Help Instruction File:

Bioreactor Module Overview

Provided by the Office of Surface Mining Reclamation and Enforcement (OSMRE), the Pennsylvania Department of Protection (PADEP), the U.S. Geological Survey's (USGS) and the West Virginia Department of Environmental Protection (WVDEP).

Bioreactor Module Overview

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1.0 Objective

A Bioreactor is a passive treatment system component (meaning no machinery or daily chemical addition required for its operation) that is typically used to treat acidic or alkaline mine drainage.

The objectives of this overview are to: (1) Provide a basic understanding of the theory and application of Bioreactors and (2) Provide an overview of the Bioreactor Module to guide users in developing an estimate of the cost to construct, operate, and maintain Bioreactors for treating mine drainage. Therefore, this overview will be presented in two sections, **Treatment Component Overview** and **Bioreactor Module Overview**.

2.0 Treatment Component Overview

The following section is organized into three sections, (1) Physical and Hydraulic Description and (2) Application and Treatment Chemistry, and (3) Bioreactor Conceptual Treatment Module. The first section provides a physical description and hydraulic profile for a Bioreactor to provide context for users of AMDTreat. The second section describes the common application of the Bioreactor component, and the third section shows a generalized conceptual model describing the treatment chemistry to help familiarize users with terms and concepts presented throughout the AMDTreat modules.

2.1 Physical and Hydraulic Description

The term “Bioreactor” is a generic term used to describe a reactor that utilizes biological-mediated reactions for water treatment. Each industry uses the term Bioreactor to describe an archetypical treatment system unique to that industry. Thus, it is important to properly describe the type of treatment system inferred when the term Bioreactor is used to describe its’ use in coal mine drainage treatment in the Eastern U.S. The proceeding discussion describes the Bioreactor treatment component represented and modeled in AMDTreat.

A Bioreactor is an impoundment consisting of four or five distinct “material layers” (Figures 1 and 2). Whereas Vertical Flow Ponds (VFP) contain a layer of compost overtop a layer of limestone, Bioreactors differ in that they contain a single homogenized mixture of biomass and limestone in one layer. The Bioreactor biomass is a mixture of limestone fines, manure, hay and wood chips with some designs calling for very specific species and mixture percentages (Figures 3 & 4). Limestone or other stone is typically used even if the water is net alkaline to help preserve porosity and maintain open flow paths. The size of stone varies depending on the designer’s preference, but most stone mixed into the Bio Mix layer is less than ¾” and often it is ¼” in diameter (commonly referred to as fines). Without such a matrix, decaying biomass would eventually compact and cause hydraulic failure. Both wood chips and stone help to provide some level of porous structure to the manure and hay.

The Bio Mix layer is typically 3.0 to 4.0 ft deep and a 2.0 to 4.0 ft freeboard layer is used to allow head pressure to build up and help force water through the Bio Mix layer as permeability decreases due to material decay and compaction. In the field, a Bioreactor looks identical to a VFP since both have a water layer that covers the reactive materials, and both have a similar piping design. Water flows into the Bioreactor at the top of the freeboard layer and flows vertically through the water layer and then through the Bio Mix layer. Water is collected through a collection piping network at the bottom of the impoundment typically contained within a drainage aggregate layer and transported through the embankment to a conveyance ditch and/or oxidation/settling pond. The collection piping network (i.e. trunk & spur pipes) is bedded in aggregate to protect the perforated pipe from becoming clogged by organic debris from the Bio Mix layer (Figures 5 through 9).

Many Bioreactors have flush values installed on the effluent pipe; however, they are rarely flushed to avoid compacting the Bio Mix layer by inducing a sudden drop in pore pressure and the fear of clogging the perforated pipe with the Bio Mix layer materials. In addition, long duration flushing is not advised as anoxic conditions must be maintained within the Bio Mix layer to prevent metal sulfide oxidization. However, periodic short duration flushes can occur to keep the effluent pipes clear of iron sulfide, elemental sulfur, calcite, microbial mats, and other debris that can accumulate within the collection piping network and effluent pipe. Figure 10 shows a picture of a short-term flush of elemental sulfur from a Bioreactor effluent pipe.

Proper planning is required for mixing and placing the Bio Mix layer materials. It is important to create a homogenized mixture to prevent variations in permeability that will result in short circuiting of flow. It is important to discuss with the contractor the different ways to uniformly mix the different Bio Mix components to ensure a homogenized mixture. Additionally, the Bio Mix layer must be carefully placed to avoid compaction (Figures 11 through 13). There have been instances of newly constructed Bioreactors not being able to transmit the flow through the system due to compaction issues caused by improper construction techniques associated with the placement of the Bio Mix layer. Finally, estimating the amount of Bio Mix layer materials required can be difficult due to the decrease in volume that occurs when the organic materials are saturated and slightly compacted. Users can adjust the "shrinkage factor" variable in AMDTreat to increase the volume of dry materials to account for the shrinkage that will occur when the materials are mixed and saturated. Often, newly constructed Bioreactors are initially filled and then allowed to sit and incubate to promote microbial growth and create a low redox potential to prepare the Bioreactor for treatment (Figure 14).

2.2 Application and Treatment Chemistry

A Bioreactor is a type of "passive" treatment system component used to treat net-acidic or net-alkaline mine drainage. The term "passive" refers to the inability to exert operational control to adjust treatment in response to changing influent or effluent conditions. Net-acidic mine drainage describes solutions that contain more acid-producing than acid-consuming species when the water is "treated", and net alkaline mine drainage contains an excess of acid-consuming species.

The primary objective of Bioreactors is to precipitate pollutants (dissolved metals) as sulfide minerals. Whether an additional objective of a Bioreactor is to generate alkalinity depends on whether the Bioreactor is treating net acidic or net alkaline water. The decision to precipitate a dissolved metal pollutant as a sulfide mineral, as opposed to hydroxide, is largely based on sulfides having a lower solubility, thus lower dissolved metal effluent concentrations can be achieved. Figure 15 shows the difference between sulfide versus hydroxide solubility for selected elements. For example, the lowest solubility for $Zn(OH)_2$ is ~ 3.0 mg/L at pH 10, however, a concentration of 0.0003 mg/L can be achieved at pH 5.0 if precipitated as ZnS. Figure 16 is a phase diagram for the iron sulfur system. Bioreactors produce a biogeochemical environment, mostly through the use of easily oxidizable organic matter to create anerobic/anoxic conditions, to lower the redox potential of the system to promote chemical reduction and metal sulfide precipitation. Mine drainage entering the Bioreactor will typically plot within the sulfate stability field and end up in the pyrite stability field after flowing into the Bio Mix layer, note the direction of the arrow on Figure 16. Thus, measuring and tracking both pH and Eh of a Bioreactor provides useful information on the condition and health of the Bio Mix layer.

While lower concentrations can be achieved by precipitating dissolved metal pollutants as sulfides, there are other factors to consider when selecting the most appropriate type of passive treatment system for a site. Most reductive reactions are biologically mediated; thus, the kinetics are dependent on nutrients, temperature, pH, and other factors that are difficult to control. For example, Figure 17 shows how seasonal temperatures affect sulfate reduction and alkalinity production. In general, there is a large difference between the influent and effluent sulfate concentrations in the warmer months and smaller difference in the colder months. In addition, the graph shows a gradual decline in effluent alkalinity as the easily degradable organic matter is depleted over time. Even with a gradual decline in alkalinity over a five-year period, the seasonal effect on alkalinity production is still apparent. In the winter of 2008, there was very little sulfate reduction (influent sulfate ≈ effluent sulfate). In addition to temperature effects, the kinetics of sulfate reduction are pH dependent with effective sulfate reduction occurring when the pH is greater than 5.5. Thus, limestone is required for low pH water but may not be required for alkalinity production for circumneutral pH mine drainage.

For certain effluent criteria Bioreactors will be the only passive treatment option because of the low solubility of metal sulfides, however, in most other situations other limestone-containing passive treatment components should be considered due to their advantages. First, unlike vertical flow ponds and limestone beds, metal acidity is not released and treated but rather is precipitated and stored within the Bioreactor. Thus, at some future time (i.e. during system rehabilitation) the acidity stored in the sulfide minerals within the Bio Mix layer will have to be permanently stored in a reducing environment to promote stability or amended with an alkali reagent and allowed to oxidize to produce a stable oxide mineral phase. This is a disadvantage compared to other limestone passive systems which precipitate stable metal oxides and hydroxides. Precipitating and storing large amounts of metal sulfide poses a problem and there have been instances where metal sulfides started to oxidize, and Bioreactor effluent sulfate concentrations are greater than the influent. In addition, Bioreactors are difficult and expensive to build compared to most other alkalinity producing passive components and can have permeability issues over time as organics within the Bio Mix layer decay. Bioreactors should not be placed near residential or public areas due to nuisance odors and excess hydrogen sulfide gas production in the effluent. There have been several instances of odor complaints made by residents living within a half mile of Bioreactors. Finally, precautions must be taken when Bioreactors are first saturated after construction as they will discharge elevated amounts of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and nutrients for several months and if not adequately addressed within the system can pose a significant risk (i.e. reduced dissolved oxygen) to receiving streams. (Figures 18 & 19). For these reasons, Bioreactors should only be used in situations where no other alkalinity producing treatment components can achieve the applicable effluent criteria or system goals.

