Help Instruction File:

Vertical Flow Pond (VFP) 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).

VFP Module Overview

Table of Contents

1.0 Objective

A Vertical Flow Pond (VFP) is a passive treatment system (meaning that no machinery is required for its operation) that is typically used to treat acidic mine drainage of low to moderate flow with low to moderate acidity and dissolved metals, and low pH.

The objectives of this overview are to: (1) Provide a basic understanding of the theory and application of VFP and (2) Provide an overview of the VFP Module to guide users in developing an estimate of the cost to construct, operate, and maintain VFPs for treating mine drainage. Therefore, this overview will be presented in two sections, **Treatment Component Overview** and **VFP 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) VFP Conceptual Treatment Module. The first section provides a physical description and hydraulic profile for a VFP to provide context for users of AMDTreat. The second section describes the common application of the VFP 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 geometric shape of a VFP is an inverted trapezoidal prism consisting of four distinct "layers" (Figure 1). The bottom layer is filled with limestone ranging from 1.5 to 3.5 inches in size (AASHTO #1 or #3) and is commonly 3.0 ft thick. Overlying the limestone layer is the compost mixture layer. The compost mixture layer is commonly between 0.5 and 1.5 ft thick and consists of mushroom compost or other composted organic matter. Some designers incorporate limestone fines, typically 10 to 25% by volume, into the compost layer as additional treatment media. A 1.0 ft deep water layer is positioned above the compost mixture layer and serves to keep the compost saturated and anoxic. The topmost layer is the freeboard layer, which is used to accommodate changes in the water depth from either a large surge in flow or from a gradual decrease in the permeability of the compost and/or limestone layers due to the accumulation of metal precipitates on top of or within the layers.

Mine water flows into the top of the VFP and then flows vertically downward through the water, compost and limestone layers. As shown in Figure 3, a piping network at the base of the limestone layer is designed to uniformly draw water from the limestone layer. The piping network converges to a single trunk pipe that extends through the embankment and either upwards via a pipe or through a water level control device that can regulate the water surface within the VFP and facilitate drainage of the VFP for maintenance. Treated water is then typically discharged to a rock-lined ditch that flows to a setting pond.

Figures 2 and 3 are schematics showing typical material layers and piping network for VFPs. Figure 4 shows the installation of a clay liner during construction of a VFP, and Figure 5 shows a typical effluent and flushing piping network. Figure 6 shows the compost layer and Figures 7 and 8 are photos of completed and operating VFPs. Figure 9 is an interesting aerial photograph taken in 1998 near Boynton, PA showing the aftermath of a F3 Tornado passing directly over two VFPs followed by a Wetland and Settling Pond. The VFP system was unscathed and continued to produce net alkaline water for more than 15 years after without intervention.

2.2 Application and Treatment Chemistry

A Vertical Flow Pond (VFP) is a type of "passive" treatment system used to treat net-acidic mine drainage. The term "passive" refers to the inability to exert operational control to adjust treatment to respond 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". Therefore, a net-acidic solution is one where the acidity of the solution is greater than the alkalinity (net acidity = acidity – alkalinity). VFPs are used to impart alkalinity to mine drainage and turn the net-acidic water to net-alkaline (alkalinity > acidity) for the purpose of treatment. Once mine drainage is changed to a net alkaline condition, acid-producing reactions, such as the oxidation and precipitation of ferrous iron, can occur with the pH remaining above 6.0.

Net-acidic coal mine drainage in the eastern U.S. is typically low pH (e.g., < 5) and may contain ferric and ferrous iron, aluminum, and manganese. Another, less common type of net-acidic mine drainage contains alkalinity, ferrous iron, and is characterized by pH ranging from 5.5 to 7.0. However, the acidity that will be released upon oxidation and precipitation of ferrous iron is greater than the alkalinity, making it net-acidic drainage. Thus, the pH will decrease to below 4.0 after precipitation. VFPs are best suited to treat low-pH net-acidic drainage, and anoxic limestone drains (ALD) are best suited for circumneutral pH net-acidic drainage. The solubility of aluminum is largely pH dependent, so the geochemical behavior of aluminum will be similar in Vertical Flow Ponds, Limestone Beds, and ALDs. As the mine water pH is increased to ~ 5.5, most of the aluminum will precipitate and cause hydraulic issues by clogging the limestone void spaces. However, Vertical Flow Ponds and Limestone Beds are much more suitable for treating aluminum-rich mine water since they have much larger cross-sectional area perpendicular to flow and are also capable of periodically flushing some of the precipitates as part of their normal operating conditions. Aluminum will still precipitate, but the larger surface area and flushing will allow the beds to function longer before hydraulic failure. In addition, Vertical Flow Ponds and Limestone Beds contain freeboard that allows the buildup of hydraulic head to continue to force the flow of water through the bed as aluminum precipitate accumulates in the limestone layer and impact the permeability of the bed. Since ALDs have no freeboard layer they lack the ability to increase hydraulic head without causing the rerouting of water around the ALD in surface mine discharges or increasing the mine pool elevation in underground mine discharges. Thus, ALDs are better suited for treating waters void of ferric iron, aluminum, and dissolved oxygen.

2.3 VFP Conceptual Treatment Model

The following discussion presents a conceptual treatment model for VFPs treating low pH mine drainage containing ferrous and ferric iron, aluminum, and manganese:

2.3.1 Freeboard Layer: The freeboard is designed to accommodate fluctuations in flow or increasing water elevation due to permeability or plugging of layer materials from metal hydroxides or sediment. It doesn't perform a specific purpose pertaining to geochemical treatment of the mine drainage.

2.3.2 Water Layer: The low pH drainage entering the water layer is prone to gas exchange reactions with the atmosphere (O_2 in-gassing and CO_2 degassing) and, under certain conditions, low-pH biotic iron oxidation may occur and increase the concentration of dissolved ferric iron.

