

SOVEREIGN CONSULTING INC.

TECHNICAL MEMORANDUM

Date: December 9, 2015

To: John Naisbitt, Amulsar Project Lead From: James Gusek, Guadalupe Fattore CC: Larry Breckenridge (GRE), File

RE: AMULSAR PASSIVE TREATMENT SYSTEM (PTS) DESIGN BASIS

1.0 INTRODUCTION

Lydian International LTD. (Lydian) proposes to mine gold at the Amulsar Project (the Project) located near Jermuk, Armenia. Gold will be extracted from a lined Heap Leach Facility (HLF) that is irrigated with cyanide solution. The ore will be recovered from two open pits and some of the overburden rock from these pits, which has been characterized by others, will be deposited in an engineered storage facility hereafter referred to as the Barren Rock Storage Facility (BRSF). The site is predicted to produce Acidified Mine Influenced Water (MIW) from Acid Rock Drainage (ARD) reactions primarily from the pit and from the BRSF (GRE 2014a).

Starting in the 5th year of the mine life, the project will have excess MIW. This water will be directed to a passive MIW treatment system prior to its discharge into the Apra River downstream from the Kechut Reservoir.

The Passive Treatment System (PTS) is designed to treat ~11 L/s. This flow rate is sufficient to manage excess mine water late in the mine life, and it is sufficient to treat the MIW coming from the toe of the BRSF upon closure. Because the influent water quality changes little from the 5th year of mining to closure, the system can easily function during operations and post-closure. Indeed, it is a significant advantage to start the system during operations because it provides more flexibility in startup and more water management options if initial designs underperform. In order to benefit from the storage present in the PD-8 pond, and in order to discharge to a river downgradient from the Lake Sevan catchment, the PTS is located near the HLF downgradient from the PD-8 MIW storage pond. GRE developed predictive models of the operations-phase MIW quality and post-closure BRSF toe discharge water quality (GRE, 2014a and 2014b), and these simulations were used as the design basis for the PTS.

The purpose of this technical memorandum is to provide a summary regarding preliminary plans to implement a PTS to remediate MIW associated with the project during operations and post-closure. The remediation strategy is to collect the MIW from PD-8 during operations, and from the toe of the BRSF upon closure. The MIW will be conveyed via gravity in a pipeline from the PD-8 pond. Any treatment that may



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occur in the pond (i.e., assumed oxidation of ammonia to nitrate) renders the pond to be a part of the PTS within the context of this report. Although there will be some equilibration and potentially some biological preconditioning "treatment" that could be initiated in the pond, the main function of the PD-8 pond in regard to the PTS will be for equilibration of flow surges mainly from seasonal variations.

The design is based on Sovereign's current understanding of the site plans and the projected chemical composition of MIW during operations and post-closure. The final design of the PTS would be based on bench and pilot scale test verification which should commence well in advance of large scale operations to validate the key sizing values assumed at this conceptual stage of the treatment system design. Again, this conceptual design is based on professional judgment, Sovereign's experience with similar MIW, and published technical papers referenced herein.

The PTS will be constructed on available sloping ground between the PD-8 pond and the HLF ponds. It is adjacent to the highway to Jermuk. The PTS components will include:

- The PD-8 pond;
- Nitrate Reducing Biochemical Reactor (BCR);
- Aerobic Polishing Wetland (APW) No. 1;
- Sulfate Reducing BCR;
- Sulfide Scrubbing Unit;
- APW No. 2;
- Manganese Removal Beds (MRB); and
- A discharge pipe to the Apra River tributary located downgradient from the HLF ponds.

Preliminary design assumptions follow.

- All flows are gravity-driven.
- The PTS will treat 40 m³ per hour (11.1 L/sec.
 - During operations the seepage will be a blend of MIW from all sources in the project (Golder 2015). This includes pit dewatering and BRSF seepage.
 - Post-closure the seepage will be a blend of MIW and natural ground water flow occurring in the BRSF footprint that mixes with MIW in the drains beneath the BRSF.
 Episodic seasonal flows above this design value will be moderated in the BRSF Toe Pond (PD-7) and in PD-8, both of which will act as a flow equalization basin.
- The design flow rate (11.1 L/sec) includes a 30% safety factor.
- Two sequential sets of BCRs will be required. The first set will address elevated nitrate levels derived from blasting agent residue in the barren mine rock. The second set will address expected sulfate levels in the MIW. Both sets will improve the pH to circumneutral.
- To facilitate long-term maintenance, a typical BCR set is arranged with two identical BCRs plumbed in parallel. Thus, while one BCR is being refurbished (approximately every two decades), the other BCR would continue to function.
- The PTS will be built for low visual impact with the two sets of BCRs buried beneath a vegetated soil cover. This design feature will also protect the components during harsh winter temperatures and from contact with or damage from grazing animals.

The sulfide scrubber unit will be filled with an inexpensive sacrificial metal such as iron provided by:

- A natural mineral source such as limonite or goethite [Fe(OH)₃], hematite [Fe₂O₃], magnetite [Fe₃O₄], or
- Zero valent iron (ZVI) derived from a local source of scrap iron such as steel food cans that were procured from the local communities over the life of the mine.

The sulfide scrubber media mixture will also include a locally-available organic component (such as wood chips) to minimize plugging.

The two aerobic polishing wetlands (positioned after each BCR) will be populated with native plant species (including a local species of sphagnum peat moss) and configured to appear like a natural wetland ecosystem as much as practical.

All main conveyance pipes will be buried at least one meter below the prevailing ground surface or be sloped to drain for freeze protection. Long pipe runs will be fitted with camouflaged cleanouts every 50 to 60 meters to allow periodic cleaning or inspection, if the need arises.

Water will be discharged to the nearest feasible seasonal tributary of the Apra River downgradient of the HLF ponds. From these drainages, it will flow to the Arpa River downgradient from the Kechut Reservoir.

Natural springs have been observed within the footprint of the proposed BRSF (Golder 2014a). A portion of the flow discharging from these springs comes from ephemeral springs, and a portion comes from perennial springs. This portion of the ephemeral spring flow is expected to decrease in response to the overlying BRSF which is designed to minimize and as much as practical, eliminate recharge to the shallow groundwater aquifer(s) that feed the natural springs. However, some regional, perennial spring flow is still expected and this flow will mix with nominal infiltration through the barren mine rock in the BRSF.

The expected composition of the MIW was developed by GRE using the PHREEQC mixing model (GRE 2014a). This is discussed further in Section 4. Expected nitrate levels derived from blasting residue in the barren rock were estimated by Golder Associates Inc. (Golder, 2014b).

The general schematic view of the PTS process is provided in Figure 1. All flows to the PTS will be by gravity; the system will be designed to operate unattended.

