Help Instruction File:

Manganese Removal Bed 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).

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1.0 Objective

A Manganese Removal Bed (MRB) is a passive treatment system component that is typically used to treat pH > 6.0 mine drainage void of dissolved iron and suspended solids. MRBs have successfully treated discharges with flow rates greater than 500 gpm when using the aforementioned criteria. Some MRBs have consistently removed manganese to less than 0.1 mg/L and achieved NPDES standards for manganese for over twenty years with minimal maintenance.

The objective of this overview is to: 1. Provide a basic understanding of the theory and application of Manganese Removal Beds (MRB) and 2. Provide an overview of the module that guides users to develop a cost estimate to construct, operate, and maintain MRBs for treating mine drainage. Therefore, this overview will be presented in two sections, **Treatment Component** and **MRB Module Overviews**.

2.0 Treatment Component Overview

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

2.1 Physical and Hydraulic Description

The geometric shape of a MRB is an inverted trapezoidal prism consisting of two or three distinct "layer materials" (Figures 1 and 2). MRBs always have a limestone and freeboard layer but may or may not have a liner layer depending on the quality of the soil. Physically, MRBs differ from limestone beds in three distinct ways: 1) lack of a water layer, 2) flow configuration is always horizontal, and 3) the stone size is often smaller for greater surface area. They lack a water layer (some LBs also lack a water layer) to force all the water to be in contact with the manganese-coated limestone surfaces to promote the autocatalytic reaction between dissolved and solid manganese. A horizontal flow bed with a water layer would result in water flowing across the top of the bed minimizing contact with the limestone. In addition, horizontal flow is preferred to maintain oxic conditions. Vertical flow treatment components (e.g., VFP) are limited to the dissolved oxygen concentration at the point water enters the limestone and a low dissolved oxygen concentration may be rate limiting for waters containing Mn^{2+} greater than 27 mg/L. Thus, it is common practice to use horizontal flow and install alternating vertical baffles (downflow followed by an up-flow baffle) within the limestone layer to force water near the surface for oxygen replenishment (Figure 3). Alternatively, trenches within the limestone bed can be installed perpendicular to horizontal flow across the width of the MRB to create a short channel of open water for oxygen in-gassing (Figure 4). Since the application of MRBs is limited to water void of suspended solids, ferric and ferrous iron, and aluminum, smaller stone size (3/4" to 1.5", which is equivalent to an AASHTO #5) is often used to increase the surface area for microbial growth and manganese oxide coatings.

In many cases, an open ditch or a single pipe is used to direct water into the MRB (Figure 3) and header pipe is often used at the end of the bed to collect water for discharge out of the MRB. However, MRBs are also constructed with a header pipe at the influent to help distribute flow and, at times, a single pipe or ditch is used to control the effluent and water level. The combination of the long retention time and long flow path lessens the focus on designing elaborate influent and effluent piping systems to control flow distribution. In addition, the precipitated manganese oxides are not a low-density floc that spontaneously nucleates in the water column and settles in the porosity (void space) like iron and aluminum hydroxides. But rather, manganese oxides are a mineral scale that grows on the surface of the limestone (Figure 5). Thus, MRBs are not fitted with flush pipes, but instead use mechanical excavators periodically to breakup portions of the bed that are completely scaled shut, which is typically near the influent end of the MRB where manganese oxides concentrate and removal rates are highest.

Figures 6, 7, and 8 provide a visual description of properly functioning MRBs and Figure 8 shows the issues with installing MRBs on water containing dissolved iron.

2.2 Application and Treatment Chemistry

A Manganese Removal Bed (MRB) is a type of "passive" treatment system component used to treat 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-alkaline mine drainage describes solutions that contain more acid-consuming than acid-producing species. MRBs are often placed at the end of a treatment "train" or system after the water has turned net alkaline and is void of any solids and dissolved aluminum, iron, or any other species that will precipitate and clog the bed. MRBs are physically similar to ALDs but are not buried. Thus, they may have a small cross-sectional surface area perpendicular to flow and will easily plug if placed on mine drainage that either contains sediment/solids or will produce solids through the precipitation of metals when in contact with the limestone. It is good practice to limit the application of MRBs to net alkaline water containing dissolved manganese to avoid potential hydraulic issues caused by solids/sedimentation.