2.3.3 Compost Mix Layer: As the water flows vertically down into the compost mixture layer, the chemically reducing environment promotes the consumption of dissolved oxygen by organic matter to produce CO_2. The decrease in redox potential promotes sulfate reduction and reduction of ferric to ferrous iron. The reduction of ferric to ferrous iron is important to keep iron soluble (dissolved) as pH is increased in the limestone layer. Otherwise, ferric iron is insoluble at pH > 4.0 and would cause the accumulation of ferric iron precipitate, and eventual clogging or short-circuiting of the limestone layer (Figures 10, 11, & 12). Sulfate reduction in the presence of ferrous iron will produce the formation of iron mono sulfides, thus some ferrous iron precipitation will occur in a highly functioning compost layer (Figure 13). Some designs opt to mix limestone fines into the compost to increase pH, which increases the kinetics of sulfate reduction. In addition, if the limestone fines increase the pH to ~ 5.5, aluminum precipitation will occur in the compost layer and help protect the underlying limestone layer from becoming clogged. Periodic maintenance and replacement of the compost layer due to aluminum clogging is easier than removing the limestone layer. An additional benefit of the compost layer is the production of CO_2 from the oxidation of organic matter. The increased carbon dioxide partial pressure (pCO_2) production will drive limestone dissolution and increase alkalinity in the limestone layer. Typically, dissolved manganese remains unchanged in the water and compost mixture layers.

2.3.4 Limestone Layer: The drainage exiting the compost mixture layer and entering the limestone layer should be anoxic and elevated in CO_2. If the drainage entering the limestone layer contains aluminum, precipitation will occur as the pH is increased to above 5.5. Over time, the aluminum precipitation will decrease the permeability and cause hydraulic issues within the limestone layer (Figure 14). If the drainage contains ferrous iron, some oxidation of ferrous iron may occur, but the amount should be limited due to the lack of electron acceptors ($O_{2(aq)}$) and the slow kinetics of abiotic iron oxidation at pH ~ 6.5. The amount of alkalinity the limestone can produce depends on the amount of metal acidity released in the limestone layer and the pCO_2 of the solution. Considering these limitations, there are instances of VFPs incapable of making a solution net alkaline. A properly functioning limestone layer will discharge a solution pH between 6.2 and 7.0. Ferrous iron will remain soluble and dissolved manganese will be unaffected. VFPs are not a suitable treatment solution for manganese. In theory, the net alkaline drainage containing ferrous iron and manganese is collected in the piping network at the bottom of the limestone layer and discharged to a ditch or settling pond.

2.3.5 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.

2.3.6 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 VFP 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*, then select a method to determine the amount of limestone contained in the limestone layer of the VFP. Next, users specify design parameters such as the depth of the compost mixture layer, and unit costs for items affecting the capital cost to construct the VFP. 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 VFP 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: Users can select from five different methods to size the VFP: (i) Retention Time, (ii) Bureau of Mines, (iii) Alkalinity Generation Rate, (iv) User-specified Limestone Quantity, and (v) User-specified Dimensions. The module offers two different approaches to sizing VFPs. The first approach calculates the mass of limestone (tons) in the limestone layer before determining other dimensions. The Retention Time, Bureau of Mines, Alkalinity Generation Rate and User-Specified Limestone Quantity methods utilize this approach. The first approach is the most common as it relates the sizing of the treatment system based on flow and water quality characteristics. The second approach requires users to specify the length and width of the freeboard layer (user-specified Dimensions method) before calculating the remaining dimensions of the VFP. The second approach is often used when the land area available for treatment is restricted, when reverse engineering, or when developing a cost estimate for an existing treatment system.

Calculate Mass of Limestone in Limestone Layer

3.2.2.1 Retention Time – The user enters the desired time to retain the water in the void spaces between the individual pieces of limestone. The mass of limestone required to achieve the user-specified retention time is calculated by multiplying the *Design Flow* rate by the *Retention Time* to determine the volume required to retain the water (Equation 1). The calculated volume is then divided by the porosity of the limestone layer to calculate the total volume of the limestone layer (Equation 2).

Volume Required for Water (yd^3) =

$$\mathit{Design\ Flow}\ (\text{gpm}) \times \frac{60\ \text{min}}{1\ \text{hr}} \times \mathit{Retention\ Time}\ (\text{hrs}) \times \frac{1\ \text{yd}^3}{201.974\ \text{gal}} \qquad \textbf{(1)}$$

Limestone Layer Volume (yd^3) =

$$\frac{\text{Volume Required for Water (yd}^3)}{\text{Limestone Porosity (\%)}} \qquad \textbf{(2)}$$

The porosity represents the percent (%) of void space in the limestone layer (volume of the voids in between individual pieces of limestone/total volume of the voids and the limestone). Users can specify a value for porosity to match the gradation of limestone they plan to use in the limestone layer. Users can specify the porosity value under the *Limestone* section, which is located under the *Layer Materials* subheading. Based on the user-specified porosity value, AMDTreat calculates the *Bulk Density* of the limestone. The mass of the limestone required in the limestone layer is calculated by multiplying the limestone layer volume by the *Bulk Density* (Equation 3).

Limestone Mass (tons) =

$$\mathit{Limestone\ Volume}\ (\text{yd}^3) \times \frac{27\ \text{ft}^3}{1\ \text{yd}^3} \times \mathit{Limestone\ Bulk\ Density}\ \left(\frac{\text{lbs}}{\text{ft}^3}\right) \times \frac{1\ \text{ton}}{2000\ \text{lbs}} \qquad \textbf{(3)}$$

Results from bench-scale testing indicate that a retention time of 16 hours is a good balance between maximizing alkalinity production and the size of the treatment system (mass of limestone). Some professionals conduct "cubitainer" testing to determine the amount of time required to achieve net alkaline conditions. A cubitainer is filled with limestone and mine drainage, with care taken to prevent off-gassing of carbon dioxide (CO_2) from the mine drainage, and alkalinity is measured over time. Some professionals find it appropriate to add a safety factor to the retention time since the retention time and contact between limestone and mine drainage will change as soon as limestone starts to dissolve.

See Section 3.2.2.7 to 3.2.2.9 for volume calculations for the other layers.

3.2.2.2 Bureau of Mines - The Bureau of Mines was an agency in the U.S. Department of Interior that is now retired but was instrumental in conducting some of the early research in how to design passive treatment systems (Hedin and Watzlaf, 1994). A method they developed to determine the mass of limestone needed in passive treatment systems was to perform two calculations. The first calculation is to determine the mass of limestone required to retain the water for a given retention time. This calculation is the same as Equation 3, described above for the retention time sizing method.

A second calculation (Equation 4) is used to determine the mass of limestone required to neutralize the acid loading of the mine drainage for a specified time frame (*Neutralization Period*). The mass of limestone required to neutralize the acid loading is determined by multiplying the user-specified *Design Flow* by the *Net Acidity* and the *Neutralization Period*. The resultant value is divided by both the *Purity* and *Dissolution Efficiency* of the limestone to correct for the portion of limestone that will not dissolve to produce alkalinity and the fact that larger pieces of limestone are not likely to efficiently dissolve due to a loss of surface area from weathering and mineral precipitate coatings (i.e. iron hydroxide) that form on the surface and disrupt dissolution. A *Dissolution Efficiency* of less than 100% will increase the mass of limestone required in the VFP to compensate for the mass of limestone that is unlikely to dissolve. Users can specify the *Purity* and *Dissolution Efficiency* of limestone under the *Limestone* section, which is located under the *Layer Materials* subheading.