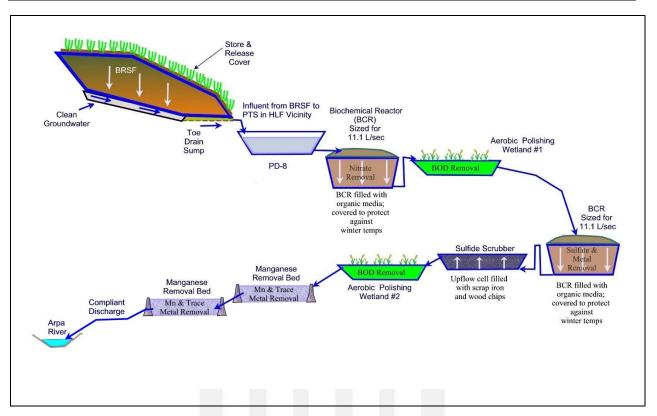


Figure 1 – Conceptual Passive Treatment System Schematic Process Flow Diagram

2.0 PASSIVE TREATMENT BACKGROUND

2.1 General Considerations

The technical literature is replete with references that describe passive treatment processes including Gusek, 2008; Gusek & Figueroa, 2009; and Gusek, 2009. Gusek (2008) proposed the following definition and discussion:

Passive treatment is a process of sequentially removing contaminants and/or acidity in a natural-looking, man-made bio-system that capitalizes on ecological, and/or geochemical reactions coupled with physical sequestration. The process does not require power or chemicals after construction, and lasts for decades with minimal human help.

For further information, the publications cited above are recommended; some of these can be downloaded for free from the Internet.

Passive treatment systems are typically configured as a series of sequential process units because no single treatment cell type works in every situation or with every MIW geochemistry. It is an ecological/geochemical process because most of the reactions (with the exception of limestone dissolution) that occur in passive treatment systems are biologically assisted. Lastly, it is a removal process because the system must involve the filtration or immobilization of the metal precipitates that are formed. Otherwise,

they would be flushed out of the system, and the degree of water quality improvement would be compromised.

Man-made passive treatment systems employ the same principles as do natural wetlands, but they are designed to optimize the competing processes occurring naturally in a wetland ecosystem. Aerobic and anaerobic zones "competing" in a natural wetland are shown on Figure 2.

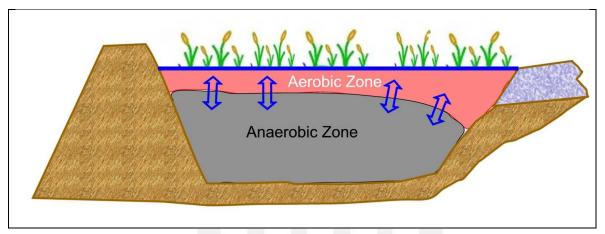


Figure 2 - Natural Wetland Oxidation-Reduction Zones

There are many natural analogues for passive treatment systems, including:

- Ferricrete deposits,
- Iron terraces,
- Bog iron ore (ochre) and metal deposits, and
- Manganocrete deposits.

There are basically three kinds of passive treatment technologies available for treating MIW:

- Abiotic, limestone-based methods for treating net-acidic MIW have been effective in adding alkalinity; a subset of this method uses a semi-biological zone to condition MIW for subsequent limestone dissolution.
- **Biochemical Reactors** (BCRs) are typically applicable to metal mine drainage with low to high acidity and a wide range of metals; this technology can function with or without plants to address nitrate and sulfate.
- Aerobic Cells containing cattails, other plants, and algae are typically applicable to MIW where iron and manganese and mild acidity are problematic and/or only trace concentrations of heavy metals occur. This method also can be used to polish biochemical oxygen demand (BOD) from BCR effluents and adsorb trace metals on to iron or manganese oxides.

Most passive treatment systems employ one or more of these cell types.

The technical community of regulators and engineers that specializes in passive water treatment should be familiar with the passive treatment "decision tree" that was published by the former US Bureau of Mines (USBM) about 20 years ago. See Figure 3 (Hedin et al., 1994).

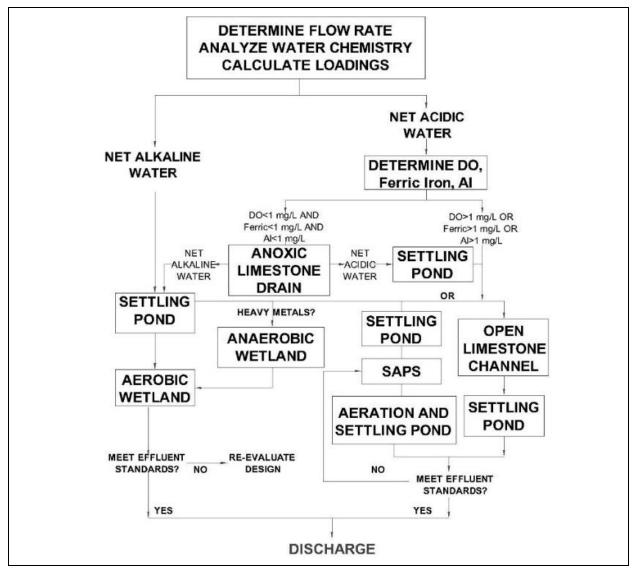
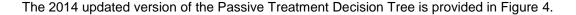


Figure 3 – 1990's Passive Treatment Decision Tree (Focus on coal MIW)

The USBM decision tree was originally intended to address MIW from coal mines. Since then, however, the breadth of passive treatment has expanded to embrace precious and base metal mines, uranium mines, and even gravel pits. Each MIW has its unique signature, either imposed by the natural geochemical conditions of the ore body and surrounding mine waste, or by resource recovery processes that may include heap leaching or traditional hydrometallurgical technologies. In the context of the elements of the periodic table, the decision tree certainly could be improved as it was originally developed to focus on coal geology derived MIW which typically contains acidity/alkalinity, iron, aluminum and manganese. For example, the expanded decision tree could consider residual ammonia or nitrates from blasting, cyanide from heap leach

pad rinsing, trace amounts of selenium, or other parameters that may require passive treatment at a given mine, coal or otherwise.



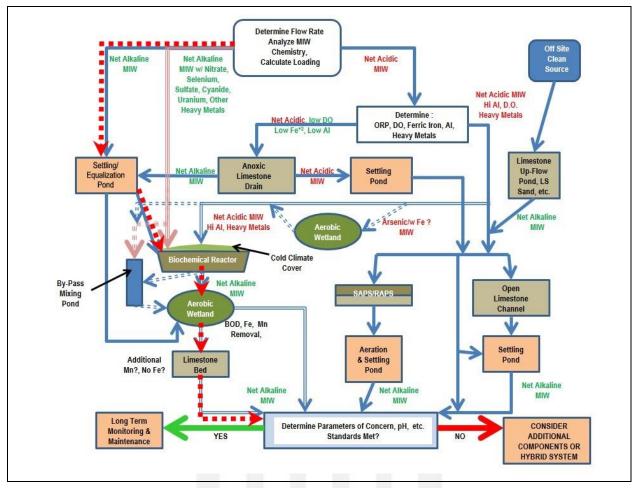


Figure 4 – 2014 Passive Treatment Decision Tree (Focus on metal mine and coal MIW)

Note that Figure 4 addresses MIW containing nitrate and sulfate (primary constituents of concern in the MIW) which are shown being addressed along the decision flow path (bold red arrows) in the biochemical reactor with a cold-climate cover. While the MIW is not projected to be net alkaline, it is expected to be only mildly acidic and is shown following the net alkaline PTS component selection flow path for convenience in Figure 4.

As discussed in Section 4.0, the MIW contains more than nitrate and sulfate. Developing an individual decision tree for each MIW element or suite of elements and their species would be a daunting task and would probably introduce more confusion where simplicity is desired.

Instead, a suite of "Periodic Tables of Passive Treatment" have been developed as useful design tools to satisfy the need to embrace a larger range of MIW chemistries. Gusek (2009) developed the first of these "custom" periodic tables; it focused on identifying passive treatment methods (under either oxidizing or reducing conditions) that have been observed to work on specific elements or species of elements typically found in MIW. The concept was subsequently re-visited (Gusek, 2013) with a closer focus on adsorption phenomena and other processes. Both of these papers are included in Appendix A.