Theoretically, the dominate form of manganese in water under reducing conditions is an aqueous form until a pH of 10.0. The dominate form of manganese in oxic conditions is a precipitate at pH greater than 3.0; however, abiotic oxidation is very slow until pH > 9.0 (Figure 9).

MRBs show strong manganese removal when pH is > 6.0. The exact manganese removal mechanism(s) is poorly understood but appears to have both abiotic and biotic components. Many studies have shown biotic mechanisms are important for manganese oxidization at circumneutral pH involving bacteria, fungi, and algae that appear to mediate removal. Laboratory studies show a decrease or cessation of manganese oxidation when fungicides, radiation, or other biological neutralizers are added to samples obtained from MRBs. Some designers have paid for MRBs to initially and periodically be inoculated with manganese-oxidizing bacteria and other biological catalysts, however, the vast majority of existing MRBs have never been inoculated and achieve consistent manganese removal. The abiotic manganese removal mechanism relates to adsorption of dissolved manganese to manganese oxides, which effectively sequesters manganese as a form of treatment where it can be eventually oxidized and precipitated as an oxide. Analysis of scale precipitate in MRBs revealed the presence of manganese oxides Birnessite and Todorokite. Again, manganese oxide precipitate in MRBs is not a floc but rather a mineral scale that will cement individual pieces of limestone together causing hydraulic/plugging issues. However, it may take over a decade to experience hydraulic issues due to scaling in a properly sized MRB and they can easily be rehabilitated by using an excavator to break up the scale by stirring and cleaning the limestone and re-establish the diffuse horizontal flow pattern.

Some MRBs have been successfully constructed using sandstone but most are constructed using limestone since the unit cost is similar in Northern Appalachia. The depth of the limestone layer should be no more than 4.0 ft and 2.0-2.5 ft is preferable. Excavation of MRBs show diminishing manganese-coated limestone on beds deeper than 3.0 ft and oxidation-reduction potential (ORP) readings support chemically reducing conditions. Beds constructed 6.0 ft deep lack any manganese precipitation near the bottom due to the reducing/anoxic conditions.

Since the exact manganese removal mechanisms are poorly understood, designs parameters for an MRB have not been optimized, however, in general the following guidelines are useful:

1. One-two days of hydraulic retention, although shorter times can be successful;
2. Horizontal flow,
3. Depth of stone layer < 4.0 ft,
4. ¾ to 1 ½-inch limestone diameter (AASHTO #5);
5. Use of hydraulic baffles (periodically force water to the limestone surface) and/or trenches to allow for reoxygenation of water; and
6. Use of limestone already coated with manganese oxide (from an existing MRB) in the beginning of a newly constructed MRB to propagate Mn removal or it can take up to six months to achieve effective and consistent manganese removal.

2.3 Manganese Removal Bed Conceptual Treatment Module

The following discussion presents a conceptual treatment model for MRBs treating low pH mine drainage containing elevated concentrations of aluminum and manganese and low concentrations of iron.

2.3.1 Freeboard Layer: The freeboard is designed to accommodate fluctuations in flow or increasing water elevation due to decreased permeability over time. It doesn't perform a specific purpose pertaining to geochemical treatment of the mine drainage

2.3.4 Limestone Layer: Net alkaline water entering the MRB will continue to react with limestone until equilibrium with calcite ($CaCO_3$) is achieved. While the top of the MRB is open to the atmosphere, gas exchange is limited to diffusion due to a lack of turbulence from laminar flow and protection from the wind within the MRB limestone layer. As a result, some MRBs maintain pH below 7.0 due to elevated carbon dioxide levels and other MRBs achieve pH as high as 7.7 if carbon dioxide can be effectively exsolved (off-gassed). Similarly, oxygen will diffuse into the top of the limestone layer to promote manganese oxidation but it may be beneficial to design two MRBs with a hydraulic drop in-between the two MRBs (operated in series) to facilitate effective oxygen transfer, as opposed to designing one large MRB that depends on diffusion, for water containing high manganese concentrations (e.g., Mn > 30 mg/L).

The rate equation for manganese oxidation shown below illustrates the dependence of concentration on the oxidation rate. Thus, most manganese removal occurs at the beginning and near the top of the MRB where oxygen concentrations are highest. Excavating areas of the limestone in numerous MRBs confirms the theory that limestone near the beginning and top of the bed is coated more than limestone near the middle or effluent portions of the MRB. Over time, the accumulation and growth of Birnessite scale (manganese oxide mineral) near the influent will reduce porosity and cause the water to flow on top of the limestone until an uncemented/unplugged portion of the MRB is encountered. Periodic agitation of the limestone with an excavator will be required to reestablish porosity and allow water to flow through the manganese oxide coated limestone to sustain removal.

$$\frac{d\mathrm{Mn}^{2+}}{d\mathrm{Time}} = \mathrm{k}_1[\mathrm{Mn}^{2+}][\mathrm{MnO}_2] - \mathrm{k}_2[\mathrm{Mn}^{2+}]\mathrm{C}_{bact}$$

3.0 Manganese Removal Bed Module Overview

3.1 Layout and Workflow

The general layout of the AMDTreat modules includes the left-hand side for user inputs and calculated outputs are on the right-hand side. 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 of the module is for users to start at the top left-hand side and enter the *Design Flow* and *Dissolved Manganese* concentration. The user then selects a sizing method to determine the amount of limestone contained in the MRB. Next, users specify design parameters, such as the depth of the water within the limestone (saturation depth) and depth of the limestone layers, and unit costs for items affecting the capital cost to construct the MRB. Finally, users can enter a capital cost not captured by the module into the Other Items section, which includes such items as valves, flow distribution structures, and water level control structures.

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 MRB 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 are 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 used 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 four different methods to size the Manganese Removal Bed: Retention Time, Kinetics, User-specified Limestone Quantity, and User-specified Dimensions. The module offers two different approaches to sizing MRBs. The first approach calculates the mass of limestone (tons) in the limestone layer before determining other dimensions. The Retention Time, Kinetics, 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 MRB. 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).

$$\textit{Volume Required for Water } (yd^3) = \textit{Design Flow} \text{ (gpm)} \times \frac{60 \text{ min}}{1 \text{ hr}} \times \textit{Retention Time} \text{ (hrs)} \times \frac{1 \text{ yd}^3}{201.974 \text{ gal}} \tag{1}$$

$$\text{Limestone Layer Volume (yd3)} = \frac{\text{Volume Required for Water (yd}^3)}{\text{Limestone Porosity (\%)}} \tag{2}$$

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.*

$$\textit{Limestone Mass (tons)} = \textit{Limestone Volume} \text{ (yd}^3) \times \frac{27 \text{ ft}^3}{1 \text{ yd}^3} \times \textit{Limestone Bulk Density} \left(\frac{\text{lbs}}{\text{ft}^3}\right) \times \frac{1 \text{ ton}}{2000 \text{ lbs}} \tag{3}$$

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 Kinetics - This sizing method calculates the mass of limestone needed based on the user selected rate constant value (k), desired manganese (Mn) effluent concentration from the MRB, stone gradation, void space (porosity), and the total and saturated limestone depths. Average surface area and volumes in the database are used for each stone gradation.

The rate constant (k1) used in the kinetics equation for MRBs consists of [$k_1 = 10^{-3.35}$ $hr^{-1}(m_s^2/m_v^3)^{-1}$], which was determined by Means & Rose (2005) based on manganese concentration vs retention time data for six treatment sites in Pennsylvania based on the surface area of limestone per cubic meter of limestone bed.

The kinetics equation consists of:

$$A = -0.276 * Q * \left(\frac{Log\left(\frac{Mn}{Mn_O}\right)}{(k_1 * S * D)}\right); \quad \textbf{(4)}$$

whereby A is surface area of the inundated (saturated) portion of MRB, Q is design flow, Mn is the effluent manganese concentration, Mn_o is the initial manganese concentration, k1 is a rate constant, S is the average surface area of a limestone particle (based on AASHTO size), D is the water saturation depth of limestone layer.

Effluent manganese concentration is the amount of dissolved manganese not removed that will be allowed to discharge from the MRB. The MRB is sized to remove the difference between the dissolved manganese concentration in the influent water and the MRB effluent.

3.2.2.3 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 MRB. 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.

3.2.2.4 User-Specified Dimensions - Mine drainage discharges often emerge at the base of hillsides. The available land area for constructing a treatment system between the point of emergence and the receiving stream can be limited. The use of other sizing methods may produce a MRB that is larger than the available land area. A smaller MRB can be designed for the site, but it will most likely require more maintenance and prematurely plug due to high metal loading per unit area/volume. Alternatively, a smaller MRB could be designed to treat only a portion of the mine drainage while bypassing the rest. 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 MRB layers.