Limestone Mass to Neutralize Acid (tons) =

$$\frac{Design\ Flow\ (\text{gpm}) \times \frac{1\ \text{ft}^3}{7.48\ \text{gal}} \times \frac{525600\ \text{min}}{1\ \text{year}} \times Net\ Acidity \times \frac{1\ \text{lb}}{453592\ \text{mg}} \times \frac{28.3168\ \text{L}}{1\ \text{ft}^3} \times Neut.Period\ (\text{yrs}) \times \frac{1\ \text{ton}}{2000\ \text{lbs}}}{Purity\ (\%\ \text{CaCO}_3\ \text{by weight}) \times Dissolution\ Efficiency\ (\%)} \qquad \textbf{(4)}$$

The mass of limestone required to retain the water for a specified time (*Retention Time*) is added to the mass of limestone required to neutralize the acidity loading for the *Neutralization Period* to determine the total mass of limestone required for the VFP limestone layer (Equation 5). This method ensures the user-specified *Retention Time* is preserved, to generate maximum alkalinity, at the end of the user-specified *Neutralization Period* when the limestone mass dedicated to neutralizing the acidity load is nearly depleted.

Total mass of limestone (Bureau of Mines method) =

$$\text{Retention Time Limestone mass (Eq. 3)} + \text{Limestone mass, neutralization (Eq. 4)} \qquad \textbf{(5)}$$

See Section 3.2.2.7 to 3.2.2.9 for volume calculations for the other layers.

3.2.2.3 Alkalinity Generation Rate - This method calculates the mass of limestone required based on an expected rate of alkalinity production, or acidity neutralization, per area of limestone. Since the limestone depth in VFPs 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) by evaluating 29 operating VFPs and identifying a relationship between effluent net alkalinity and influent acidity (raw mine drainage) loading per unit area. Dr. Rose suggested a design guideline for the alkalinity generation rate (or acidity neutralization rate) of 25 grams of influent acidity/m^2 of limestone surface area/day.

AMDTreat calculates the mass of limestone by dividing the daily influent acidity load (gal/day) by the user-specified *Alkalinity Generation Rate* ($g/m^2/day$) to calculate the limestone surface area requirement (Equation 6). The surface area is multiplied by the user-specified limestone layer depth to determine the volume required in the limestone layer (Equation 7). AMDTreat uses the user-specified porosity of the limestone material to determine the bulk density of loosely placed limestone. The limestone layer volume is multiplied by the bulk density to calculate the mass of limestone required, as shown in Equation 3.

Limestone Surface Area (ft^2) =

$$\frac{\text{Daily influent acidity load } (\frac{g}{day})}{\text{Alkalinity generation rate } (\frac{g}{m^2}/d)} \times \frac{10.7639 \text{ ft}^2}{1 \text{ m}^2} \qquad \textbf{(6)}$$

Limestone Volume (ft^3) = Limestone Surface Area (ft^2) x Limestone Layer Depth (ft) **(7)**

See Section 3.2.2.7 to 3.2.2.9 for volume calculations for the other layers.

3.2.2.5 User-Specified Limestone Quantity (tons) - If users have their own method for determining the mass of limestone, the User-Specified Limestone method can be used to calculate the dimensions of the limestone layer and remaining layers of the VFP. The mass of limestone is entered, and the user-specified porosity value for the limestone layer is used to calculate the volume and retention time of the limestone layer. See Section 3.2.2.7 for volume calculations for the other layers.

3.2.2.6 User-Specified Dimensions - Mine drainage discharges often emerge at the base of hillsides. The available land area, between the point of emergence and the receiving stream, for constructing a treatment system is normally limited. The use of other sizing methods may produce a VFP size that is larger than the available land area. A smaller VFP can be designed for the site, but it will most likely require more maintenance and prematurely plug due to higher metal loading per unit area/volume. To use the freeboard sizing method, enter the top length and width of the freeboard. AMDTreat then uses the user-specified side slopes and depths to calculate the dimensions and volumes of the VFP layers.

Volumetric Calculations

3.2.2.7 Volumetric Calculations – AMDTreat models all passive treatment systems, including VFPs, 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, compost mix layer, limestone 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.

3.2.2.8 Calculations for Retention Time, Bureau of Mines, Alkalinity Generation Rate, and User-Specified Limestone Sizing Methods – The equation for an inverted trapezoidal prism is:

$$V = \left(\frac{W_T L_T + W_B L_B}{2}\right) D \quad (8)$$

<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 limestone layer. Therefore, AMDTreat calculates the volume of the limestone layer and users are required to specify the depth of the limestone layer, inside slope, and length-to-width ratio for the bottom of the limestone layer. The unknowns are the length and width of the top and bottom dimensions of the trapezoidal prism for the limestone layer. Since the depth and inside side slope of the VFP is known, the top width and length of the limestone 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 limestone layer. The resultant equation is a quadratic:

$$L_{BLL} = \frac{-\left(\frac{2DR}{S} + \frac{2D}{S}\right) \pm \sqrt{\left(\frac{2DR}{S} + \frac{2D}{S}\right)^2 - 4(2R)\left(\frac{4D^2}{S^2} - \frac{2V}{D}\right)}}{2(2R)} \quad (9)$$

<u>Where:</u>
V = Volume of Limestone Layer
L_{BLL} = Bottom Length of Limestone Layer
D = Depth of Limestone Layer
S = Inside Side Slope of Vertical Flow Pond
R = Length to Width Ratio of Bottom of Limestone Layer

Once the bottom length is known, the bottom width of the limestone layer (W_{BWL}) is calculated by dividing the bottom length by the user-specified value for length-to-width ratio for bottom of the Vertical Flow Pond:

$$W_{BWL} = \frac{L_{BLL}}{R} \quad (10)$$

NOTE: AMDTreat will produce an error message if the calculated Bottom Width is less than 10 ft. See Section 3.4 for additional information.