2.3 Bioreactor Conceptual Treatment Model

The following discussion presents a conceptual treatment model for Bioreactors treating low pH mine drainage containing aluminum, iron, aluminum, and/or manganese:

2.3.1 Water Layer: It is important to maintain at least a 2 ft deep water layer to help preserve a reducing environment in the Bio Mix layer. The low pH discharge will first enter the water layer and will have gas exchange reactions with the atmosphere (O_2 in-gassing). In addition, $CO_{2(g)}$ will increase in the water layer as bubbles of CO_2 gas produced from the oxidation of organic matter in the Bio Mix layer rise to the water layer (Figure 20). In some cases, low-pH biotic iron oxidation and precipitation occurs in the water layer due to the nutrients from the Bio Mix layer and the low pH condition of the water. Often a layer of dense ferric iron precipitate will form at the interface between the Bio Mix and water layers that can cause permeability issues (Figure 21).

2.3.2 Bio Mix Layer: The pH will increase as mine drainage flows from the water layer into the Bio Mix layer. Carbonic acid and pH acidity will react with limestone fines and cause the pH to increase and strong aluminum precipitation will occur as the pH reaches 5.5. Dissolved oxygen will be consumed by the oxidation of organic matter and the redox condition of the layer will decrease.

$$C_6H_{12}O_6 + 6O_2 = 5CO_2 + H_2O$$

Spent mushroom compost can be used in Bioreactors in the Eastern U.S. due to its availability and since the compost contains remnants of nutrients from fertilizer added to enhance the growth of mushrooms. As a result, dissimilatory nitrate reduction may occur.

$$CH_2O + NO_3^- + 2H^+ = CO_2 + ½\ N_2 + H_2O$$

A decreasing redox condition along with various mechanisms will cause sulfate and ferric iron to reduce to sulfide and ferrous iron and iron monosulfide (FeS) will form. The continued production of CO_2 along the flow path will further drive limestone dissolution and the solution may even achieve equilibrium with calcite. There have been some instances of a slight decrease in manganese, presumably due to adsorption reactions, but most Bioreactors do not remove significant concentrations especially not consistent enough to be considered a form of manganese treatment. Alkalinity production from sulfate reduction and limestone dissolution, coupled with high concentrations of carbon dioxide, can achieve alkalinity concentrations ranging from several hundred to over one thousand mg/L as $CaCO_3$. As the highly reduced water exits the Bioreactor, O_2 in-gassing can oxidize the sulfides and cause the precipitation of elemental sulfur. In addition, CO_2 outgassing will raise the pH and the solution may become supersaturated with respect to calcite and result in calcite precipitation. Both elemental sulfur and calcite are whitish-colored precipitates. Figure 22 is a picture of a Bioreactor effluent where the milky-white water flowing through the rock energy dissipater contains both elemental sulfur and calcite precipitates. It is important to have a settling pond after a Bioreactor to capture these and other precipitates. In addition, it is important to have ample turbulence and hydraulic drops between the Bioreactor and settling pond to promote the oxidation of reduced sulfur species and outgassing of H_2S gas before discharging the effluent to the receiving stream. The oxygen addition will also help to decrease the increased BOD and COD concentrations that typically occur in a Bioreactor effluent.

Bioreactors will have a redox boundary within the Bio Mix layer that separates oxidizing and reducing conditions. The boundary will migrate downwards over time as the easily-oxidizable carbon is exhausted and dissolved oxygen and other electron acceptors can exist and penetrate further down within the Bio Mix layer. As the boundary approaches the bottom of the Bio Mix layer, the Bioreactor can discharge ferrous sulfide and this may signify that the redox boundary is near the bottom and the Bio Mix layer requires replacement or there is insufficient retention time and/or carbon source to reduce the iron and sulfate higher up in the Bio Mix layer. Figure 22 shows a black precipitate of iron monosulfide at the base of a Bioreactor effluent pipe. Hydrogen peroxide was added to the black precipitate to oxidize the iron sulfide to ferric hydroxide in order to confirm the iron monosulfide mineral. There are several instances where the replacement of the Bio Mix layer was neglected, and the Bioreactor started to discharge over 60 lbs/day of suspended iron monosulfide to a settling pond (Figure 23). It is difficult to control the redox condition of a pond and without proper control tons of iron monosulfide could oxidize and discharge a large load of acidity to a receiving stream. For these reasons, Bioreactors need to be properly sized, have enough monitoring, and a safety plan to prevent oxidation and discharge of stored acidity in the form of metal sulfides.

2.3.3 Drainage Aggregate Layer: The Drainage Aggregate Layer is discussed in more detail in the Layer Materials section, as it doesn't perform a specific purpose pertaining to geochemistry treatment of the mine drainage.

2.3.4 Pipe Layer: The Pipe Layer is discussed in more detail in the Layer Materials section, as it doesn't perform a specific purpose pertaining to geochemistry treatment of the mine drainage.

2.3.5 Liner Layer: The Liner Layer is discussed in more detail in the Layer Materials section, as it doesn't perform a specific purpose pertaining to geochemistry treatment of the mine drainage.

3.0 Bioreactor Module Overview

3.1 Layout and Workflow

In general, inputs are on the left-hand side of the module and calculated outputs are on the right. The module inputs on the left-hand side are arranged into five sections: (1) Water Quality and Flow Input, (2) Sizing Methods, (3) System Properties, (4) Layer Materials, and (5) Other Items. The workflow for the module is for users to start at the top left-hand side. Enter the *Design Flow* and *Net Acidity*. The user then selects a sizing method to determine the amount of Bio Mix layer materials are necessary for the Bioreactor. Next, users specify design parameters such as the depth of the Bio Mix layer, and unit costs for items affecting the capital cost to construct the Bioreactor. Finally, users can enter any capital cost not captured by the module into the *Other Items* section.

Module output is provided on the right-hand side of the module. Module outputs on the right-hand side are arranged into four sections: (1) Sizing Summary, (2) Capital Cost, (3) Annual Cost, and (4) Net Present Value. The sizing summary provides dimensional details for the system. The estimated cost to construct and operate the Bioreactor is provided under the *Capital Cost* and *Annual Cost* headings. Lastly, users can opt to conduct a Net Present Value (NPV) to obtain the total cost to operate and maintain a treatment system for a defined time period.

A general overview of the module input and output sections is presented below, however, users are directed to the numerous tool tips located in the module that provide additional detailed information, such as definitions of terminology. In most cases, the tool tips are accessed by clicking on the information icon ( ) in each of the subheadings in the module.

3.2 Module Inputs

3.2.1 Water Quality and Flow Input: The Water Quality and Flow Input section is where users specify the design flow and water quality to size the passive treatment system component. The definitions for the required input can be found in the tool tip for this section. Click on the information icon ( ) on the right side of the Water Quality and Flow subheading.

3.2.2 Sizing Methods: The module offers two different approaches to sizing Bioreactors. The first approach calculates the volume of the Bio Mix layer before determining other dimensions. Users can select from four different methods to calculate the volume of the Bio Mix layer (see each method described below). The second approach requires users to specify the top length and width of the freeboard before calculating the remaining dimensions of the Bio Mix layer. The first approach is the most common as it relates the sizing of the treatment component based on flow and water quality characteristics. The second approach is common when the land area available for treatment is restricted or when someone wants to reverse engineer or develop a cost estimate for an existing treatment system component.

Volume of Bio Mix Sizing Methods (Bio Mix Layer)

3.2.2.1 Sulfate Reduction – The user enters a rate of sulfate reduction (moles of sulfate reduced per volume of Bio Mix per day) along with the amount of sulfate to be reduced, AMDTreat uses this information along with the design flow rate to calculate a sulfate reduction load and a required Bio Mix layer volume. Users can specify the makeup of the Bio Mix layer by adjusting the material percentages and densities under the Bio Mix subheading located under the Layer Materials section. The "Other Percentage" and "Other Density" input boxes under the Bio Mix subheading can be used to specify additional materials other than manure, hay, limestone fines, and wood chips. AMDTreat utilizes the user-specified "shrinkage factor", located under the Bio Mix subheading, to increase the volume of the Bio Mix layer to account for the volume reduction that occurs when the materials are saturated and compressed. After the volume of the Bio Mix layer is determined, AMDTreat uses the values for side slopes and water and freeboard depth to calculate the remaining dimensions of the Bioreactor.