2.2 Special Considerations

Sulfate removal from MIW containing trace metal concentrations is a special design challenge. While the sulfate reducing BCR is quite capable of converting sulfate (SO₄-²) to sulfide ion (S-²), this reaction is reversible. Certain bacteria are known to oxidize sulfide back into sulfate and the process gains in the sulfate reducing BCR would be lost unless the dissolved sulfide is sequestered. The sulfide scrubber shown in Figure 1 is filled with a sacrificial metal (scrap iron) and an organic component (e.g., wood chips). The wood chips are present to preserve the already anoxic conditions and to prevent plugging; the scrap iron or other inexpensive iron-containing material will scavenge the sulfide ion and an iron-sulfide residue will be formed. The iron and organic components comprising the scrubber media can be flexible. Other inexpensive iron-bearing materials could include raw iron ore such as magnetite or hematite (iron oxides). Straw, corn stalks, winery waste, or other locally- or regionally-available agricultural wastes could be substituted for the wood chips.

This passive process has not seen wide usage but available unpublished bench and demonstration scale data suggest that it is appropriate at the Amulsar PTS site.

Nitrate removal in a BCR is not dependent on the presence of metals. Nitrate is reduced to atmospheric nitrogen (N_2) .

3.0 PASSIVE TREATMENT DEVELOPMENT

3.1 A Brief History

Nature has been passively removing dissolved metals from acidic to net alkaline water for eons; examples include pyrite occurrences in coal beds, bog iron ore (limonite) and copper deposits (McDonald et al 1976). Elevated levels of metals in wetlands have been used extensively as a geochemical prospecting technique (Salmi 1955, 1959). Wetlands and bogs have long been recognized as nature's method of improving water quality. Contaminant reductions can occur through the precipitation of hydroxides, precipitation of sulfides and pH adjustments and other reactions/processes. Local conditions, oxidation state, and water and substrate chemistries dictate whether these natural reactions will occur under oxidizing (aerobic) or reducing (anaerobic) conditions.

It has been about 35 years since the pioneering work of a group of researchers at Wright State University documented water quality improvements in a natural Sphagnum peat bog in Ohio that was receiving low pH, metal laden water (Huntsman et al., 1978). Independently, a group at West Virginia University found similar results at the Tub Run Bog (Lang et al., 1982). At the same time, scientists in Minnesota documented trace metal removal in a natural wetland receiving drainage from a nickel ore stockpile (Eger et al, 1980).

Early passive treatment work was focused on coal geology derived MIW, primarily in the Eastern US. A number of research groups evolved, including: the former U.S. Bureau of Mines, the Tennessee Valley Authority, and various academic communities including Penn State, West Virginia University, and the Colorado School of Mines (Wildeman et al., 1993 and Hedin, 2002). As of 1988, all seemed to agree that there were a number of biogeochemical mechanisms involved in metals removal and water quality improvements in wetland type environments (either natural or man-made), but there was some disagreement on which mechanisms were the most important. For coal mine systems characterized by moderate amounts of iron and manganese, aerobic systems dominated by plants and limestone appeared to be the best means of raising pH (via photosynthesis and neutralization reactions) and precipitating iron through hydrolysis reactions. Researchers in the western USA, primarily Wildeman, Klusman, and Cohen at the Colorado School of Mines, considered sulfate reducing bioreactor (aka biochemical reactor) systems the most appropriate for metal mine ARD. According to personal observations by this author, two "camps" had evolved, each thinking that they had the magic bullet.

The American Society of Surface Mining and Reclamation (ASSMR) Conference in Durango, Colorado in 1991 was important, for the different "camps" collaborated for the first time, presenting a short course on passive treatment. Each camp had the opportunity to present its case and view what the other camp's approach had to offer. The course was well attended and many participants stayed after its official end, despite long travels home. It is safe to say that both camps came to recognize the strengths and weaknesses of the two approaches and how the two could be integrated into hybrid systems to treat a variety of ARD/MIW situations. Subsequently, researchers including Andre Sobolewski (1997), Wildeman and Pavlik (2000), Eger et al. (1980), ITRC (2003) and others have documented the ability of natural wetlands to remediate ARD.

Thus, in the past two decades, a number of passive treatment milestones have been achieved (see Gusek and Wildeman, 2002) and a standard passive treatment system (PTS) practitioners' "tool box" has evolved and continues to evolve as new challenges are met and overcome.

Full scale passive treatment systems are common in the coal mining region of the eastern United States and are increasingly used in metal mining areas. One of the largest passive systems was built in 1996 to treat 1200 US gpm (76 L/s) of lead mine drainage (Gusek et al., 2000).

3.2 Supporting Documents – The GARD Guide

The GARD Guide (Global Acid Rock Drainage Guide) was sponsored by the International Network for Acid Prevention (INAP) with the support of the Global Mining Alliance; whose members represent most of the international mining community. The guide deals with the prediction, prevention, mitigation and treatment of drainage produced from sulfide mineral oxidation, often termed ARD or MIW.

The GARD Guide is intended as a state-of-practice summary of the best practices and technology to assist mine operators, regulators, and stakeholders to address issues related to mine drainage.

Methods used to passively treat mine drainage issues at Amulsar are consistent with the "state of the art" recommendations found in the GARD guide and other guidance documents in the technical literature.

4.0 PTS DESIGN VALUES

4.1 Treatment Flow Rates

Sovereign has assumed a PTS design flow with at 40 m³/hour or 11.1 L/sec. This is a 30% safety factor applied to post-closure predicted flow rates (GRE 2014a and GRE 2014 b). This steady flow rate would be delivered to the PTS with a floating weir intake unit that will be installed in the PD-8 pond. This inexpensive design feature could be included during the PD-8 pond construction and engaged upon site closure.

4.2 Expected Operations-Phase Water Quality entering the PTS

The influent water quality modeling is presented in the Geochemical Characterization and Water Quality Prediction Report (Update) from September 2014 (GRE 2014a). Table 1 shows the expected operations-phase influent water quality based on geochemical modeling.

Table 1: Predicted Influent PTS Water Quality during Operations

Quality indicators	Unit	Arpa MAC Standards Quality Category II	Worst-Case Operations-Phase Mine Contact Water
рH			3.92
Acidity	mg CaCO₃/I		157.2
Aluminum	mg/l	0.144	27.2
Arsenic, total	mg/l	0.02	0.0173
Barium	mg/l	0.028	0.0214
Beryllium	mg/l	0.000038	0.00201
Boron	mg/l	0.45	0.00918
Cadmium, total	mg/l	0.001014	3.59E-04
Calcium	mg/l	100	12.5
Chloride ion	mg/l	6.88	0.215
Chromium, total	mg/l	0.011	6.60E-10
Cobalt, total	mg/l	0.00036	0.104
Copper, total	mg/l	0.021	9.68E-15
Iron, total	mg/l	0.072	5.65E-07
Lead, total	mg/l	0.01014	0.0404
Lithium	mg/l	0.003	0.01005
Magnesium	mg/l	50	5.11
Manganese, total	mg/l	0.012	0.00160
Nickel, total	mg/l	0.01034	0.0618
Nitrate ion	mg N/l	2.5	2.35
Nitrite ion	mg N/l	0.06	4.01E-13
Phosphate ion	mg/l	0.1	8.07E-12
Potassium	mg/l	3.12	6.39
Selenium, total	mg/l	0.02	0.00874
Silicate ion	mg Si/l	25	4.25E-07
Sulfate ion	mg/l	16.04	97.3
Total phosphorus	mg/l	0.2	0.866
Vanadium, total	mg/l	0.01	0.00237
Zinc, total	mg/l	0.1	0.381

Values that exceed standards are shown in bold.