Volumetric Calculations

3.2.2.5 Volumetric Calculations - AMDTreat models all passive treatment systems, including MRBs, 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, limestone layer, and liner layer. 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, or (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. The two approaches are provided below

3.2.2.6 Calculations for Retention Time, Kinetics, and User-Specified Limestone Sizing Methods –

The equation for an inverted trapezoidal prism is:

$$V = \left(\frac{W_T L_T + W_B L_B}{2}\right) D \quad \textbf{(5)}$$

Where:
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 MRB 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 (6) is rearranged to solve for the bottom length of the limestone layer. The resultant equation is a quadratic:

$$L_{BLL} = \frac{-\left(\frac{2DR}{S} + \frac{2D}{S}\right) \pm \sqrt{\left(\frac{2DR}{S} + \frac{2D}{S}\right)^2 - 4(2R)\left(\frac{4D^2}{S^2} - \frac{2V}{D}\right)}}{2(2R)} \quad \textbf{(6)}$$

Where:
V = Volume of Limestone Layer
L_{BLL} = Bottom Length of Limestone Layer
D = Depth of Limestone Layer
S = Inside Side Slope of MRB
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 MRB:

$$W_{BWL} = \frac{L_{BLL}}{R} \quad \textbf{(7)}$$

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:

$$L_{TLL} = L_{BLL} + 2 * S * (D_{LL}) \quad \textbf{(8)}$$

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 MRB (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 freeboard layer can be determined using a similar approach:

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

$$L_{BFL} = L_{TLL} \quad \textbf{(9)}$$

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

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

<u>Where:</u>
S =Inside Side Slope of MRB (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 the limestone layer volumes, except for the freeboard layer. It is assumed the freeboard layer is constructed with a portion of the excavated earth:

$$MRB\ Exavation\ Volume = Limestone\ Volume \quad \textbf{(11)}$$

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

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

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

<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 MRB (Run/Rise)

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

The volume of the freeboard layer is determined by:

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

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

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

$$L_{TLL} = L_{BFL} \quad \mathbf{(14)}$$

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

Lastly, the excavation volume is equal to the limestone layer (Equation 11). The model assumes that 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 specify the inside slope of the MRB, the limestone layer bottom length-to-width ratio, and the excavation unit cost.

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 treatment system components, such as MRBs, limestone is used 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 decreased permeability over time or plugging of layer materials from metal hydroxides or sediment. The pipe layer is located at the very bottom of the impoundment and is designed to transport water out of the MRB 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 MRB 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 within the limestone layer due to increased flow events or clogging of the treatment media. In most passive systems, the influent to the MRB 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 MRB and to prevent water from overtopping the embankment. The bottom of the freeboard layer is the top of the limestone layer for the MRB. A typical freeboard layer depth is between 1.0 and 3.0 feet.

3.2.4.2 Limestone Layer: The limestone layer is where manganese removal occurs in an MRB. Users can specify the depth, saturated depth (depth of limestone layer with water), porosity, stone gradation (four different AASHTO sizes), unit cost for both the material and placement of limestone in this section. If users plan to use another type of stone in the MRB, the unit cost and other variables can be adjusted. A typical limestone layer depth in an MRB is 2.0-3.0 feet.

3.2.4.3 Pipe Layer: Piping is necessary to distribute the water and promote flow horizontally through the treatment media and collect the water and discharge it out of the MRB. The MRB module offers users two methods to estimate the cost to purchase and install the piping network, the AMDTreat Piping Calculator or User-Specified Piping Layout. The AMDTreat Piping Calculator default piping layer for an MRB assumes the influent consists of a single pipe carrying mine drainage into the MRB that will connect to a perforated header pipe through a "tee" connector to distribute the flow across the top width of the limestone layer. The effluent pipe is assumed to be a perforated header pipe buried in the limestone layer at the downstream end that connects to a single pipe using a "tee" connector that transports the water through the embankment to a water level control structure and out of the MRB. Users that desire to customize their piping design can select User-Specified Piping Layout and specify the size and length of header or other pipes.

3.2.4.4 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 from leaking from the impoundment(s), including Clay, Synthetic (i.e. PVC), and Geosynthetic Clay (GCL) 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 MRB 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 Geosynthetic Clay liners is determined by calculating the inside sloped area and the bottom area of the MRB 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.