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

The top length of the limestone layer is calculated by:

$$L_{TLL} = L_{BLL} + 2 * S * (D_{LL}) \quad (11)$$

Where:
L_{TLL} =*Top Length of Limestone Layer*
L_{BLL} = *Bottom Length of Limestone Layer*
D_{LL} = *Depth of Limestone Layer*
S =Inside Side Slope of Vertical Flow Pond (rise/run)

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

Compost Mix Layer
The bottom length of the compost mix layer (L_{BCML}) is equal to the top length of the limestone layer (L_{TLL}).

$$L_{BCML} = L_{TLL} \quad (12)$$

The top length of the compost mix layer (L_{TCML}) is calculated by:

$$L_{TCML} = L_{BCML} + 2 * S * (D_{CML}) \quad (13)$$

Where:
S =Inside Side Slope of Vertical Flow Pond (rise/run)
D_{CML} = *Depth of Compost Mix Layer*

Equation (8) is used to calculate the volume of the compost mix layer.

Water Layer
The bottom length of the water layer (L_{BWL}) is equal to the top length of the compost mix layer (L_{TCML}).

$$L_{BWL} = L_{TCML} \quad (14)$$

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

$$L_{TWL} = L_{BWL} + 2 * S * (D_{WL}) \quad (15)$$

Where:
S =Inside Side Slope of Vertical Flow Pond (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 (8) is used to calculate volume of the water layer.

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

$$L_{BFL} = L_{TWL} \quad (16)$$

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

$$L_{TFL} = L_{BFL} + 2 * S * (D_{FL}) \quad (17)$$

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

Equation (8) 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. Thus:

$$VFP\ Exavation\ Volume = Water\ Volume + Compost\ Mix\ Volume + Limestone\ Volume \quad (18)$$

3.2.2.9 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, compost mix, and limestone layer depths to calculate the dimensions and volumes of the individual layers of the VFP.

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

$$L_{BFL} = L_{TFL} - 2 * S * (D_{FL}) \quad (19)$$

Where:
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 VFP (Run/Rise)

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

NOTE: AMDTreat will produce an error message if the calculated Bottom Width is less than 10 ft. See Section 3.4 for additional information.

The volume of the freeboard layer is determined by:

$$V_{FL} = \left(\frac{W_{TFL}L_{TFL} + W_{BFL}L_{BFL}}{2}\right) D_{FL} \quad (20)$$

Where:
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
D = Depth of Freeboard Layer

Water Layer

The top length of the water layer (L_{TWL}) is equal to the bottom length of the freeboard layer (L_{BFL}).

$$L_{TWL} = L_{BFL} \quad (21)$$

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 (19) to calculate the bottom width and length of the water layer. Equation (20) is used to calculate the volume of the water layer.

Compost Mix and Limestone Layers
The same approached used to calculate the dimensions of the water layer are used to calculate these layers.

Lastly, the excavation volume is determined by adding the volumes for the water, compost mix, and limestone layers (Equation 18). 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 VFP.**

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., limestone, compost) to provide treatment for many years. For some passive systems, such as VFPs, 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 system. 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 VFP or to flush the system in order to remove metal hydroxide precipitates that accumulate in the limestone layer. The *Layer Materials* section is where users can control the depth and other characteristics of the materials used in the various VFP layers.

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 most passive systems, the influent to the VFP is within or at the top of the freeboard layer. An emergency spillway is incorporated into the freeboard layer just below the influent elevation to prevent the restriction of water flowing into the VFP and to prevent water from overtopping the embankment. The bottom of the freeboard layer is the top of the water layer for the VFP. A typical freeboard layer depth is between 1.0 and 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 VFP. 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 is manipulated to control the growth of aquatic plants that may occur in VFPs. A typical water layer depth is between 1.0 and 2.0 feet.

3.2.4.3 Compost Mix Layer: The compost mix layer is used to control the redox potential as described in the Application and Treatment Chemistry section located above. Users can specify the thickness, unit cost, and placement cost of compost in the Compost Mix Layer section. Users can also allow limestone fines to be mixed with the compost to increase pH and promote aluminum precipitation. Limestone fines are commonly specified to comprise roughly 10 to 25% by volume of the compost mixt layer. A typical compost mix layer depth is between 1.0 and 2.0 feet. Thickness less than 1.0 ft may not create a chemically reducing environment and thickness greater than 2.0 feet may compact and cause permeability issues.

3.2.4.5 Limestone Layer: The limestone layer is the main source of alkalinity generation in a VFP. Users can specify the depth, purity, dissolution efficiency, porosity and unit cost for both the material and placement of limestone in this section. A typical limestone depth is 3.0 feet and limestone used in passive treatment systems such as VFPs normally have purity greater than 85% calcium carbonate ($CaCO_3$) by weight. The dissolution efficiency is used to compensate for limestone losing surface area and becoming less reactive as it dissolves/weathers and as a safety factor for additional limestone to compensate for potential plugging issues.

3.2.4.6 Pipe Layer: The pipe layer considers the piping required between the limestone and liner layers necessary to force the water to flow vertically through the treatment media, collect the water and discharge it out of the VFP. The VFP module offers users two methods to estimate the cost to purchase and install an effluent piping network, the **AMDTreat Piping Calculator** or **User-Specified Piping Layout**.

The default design of the **AMDTreat Piping Calculator** assumes a large-diameter “trunk” of solid pipe that extends along the middle of the limestone layer bottom length (Figures 3 & 5). “Spur” pipes are typically smaller diameter pipes that extend perpendicular from the trunk pipe across the entire bottom width of the limestone layer. The spur pipes are perforated and are intended to evenly draw water downwards through the treatment media into the pipes and into the trunk pipe for discharge from the VFP. Users can specify the spacing between the spur pipes to promote an even flow distribution or to maximize flow velocity during flushing events to remove accumulated metal precipitates from the limestone layer.

Historically, designers have developed a wide variety of piping systems to accommodate the hydraulic functionality of VFPs. In many instances piping systems designed to flush the limestone layer are physically separated from the primary discharge flow pipe network (Figures 14 & 15). Additionally, some designers have incorporated zonal flush pipe systems which allow for flushing metal precipitates in areas of the limestone bed that are most susceptible to plugging, such as the area of the bed nearest the influent and at the top of the Limestone Layer (Figure 16). Users that desire to customize their piping design can select **User-Specified Piping Layout** and specify the size and length of trunk and spur pipes.

3.2.4.7 Liner Layer: Many mine sites lack the soil characteristics required to prevent a leaky passive treatment system. AMDTreat offers three types of liner systems that prevent water from leaking from the impoundment, including Clay, Synthetic (i.e. PVC), and Geosynthetic Clay liners. The volume of clay required is calculated from the entire inside sloped area of the pond, from the top of freeboard to the base of the limestone (bottom of pond), plus the bottom area of the VFP and multiplying it by the user-specified thickness (typically 0.5 to 1.0 foot) and unit cost to purchase and install the clay liner. The area required for Synthetic or Geosynthetic Clay liners is determined by calculating the inside sloped area and the bottom area of the VFP similar to the clay liner and adding an additional 2.0 ft of length on all sides to accommodate the incorporation 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 Geo-Synthetic Clay liner from the excavated material inside the surface of the pond and/or the limestone layer.

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 VFP.**

3.2.5.1 Valves: - Valves can be used at various locations in the piping network of passive treatment systems. They can be placed at the intake of a collection system, downflow of a flow splitting device to shut off flow to a cell during maintenance, or at the downstream end of a system to allow for flushing of the limestone layer. Other valve configurations are possible, depending on system design requirements, which vary due to designer's preference or water quality constraints. Valves can range from heavy duty stainless steel industrial models to lighter grade simple Polyvinyl Chloride (PVC) valves, again depending on system requirements, intended lifecycle, and designer's preference. The cost of the valves can vary greatly depending on the materials used for construction and intended duty cycle.

3.2.5.2 Intake Structures: Various methods of intake systems are used in passive treatment system design. Deep mine discharges with intact wet seals can be collected with simple pipe connections or open top structures to allow for inspection and cleanout. In cases where there is no pipe discharging from a deep mine, custom intakes need to be designed based on site constraints, water quality and flow to collect the deep mine discharge and connect it to a conveyance pipe or open channel leading to a flow splitting device or treatment system. Surface discharges or seeps can be collected with subsurface drainage infrastructure (French drains) or open top devices such as catch basins with appropriately designed openings. Stream intakes are typically designed to capture base design flows while allowing stormwater flows to bypass the intake, assuming the surface discharge is diluted with non-AMD stormwater runoff. These types of intakes typically consist of concrete boxes or weirs with pipe openings to convey the base flow to a flow splitter or treatment system. There are many options available to capture water for treatment, and designers should select an alternative that fits the discharge and does not create an undue maintenance burden. Depending on water chemistry, any concrete used in intake structures must be coated inside and out with a heavy-duty epoxy paint or other suitable coating to prevent dissolution of the concrete from acidic conditions. An example of an open-top concrete intake structure is shown in Figure 19 at the end of this document.

3.2.5.3 Flow Distribution: Many passive treatment systems include multiple treatment cells or bypasses that require that the flow is split into multiple parts. Flow can be split with concrete structures or by large diameter pipes with multiple outlets. As mentioned in the Intake structure section, depending on water chemistry, any concrete used in intake structures must be coated inside and out with a heavy-duty epoxy paint or other suitable coating to prevent dissolution of the concrete from acidic conditions. Sample Flow Distribution Structures are shown in Figures 17, 18, 20 & 21.

3.2.5.1 Water Level Control Structures: Water level control structures are exactly as the name implies, a structure or series of structures used to control the level of water within the treatment component. Typically, the structure allows for the adjustment or manipulation of the water level for various reasons such as the need for greater head pressure to force the water through the treatment materials and outlet piping or lowering of the water level for maintenance. Common water level outlet structures may include a PVC box-like structure with removable stop logs (Figures 22 & 23) or vertical standpipes with Fernco fittings (Figure 16) both of which are installed in the downstream embankment and hydraulically connected to the piping layer within the treatment component and the effluent pipe for discharge to the subsequent treatment component.

3.2.5.1 Outlet Protection Structures: These are typically rip-rap structures constructed in a trapezoidal shape, which are at the outlet of the effluent pipe from the water level control structure and the inflow to the next downstream treatment component. The purpose of these structures is to dissipate the energy generated by the gravity flow of water downslope in the effluent pipe from a water level control structure and prevent scouring/erosion at the point of discharge. A secondary benefit of the outlet protection structures is the potential to add dissolved oxygen into the water as it is agitated from striking the rip-rap material. It is important that an outlet protection structure be properly designed to provide the most appropriate rip-rap size (stone size) and the actual dimensions of the structure. Refer to Figure 24 for a photo of an outlet protection structure situated at the pipe discharge from a water level control structure.

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 mass of limestone required for the limestone layer is provided on the right side of the Sizing Summary heading.

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 VFP.

3.3.3 Annual Cost: Since a VFP is a passive treatment system component, the only annual cost considered is the cost for maintenance. Annual costs, such as sampling, labor, and snow removal are "project-wide" costs since they apply to an entire treatment site, not each individual treatment component. Sampling, Labor, and Site Development (i.e. Clearing/Grubbing/Revegetation) modules are located under the "Project Modules" section of the main user interface and capture these types of annual costs.

Annual maintenance costs for VFPs include periodic "flushing" of the piping network to evacuate metal hydroxide precipitates from the limestone layer, maintaining clear influent and effluent piping, and manipulating the water level control structure (e.g. Agri Drain) to change the water level in the VFP. It is assumed that some years will not require the full amount of funds set aside for maintenance, but funds will eventually be used over the system life. Users can estimate the annual maintenance costs by assuming a percentage of the capital cost (the more expensive the system, the more expensive the maintenance) or specify an 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.

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

- Inflation Rate: 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.

- Rate of Return: 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 22). 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.

Cost to rebuild pump motor in 20 years =

$Present\ Day\ Cost \times (100\% + Inflation\ Rate)^{20}$ = \$20,000 × (100% + 5%)^{20} = \$53,065 **(22)**

Cost to rebuild pump motor in twenty years is equal to present day cost multiplied by parentheses one hundred percent plus inflation rate close parentheses to the power of twenty.

- 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 VFP. 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.

Limestone: The limestone can require maintenance and periodic partial replacement. Limestone becomes clogged with metal precipitate as the compost mix effectiveness decreases. Therefore, the default recommendation in AMDTreat is to replace 50% of the limestone every 10 years. The limestone replacement would likely be completed at the same time the Compost Mix is replaced.

Compost Mix: A portion of the Compost Mix may need to be replaced as it becomes less effective producing anaerobic conditions. Based on the historical experience of maintaining VFPs, AMDTreat recommends planning to replace 50% of the Compost every 10 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 Limestone and/or Compost Mix is being replaced. The default assumption is to replace 50% of the Compost every 10 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 25 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 Error Messages

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 assumptions that follow are important for the VFP module.

1. The VFP is assumed to be constructed on a flat surface, where the water, compost, and limestone layers are excavated at or below the existing or original ground. A portion of that material is used to construct the freeboard embankments which are considered fill material above the existing or original ground (see Figure 2). The program assumes an on-site balance of cut and fill material. However, if this is not the case, the user can modify excavation cost default values to reflect the anticipated conditions.

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

3. AMDTreat requires the bottom length of the VFP must be equal to or lager than the Bottom Width. In addition, AMDTreat will produce an error message if the input values create a Bottom Width less than 10 ft. The error message notifies users they must change the Design Flow rate, values associated with the selected sizing methodology (e.g. retention time), the inside slope of the VFP or the depths associated with any of the layers. In most cases, users will focus on decreasing the depth of one of the layers to eliminate the error. AMDTreat assumes a VFP with a Bottom Width of less than 10 ft is not practical to construct.

4. None of the sizing methods provide a "design life" that properly accounts for both: a) the amount of limestone required to neutralize the acidity loading for a defined time frame, and b) hydraulic and treatment issues caused by the accumulation of metal hydroxide precipitates within the void spaces of the treatment media. Some sizing methods, such as the *Bureau of Mines*, account for reagent requirements. Others, like the *Alkalinity Generation Rate*, indirectly try to address plugging issues by controlling the metal loading applied to a unit surface area.

5. In general, the goal of the VFP sizing methods is to provide an estimate of the mass of limestone required to generate net alkaline conditions. None of the sizing methods are based on achieving effluent water quality criteria or requirements. That said, a properly sized VFP treatment system should generate pH > 6.0 and be net alkaline, which will decrease aluminum and ferric iron solubility to less than 1.0 mg/L. Some VFPs discharge ferrous iron as they are designed to promote ferrous iron solubility within the compost mix layer and virtually all VFPs will not affect dissolved manganese concentrations.

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

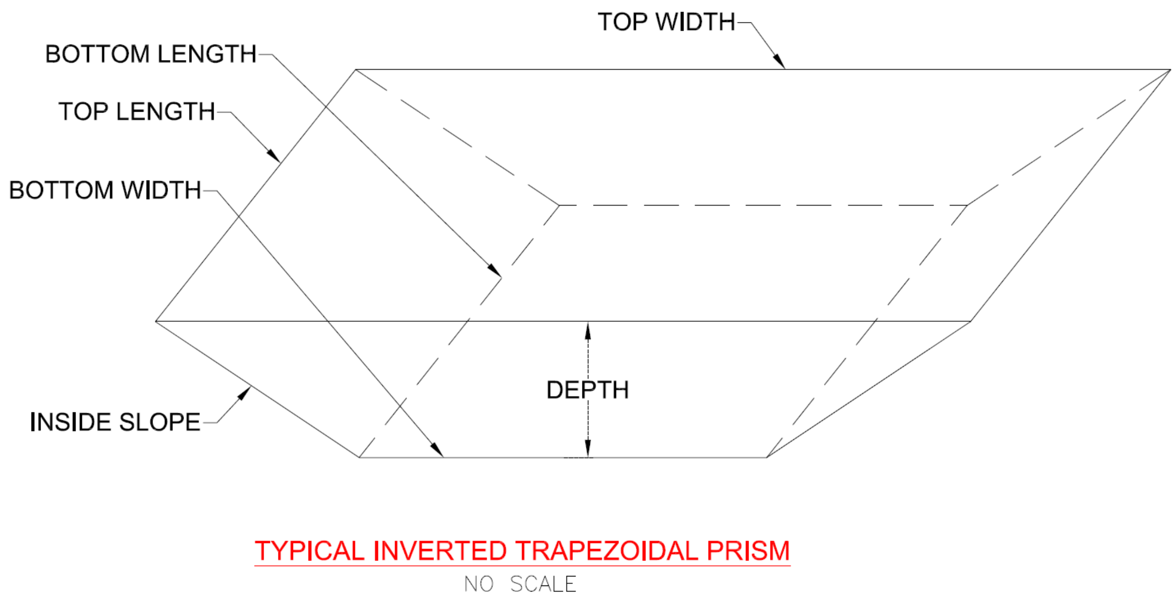

Figure 1: Typical Inverted Trapezoidal Prism

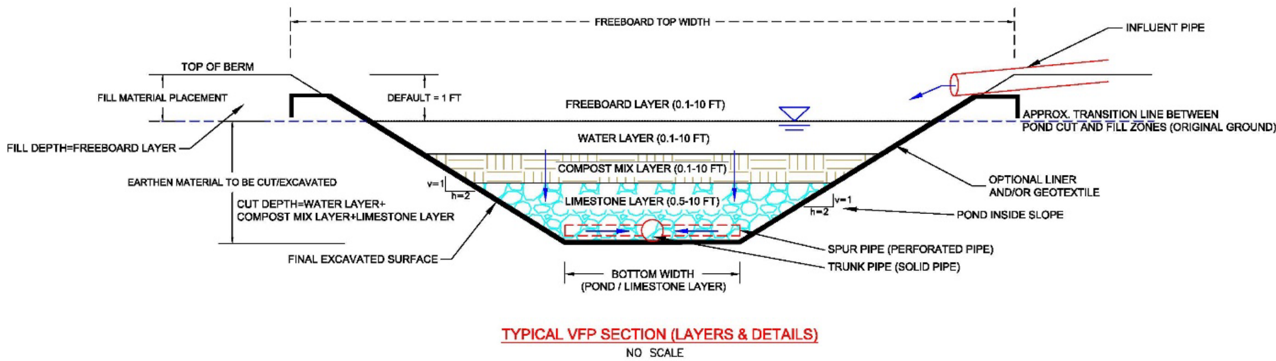

Figure 2: Typical Cross Section View of a Vertical Flow Pond (VFP) Showing the Common Layers and Components

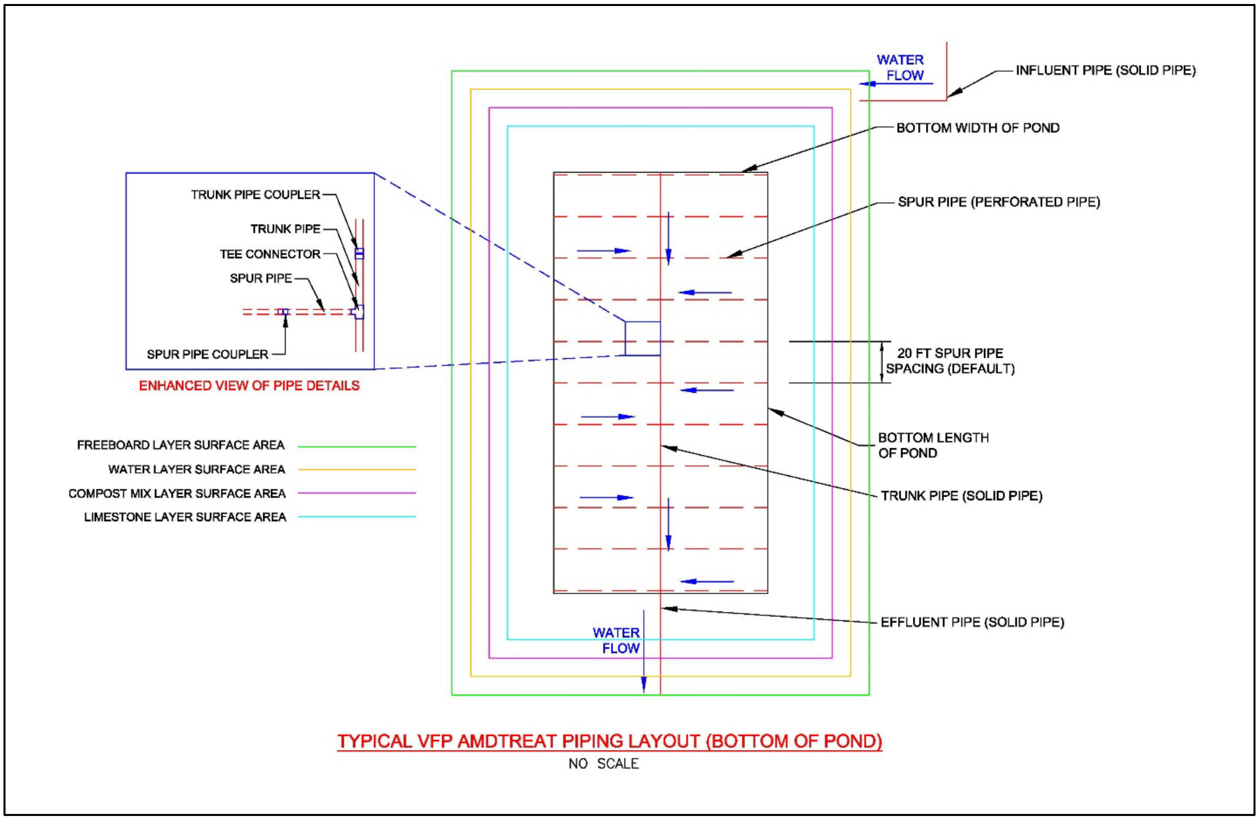

Figure 3: Plan View of the Vertical Flow Pond (VFP) to Illustrate Common Piping Layout and Components (Used in AMDTreat Piping Calculator) and the Layer Surface Areas

Figure 4: Installation of a clay liner during the construction of a VFP.

Figure 5: Excavator carefully covering the underdrain piping network (used for discharge and flushing) with limestone in preparation to construct a 3.0 ft thick limestone layer. A 1.5 ft thick compost layer will follow to finish the VFP. The excavator is covering a "spur" pipe. The spur pipes are connected to the larger "trunk" pipe oriented parallel to the bed. This is the type of piping configuration modeled in AMDTreat.

Figure 6: Constructed VFP after installation of compost layer. Vertical pipes are connected to underdrain system and used to maintenance underdrain pipes if clogging occurs. Clean out pipes are no longer typically used.

Figure 7: Newly constructed vertical flow pond. Inlet water control structure is shown. The reddish tint to the water in the background is due to low pH iron oxidation occurring on the top of the compost layer. Raw water pH is 2.8.

Figure 8. Two 2.5-acre vertical flow ponds flowing into a polishing wetland. Note the instream precipitation of metals caused by the alkaline effluent mixing with the acidic receiving stream.

Figure 9. Photo showing the path of a F3 Tornado that pasted directly over a VFP treatment system. No damage to the VFP was caused by the Tornado.

Figure 10. Photo showing the top of the Limestone Layer in a VFP after the compost layer was removed to perform an autopsy to identify the cause of failure. The 6 inch thick compost was insufficient to provide the retention time required to fully reduce the large ferric iron load to ferrous iron. Thus, the ferric iron oxidized and precipitated within the porosity of the limestone layer causing hydraulic failure. After this event, VFPs were designed with 12 to 18” of compost.

Figure 11. Close up photo of the 1.5 ft cross section of the Limestone Layer after removal of a thin and ineffective Compost Layer. Note the ½” layer of iron hydroxide on top of the Limestone Layer that caused hydraulic failure. In addition, iron hydroxide precipitate filled the void space within the 1 to 2” limestone fragments.

Figure 12. Rhodamine dye test to identify area where short circuiting is occurring. Dye was detected in the VFP effluent after 30 mins and the spread of the dye shown in photo remained constant for 8 hours indicating the location of the short circuit. This area was excavated and carefully rebuilt to eliminate the short circuit caused by poor construction practices.

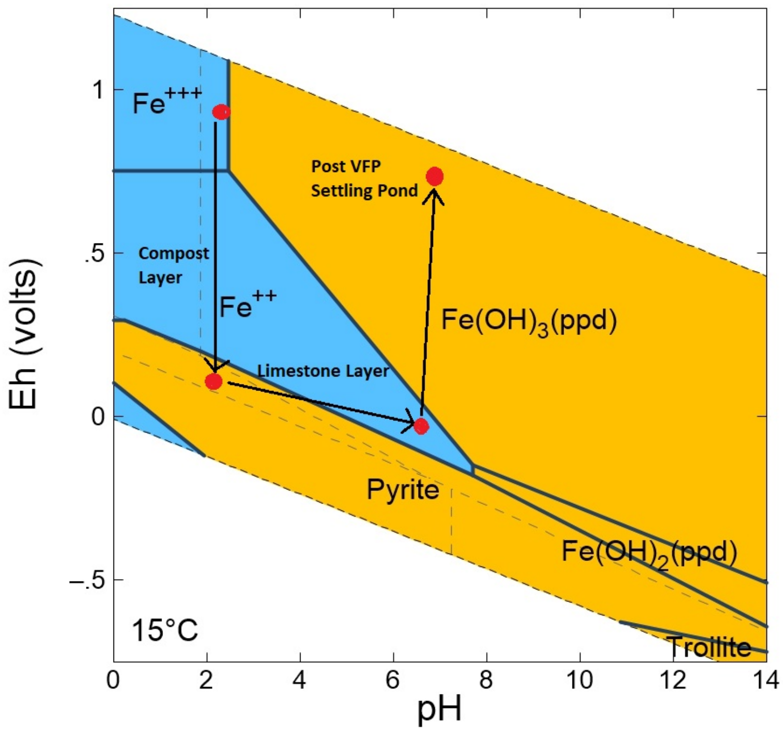

Figure 13. Pourbaix diagram of the iron-sulfur system to help explain how the different layers in a VFP control the iron/sulfur geochemistry. The top left red circle represents the Eh/pH condition of the raw water that is dominated by ferric iron. As the water flows through the compost layer, the Eh decreases along the vertical black line and the Eh/pH condition may stabilize in the pyrite stability field denoted by the red circle at the bottom left. As the Eh lowers, ferric iron to ferrous iron and sulfate is reduced to sulfide and iron sulfide (pyrite) can form in the compost. If limestone fines are added to the compost the vertical line may be more diagonal to represent an increase in pH. The water then enters the limestone layer and the residual ferrous iron remains soluble as limestone dissolves and increases the pH. The horizontal black line represents the evolution of the Eh/pH condition as water travels though the limestone layer. Lastly, water is discharged from the VFP through a pipe and splashes on the ground before flowing to a settling pond. The increase in dissolved Oxygen increases the Eh condition and causes the remaining ferrous iron to oxidize and precipitate as Fe(OH)3.

Figure 14. Whiteish aluminum hydroxide sludge accumulating within the Limestone layer due to the increase in pH. Note the flush pipe had little effect on preserving the porosity near the pipe.

Figure 15. Gentleman on right turning a flush valve to flush a VFP. Note the flushing of the whiteish aluminum hydroxide precipitate.

Figure 16. Zonal Piping system. The smaller diameter pipes on the left are located at the top of the Limestone layer. Note the ferric hydroxide precipitate accumulated at the base of the pipe. Ferric iron not reduced in the compost layer precipitates at the top of the Limestone Layer as the pH is increased to > 4.0 and ferric iron becomes insoluble. The pipes on the right are at the base of the Limestone layer where the pH is increased to 6 and aluminum becomes high insoluble. Note the accumulation of the whitish aluminum hydroxide precipitate.

Figure 17. Flow distribution structure. A discharge is piped to the structure and the flow is distributed between three pipes that flow to three VFPs arranged in parallel.

Figure 18. Inside view of Flow distribution structure. The untreated discharge enters through the bottom pipe and is distributed between the top three pipes that feed three VFPs in parallel.

Figure 19 – Open Top Intake Structure with Weir. Water level is controlled by weir and baseflow is forced to flow through trashrack and into the intake structure.

Figure 20 – Flow Splitter Box Prior to Installation. Pipe Gaskets are cast in place in precast yard.

Figure 21 – Flow Splitter Box Installed with Orifice Plate to regulate Flow and Bypass Pipe to prevent Hydraulic Overloading of Treatment Cell

Figure 22 – Photo of Water Control Structure (Agri Drain brand) being installed into an embankment. The water control structure is placed inside a corrugated pipe to protect against soil pressure. Without protection, the box could deform and prevent operators from being able to adjust stop logs to control water level. Stop logs are removed and shown to the right of the corrugated pipe.

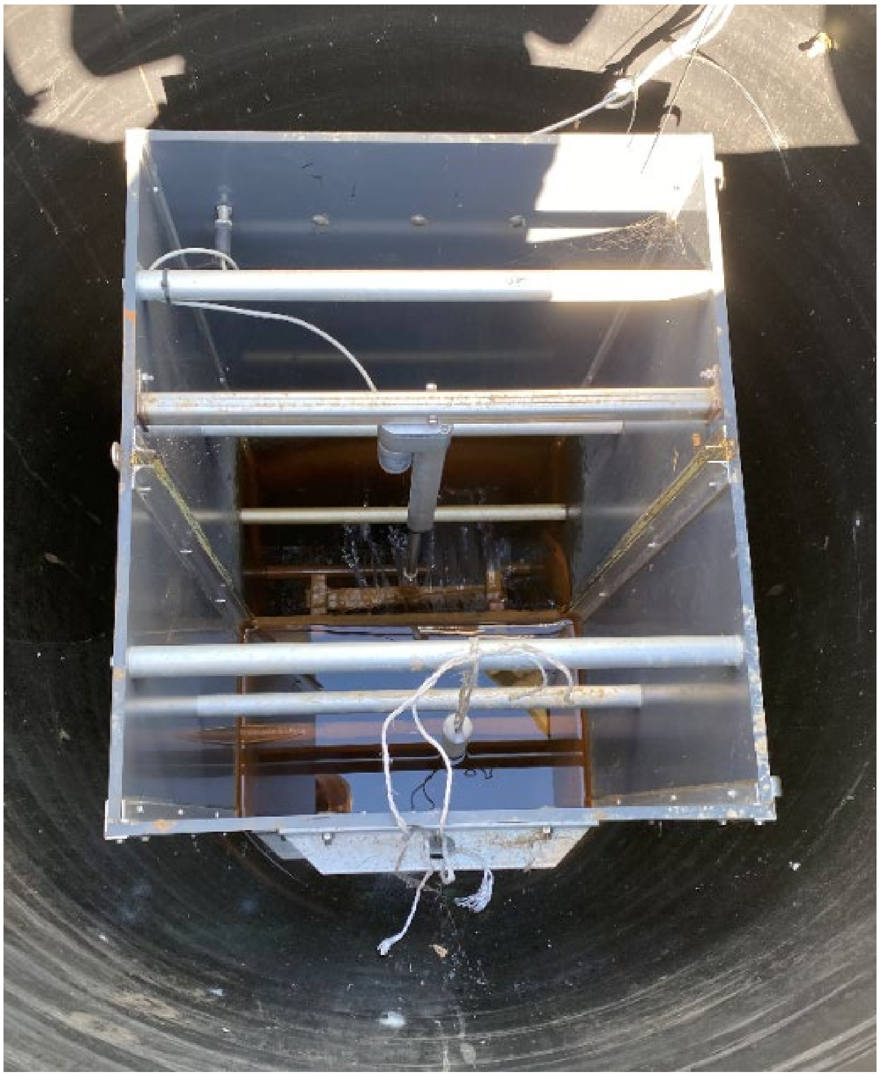

Figure 23 – Looking down into an Agri Drain water control structure. Note the water flowing overtop of the stop logs, which set the water elevation in the VFP. Additional stop logs can be placed into the metal channels in the center of the box to increase the water elevation.

Figure 24 – Outlet protection structure designed to prevent channel erosion