A geochemical model must always be compared to any available on-site data to determine if the model is accurately simulating the concentrations of trace metals. As a result, the values in Table 1 were compared to existing ARD coming from mine waste in Site 13 and Site 27 (shown in Table 2).

Manganese

Nickel

Sulfate as

SO4

Zinc

mg/L

mg/L

mg/L

mg/L

Historic Waste Leachate, Site 13 May 2014 **Baseline** Unit Constituent **Surface** Site 13 Site 27 Water May 2014 рΗ pH units 4.78 3.28 6.38 mg/l as Acidity 15.1 102 <DL CaCO₃ Aluminum 0.176 2.27 0.18 mg/L Arsenic mg/L <0.001 <0.001 0.003 Barium mg/L 0.0096 0.0054 0.0161 Boron mg/L < 0.010 < 0.010 < 0.010 <0.0005 Cadmium < 0.0005 < 0.0005 mg/L Copper mg/L 0.0000075 0.0000543 0.0000057 Iron mg/L 0.363 3.22 3.73 Lead mg/L < 0.001 < 0.001 < 0.001

0.022

< 0.003

12.6

0.0225

0.0152

0.0035

43.7

0.0307

0.382

< 0.003

35.7

0.0325

Table 2: Chemistry of On-Site ARD and Baseline Water Quality

The geochemical model appears to under predict iron and manganese. As a result, the PTS considers a worst-case water quality that incorporates the prediction in Table 1 with the empirical data in Table 2 whenever Table 2 values exceed those in Table 1. This ensures an influent water quality that is firmly grounded in the empirical site data. Background receiving water quality was not considered even though some values in background exceed Arpa II standards.

4.3 Expected Post-Closure BRSF Seepage Chemical Parameters.

Upon closure, only seepage from the BRSF will be directed to the PTS. Using the same geochemical modeling techniques as applied to Section 4.2 (GRE 2014a), the post-closure BRSF seepage water quality was predicted (see Table 3).

Table 3: Predicted BRSF Toe Drain Seepage Chemistry and PTS Management Zone

Parameter	Units	Initial/ Feed Value	PTS Management Zone				
Conventional Parameters							
pH	s.u.	3.5	NO ₃ -BCR				
Total suspended solids	mg/L	UNK	PD-7				
Nitrate (as N)	mg/L	42	NO ₃ -BCR				
Sulfate	mg/L	105	NO ₃ -BCR & SO ₄ -BCR				

Parameter	Units	Initial/ Feed Value	PTS Management Zone
Sulfide (from SO ₄ -BCR)	mg/L	32	Sulfide scrubber
BOD (from BCRs)	mg/L	10	Aerobic Polishing Wetlands 1 & 2
Dissolved Metals			
Aluminum (Al)	mg/L	2.27	NO ₃ -BCR
Barium (Ba)	Mg/L	0.005	SO ₄ -BCR
Cobalt (Co)	mg/L	0.006	SO ₄ -BCR
Copper (cu)	mg/L	0.054	SO ₄ -BCR
Iron (Fe)	Mg/L	3.22	SO ₄ -BCR
Manganese (Mn)	mg/L	0.002	Manganese Removal Bed
Zinc (Zn)	mg/L	0.307	SO ₄ -BCR

4.4 Discharge Chemistry Targets

The treated water is targeted to meet the discharge criteria as provided in Table 4 below.

Table 4: Treatment Chemistry Targets - Monitoring Point PTS Effluent

Parameter	Units	Category II Arpa River MAC Values
Conventional Parameter		
pН	s.u.	6.5 to 9.0
Total suspended solids	mg/L	15.0
Nitrate (as N)	mg/L	2.5
Sulfate	mg/L	16.04
Sulfide (from SO ₄ -BCR)	mg/L	N.D.
BOD (from BCRs)	mg/L	N.D.
Total Metals		
Aluminum (Al)	mg/L	0.144
Barium	mg/L	0.028
Cobalt (Co)	mg/L	0.036
Copper (Cu)	mg/L	0.021
Iron (Fe)	mg/L	0.072
Manganese (Mn)	mg/L	0.012
Zinc (Zn)	mg/L	0.10

The conceptual PTS has been designed with several redundant processes. If additional processes (e.g., peat polishing cells) are required to meet the above targets, they would likely be appended to the aerobic polishing wetland #2, the final unit in the PTS.

5.0 TREATMENT PROCESSES

As shown in Figure 1, the proposed PTS will consist of seven units. The units are characterized with respect to the predominant aerobic (oxidizing) or anaerobic (reducing) conditions within the cells as follows:

Oxidizing/Aerobic Conditions

equalization pond (PD-8),

Reducing / Anaerobic Conditions

aerobic polishing wetland #1,

- aerobic polishing wetland #2, and
- manganese removal bed.
- nitrate reducing biochemical reactor,

- sulfate reducing biochemical reactor, and
- sulfide scrubber.

Discussions of the processes/conditions expected in each portion of the PTS follow.

5.1 Constituents of Concern Removal Kinetics in Aerobic Zones of the PTS

The PD-8 is expected to behave like an aerobic wetland because of its large surface area and relatively shallow depth (fully mixed, no stratification). Aerobic wetlands are engineered treatment systems that are designed to mimic the treatment processes that occur in naturally-occurring wetlands. Aerobic wetlands can treat a variety of constituents including suspended solids, biochemical oxygen demand (BOD), and metals (Kadlec and Knight 1996).

5.1.1 Ammonia Oxidation to Nitrate

According to Golder (2014b), nitrogen loading from MIW is projected to be dominated by two species: ammonia and nitrate, proportioned about equally between them. The nitrate-BCRs are ineffective in removing ammonia. However, the expansive area and long retention time provided by the PD-8 pond is expected to oxidize the ammonia present to nitrate, thus pre-conditioning the MIW for the first de-nitrifying BCR.

5.1.2 Metals (if present) Removal

If appropriately sized, aerobic wetlands can remove iron and manganese via iron hydroxide and manganese oxide precipitation, respectively. Metals removal from wetlands is typically calculated as a mass area loading factor with units of grams per day per square meter (g/d/m²) or gdm, whose origin is described below. Some technical references cite this value in units of grams per square meter per day (g/m²/d).

5.1.3 Biochemical Oxygen Demand (BOD)

BOD removal in metal mine PTS applications is required down gradient of the BCR units, as these effluents are typically anoxic and contain dissolved organic carbon. Typical BCR effluent BOD values typically decrease to about 10 mg/L after about five to 10 pore volumes are treated. Thereafter, the rule of thumb for BOD removal is about 1.3 m² of aerobic wetland water surface per liter per minute (L/min) of flow. Due to the cold climate at Amulsar, this value was conservatively quadrupled to 5.2 m² per L/min.