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 MRB component.**

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-hand 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 MRB component of the passive treatment system.

3.3.3 Annual Cost: Since an MRB 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 MRBs include periodic "flushing" of the limestone layer to evacuate accumulated metal hydroxide precipitates from the limestone 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 MRB 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 frame. 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 for the NPV calculation is to determine the financial investment required to pay for all future costs of the treatment system components.

- 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 (e.g., limestone).

- 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 motor component of the pump to be rebuilt every 20 years. Let's assume the present-day cost to purchase the pump is $500,000 and the cost to remove, rebuild, and reinstall the pump motor is only $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. In addition, let's 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 tell us the size of investment required to generate the income to pay for the future costs over 50 years.

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.

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

- 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 span 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 five recapitalization items for MRB. 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, mostly due to clogging from metal precipitate. Therefore, the default recommendation in AMDTreat is to replace 50% of the limestone 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 is being replaced. The default assumption is to replace 50% of the Limestone 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 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 MRB module.

1. The MRB is assumed to be constructed on a flat surface, where the water and limestone layers are excavated at or below the existing or original ground. A portion of the excavated material is then used to construct the freeboard embankments above the existing or original ground (see Figure 2). AMDTreat 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 based on the site characteristics.

2. The geometric shape of a MRB is an inverted trapezoidal prism (Figure 1). The volumetric equation for a trapezoidal prism is used to calculate the MRB layer volumes.

3. 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 *Alkalinity Generation Rate*, indirectly attempt to address plugging issues by controlling the metal loading applied to a unit surface area.

4. In general, the goal of the MRB sizing methods is to provide an estimate of the limestone mass required to generate net alkaline conditions. None of the sizing methods are based on achieving effluent water quality criteria or requirements. With that said, a properly sized MRB treatment system should generate pH > 6.0 and net alkaline water, which in theory will decrease aluminum and ferric 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

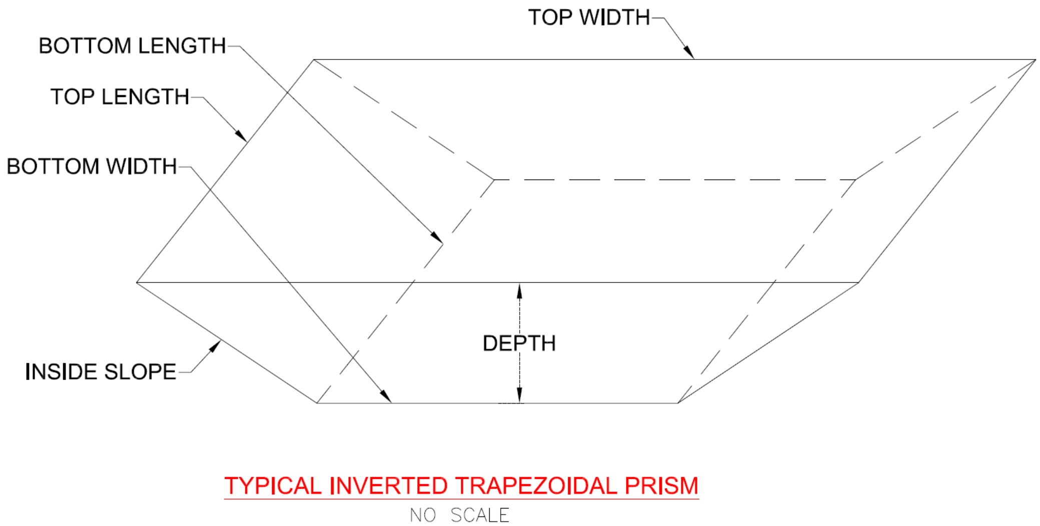

Figure 1: Typical Inverted Trapezoidal Prism

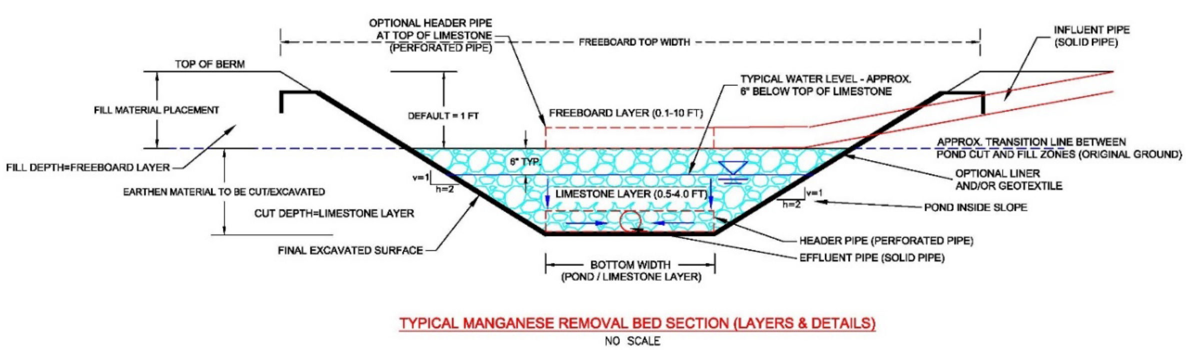

Figure 2: Typical Cross Section View of a Manganese Removal Bed (MRB).

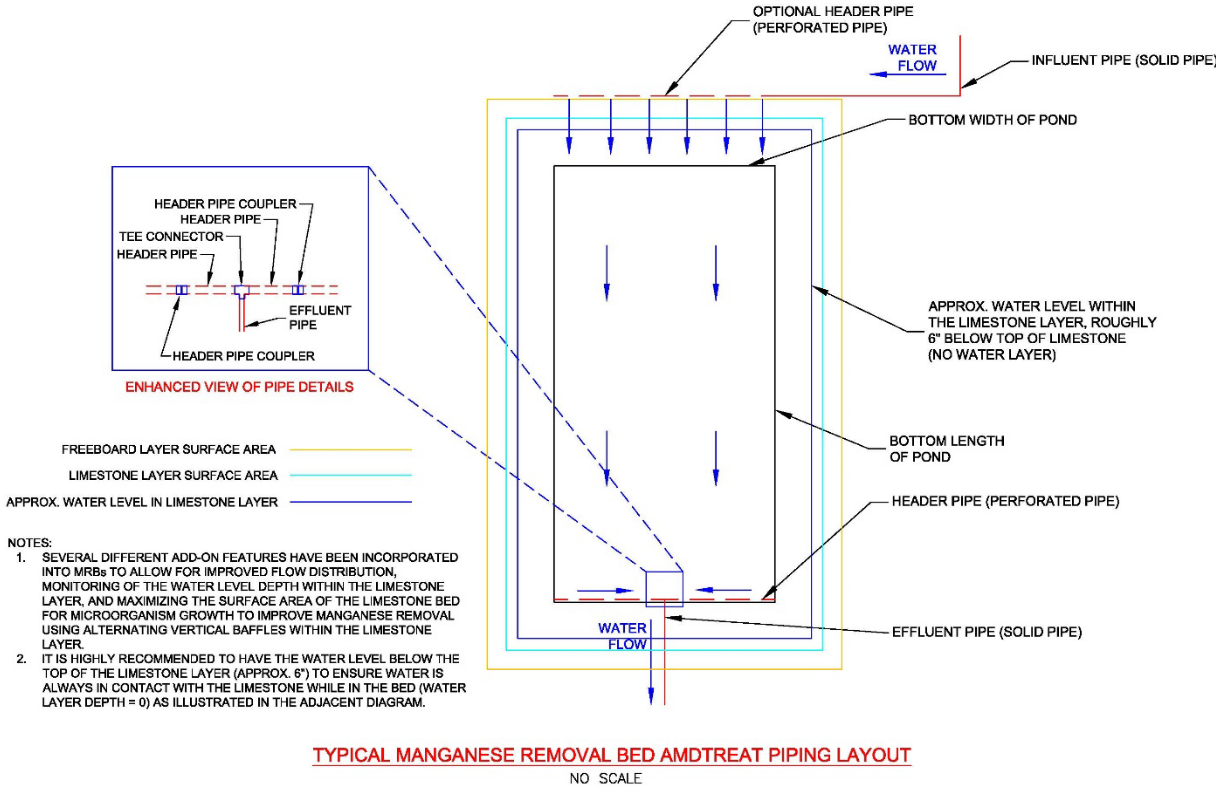

Figure 3: Diagram showing the default influent and effluent piping scheme used in AMDTreat for a MRB.

Figure 4: Manganese removal bed treating 60 gpm flow on the Flight 93 Memorial grounds near Somerset, Pa. The open-water trench is used to reoxygenate the water to facilitate manganese removal.

Figure 5: A manganese removal bed that has achieved less than 0.1 mg/L for over 20 years with minimal maintenance. Most of the maintenance involves using a mechanical excavator to break up the manganese scale at the beginning of the bed. A small depression trench was installed here to permit the build up of hydraulic head to force the water into the stone. This bed treats 20 gpm and a raw manganese concentration of 30 mg/L using a uniform sized ¾” limestone.

Figure 6: This large MRB was used to treat a flow of 600 gpm containing a manganese concentration of 8 mg/L. The bed contained more than ten thousand tons of limestone ranging in size from 4 to 6 inches.

Figure 7: MRB showing blackish-brown manganese coated limestone. Influent pipe shown at bottom right and large baffle used to prevent short circuiting.

Figure 8: A typical example of maintenance issues caused by installing MRB on water containing iron or other voluminous flocculent. In this case, an ALD is installed in the hillside and the oxidation ponds were undersized and discharged suspended ferric hydroxide and dissolved ferrous iron into the MRB causing hydraulic failure. The oxidation ponds should have been larger to fully oxidize the iron and a wetland should have been used before the MRB to remove suspended iron floc to less than 0.5 mg/L. The photo shows an excavator was used to install a trench to promote infiltration and reestablish flow. An additional drawback from discharging ferrous iron into a MRB is that a redox reaction between dissolved ferrous iron and precipitated manganese oxide will cause the manganese to re-dissolve while oxidizing the iron leading to decreased manganese treatment.

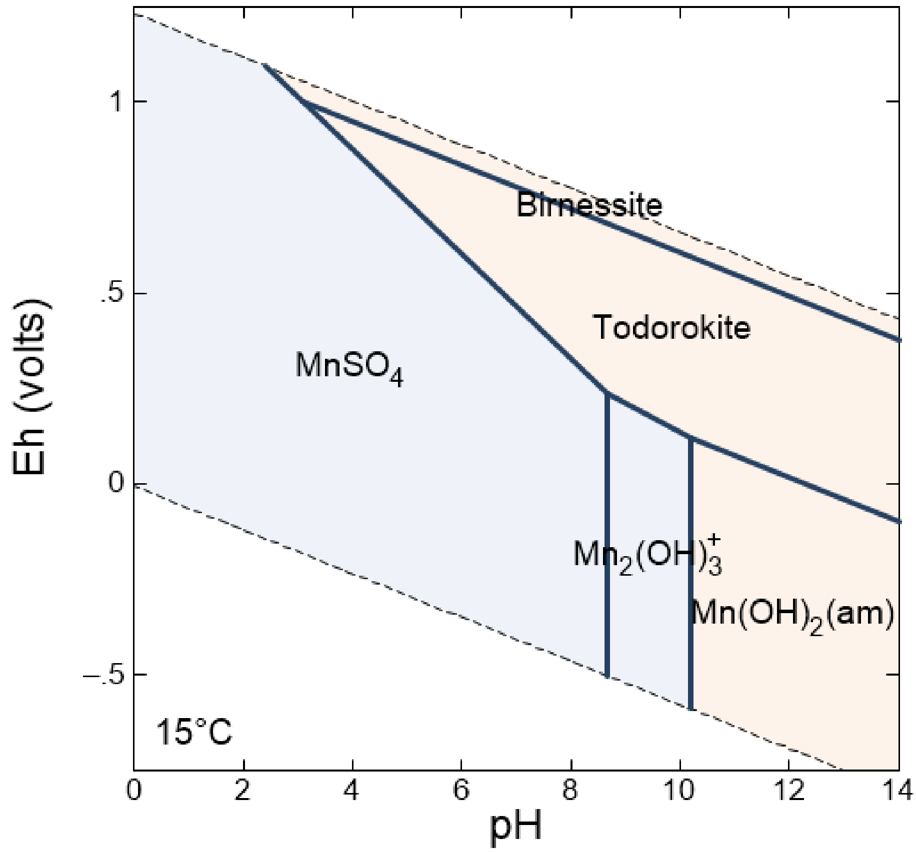

Figure 9: Pourbaix diagram illustrating manganese stability at various Eh/pH conditions.