3.2.2.2 Alkalinity Generation Rate - This method calculates the volume of the Bio Mix layer required based on an expected rate of alkalinity production, or acidity neutralization, per unit area of Bio Mix layer. Since the depth of the Bio Mix layer in Bioreactors is commonly 3 feet, the alkalinity generation rate could be viewed as the alkalinity production per unit volume (ft^3). Penn State University professor emeritus Dr. Art Rose developed this method (Rose, 2004) for vertical flow ponds (see VFP help file) so the default value is for sizing a VFP but this method may be used to size Bioreactors based on a predicted rate of alkalinity generation. AMDTreat calculates the volume of Bio Mix layer by dividing the daily influent acidity load of the mine drainage (g/day) by the user-specified alkalinity generation rate ($g/m^2/day$) to calculate the Bio Mix layer surface area requirement (m^2). The surface area is multiplied by the user-specified Bio Mix layer depth to determine the volume required in the Bio Mix layer. AMDTreat utilizes the user-specified values for the different Bio Mix materials (specified under the Bio Mix subheading) along with the shrinkage factor to calculate the volume and mass of the Bio Mix layer.

$$\text{Limestone Surface Area } (ft^2) =$$

$$\frac{\text{Daily influent acidity load } (\frac{g}{day})}{\text{Alkalinity generation rate } (\frac{g}{m^2}/d)} \times \frac{10.7639\ ft^2}{1\ m^2} \qquad \textbf{(1)}$$

$$\text{Limestone Volume } (ft^3) = \text{Limestone Surface Area } (ft^2) \times \text{Limestone Layer Depth } (ft) \qquad \textbf{(2)}$$

See Section 3.2.2.5 to 3.2.2.7 for volume calculations for the other layers.

3.2.2.3 Pilot Test Results - If users have their own method for determining the volume of Bio Mix required for the treatment of mine drainage, the Pilot Test Results sizing method should be used to size the Bioreactor. Often lab (bench) or pilot testing is used to help with Bioreactor design and these tests can reveal a volume and mixture proportions (percentage) of Bio Mix required to treat each gallon per minute of discharge flow. Users can specify the cubic feet of Bio Mix required to treat each gallon per minute of flow to determine the volume of the Bio Mix layer. AMDTreat utilizes the user-specified values for the different Bio Mix materials (specified under the Bio Mix subheading) that the user may have determined during testing along with the shrinkage factor to calculate the volumes and masses of the different materials that make up the Bio Mix layer.

3.2.2.4 User-Specified Dimensions - Mine drainage discharges often emerge at the base of hillsides and the available land area, between the point of emergence and the receiving stream, for constructing a treatment system can be limited. The use of other sizing methods may produce a Bioreactor that is larger than the available land area. Some folks may accept a smaller Bioreactor size, but this will most likely require more maintenance and prematurely plugging due to high metal loading per unit area/volume or only treating a portion of the mine drainage and bypassing the rest both resulting in limited improvements. Additionally, the Bioreactor may have insufficient retention time to precipitate and settle iron sulfide so the system could discharge iron sulfide solids, which is highly undesirable considering its instability and a stored source of acidity in the subsequent components of the system. In these cases, users can utilize this sizing method by entering the top length and width of the freeboard and AMDTreat will account for the user-specified side slopes and layer depths to calculate the dimensions and volumes of the selected Bioreactor layers.

3.2.2.5 Volumetric Calculations – AMDTreat models all passive treatment systems, including Bioreactors, as an “inverted” trapezoidal prism (Figure 1). AMDTreat calculates the overall dimensions of a passive treatment system by first breaking up the system into individual layers, such as the freeboard layer, water layer, bio mix layer, drainage aggregate layer, etc. Each individual layer and the geometric shape of the overall system is modeled as an inverted trapezoidal prism. AMDTreat sizing methods fall into one of two categories: (1) Users input information that is used to calculate a layer volume or surface area is calculated or users specify the mass of limestone, (2) Users specify the top width and length of the freeboard. In either case, AMDTreat uses the information generated by the sizing method, along with user-specified depths, side slopes, and length to width ratios to determine the dimensions of a layer shaped as an inverted trapezoidal prism. What differs is the approached used to calculate the geometry.

3.2.2.6 Calculations for Sulfate Reduction, Alkalinity Generation Rate, and Pilot Test Sizing Methods – The equation for an inverted trapezoidal prism is:

$$V = \left(\frac{W_T L_T + W_B L_B}{2}\right) D \qquad \mathbf{(3)}$$

<u>*Where:*</u>
V = Volume of trapezoidal prism
$L_T W_T$ =Length & Width of top of prism
$L_B W_B$ =Length & Width of bottom of prism
D = Depth

These sizing methods determine the volume of the Bio Mix layer. Therefore, AMDTreat calculates the volume of the Bio Mix layer and users are required to specify the depth of the Bio Mix layer, inside slope, and length-to-width ratio for the bottom of the Bio Mix layer. The unknowns are the length and width of the top and bottom dimensions of the trapezoidal prism for the Bio Mix layer. Since the depth and inside side slope of the Bioreactor is known, the top width and length of the Bio Mix layer can be written in terms of the bottom length and width to reduce unknowns in the equation. Furthermore, since the bottom length-to-width ratio is known, the bottom width can be written in terms of the bottom length. Now Equation (8) is rearranged to solve for the bottom length of the Bio Mix layer. The resultant equation is a quadratic:

$$L_{BLL} = \frac{-\left(\frac{2DR}{S} + \frac{2D}{S}\right) \pm \sqrt{\left(\frac{2DR}{S} + \frac{2D}{S}\right)^2 - 4(2R)\left(\frac{4D^2}{S^2} - \frac{2V}{D}\right)}}{2(2R)} \qquad \mathbf{(4)}$$

<u>Where:</u>
V = Volume of Bio Mix Layer
L_{BLL} = Bottom Length of Bio Mix Layer
D = Depth of Bio Mix Layer
S = Inside Side Slope of Bioreactor
R = Length to Width Ratio of Bottom of Bio Mix Layer

Once the bottom length is known, the bottom width of the Bio Mix layer (W_{BWB}) is calculated by dividing the bottom length by the user-specified value for length-to-width ratio for bottom of the Bioreactor:

$$W_{BWB} = \frac{L_{BLB}}{R} \qquad \textbf{(5)}$$

The two remaining unknown dimensions of the Bio Mix layer are the top length and width.

The top length of the Bio Mix layer is calculated by:

$$L_{TLB} = L_{BLB} + 2 * S * (D_{LL}) \qquad \textbf{(6)}$$

<u>*Where:*</u>
L_{TLB} =Top Length of Bio Mix Layer
L_{BLB} = Bottom Length of Bio Mix Layer
D_{BL} = Depth of Bio Mix Layer
S =Inside Side Slope of Bioreactor (rise/run)

The top width of the Bio Mix layer is determined by the same approach. Now that all the dimensions of the Bio Mix layer are known, the dimensions of the water and freeboard layers can be determined since a similar approach:

<u>Water Layer</u>
The bottom length of the water layer (L_{BWL}) is equal to the top length of the Bio Mix layer (L_{TLB}).

$$L_{BWL} = L_{TLB} \qquad \textbf{(7)}$$

The top length of the water layer (L_{TWL}) is calculated by:

$$L_{TWL} = L_{BWL} + 2 * S * (D_{WL}) \qquad \textbf{(8)}$$

Where:
S =Inside Side Slope of Bioreactor (rise/run)
D_{WL} = Depth of Water Layer

The same approach used to calculate the bottom and top width of the water layer. Then Equation (3) is used to calculate volume of the water layer.

<u>Freeboard Layer</u>
The bottom length of the freeboard layer (L_{BFL}) is equal to the top length of the water layer (L_{TWL}).

$$L_{BFL} = L_{TWL} \qquad \textbf{(9)}$$

The top length of the freeboard layer (L_{TFL}) is calculated by:

$$L_{TFL} = L_{BFL} + 2 * S * (D_{FL}) \qquad \textbf{(10)}$$

<u>Where:</u>
S =Inside Side Slope of Bioreactor (rise/run)
D_{FL} = Depth of Freeboard Layer

Equation (3) is used to calculate the volume of the freeboard layer.

In addition to assuming all passive treatment systems are constructed as an inverted trapezoidal prism, an additional assumption is that the excavation volume is equal to the summation of all the individual layer volumes, except for the freeboard layer. It is assumed the freeboard layer is constructed with a portion of the excavated earth. trapezoidal prism: Thus:

$$\begin{aligned} &Bioreactor\ Exavation\ Volume \\ &\qquad = Water\ Volume + Bio\ Mix\ Volume + Drainage\ Aggregate \qquad \textbf{(11)} \end{aligned}$$

3.2.2.7 Calculations for User-Specified Dimensions Sizing Method – When users specify the top width and length of the freeboard for a system, AMDTreat uses the user-specified values for inside side slope and the freeboard, water, and bio mix layer depths to calculate the dimensions and volumes of the individual layers of the Bioreactor.

The bottom length of the freeboard layer (L_{BFL}) is calculated by:

$$L_{BFL} = L_{TFL} - 2 * S * (D_{FL}) \qquad \textbf{(12)}$$

<u>Where:</u>
L_{BFL} = Bottom Length of Freeboard Layer
L_{TFL} =User-Specified Top Length of Freeboard Layer
D_{FL} = Depth of Freeboard Layer
S =Inside Slope of Bioreactor (Run/Rise)

The bottom width of the freeboard layer is calculated using the same approach.

The volume of the freeboard layer is determined by:

$$V_{FL} = \left(\frac{W_{TFL}L_{TFL} + W_{BFL}L_{BFL}}{2}\right) D_{FL} \qquad \mathbf{(13)}$$

<u>Where:</u>
V_{FL} = Volume of trapezoidal prism-shaped Freeboard Layer
W_{TFL} = Top Width Freeboard Layer
L_{TFL} = Top Length Freeboard Layer
W_{BFL} = Bottom Width Freeboard Layer
L_{BFL} = Bottom Length Freeboard Layer
DFL = Depth of Freeboard Layer

<u>Water Layer</u>
The top length of the water layer (L_{TWL}) is equal to the bottom length of the freeboard layer (L_{BFL}).

$$L_{TWL} = L_{BFL} \qquad \mathbf{(14)}$$

Now that the top width and length of the water layer is known, the user-specified values for inside slope and depth of water layer are used in Equation (12) to calculate the bottom width and length of the water layer. Equation (13) is used to calculate the volume of the water layer.

<u>Bio Mix and Drainage Aggregate Layers</u>
The same approached used to calculate the dimensions of the water layer are used to calculate the bio mix and drainage aggregate layer.

Lastly, the excavation volume is determined by adding the volumes for the water, bio mix, and drainage aggregate layers (Equation 16). The model assumes the excavated earth is used to construct the freeboard layer and any excess material is disposed of on-site.

3.2.3 System Properties: The Systems Properties section allows the user to input the inside slope of the pond, the limestone layer bottom length-to-width ratio, and the excavation unit cost. **AMDTreat suggests default quantities and unit costs for construction of a single Bioreactor.**

3.2.4 Layer Materials: Unlike active treatment systems, which require the continuous addition of chemicals to maintain treatment of mine drainage, passive treatment systems typically consist of impoundments filled with enough reagent (e.g., Bio Mix) to provide treatment for many years. For some passive treatment system components, such as vertical flow ponds (VFP), different reagents are used at different elevations within the impoundment to manipulate the geochemistry and control oxidation/reduction and solubility reactions as the mine drainage flows through the component. AMDTreat considers each reagent or material as a “layer” in the impoundment. Both “reagent” and “material” are used to describe layers because not all layers are comprised of reagents or materials meant to manipulate water chemistry. For example, the freeboard layer is designed to accommodate fluctuations in flow or increasing water elevation due to permeability or plugging of layer materials from metal hydroxides or sediment. The piping layer is located at the very bottom of the impoundment and is designed to transport water out of the system or flush the system in order to remove metal hydroxide precipitates that accumulate in the Bio Mix or limestone layer. The Layer Materials section is where users can control the depth and other characteristics of the materials/layers used in a Bioreactor or whether to even include a layer based on a designer’s preferences.

3.2.4.1 Freeboard Layer: Users specify the depth of the freeboard layer designed to produce enough storage to accommodate increases in the water layer due to increased flow events or clogging of the treatment media in lower layers. Since the Bio Mix layer has lower initial permeability than limestone-based systems and loses permeability as the organic matter decays and compacts, Bioreactors may have more freeboard than other types of passive components. Designers may want to consider having a foot of freeboard for every foot of Bio Mix layer to ensure hydraulic head can increase to force flow through the Bio Mix layer as permeability decreases. As with most passive components, the influent to the Bioreactor is within or at the top of the freeboard layer. An emergency spillway is incorporated into the freeboard layer just below the influent elevation (if the top of the water layer is lower than the influent elevation) to prevent the restriction of water flowing into the Bioreactor and to prevent water from overtopping the embankment. The bottom of the freeboard layer is the top of the water layer for the Bioreactor. A typical freeboard layer depth for a Bioreactor is 2.0-3.0 feet.

3.2.4.2 Water Layer: The water layer maintains the saturation of the treatment media and helps to disperse the water flow across the surface area of the Bioreactor. The depth of the water layer is often manipulated to maintain equilibrium as the treatment media clogs with sediment or metal hydroxide precipitates and to control gas exchange of the lower layers with the atmosphere. At times, the water elevation may need manipulated to control the growth of aquatic plants that may occur in Bioreactors. A typical water layer depth is between 2.0 and 3.0 feet. Bioreactors may have deeper water layer depths to help maintain anoxic conditions in the Bio Mix layer.

3.2.4.3 Bio Mix Layer: The Bio Mix layer typically consists of manure, hay, limestone fines, and wood chips to create an anerobic environment for sulfate reduction to occur. The purpose of the Bio Mix layer is to create a geochemical environment to induce sulfate reduction and metal sulfide precipitation. In addition, the Bio Mix layer is the source of alkalinity generation in a Bioreactor. Users can specify the layer depth, shrinkage factor, percent composition, density, and unit cost for each material to be used and the mixing/placement of the Bio Mix layer in this section. The Bio Mix depth is typically 3.0 to 4.0 feet and must contain a supportive matrix, such as stone and/or wood chips, to maintain permeability as the manure and hay decay.

3.2.4.5 Drainage Aggregate Layer: For Bioreactors, it is very important to embed the effluent piping network in an aggregate layer to protect the perforated pipes from becoming clogged with the Bio Mix layer materials (Figures 6, 7 & 24). The drainage aggregate layer is used to calculate the amount of aggregate required to embed the effluent pipe network. Note, the drainage aggregate layer depth should be equal to or greater than the largest diameter pipe to be used in the collection piping network (trunk and spur pipes).

3.2.4.6 Pipe Layer: The piping layer considers the piping required to convey the water into and/or out of the Bioreactor. The majority of the piping layer is situated between the Bio Mix and liner layers. Additionally, the piping layer in AMDTreat accounts for the influent/effluent pipes. The Bioreactor module offers users two methods to estimate the cost to purchase and install a piping network, the AMDTreat Piping Calculator or User-Specified Piping Layout. The default design of the AMDTreat Piping Calculator for a Bioreactor is the same as for a Vertical Flow Pond (VFP). The effluent piping network consists of a "trunk" pipe that extends the bottom length of the Bioreactor and "spur" pipes that extend the width of the system and are connected perpendicular to the trunk pipe. Users can specify the distance between the spur pipes by manipulating the Spur Pipe Spacing values in the Pipe Layer subheading. The spur pipes are attached to the trunk pipe using a "tee" connector while the trunk pipe may be connected to the effluent pipe using a coupler depending upon the pipe orientation.

3.2.4.7 Liner Layer: Many mine sites lack the soil characteristics required to prevent leaky passive treatment system components. AMDTreat offers three types of liner systems that prevent water leakage from the impoundment(s), including Clay, Synthetic (i.e. PVC), and Geosynthetic Clay (GCL) liners. The volume of clay liner required is calculated from the entire inside sloped area of the pond, from the top of freeboard to the base of the drainage aggregate layer (bottom of pond), plus the bottom area of the Bioreactor and multiplying it by the user-specified compacted thickness (typically 0.5 to 1.0 foot) and unit cost to purchase and install the clay liner. The area required for synthetic or GCL liners is determined by calculating the inside sloped area and the bottom area of the Bioreactor similar to the clay liner and adding an additional 2.0 ft of length on all sides to accommodate the incorporation ("tie in") of the liner into the embankment near the top of the freeboard layer to secure the liner system. AMDTreat provides the option of adding non-woven geotextile as a separate material for all liner systems. Non-woven geotextile separation material is commonly used to protect the synthetic or geosynthetic clay liner from the excavated inside surface of the pond and/or the limestone layer from the excavated surface of the pond or selected liner material. Figure 25 shows non-woven geotextile being placed on top of a synthetic liner during the construction of a Bioreactor.

3.2.5 Other Items: The *Other Items* section allows users to consider the capital cost of inlet and outlet structures, valves, and flow distribution structures. **AMDTreat suggests default quantities and unit costs for construction of a single Bioreactor.**

3.3 Module Outputs

3.3.1 Sizing Summary: The Sizing Summary section contains all the calculated module outputs, such as the dimensions, volumes, and plug flow retention times for the various layers. The total mass of Bio Mix materials required for the Bio Mix layer is provided on the right-hand side of the Sizing Summary heading, which is further broken down by material within this section.

3.3.2 Capital Cost: This section provides the estimated costs for the various user-specified components and the total estimated cost to construct the entire Bioreactor component of the passive treatment system.

3.3.3 Annual Cost: Since a Bioreactor is a passive treatment system component, the only annual cost considered is the cost for maintenance. Annual costs, such as sampling, labor, and access road maintenance are "project-wide" costs since they apply to an entire treatment site, not each individual treatment component. Sampling, Labor, and Site Development (i.e. snow plowing) modules are located under the "Project Modules" section of the Main User Interface and capture these types of annual costs.

Annual maintenance costs for Bioreactors may include periodic "flushing" of the drainage aggregate and piping layer to evacuate accumulated metal sulfide precipitates from the stone void spaces, maintaining clear influent and effluent piping, and manipulating the water level control structure (e.g. Agri drain) to change the water level in the Bioreactor as needed. It is assumed that some years will not require the full amount of funds set aside for annual maintenance but will eventually be used over the system life. Users can estimate the annual maintenance costs by assuming a percentage of the capital cost (more expensive the system, the more expensive the maintenance) or specify a known annual maintenance cost amount.

3.3.4 Net Present Value: The Net Present Value (NPV) section determines the cost to operate a treatment system component over a specified time period. The NPV calculates the present-day financial investment required to generate the income to pay for future operation and equipment/materials replacement costs. Both **Financial Variables** and **Cost Categories** are required to calculate the NPV.

3.3.4.1 Financial Variables - The *Term of Analysis*, *Inflation Rate*, and *Rate of Return* are three variables used in the NPV calculations. The default values for these terms are shown under the *Net Present Value* section of each module. Users must access the *Net Present Value* menu at the top of the main user interface to change the default values as they would apply to all modules used for an entire treatment system. While NPV is determined for each AMDTreat module activated by the user, the goal is to determine a total NPV for an entire mine drainage treatment system project (a collection of cost estimates for individual modules creates a treatment system project in AMDTreat). Therefore, a single value for *Term of Analysis*, *Rate of Return*, and *Inflation Rate* is applied to all modules and cannot vary between modules.

- <u>Term of Analysis</u>: The time period used by the NPV calculation to determine the financial investment required to pay for all future costs of the treatment system.

- <u>Inflation Rate</u>: Represents the average price increase of goods and services over time. AMDTreat uses the inflation rate to calculate the future cost of the annual operation and maintenance (O&M) and recapitalization items.

- <u>Rate of Return</u>: Describes the expected profit on an investment.

3.3.4.2 Cost Categories - For each treatment module, AMDTreat provides a list of recommended equipment and materials that require recapitalization. In addition, AMDTreat provides recommendations (default values) for life cycle and replacement percentage. Users can click on the default values for *Life Cycle* or *Replacement Percentage* and use the +/- buttons to change the default values. In addition, users can select *Custom Cost* and enter a new cost to represent the current cost of the equipment.

Users can add new recapitalization items or deactivate/delete existing items for calculating the NPV.

An example of how the recapitalization variables are used to determine NPV is to consider the following hypothetical scenario. Assume a vertical turbine pump has a life cycle of 50 years but requires the pump motor to be rebuilt every 20 years. Assume the present-day cost to purchase the motor is $500,000, and the cost to remove, rebuild, and reinstall the pump motor is $20,000. Now assume we want to determine the amount of investment required today (NPV) to generate the income to pay for the future cost of rebuilding the pump motor over a 50-year *Term of Analysis*, which is also equal to the life cycle of the pump. Assume an *Inflation Rate* of 5.0% and *Rate of Return* of 8.1%. The goal is to place the money in a relatively secure investment vehicle to generate 8.1% annually. The NPV will calculate the size of investment required to generate income for future costs.

There are several ways to model the replacement cost. One way is to replace 4% of the present-day cost of the pump (4% of $500,000 = $20,000) with a life cycle of every 20 years. If the *Term of Analysis* is 50 years, then the entire pump would not require recapitalization since the life cycle of the pump is 50 years. However, the motor would require two replacements (50 years / 20 years = 2.5 rounded down to 2).

To determine the NPV to recapitalize rebuilding of the motor, AMDTreat calculates the future cost to rebuild the motor at each life cycle, 20 and 40 years. The program uses the *Inflation Rate* to inflate the present-day default cost to rebuild the motor in 20 and 40 years from now. While the present-day cost to rebuild the pump motor is $20,000, the future cost to rebuild the motor in 20 years at a 5.0% *Inflation Rate* is $53,065 and $140,799 in 40 years (Equation 8). Assuming an 8.1% *Rate of Return*, the 50-year NPV for the pump is $17,422. In other words, an initial investment of $17,422 is needed at an annual *Rate of Return* of 8.1% to generate the investment income required for the two motor rebuilds over the 50-year life cycle of the pump.

$$\begin{gathered}\textit{Cost to rebuild pump motor in 20 years} = \\ \textit{Present Day Cost} \times (100\% + \textit{Inflation Rate})^{20} = \$20{,}000 \times (100\% + 5\%)^{20} = \$53{,}065 \qquad \textbf{(15)}\end{gathered}$$

- Annual Operation and Maintenance Cost: By default, AMDTreat transcribes the annual O&M cost from the Annual Cost section to the Net Present Value section. The program assumes the module is being used to first estimate the annual cost for a treatment system component, so it automatically transcribes the annual cost to the NPV section. If this is not the case or the user wants to use some other annual cost, the “Use Custom” box can be selected to allow the user input of a different annual cost to utilize in the NPV calculation.

- Recapitalization Cost: Certain treatment system components, especially mechanical and water conveyance equipment, require periodic replacement. The recapitalization cost of an item is an estimate of the amount of money required to pay for future replacement costs for the item. In addition to the Financial Variables described above, three additional values are required to calculate the NPV of recapitalization costs, the Present-Day Equipment Cost, the Life Cycle, and the Replacement Percentage.

- Default Cost: This represents the current cost to purchase the equipment or material.

- Life Cycle: The time frame between equipment or material replacement is termed as its Life Cycle. Some equipment manufacturers provide recommended life cycles for their equipment to provide consumers with an estimate of how long the equipment is expected to be operational. Some life cycles, such as those used for treatment media (limestone), are based on best professional judgement. Some operators prefer to periodically purchase and replace equipment before failure to preserve the continuity of operations, while others wait until failure to replace an item.

- Replacement Percentage: The Replacement Percentage is an adjustment factor to the Default Cost to accommodate situations where the entire piece of equipment or all of the material does not require recapitalization. For example, a passive treatment component may be designed to contain enough limestone to neutralize the acidity load for 20 years, however, the accumulation of metal hydroxide precipitates within the void space of the limestone layer may require that 25% of the limestone be replaced every 7 years to prevent hydraulic failure such as plugging or short-circuiting. For this scenario, the initial cost of the limestone making up the limestone layer is discounted by 75% and assigned a life cycle of 7 years to determine the amount of money required to cover the cost of replacing 25% of the limestone layer every 7 years over the Term of Analysis.

3.3.4.3 Rationale for Recapitalization Recommendations:

Recapitalization recommendations are based on professional experience of the AMDTreat Team and may not apply to all situations. Users are encouraged to customize the recapitalization assumptions to their treatment scenario. AMDTeat Team members are located in Pennsylvania and West Virginia and have collective experience in design, funding, and/or operation/maintenance for over 100 passive treatment systems. Most passive treatment systems constructed in Pennsylvania and West Virginia are less than 15 years old, thus the industry is still gaining experience in lifecycles for various components. However, the AMDTreat Team held discussions on personal experience to develop a list of recapitalization recommendations. Users may have different experience and opinions.

By default, AMDTreat includes a list of six recapitalization items for Bioreactor. The items are listed even if they are not selected for the treatment system. The purpose of this is to inform the user of items they should think about recapitalizing or including in their treatment design. For example, Liner is listed as a recapitalization item even if no liner is selected in the cost estimation. In this case the recapitalization cost is set to $0.00 but the item is still shown as a reminder to the user that a Liner is a common item that should be considered. If a liner is included in the cost estimation, the estimated liner cost is used to calculate a recapitalization cost for liner. Users can delete or modify any of the default Recapitalization items by either deselecting the item or by setting the Replacement % to zero. If the item is deselected the Total Cost for the item will still be shown but the cost will be subtracted from the Net Present Value Cost, shown in the Net Present Value Heading.

Bio Mix: A portion of the Bio Mix may need to be replaced as it becomes less effective of producing anaerobic conditions. Based on the historical experience of maintain Bioreactors, AMDTreat recommends planning to replace 100% of the Bio Mix every 15 years.

Drainage Aggregate: A portion of the Drainage Aggregate may need replaced as it may be become clogged with precipitate. The default assumption is to replace 50% of the drainage aggregate every 15 years.

Liner: Often liners are destroyed, especially synthetic, while conducting maintenance on passive treatment systems, if the equipment operator is inexperienced with passive systems. Thus, AMDTreat recommends planning to replace a portion of the liner while the Bio Mix and/or Drainage Aggregate is being replaced. The default assumption is to replace 50% of the Bio Mix every 15 years, so the same assumptions are recommended for Liner recapitalization.

Pipe: Piping is often exposed at the surface and can become damaged by vandalism, falling trees, and other factors. AMDTreat assumes 50% of the piping will require replacement after 15 years of service.

Other Items: The Other Items section in AMDTreat includes Flow Distribution Structures, Water Level Control Structures, and Outlet Protection Structures. These structures are often durable, and many treatment systems have never experienced replacement of these items, however, AMDTreat Team members have had at least one experience of each of these items requiring replacement, thus the Team wanted to include these items for replacement consideration.

3.4 Assumptions of Design Sizing and Costs

AMDTreat is a cost estimation model that uses assumptions to provide treatment sizing and both capital and annual cost estimates. While there are many assumptions in the program, the ones provided below are important to consider for the Bioreactor module.

1. The Bioreactor is assumed to be constructed on a flat surface, where the water and Bio Mix layers are excavated or below the existing or original ground, and a portion of that material is used to construct the freeboard embankments which is considered fill material above the existing or original ground (see Figure 1). The program assumes an on-site balance of cut / fill, however, if this is not the case, the user can modify excavation cost default values to reflect the anticipated conditions based on the site characteristics.

2. The geometric shape of a Bioreactor is an inverted trapezoidal prism. The volumetric equation for a trapezoidal prism is used to calculate the Bioreactor layer volumes.

3. None of the sizing methods provide a “design life” that properly accounts for the hydraulic and treatment issues caused by the compaction due to the decay of organic matter and the accumulation of metal sulfide precipitates within the void spaces of the treatment media.

4. In general, the goal of the Bioreactor sizing methods is to provide an estimate of the Bio Mix layer mass required to create a reducing environment to precipitate metal sulfides. None of the

sizing methods are based on achieving effluent water quality criteria or requirements. With that said, a properly sized Bioreactor treatment component should generate pH > 6.0 and net alkaline water, which in theory will decrease aluminum and iron solubility to less than 1.0 mg/L.

4.0 References

Hedin, R.S. and Watzlaf, G.R., 1994. The effects of anoxic limestone drains on mine water chemistry. Proceedings of the 3rd International Conference of the Abatement of Acidic Drainage, Volume 1, Pittsburgh, PA. U.S. Bureau of Mines SP 06B-94, p. 185–194.

Rose, A. W., 2004. Vertical flow systems – Effects of time and acidity relations. Proceedings, American Society of Mining and Reclamation, Morgantown, WV, April 18-24, 2004, p. 1595-1615. https://www.asrs.us/Portals/0/Documents/Conference-Proceedings/2004/1595-Rose.pdf

5.0 Figures

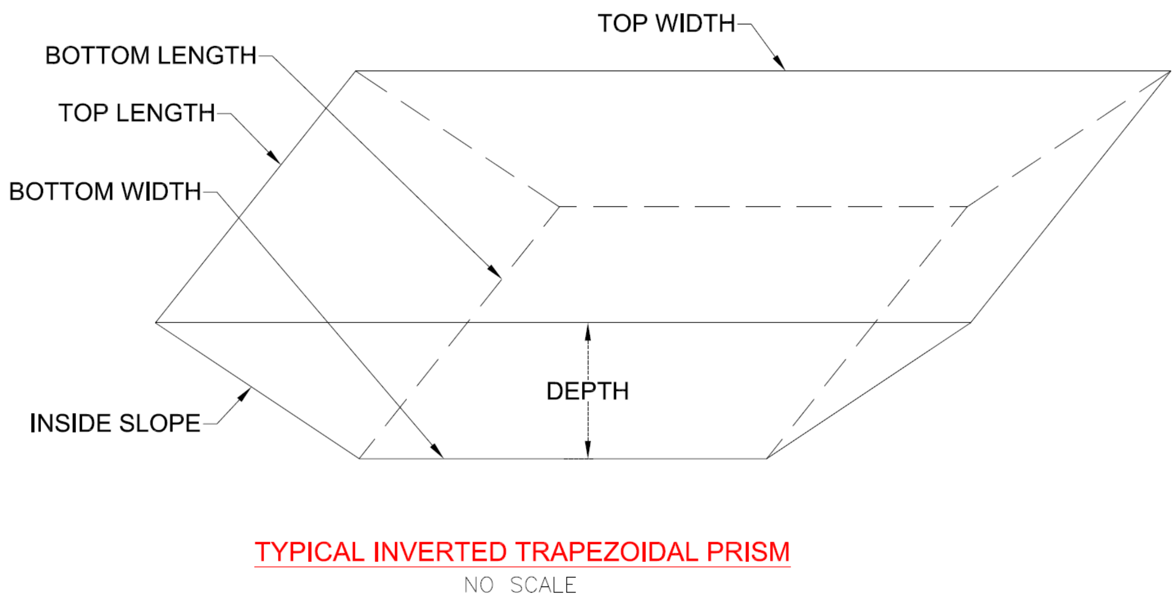

Figure 1: Typical Inverted Trapezoidal Prism

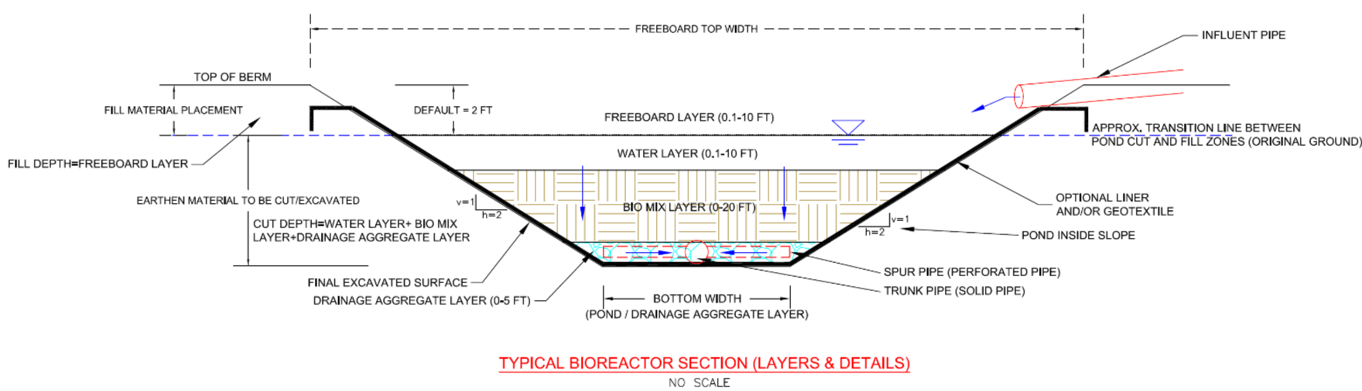

Figure 2: Typical Cross Section View of a Bioreactor showing the Common Layers and Components

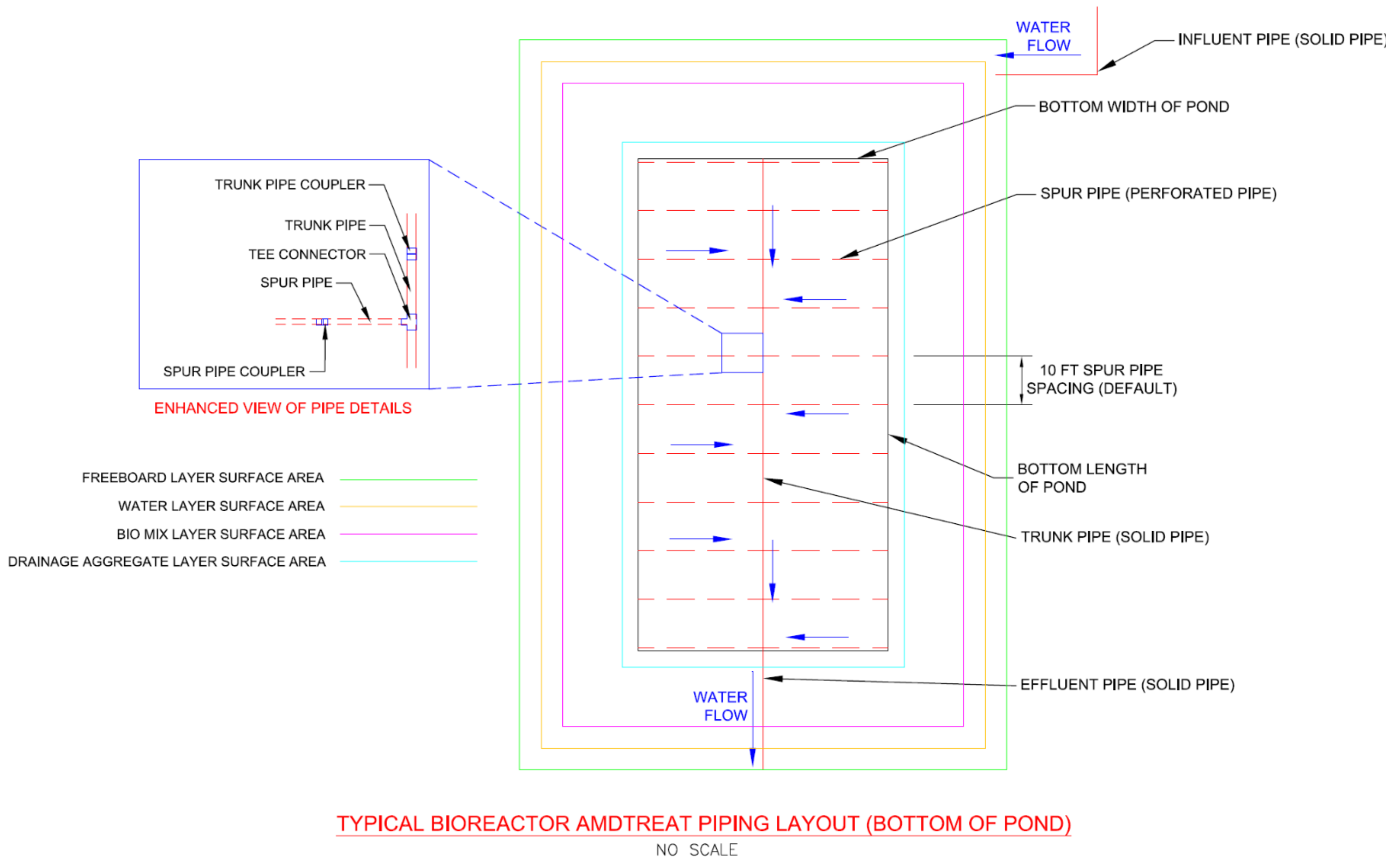

Figure 3: Plan View of the Bioreactor to Illustrate Common Piping Layout and Components (Used in AMDTreat Piping Calculator) and the Layer Surface Areas.

Figure 4: Staging area for making the Bio Mix. Picture shows piles of manure, limestone fines, wood chips, and hay bales.

Figure 5: Large pile of Bio Mix (manure, compost, hay, woodchips, limestone) in preparation to be placed in Bioreactor.

Figure 6: Lateral piping network placed overtop of non-woven geotextile and synthetic liner. Note the pipes placed in rock bedding to protect perforated openings.

Figure 7: Close up image of effluent collection pipe embedded in rock shown in Figure 5. Image shows spur pipes (bottom left) connecting into the trunk (header) pipe (bottom right).

Figure 8. Excavator installing rock bedding for piping network.

Figure 9: Bioreactor under construction showing effluent collection pipe embedded in rock (bottom right) to be covered by Bio Mix layer. Pipe cleanouts were installed along the side slopes to remove debris if collection piping becomes clogged. Once a common practice, cleanout pipes are now sparingly used because of short circuiting issues experienced by flow along the sides of the clean out pipes.

Figure 10: Alternative piping network design. Spur pipes are aligned parallel to the longest dimension of the Bioreactor and the trunk (header) pipe is positioned across the width of the bioreactor. The piping network is embedded in stone to protect the perforations from the overlain Bio Mix layer.

Figure 11: Short term flush of a Bioreactor effluent pipe to prevent build up of precipitates. Whitish elemental sulfur flushed into a subsequent pond filled with ferrous monosulfide. FeS particulates constantly discharge from this bioreactor to the settling pond due to an insufficiently sized Bio Mix layer.

Figure 12: Truck end-dumping the Bio Mix material and excavator trying to carefully smooth out the surface to obtain a uniform thickness to promote a uniform flow pattern. Extreme caution must be used to prevent compaction of the Bio Mix material, which is irreversible.

Figure 13: Bio Mix being spread over top of a non-woven geotextile and synthetic liner system during the construction of a 2.0 acre Bioreactor.

Figure 14: Bioreactor filled with Bio Mix layer right before the initial filling with water and incubation period. Care was taken to create a uniform Bio Mix layer depth, however, the picture shows peaks and valleys within the Bio Mix that differ by up to a foot and will affect the flow pattern. Thus, this Bioreactor contains three separate piping systems (right side, middle, and left side of Bioreactor) that are controlled by three separate water control structures (e.g. Agri-drain boxes) to help equalize the uneven flow patterns caused by the variable thickness and homogeneity created during the construction.

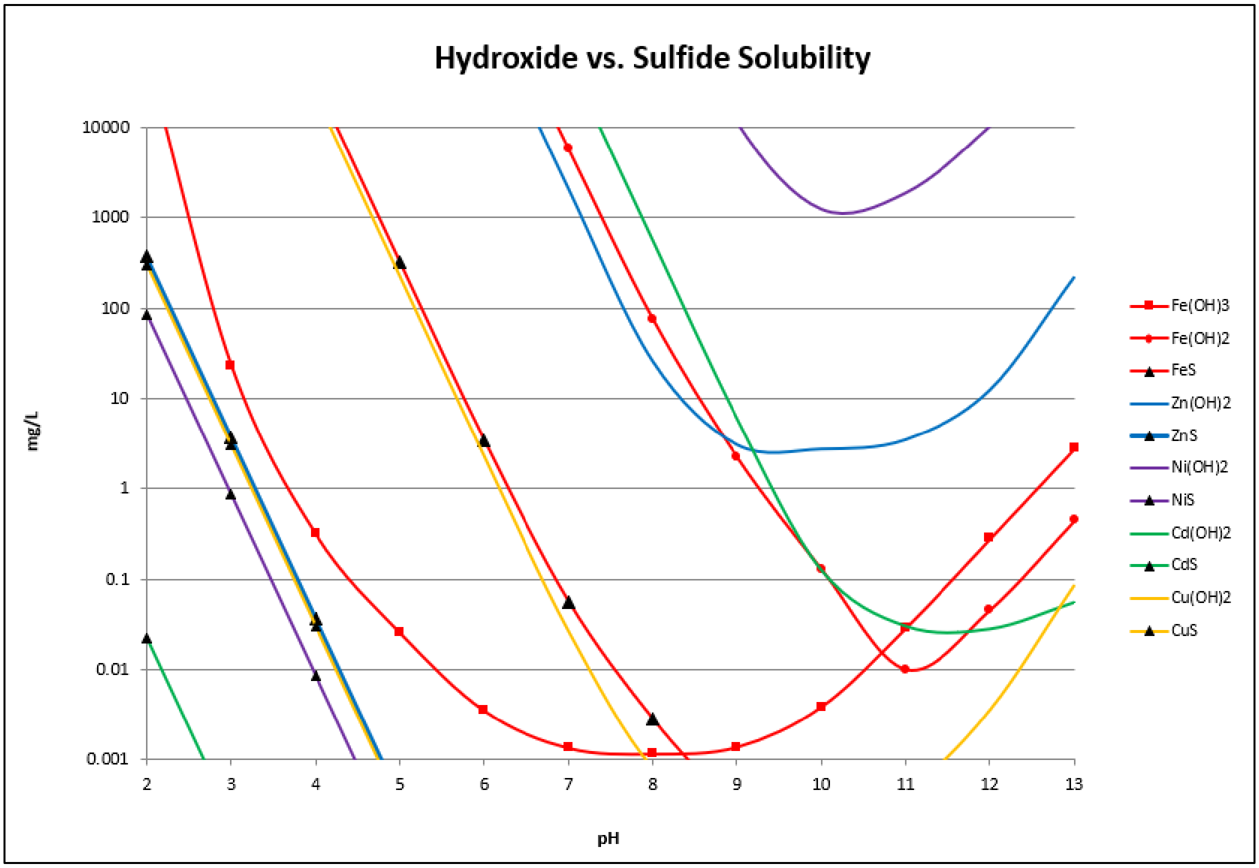

Figure 15: Solubility of metal hydroxide vs. sulfides for various elements

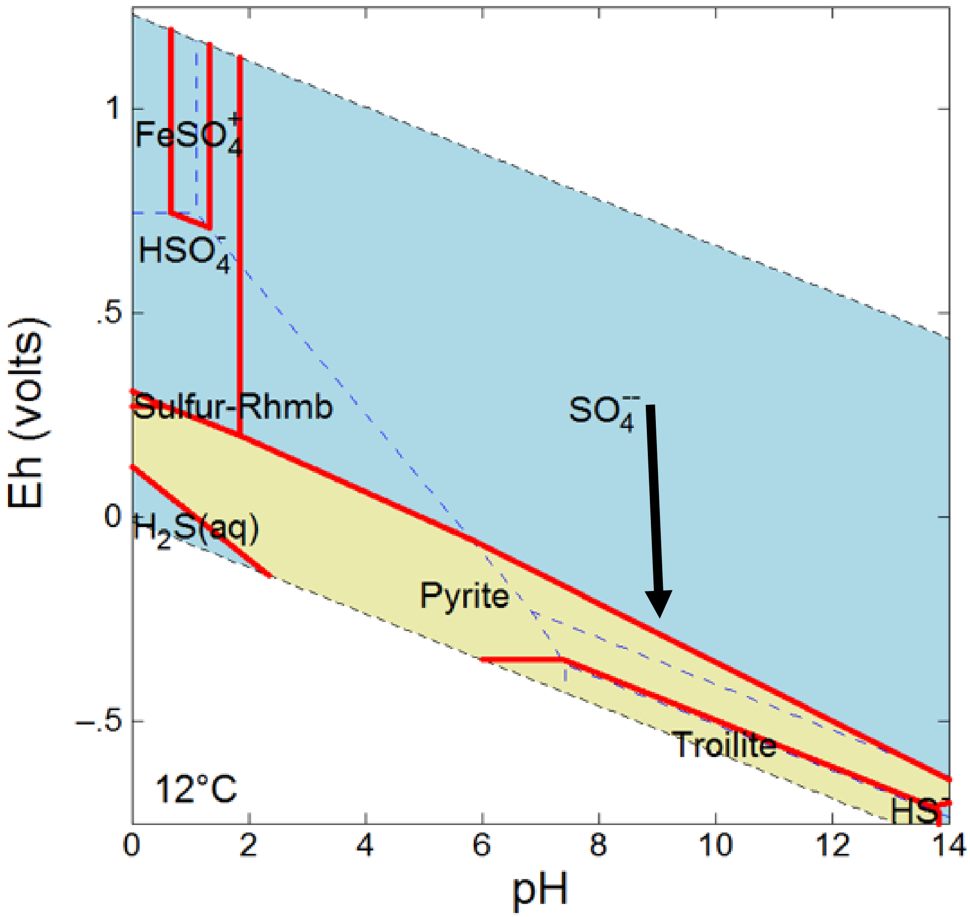

Figure 16: Pourbaix diagram for an aqueous iron/sulfur system. Most mine drainage would plot within the SO_4^{2-} stability field. The goal of a Bioreactor is to create an Eh/pH condition that plots in the pyrite stability field.

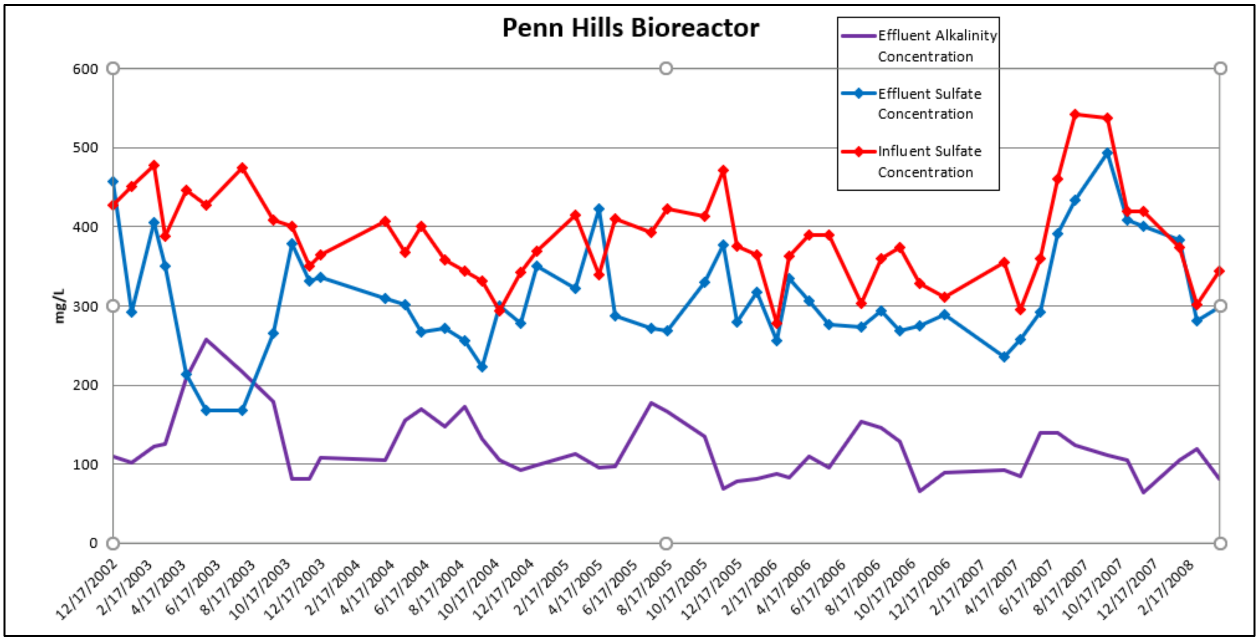

Figure 17: Monthly Influent and effluent sulfate concentration and effluent alkalinity concentrations for a Bioreactor over a five-year period.

Figure 18: Newly constructed Bioreactor being filled with mine drainage in preparation for a two-week incubation period.

Figure 19: First discharge of a newly constructed Bioreactor after the incubation period. The organic-rich water with elevated BOD & COD is an environmental concern if not appropriately treated in the subsequent ponds.

Figure 20: Discharge of a Bioreactor into the receiving stream right after the incubation period. Designers did not take proper precautions to treat the high BOD Bioreactor effluent water during the first few months of operation.

Figure 21: Photo showing a 3.0 by 3.0 ft area of the top of a Bio Mix layer under the water layer. One to two-inch diameter holes can be observed made by CO_2 produced in the Bio Mix layer. The pH 2.7 mine water entering the Bioreactor and low pH iron oxidization is causing a ferric hydroxy sulfate mineral crust on top of the Bio Mix layer.

Figure 22: The milky-white water flowing out of a Bioreactor and through an outlet protection structure contains both elemental sulfur and calcite.

Figure 23: Black precipitate at the base of a bioreactor effluent pipe (black coated rocks to left of white pipe). Hydrogen peroxide is added to the black precipitate and the oxidation to produce an orange-red color ferric hydroxide confirms the precipitate as iron sulfide.

Figure 24: This photo is of the outfall from a Bioreactor effluent pipe. Note the black-colored pond in the background receiving this effluent. This Bioreactor contains an insufficient volume of Bio Mix layer needed to precipitate and settle the entire ferrous iron concentration and as a result ferrous sulfide (FeS) reactions continue to occur as the water is discharged from the Bioreactor. The Bioreactor discharges sixty (60) pounds of FeS as particulate matter every day, which is captured by the settling pond creating a potential environmental hazard in the form of stored acidity. To compound the seriousness of the iron sulfide accumulation, a drinking water reservoir is shown at the very top of the photo that receives the final effluent from this Bioreactor treatment system.

Figure 25: While the photo is not a Bioreactor, the collection piping network shown here is the same configuration as the default piping in AMDTreat (if the AMDTreat Piping Calculator is used). A large trunk pipe extends along the center of the bottom length of the treatment component and spur pipes extend the width to collect and transport treated water out of the pond. The entire effluent piping network in a Bioreactor should be embedded in a drainage aggregate layer to protect the spur pipe perforations from become clogged with Bio Mix material. In this photo the excavator is covering a spur pipe with drainage aggregate.

Figure 26: Non-woven geotextile being placed on top of a synthetic liner during the construction of a Bioreactor.