The PTS contains multiple trains of BCRs, one train for nitrate removal and a second train for sulfate removal. To function properly, the MIW a BCR receives should be fully oxidized. If it is not, the cellulose-degrading bacteria will not degrade the organic matter component in the BCR substrate and the nitrate-and sulfate-reducing bacterial communities will suffer for lack of nutrients. Consequently, the nitrate BCR

is followed by an aerobic polishing wetland to pre-condition/aerate the MIW for the sulfate BCR. The APW following the sulfate BCR/sulfide scrubber provides pre-conditioning for manganese removal. Note: BCRs are known to release manganese if it is present in organic substrate (typically it is found in the woody fraction of the substrate).

5.1.4 Manganese

Manganese oxide is Mother Nature's version of activated carbon. Many metals adsorb to it and the technical literature abounds with references, some written over 20 years ago (e.g., Bender et al. 1994), that document how manganese is biologically removed in aerobic passive treatment systems. Robbins and Ziemkiewicz (1997) observed the presence of 12 different biological mechanisms removing manganese in a passive treatment system at the Shade coal mine which was constructed in the early 1990s. At this site, influent manganese concentrations were reported to be reduced from 12 to 25 mg/L down to less than 2 mg/L. Manganese removal kinetics from MIW has been empirically measured in a way similar to iron as developed by Hedin (1994). Hedin observed typical manganese removal rates ranging from 0.5 to 1 g/d/m² but there may have been interfering conditions that were unrecognized at the time. More recent data suggest that higher values are possible.

However, as MIW becomes more dilute, manganese removal kinetics become less efficient. Fortunately, neither site elevation nor water temperature appears to affect the biologically-influenced manganese removal kinetics in an aerobic wetland environment.

Rose et al. 2003 discussed two manganese removal methods, a limestone bed where MIW passes through granular limestone in a plug-flow configuration and an open limestone channel configuration with a free-water surface above a bed of granular limestone. Key findings in the paper include:

Effective Mn removal [in both bed and channel configurations] requires oxidizing well-aerated water, as well as prior removal of essentially all dissolved Fe and Al, and pH above about 6.5.

Another key requirement for Mn oxidation is a low concentration of ferrous iron (Fe(II)). ...if Fe(II) is present in a solution..., the oxidation potential of such a solution is considerably below the level required for Mn oxidation to Mn(III) or Mn(IV), and Mn will not oxidize and precipitate.

Several of the [bed] systems have failed because of plugging of the inlet area with silt, leaves, Fe and/or Al precipitate, grass and other materials.

Most Mn removal rates [in limestone beds] range from 1.5 to 5 g/m²/day, with the lower values from beds with influents containing appreciable Fe and Al.

Three successful limestone-lined channels have been observed, one with a Mn removal rate of about 10 g/m²/day. A shallow bed or channel, lined with limestone, and containing algae to enhance O_2 , appears to be an improved design.

Data reported by ITRC (2010) cite a Mn removal rate of 2.6 g/d/m² at an abandoned coal mine site in Alabama.

Sovereign used a conservative value of 0.01 gdm to estimate the surface area required for manganese removal. This was driven by the very low manganese discharge limit (0.012 mg/L) – as discussed earlier, manganese removal efficiency decreases as the influent concentration becomes more and more dilute. Bench studies which develop site-specific gdm factors for manganese are recommended.

5.1.5 Selected Metallic Constituents of Concern (Co, Zn, Pb, & Ni)

If upstream processes are not as efficient as expected in the Amulsar PTS, some of the metallic constituents of concern (COCs) in the MIW are likely to adsorb to manganese oxides that should form in the manganese removal beds installed in the final treatment zones of the PTS. Review of the technical literature on this topic verified that manganese oxide minerals should indeed be capable of removing the metallic COCs in the MIW. For example, the following direct citation from Tebo et al. (2004) is offered:

Mn oxide minerals can adsorb or incorporate substantial amounts of Cu, **Co**, Cd, **Zn**, **Ni**, Sn, **Pb**, Ca, Fe, Ra, Hg, U, Pu, Po, As, Se, and Th (see multiple references in Tebo et al. 2004). These interactions have been reported to decrease dissolved trace metal and radionuclide concentrations by orders of magnitude (see multiple references in Tebo et al. 2004) even when only small amounts of Mn oxides are present (see Jenne 1968 cited in Tebo et al. 2004).

For emphasis, the metallic COCs present in the MIW are bolded in the citation above.

Removal kinetics for the metallic COCs in the manganese removal portion of the PTS are unknown. The BCR effluent will contain some biochemical oxygen demand (BOD) and will exhibit very low levels of dissolved oxygen (DO). The BOD will be managed and the DO increased in the aerobic polishing wetlands (see Figure 1).

5.2 Constituents of Concern Removal Kinetics in Anaerobic Zones of the PTS; i.e., Biochemical Reactors

Biochemical reactors are typically constructed by filling a geomembrane-lined excavation with a blended carbon/alkalinity source that is generally provided by a mixture of solid substrates (e.g., wood chips, straw, hay) to provide both short term and long term carbon sources. This blend insures a quick start up as well as long term treatment. BCR substrates also typically contain a crushed limestone component as the alkalinity source.

In order to maintain anaerobic conditions, BCRs are operated under saturated conditions and are generally fed from the top, operating in vertical down-flow configuration. (Figure 5).

Additional information on the use of biochemical reactors to treat mining influenced waters is available in the recent ITRC guidance; Biochemical Reactors for Treating Mining Influenced Water (ITRC, 2013).

A photo of a BCR is provided in Figure 6.

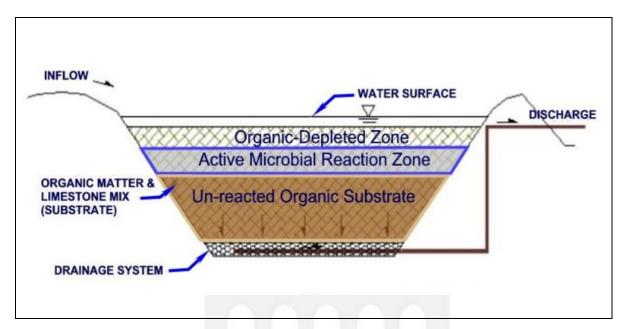


Figure 5 - BCR (NO₃ and SO₄) Schematic Cross Section View



Figure 6 - A Typical BCR in Pennsylvania, USA

5.2.1 Nitrate Removal Kinetics in the NO₃ BCRs

Nitrate derived from blasting agent residue is the first major COC that will be removed in the PTS. Denitrification is the primary removal mechanism in BCRs. The chemical reactions are facilitated by natural bacteria including *Thiobacillus de-nitrificans* in nitrate BCRs. Nitrate is reduced to atmospheric nitrogen (N₂). Minor concentrations of metal, particularly dissolved aluminum, may be removed in a nitrate BCR.

A bench scale nitrate reduction rate at a mine site in California (unpublished data) was observed to be 0.8 moles (or 11.2 grams) of nitrate (as N) removal per day per cubic meter (moles N/d/m³) of organic substrate. This value was observed for an MIW with an ambient temperature of about 15°C. For the Amulsar nitrate BCR, a much colder MIW is expected as a result of the extended exposure in the PD-8 pond. Consequently, a conservative value of 0.4 moles N/d/m³ was assumed (5.6 grams N/d/m³). At this rate, the hydraulic retention time (HRT) for the proposed nitrate BCR was about 4.2 days. This value would need to be validated with bench and/or pilot test data before this component would be sized in the final design.

5.2.2 Sulfate Removal Kinetics in the SO₄ Biochemical Reactor

Metals concentrations that elude removal in the nitrate BCR would be removed in the sulfate BCR. Sulfate reduction is the primary metal removal mechanism in BCRs. The chemical reactions are facilitated by the bacteria *Desulfovibrio* in sulfate-reducing BCRs.

The sulfate-reducing bacterial reactions (equation 1) involve the generation of:

Sulfide ion (S⁻²), which combines with dissolved metals to precipitate sulfides (equation 2).

Bicarbonate (HCO₃-), which has been shown to raise the pH of the effluent.

The sulfate reducing bacteria produce sulfide ion and bicarbonate in accordance with the following reaction (Wildeman, et al., 1993):

$$SO_4^{-2} + 2 CH_2O \rightarrow S^{-2} + 2 HCO_3^{-1} + 2 H^+$$

The dissolved sulfide ion precipitates metals (if present) as sulfides, essentially reversing the reactions that occurred to produce acidic or metal-bearing mine water. For example, the following reaction occurs for dissolved zinc, forming amorphous zinc sulfide (ZnS):

$$Zn^{+2} + S^{-2} \rightarrow ZnS$$
 2)

BCRs are typically sized based on the metals and sulfate mass loading, but only to a certain extent. As the influent becomes more dilute with respect to metals and/or sulfate, a minimum HRT design factor is adopted. This design decision was not necessary for sizing the BCR. Rather, a sulfate reduction rate observed in a demonstration BCR at a coal mine in Vancouver BC with a sulfate concentration of 600 mg/L was adopted. The "temperate" temperature sulfate reduction rate (observed at a number of sites, worldwide) is 0.3 moles (or 32 grams) of sulfate removal per day per cubic meter (moles/d/m³) of organic substrate. For the Amulsar sulfate BCR, a conservative value of 0.1 moles/d/m³ was assumed (9.6 grams SO4/d/m³). At this rate, the HRT for the proposed sulfate BCR was about 4.1 days. This value would need to be validated with bench and/or pilot test data before this PTS component would be sized in the final design.

The organic reactant in equation 1 above (CH₂O) is typically provided by cellulose-bearing materials such as wood chips, hay, and straw. It is expected that the wood chips would be obtained on or nearby (e.g. apricot orchards). To protect against acidity excursions in the BCR influent, a limestone sand component (no less than 10% by weight) is typically included in the substrate mixture. The microbial suite of *Desulfovibrio* and supporting bacterial strains of cellulose degraders and fermenting bacteria are provided in a relatively small amount of inoculum; it is typically composed of composted animal manure that is available from local farms.

The above components are included in the BCR substrate design which would also be validated in bench and pilot scale testing.

5.3 Sulfide Removal Kinetics in the Scrubber

As discussed earlier, in the absence of dissolved metals, sulfide (S⁻²) produced by the SO₄-BCR is prone to re-oxidize back to sulfate (see equation 3). This reaction is prevented by sequestering the sulfide with a sacrificial metal such as iron. See equations 4 or 5 for expected reactions with zero valent iron [scrap iron] or magnetite, respectively.

$$S^{-2} + O_2 + Thiobacillus \rightarrow SO_4^{-2}$$
 3)

$$S^2 + Fe_0 \rightarrow FeS$$
 4)

$$3S^{-2} + Fe_3O_4 + 8H^+ \rightarrow 3FeS + 4H_2O$$
 5)

Equation 5 has the advantage of consuming hydrogen ion (H+), thus raising the pH of the MIW.

The kinetics of this reaction have been studied at bench and "demonstration" scales at a coal mine site on Vancouver Island, BC, Canada (unpublished data). Based on the demonstration scrubber data available to Sovereign, an HRT of about 13 hours was assumed for sulfide scrubber cell sizing. The sulfide scrubber media was assumed to be a mixture of 40% by weight magnetite (Fe₃O₄) and 60% by weight wood chips (to preserve the anoxic character of the SO₄-BCR effluent). The media was assumed to exhibit a void ratio of 60% for estimating HRT.

The sulfide scrubber will be fed from the bottom to preserve the temperature and anoxic conditions in the SO₄-BCR effluent.

6.0 CONCEPTUAL TREATMENT SYSTEM DESIGN

Step 1 – Identify Treatment System Components

The COCs present in the MIW suggests that at least four sequential process steps need to be included in the treatment system design. These process steps were shown schematically in Figure 1. To recap, they include:

- PD-8 pond for conversion of ammonia to nitrate
- NO₃-BCR for the removal of nitrate to meet effluent standards and pre-treat the MIW so that sulfate can subsequently be reduced. Based on Sovereign experience in bench tests at another site in the western USA (unpublished data), aluminum removal and some sulfate removal are likely to occur in the NO₃-BCR.
- Aerobic polishing wetland (APW) No. 1 to settle out biosolids that form due to residual BOD, and re-oxygenate and pre-condition the anoxic BCR effluent for introduction into the SO₄-BCR.
- SO₄-BCR for the removal of sulfate to meet effluent standards and remove cobalt, nickel, lead, and zinc as sulfides and residual aluminum as aluminum hydroxy-sulfate.
- Iron- and wood chip-filled scrubber for sequestering sulfide.
- Aerobic polishing wetland cell to re-oxygenate the anoxic SO₄-BCR effluent, settle out biosolids that form due to residual BOD, and
- Manganese removal beds to precipitate manganese oxide which is likely to be leached from the BCR organic substrates. MnO₂ has an affinity to adsorb other residual parameters.

To minimize both construction and operational costs, all flows are by gravity. The system is configured to operate unattended with little if any maintenance. However, low maintenance does not mean "no" maintenance. Lydian personnel should plan to visit the system monthly during the first few years of operation. Sampling and monitoring frequency might be relaxed once the performance of the PTS is consistent.

Step 2 – Develop Approximate Component Sizes

The sizes of the treatment units were based on assumptions shown in Table 5.

Table 5: Treatment Component Design Basis Summary

Component	Design Basis
PD-8	Originally designed to satisfy operational water balance requirements: capacity varies by date (see Golder 2015)
Nitrate Reducing Biochemical Reactor	4.2 days HRT in 60% void space; substrate comprised of wood chips (10% by weight), winery waste (60% by weight), crushed limestone 20%; hay (10%); bulk substrate density 0.32 kg/L; substrate thickness 2.0 m; total BCR depth 2.9m includes gravel & pipe layer on floor and side slopes of 3H:1V; 1.5mm geomembrane underlain and overlain with geotextile; BCR is covered (see Figures 8 and 9, Section 8.1).
Aerobic Polishing Wetland #1	BOD removal based on 5.28 m ² of water surface area per liter per minute of flow; the aerobic polishing wetland is lined with 1.5 mm geomembrane underlain and overlain with geotextile; water depth 150mm; freeboard 460mm; organic matter in floor and sides 300mm thick; side slopes 3H:1V
Sulfate Reducing Biochemical Reactor	4.1 days HRT in 60% void space; substrate comprised of wood chips (10% by weight), winery waste (60% by weight), crushed limestone 20%; hay (10%); bulk substrate density 0.32 kg/L; substrate thickness 2.0 m; total BCR depth 2.2m includes gravel & pipe layer on floor and side slopes of 3H:1V; 1.5mm geomembrane underlain and overlain with geotextile; BCR is covered (see Figures 8 and 9, Section 8.1).
Sulfide Scrubber	13 hours HRT in 60% void space; substrate comprised of wood chips (60% by weight), magnetite sand (40% by weight); substrate thickness 2.0 m; total BCR depth 2.3m includes pipe layer on floor and side slopes of 3H:1V; 1.5mm geomembrane underlain and overlain with geotextile; fed from bottom.
Aerobic Polishing Wetland #2	BOD removal based on 5.28 m ² of water surface area per liter per minute of flow; the aerobic polishing wetland is lined with 1.5 mm geomembrane underlain and overlain with geotextile; water depth 150mm; freeboard 460mm; organic matter in floor and sides 300mm thick; side slopes 3H:1V.
Manganese Removal Beds (2)	Two MRBs in series, fed from top; filled with 50% crushed limestone (<100mm dia.) and 50% silicate rock (<100mm dia.); media depth 820mm; Mn removal rate of 0.01 grams Mn/day/m² of water surface on top of MRBs.
Infiltration Trench	Coarse gravel-filled trench installed along the contour 10 to 20m uphill and parallel to G. Channel with imbedded perforated PVC pipe (150mm dia.); zone between trench and channel planted with sphagnum peat moss (local species).

Step 3 – Develop Construction Footprints for Components

It is a well-accepted fact that passive treatment systems consume larger areas than active treatment systems with similar loading/treatment capacities. The dimensions of the conceptual PTS treatment units were plotted on the available land downhill from P-08 to determine if land requirements would become an engineering constraint. Table 6 provides the approximate areas required for each of the PTS components.

Table 6: PTS Treatment Component Footprint Summary

PTS Component	Approximate Total Footprint (Ha)
Nitrate BCR	1.14
Aerobic Polishing Wetland #1	0.39
Sulfate BCR	1.29

Sulfide Scrubber	0.12
Aerobic Polishing Wetland #2	0.39
Manganese Removal Bed	0.22
Total	3.6

The general conceptual layout of the PTS in relation to the HLF and P-08 is shown in Figure 7.

It appears that there is sufficient land area to construct the PTS as currently sized.

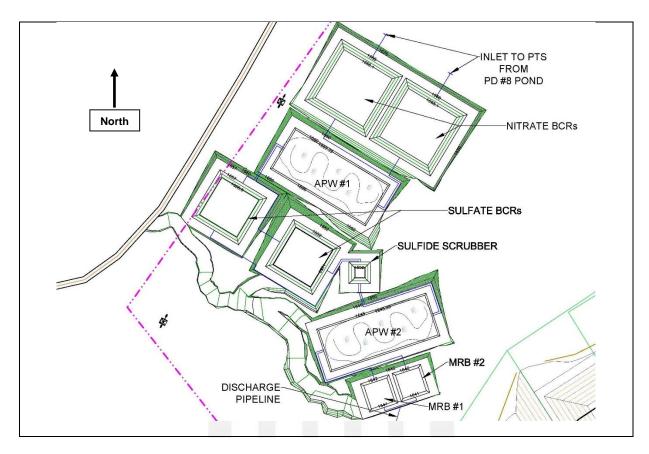


Figure 7 - Passive Treatment System General Layout, Plan View (Not to Scale)

7.0 PREDICTION OF POST-TREATMENT WATER QUALITY

The post-treatment MIW quality provided in Table 7 is based on Sovereign experience and in-house PTS component sizing models that assume nearly complete removal of the parameters of concern.

Table 7: Estimated PTS Discharge Quality

Parameter	Units	Category II Arpa River MAC Values	PD #8 Pond	Nitrate BCR	APW 1	Sulfate BCR	Sulfide Scrubber	APW 2	MRB 1	MRB 2	
	Conventional Parameters										
pН	s.u.	6.5 to 9.0	3.28	5.5	NC	6.5	NC	NC	7.5	7.5	
Nitrate (as N)	mg/L	2.5	42	<2.5	NC	NC	NC	NC	NC	NC	
Sulfate	mg/L	16.04	44	NC	NC	12.0	NC	NC	NC	NC	
Sulfide (from SO ₄ -BCR)	mg/L	N.D.	N.D.	NC	NC	-	Low	NC	NC	NC	
BOD (from BCRs)	mg/L	N.D.	N.D.	High	Low	High	High	Low	NC	NC	
				Total	Metals						
Aluminum	mg/L	0.144	2.27	NC	NC	<0.144	NC	NC	NC	NC	
Barium	mg/L	0.028	0.005	NC	NC	<0.028	NC	NC	NC	NC	
Cobalt	mg/L	0.036	0.006	NC	NC	<0.036	NC	NC	NC	NC	
Copper	mg/L	0.021	0.054	NC	NC	<0.021	NC	NC	NC	NC	
Iron	mg/L	0.072	3.22	NC	NC	<0.072	NC	NC	NC	NC	
Manganese	mg/L	0.012	0.015	NC	NC	NC	NC	NC	0.01	0.008	
Zinc	mg/L	0.1	0.307	NC	NC	<0.1	NC	NC	NC	NC	

Note: NC - No change

Modeling/design basis

Nitrate BCR Nitrate removal Rate - 0.4 moles of nitrate /m3/day

APW 1 BOD loading factor = $5.28 \text{ m}^2/\text{L/min}$

Sulfate BCR 0.1 moles of sulfate/m³/day

HRT= 50% of Quinsam coal mine scrubber design HRT due to dilute sulfide

Sulfide Scrubber levels

APW 2 BOD loading factor - 5.28 m²/L/s

MRB 1 Mn removal - A (m^2) = -0.276QLog([Mn]/[Mno])/(k1SD) MRB 2 Mn removal - A (m^2) = -0.276QLog([Mn]/[Mno])/(k1SD)

If proposed bench and pilot scale test results indicate additional process steps are required to meet Arpa River MAC standards, those processes would be <u>amended</u> to the treatment scheme rather than replace individual components. For example, such amended processes may include ion exchange media that is selective to the parameter of concern that is outside the Arpa River limits. As the amended process would be inserted at the end of the passive treatment process train, interferences from other MIW parameters is less likely.

The design criteria used to size each component of the PTS is described below:

7.1 BCR – Nitrate Removal

The primary design basis input for the BCR is the nitrate loading (flow times concentration). Metals concentrations and sulfate are inconsequential. While some incidental metals and sulfate reduction are expected in a nitrate-reducing BCR, their removal does not influence BCR sizing in this case. A design nitrate removal rate of 0.8 moles/day/m³ was obtained from the bench scale testing performed at the Hayden Hill mine site (unpublished data). A 0.4 moles NO₃/day/m³ removal rate was used to design the BCR due to the cold water temperature of the influent.

7.2 APW 1 and 2 – BOD Removal

The area required for BOD removal in the APWs was calculated based on 5.28 m² of water surface area per liter per minute of flow. This rate is four times more conservative than the BOD removal rate achieved from West Fork mine pilot scale testing (unpublished data). A full scale (4.5 m³ per minute) PTS was designed based on these test results and it operated successfully for 19 years until it was intentionally decommissioned.

7.3 BCR – Sulfate & Metal Removal

Design basis input for the BCR was 0.1 moles of sulfate per cubic meter per day, based on the Quinsam Coal Mine bench testing during the winter months (unpublished data). Table 8 indicates the sulfate loading rate and the cumulative metal loading with the exception of manganese. Based on experience, the molar ratio for sulfate and metals removal is 1:1. Table 8 shows that all the metals would be removed from the MIW. The remaining sulfate would be removed as elemental sulfur and will be converted to sulfide.

Table 8: Total Metals Loading Rate

Parameter	Units	Detention Pond (mg/L)	Total Loading (mol/day)						
	Conventional Parameters								
pН	s.u.	3.28	-						
Flow	L/day	950400	-						
Nitrate (as N)	mg/L	2.35							
Sulfate	mg/L	105	1,040						
Total Metals									
Aluminum	mg/L	2.27	120						
Barium	mg/L	0.005	0.035						
Cobalt	mg/L	0.006	0.10						
Copper	mg/L	0.054	0.81						
Iron	mg/L	3.22	54.84						
Zinc	mg/L	0.307	4.5						
	Total		180						

7.4 Sulfide Scrubber

The scrubber was designed based on half of the HRT from the Quinsam Coal Mine bench testing (unpublished data). This rate was assumed due to the relatively dilute expected sulfide levels from the Almulsar MIW compared to the Quinsam bench data.

7.5 MRB - Manganese Removal

Manganese will not be removed in the BCRs or the APWs. The following equation (Means and Rose, 2005) was used to design the MRBs:

 $A = -0.276QLog([Mn]/[Mn_o])/(k1SD)$

Where:

A = Bed area (m²)

Q = Flow Rate (L/min)

Mn = Mn effluent concentration (mg/L)

 $Mn_0 = Mn$ influent concentration (mg/L)

 $k_1 = Rate Constant (hr^{-1} (m_s^2/m_v^3)^{-1})$

S = Specific surface of limestone (m²)

D= Depth of water saturation in the bed (m)

Note: Means and Rose based their equation on manganese removal observations at 13 different PTS sites.

8.0 PTS MAINTENANCE AND COMPONENT LONGEVITY

The oldest BCR in operation was built in 1996 (Gusek, 2000) at a lead mine in Missouri, USA. Based on experience, the organic substrate in the BCR components (nitrate and sulfate units) in the PTS would need to be replaced every 20 years of operation.

The operation of the PTS should include the following activities:

- Periodic sampling of each PTS treatment unit, not just the PTS effluent, is recommended to avoid upset conditions.
- Post closure, two to three site visits per year to collect samples and inspect the site for functionality assume two field personnel are required for this effort.
- Replacement of the BCR substrate every 20 years. This will involve:
 - o purchasing fresh substrate materials and mixing them together;
 - o removing the soil and infiltration chamber combination cover;

- o exhuming and disposing the spent substrate (probably on site); and
- placing the fresh mixed substrate into the BCR and replacing the combination cover.
- Replacement of the sulfide scrubber media every 15 years. With the exception of the removal and replacement of a cover, this work will involve activities similar to replacing the BCR substrates.
- Checking for damage from animals and weather.

The aerobic polishing wetlands should be self-sustaining.

9.0 EXAMPLES OF THE TECHNOLOGY AT SIMILAR SITES

9.1 Examples of COC Removal

The technical literature is full of documented case studies where the COCs present in the MIW have been managed but no single MIW exhibits the same COCs at Amulsar. Table 8 provides a general perspective on the numerous sites where the passive treatment technology has been evaluated (bench or pilot scale testing) or implemented (full or demonstration scale). The reference column has two possible entries: U.D. or "unpublished data" or R.A. where a paper, presentation or technical publication is available in the public domain. Details of the unpublished data (which may be a confidential site) or the paper/ publication can be provided on request.

Clearly, the passive treatment technology is appropriate for a wide range of COCs. See the papers in Attachment A for a more detailed discussion.

Table 8: Examples of PTS Technology Addressing Amulsar MIW COCs

Mine Site	рН	Al	Со	Ni	Pb	Zn	NO ₃	Mn	SO₄	S ⁻²	Ref.	Cold Site?
Conf. Site, CA USA	7	•					•				U.D.	Yes
Quinsam Coal, BC Canada	7.5								٠	•	R.A.	Yes
Ferris Haggarty Mine WY USA	7.5								·		R.A.	Yes
Buffalo Valley, NV USA	8						•				R.A.	Yes
Rocky Flats, CO USA	8						•				U.D.	Yes
Ore Hill Mine, VT USA	4				•	•					U.D.	Yes
Magenta Drain, CA USA	7							•			R.A.	No
Sudan Mine, MN USA	7		•						•		U.D.	Yes
Standard Mine, CO USA	3.3		•			•		•	•		R.A.	Yes

Mine Site	рН	AI	Со	Ni	Pb	Zn	NO ₃	Mn	SO ₄	S ⁻²	Ref.	Cold Site?
Golden Cross, NZ	7.5		•			•			•		U.D.	No
Iron King Mine, AZ USA	3 to 7	•				•		•	•		R.A.	No
Royal Mtn King, CA USA	7.8			•			•				U.D.	No
Elizabeth Mine VT, USA	4	•		•		•		•	•		U.D.	Yes
Stoller Site, SC USA	4.3	•		•		•		•	•		U.D.	No
Grouse Creek, ID USA	3.2	•									U.D.	Yes
Rosita Dump, Peru	2.7	•	•	•		•		•	•		U.D.	Yes
DeLamar Mine, ID USA	2.7	•		•		•		•	•	2	U.D.	Yes
Luttrell Site, MT USA	4	•				•		•	•	2	R.A.	Yes
Golinsky Mine, CA USA	3.4	•		p.º	1	1.		V.Y			R.A.	No
PJK, MT USA	7					•		•			R.A.	Yes
N. Potato CK, TN USA	2.5	•	•		•	•		•	•		R.A.	No
MSF Mine, Brazil	7			•				•	•		U.D.	No
Fran Mine, PA USA	2.2	•				•		•	•		R.A.	Yes
Richmond Hill Mine, SD USA	4.5	•	•	•		•		•			U.D.	Yes
West Fork Mine, MO USA	7.5				•	•		•	•		R.A.	Yes
Cadillac Mine, Quebec, Canada	2.7 to 3.4	•						•	•		R.A.	Yes

Notes:

U.D. - Unpublished data

R.A. - Reference/Paper/Presentation available on request

9.2 PTS Systems in Cold Climates

The wintry climate of the site is a design challenge. The far right column of Table 6 indicates whether the site location was wintry (i.e., sub-freezing conditions might be expected for more than a month). About 70 percent of the example sites satisfy this condition.

To ensure that the BCR substrate is maintained at an ambient temperature above freezing, Sovereign has assumed that the BCR would be buried. This is a typical design strategy in cold climates. To provide an insulating layer of air above the substrate, we have included a layer of off-the-shelf, lightweight infiltration chamber units typically used in domestic septic system leach fields. See Figures 8 & 9.



Figure 8 - Septic Infiltration Chamber

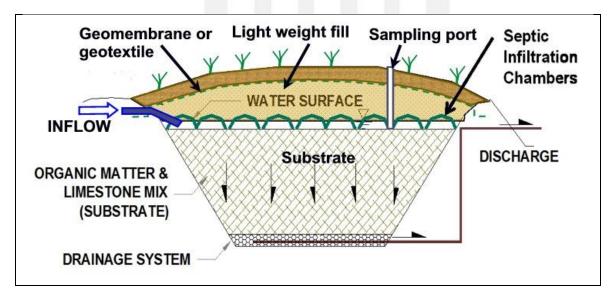


Figure 9 - Covered BCR Cross Section

The following example sites in Table 6 included a BCR cover:

- