide minerals is an important factor for two reasons: (1) certain crystalline structures are more stable and resist weathering (oxidation); and (2) due to the increased surface area, smaller crystals react faster (Wieder, and Lang, 1982). The rate of AMD formation depends upon the particle size and surface area of rocks containing the sulfide minerals. Smaller particles have increased surface area that can contact the weathering agents. Therefore, rock tailings (very fine particles) will weather faster than large boulders. Rates of weathering and production of AMD are dramatically increased in processed materials (e.g. crushed tailings from mineral processing or leaching), due to the increased amount of surface area. The rate of AMD formation is also dependent on pH and temperature. The chemical reaction rate is higher at low pH because the solubility of the metals increases and biological oxidation peaks at a pH of about 3.5. Therefore, it is generally true that as more sulfuric acid is released and the pH decreases, more leaching occurs. Both the chemical and biological reaction rates also increase with increased temperature. This is because of increased solubility of metal species and increased biological activity at higher temperatures. There are two sources of AMD, which are presented in Table 1.

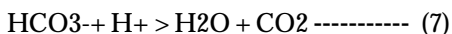
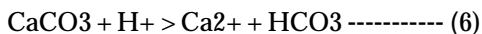
Table 1
Sources of acid mine drainage

Primary sources	Secondary sources
Mine rock dumps	Treatment sludge pounds
Tailings impoundment	Rock cuts
Underground and open pit mine workings	Concentrated load-out
Pumped/nature discharged underground water	Stockpiles
Diffuse seeps from replaced overburden in rehabilitated areas	Concentrate spills along roads
Construction rock used in roads,dams, etc.	Emergency

2. Environmental Effects

As discussed above, AMD introduces sulfuric acid and heavy metals into the environment. The environment can naturally assimilate some AMD through dilution, biological activity, and neutralization, although its capacity to treat AMD may be limited. When this treatment capacity is exceeded, drainage and surface water flowing out of mining areas can be very acidic and contain elevated concentrations of metals. The metal-laden acidic drainage and surface

water can lead to ground water contamination. The ability of the receiving environment to assimilate AMD will depend on site specific conditions such as drainage patterns and dilution, biological activity, and neutralizing capacity of the ore, waste material, tailings, and/or surrounding soils. Drainage patterns and dilution depend largely on the climate and topography of a site. Naturally occurring biological activity can attenuate the metals concentration by adsorption and precipitation of some metal species such as sulfates. Neutralization is the consumption of acidity in which hydrogen ions are consumed according to the following reactions:



The neutralization capacity of a soil depends largely on the presence of naturally occurring, acid consuming minerals. The most common mineral is calcite (CaCO_3), a major constituent of limestone, and dolomite ($\text{CaMg}(\text{CO}_3)_2$). Other neutralizing minerals include other carbonates of iron and magnesium and aluminum and iron hydroxides. As neutralization occurs, metals precipitate because of decreased solubility at higher pH.

The impact of AMD can increase over time if the neutralizing capacities of the soil are depleted. This may occur if the neutralizing minerals have a tendency to form crusts of precipitated salts or gypsum which inhibits further reaction, or if the neutralizing minerals are depleted through numerous reactions with AMD. The impact of AMD can also change if the rates of AMD formation change due to the alteration of site conditions. For these reasons, there is often a time lag after mining activities begin until AMD is detected. The times can range from 1 to 10 or more years; AMD may not be detected until after surface reclamation occurs. Acid generation, once it begins, is difficult to control, often accelerates, and can persist for centuries.

3. Environmental Impacts of Acid Mine Drainage

AMD is responsible for depositing a huge acid load to a large number of streams throughout the coal producing regions. AMD is the single largest non-point source pollution. This acid is responsible for lowering the pH and degrading the quality of the waterway. As the pH is lowered, less and less living things can tolerate these harsh conditions. At sufficiently low pH, a stream effectively is dead. AMD can work in concert with acid deposition (acid rain) to have devastating effects to waterways. AMD is also responsible for depositing a large load of heavy metals into our waterways. Iron, aluminum, and manganese are the principal metals deposited as a result of coal mining activities, but others are also possible. The effects of iron are usually visible in a stream running orange or with an orange coating on the bottom. Here iron is present in the compound yellowboy smothering aquatic plant and animal life and disrupting the food chain. When present, aluminum may be seen as white compound called gibbsite. It is toxic to many aquatic organisms and humans. For some plants it limits or stops root development. As a result, plants cannot absorb water and nutrients, are stunted, and exhibit nutrient deficiency symptoms. Manganese can interfere with normal growth processes in the aerial

plant parts, which stunts the plant, discolors it, and causes poor yields. AMD through acid and metal loading can render a waterway unsuitable for a variety of uses including human, agricultural, industrial and recreational. It degrades and destroys habitats. It is aesthetically unappealing. It is often seen in economically depressed areas adding to a sense of hopelessness.

AMD is problem because, the vast majority of natural life is designed to live and survive at near pH 7. The drainage acidifies the local water courses and so either kills or limits the growth of the river ecology. Effects are even more pronounced on vertebrate life such as fish than on plant and unicellular life. There is also a problem because of the metal contained in the drainage. As most mines extract coal rather than metalliferous minerals than the main metal of concern is iron. Its presence in water is problem more due to its physical properties than its poisonous effects. Iron may be found in two forms, ferrous and ferric When the AMD is generated it will be in the form of ferrous but latter changes in the presence of oxygen to ferric iron when it forms solid particles. The ferric irons forms a very low density solid. Very small concentrations in the water are capable of producing large volumes of precipitate, which cover the surface of land and streams close to the point of drainage. The iron coating effectively smothers the environment and prevents life from flourishing.

Heavy metals are frequently found in streams affected by acid mine drainage (AMD) which continues to be an important water pollution problem round the world. Current treatment technologies are either inadequate or too expensive to be employed at numerous abandoned mine land sites which are sources of untreated AMD. For example limestone used for pH adjustment becomes coated with iron ox hydroxide, reducing its solubility.

4. Treatment of Acid Mine Drainage - Over the past 20 years a variety of treatment systems have been developed. There are two broad classes of methodologies used to treat Acid Mine Drainage :

1. Passive Treatment - Naturally occurring chemical and biological reactions occur in a controlled microbiological – chemical reactor without powered mechanical assistance (most of the time).

2. Active Treatment - Mechanical addition of alkaline chemicals to the effluent is used raises pH and precipitate metals.

The Table 2 illustrates the different technologies available for AMD Treatment.

Table 2
Technologies available for AMD Treatment

S.No.	Passive Treatment	Active Treatment
1.	Aerobic Wetlands	Precipitation
2.	Compost/Anaerobic Wetlands	Oxidation
3.	Open Limestone Channels	Dosing with alkali
4.	Diversion Wells	Sedimentation
5.	Anoxic Limestone Drains (ALD)	Reverse Osmosis
6.	Successive Alkalinity-Producing Systems (SAPS)	Sulfidization
7.	Vertical Flow Reactors (VFR)	Ion Exchange
8.	Pyrolusite Process	

Passive Treatment of AMD - As early as 1978, many variations of AMD passive treatment systems were studied by numerous organizations on the laboratory bench-testing level. During the last 15 years, passive treatment systems have been implemented on full-scale sites throughout the United States with promising results. The concept behind passive treatment is to allow the naturally occurring chemical and biological reactions that aid in AMD treatment to occur in the controlled environment of the treatment system, and not in the receiving water body. Passive treatment conceptually offers many advantages over conventional active treatment systems. The use of chemical addition and energy consuming treatment processes are virtually eliminated with passive treatment systems. Also, the operation and maintenance requirements of passive systems are considerably less than active treatment systems. The first passive technology involved the use of natural *Sphagnum* wetlands that could improve the water quality of AMD without causing other detrimental impacts on the ecosystem. Although this concept had its limitations, it spawned research and development into other passive treatment technologies that did not follow the natural wetland paradigm. Designing a passive treatment system for AMD requires the understanding of mine water chemistry, available treatment techniques and experience. Analytical sampling of the AMD is extremely important in the selection of appropriate treatment technologies.

Passive AMD Treatment Technologies

1. Aerobic Wetland - Huntsman *et al.* (1978) and Wieder and Lang (1982) first noted amelioration of AMD following passage through naturally occurring *Sphagnum* bogs in Ohio and West Virginia. Studies by Brooks *et al.* (1985), Samuel *et al.* (1988), and Sencindiver and Bhumbra (1988) documented similar phenomena in Typha wetlands. Brodie and co-workers at the Tennessee Valley Authority (TVA) have reported extensively on their use of aerobic wetlands to treat AMD (Brodie 1993). An aerobic wetland consists of a large surface area pond with horizontal surface flow. The pond may be planted with cattails and other wetland species. Aerobic wetlands can only effectively treat water that is net alkaline. In aerobic wetland systems, metals are precipitated through oxidation reactions to form oxides and hydroxides. This process is more efficient when the influent pH is greater than 5.5. Aeration prior to the wetland, via riffles and falls, increases the efficiency of the oxidation process and therefore the precipitation process. Iron concentrations are efficiently reduced in this system but the pH is further lowered by the oxidation reactions.

A typical aerobic wetland is shown in Figure 1.

A typical aerobic wetland will have a water depth of 6 to 18 inches. Variations in water depth within the wetland cell may be beneficial for performance and longevity. Although shallow water zones freeze more quickly in winter,

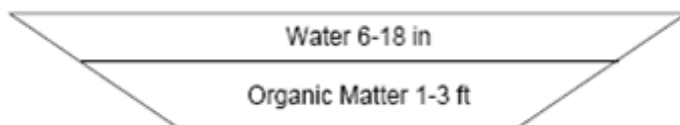


Fig. 1 Typical Section of an Aerobic Wetland

they enhance oxygenation and oxidizing reactions and precipitation. Deeper water zones provide storage areas for precipitates but decrease vegetative diversity.

2. Anaerobic/Compost Wetlands

Anaerobic or non-oxygenated wetlands are very similar to aerobic wetlands. The major difference is that the mine water flows through a layer of thick, oxygen-free compost, usually spent mushroom compost with 10 percent calcium carbonate, to breakdown the sulfates and remove the oxygen. Other compost materials include peat moss, wood chips, sawdust or hay. The iron reducing bacteria is active at low pHs and can survive in low oxygen environments. In order to breakdown the sulfates, the oxygen is consumed, thus providing a low oxygenated water after this step. When the oxygen is removed from the sulfate, the sulfide ion is free to react with the metals and precipitate as metals sulfides. Typical compost depth is 12"-24" with cattails or other wetland vegetation and 0"-3" of water. Again, this is a low cost way of treating Abandoned Mine Drainage and active mining discharges. Hedin *et al.* (1994) suggest that anaerobic wetlands to treat net acid waters be sized using a factor of 3.5 g of acidity/m²/day. A typical anaerobic/Compost wetland is shown in Figure 2.

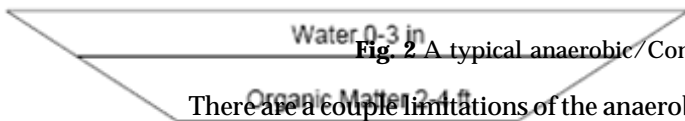


Fig. 2 A typical anaerobic/Compost wetland

There are a couple limitations of the anaerobic wetland: (1) flow and chemistry determine the holding time, (i.e. larger the flow rate, the longer the holding time), (2) if the pH is less than 3, and it is not possible to increase the holding time, the addition of alkalinity is needed to increase the pH, (3) the effectiveness of the system is decreased in the winter months due to the bacteria being less active, (4) the organic layer may need replaced as the microbes break down and consume the material, and the precipitation can clog the bottom of the cells and require maintenance, (5) the wetlands can accept discharges with an acidity up to 500 mg/L.

3. Open Limestone Channels

Open limestone channels (OLCs) introduce alkalinity to acid water in open channels or ditches lined with limestone (Ziemkiewicz *et al.* 1994). Open limestone channels may be the simplest passive treatment method. Open limestone channels are constructed in two ways. In the first method, a drainage ditch is constructed of limestone and AMD-contaminated water is collected by the ditch. The other method consists of placing limestone fragments directly in a contaminated stream. Dissolution of the limestone adds alkalinity to the water and raises the pH. Armoring or the coating of the limestone by $\text{Fe}(\text{CO})_3$ and $\text{Fe}(\text{OH})_3$ produced by neutralization reduces the generation of alkalinity, so

large quantities of limestone are needed to ensure long-term success. High flow velocity and turbulence enhance the performance by keeping precipitates in suspension thereby reducing the armoring of the limestone. Open limestone channels are sized according to standard engineering practice using the Manning equation and providing additional freeboard. Impervious liners are sometimes used under the limestone to prevent infiltration of the AMD into the groundwater table. A typical open limestone Channel is shown in Figure 3.

CROSS SECTION OF AN OPEN LIMESTONE CHANNEL

Fig. 3 A typical open limestone Channel

4. Diversion Wells

The diversion well is a simple device initially developed for treatment of stream acidity caused by acid rain in Norway and Sweden (Arnold, 1991). A schematic figure of diversion well is shown in Figure 4. Diversion wells are another simple way of adding alkalinity to contaminated waters. Acidic water is conveyed by a pipe to a downstream "well" which contains crushed limestone aggregate. The hydraulic force of the pipe flow causes the limestone to turbulently mix and abrade into fine particles and prevent armoring. The water flows upward and overflows the "well" where it is diverted back into the stream. Diversion wells require frequent refilling with clean limestone to assure continued treatment.

5. Anoxic Limestone Drains (ALD)

ALDs were first described by the Tennessee Division of Water Pollution Control (TDWPC) (Turner and McCoy 1990). An anoxic limestone drain (ALD) is a

SCHEMATIC VIEW OF A DIVERSION WELL

Fig. 4 A schematic view of Diversion Well

buried bed of limestone constructed to intercept subsurface mine water flows and prevent contact with atmospheric oxygen. Keeping oxygen out of the water prevents oxidation of metals and armoring of the limestone. The process of limestone dissolution generates alkalinity. The sole purpose of an ALD is to provide alkalinity thereby changing net acid water into net alkaline water. Retaining carbon dioxide in the drain can improve limestone dissolution and alkalinity generation. Anoxic Limestone Drains (ALD) is shown in Figure 5.

Fig. 5 Anoxic limestone drains

An ALD can be considered a pretreatment step to increase alkalinity and raise pH before the water enters a constructed aerobic wetland. In the aerobic wetland, metals can be oxidized and precipitated. ALDs are limited to the amount of alkalinity they can generate based on solubility equilibrium reactions. Also, the effectiveness and longevity of an ALD can be substantially reduced if the AMD has high concentrations of ferric iron, dissolved oxygen or aluminum. ALDs are sized based on the assumption that the drain will produce water between 275 and 300 mg/L of alkalinity. The amount of alkalinity generated is based on the solubility of the calcite within the limestone and the retention time within the ALD. Retention times of 14 to 15 hours are used as standard practice to balance construction costs and the efficiency of alkalinity generation.

6. Successive Alkalinity Producing Systems (SAPS)

SAPS were described by Kepler and McCleary (1994) and are now being extensively constructed to treat AMD from coal mining. An SAPS is a combination of an ALD with an anaerobic wetland/pond. The AMD flows through a pool of water, an organic substrate, and a limestone bed before discharging from the bottom. The organic substrate and the depth of water create the anaerobic conditions necessary to reduce the likelihood of metals precipitating and clogging the limestone. The SAPS should empty into an aerobic wetland and/or settling pond for metal removal. The typical maximum treatment is 300 ppm acidity, so SAPS are often implemented in succession. This treatment is suited for AMD with high dissolved oxygen and metal concentrations. If sulfates are higher than 2,000 ppm, gypsum precipitation may be a concern. Since the SAPS is designed for vertical flow, sufficient head can be a significant design issue.

7. Vertical Flow Reactors (VFR)

Vertical flow reactors (VFR) were conceived as a way to overcome the alkalinity producing limitations of ALD's and the large area requirements for compost wetlands. The VFR consists of a treatment cell with an underdrained limestone base topped with a layer of organic substrate and standing water. The water flows vertically through the compost and limestone and is collected and discharged through a system of pipes. The VFR increases alkalinity by limestone dissolution and bacterial sulfate reduction. Highly acidic waters can be treated by running the AMD through a series of VFRs. A settling pond and an aerobic wetland where metals are oxidized and precipitated typically follow a VFR plan. VFRs are sized based on retention times required to produce the necessary alkalinity. Retention times of 12 to 15 hours are typically used for sizing VFRs and the amount of limestone necessary is calculated as shown above for ALDs. Vertical Flow Reactors (VFR) is shown in Figure 6.

Fig. 6 Vertical flow wetland

8. Pyrolusite Process

This patented process utilizes site-specific laboratory cultured microbes to remove iron, manganese and aluminum from AMD. The treatment process consists of a shallow bed of limestone aggregate inundated with AMD. After laboratory testing determines the proper combinations, the microorganisms are introduced to the limestone bed by inoculation ports located throughout the bed. The microorganisms grow on the surface of the limestone chips and oxidize the metal contaminants while etching away limestone, which in turn increases the alkalinity and raises the pH of the water. This process has been used on several sites in western Pennsylvania with promising results. Figure 7 depicts Pyrolusite Process.

PLAN VIEW OF A PYROLUSITE BED

Fig. 7 Schematic view of Pyrolusite Bed

Active AMD Treatment Technologies

Active treatment technologies involve treating mine drainage with alkaline chemical to raise water pH, neutralize acidity and precipitate metals. Although effective active treatment is expensive when the cost of equipment, chemicals and manpower are considered (Skousen *et al.* 1990).

1. Chemical Precipitation - Removal of metals can be facilitated by neutralization using a hydroxide precipitate-caustic soda treatment. Often, chemical neutralization is accomplished with slaked lime or calcium carbonate added directly to the water.

In-Line Aeration

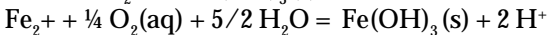
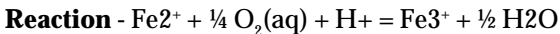
There also is In-Line Aeration and Neutralization System (ILS) which incorporates the chemical treatment processes into a functionally closed system where the treatment reactions can be more closely monitored and accelerated in order to reduce the chemical reagent costs and reaction processing times.

Electro-precipitation

Electro-precipitation processes accomplish similar results by the precipitation of metal hydroxides or by metal ion adsorption.

2. Oxidation - It is used to reduced metals (Fe²⁺, Mn²⁺) to oxidized metals (Fe³⁺, Mn⁴⁺)

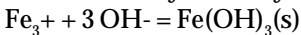
Mechanism - Transfer oxygen into water



Kinetics - slow at low pH, fast at neutral pH

Other oxidation techniques are cascade aeration, trickle filter aeration, In-line venturi aeration.

3. Dosing with Alkali - It is used to raise pH of acidic waters & Counteract acidification by metal hydrolysis, e.g.,



Mechanism - addition of alkalinity lime, hydroxide



Kinetics - fast

4. Sedimentation - This method removes metal hydroxide solids from suspension. The removal mechanism is gravity and time promotes settling of particles in a pond or clarifier. Here sufficient retention time is given to allow settling. In sedimentation large particles settle faster than small particles. Settling faster in warm water and retention time of 4-5 hours.

5. Reverse Osmosis - Membrane separation technology has been used to remove metal ions from a range of solutions via micro filtration nanofiltration and reverse osmosis.

In RO Diffusion is the movement of molecules from a region of higher concentration to a region of lower concentration. Osmosis is a special case of diffusion in which the molecules are water and the concentration gradient occurs across a semi permeable membrane. The semi permeable membrane allows the passage of water, but not ions (e.g., Na^+ , Ca^{2+} , Cl) or larger molecules (e.g., glucose, urea, bacteria). Diffusion and osmosis are thermodynamically favorable and will continue until equilibrium is reached. Osmosis can be slowed, stopped, or even reversed if sufficient pressure is applied to the membrane from the 'concentrated' side of the membrane. Reverse osmosis occurs when the water is moved across the membrane against the concentration gradient, from lower concentration to higher concentration. To illustrate, imagine a semi permeable membrane with fresh water on one side and a concentrated aqueous solution on the other side. If normal osmosis takes place, the fresh water will cross the membrane to dilute the concentrated solution. In reverse osmosis, pressure is exerted on the side with the concentrated solution to force the water molecules across the membrane to the fresh water side.

6. Ion Exchange - Ion exchange is a chemical reaction wherein an ion from solution is exchanged for a similarly charged ion attached to an immobile solid particle (i.e., ion exchange resin). Ion exchange reactions are stoichiometric (i.e., predictable based on chemical relationships) and reversible. The resins are normally contained in vessels referred to as columns. Solutions are passed through the columns and the exchange occurs. Subsequently, when the capacity of the resins is reached, the ions of interest, which are attached to the resin, are removed during a regeneration step where a strong solution containing the ions originally attached to the resin is passed over the bed.

Ion exchange is used for a variety of purposes in the metal finishing shop, including: treatment of raw water; recovery of plating chemicals from rinse water; purification of plating solutions; wastewater treatment and wastewater polishing.

CONCLUSION

Mining in general may be open or underground is one such major industry that disburses various contaminants and pollutants in to environment and significantly degrade the quality of environment and ecosystem. In coal mining acid mine drainage is presently the greatest single cause of mine related water pollution.

Little systematic work has been carried out in India to study the pollution due to acid mine drainage. The paper summarizes the potential causes of pollution of acid mine drainage and enumerates the various steps which could have been taken to minimize the pollution.

In order to minimize this pollution, precautions must be taken to ensure that rainwater does not come into contact with pyrite. Groundwater neutralized with lime or passive treatment systems, which rely on natural geochemical and biological processes for acid neutralization and precipitation- adsorption of metals, is widely used to prevent AMD. These systems include natural or man-made reed beds that are relatively inexpensive to construct for reason-

able volume of water. With the necessary AMD treatment measures in place, mine water can be treated to a potable, industrial or agricultural standard.

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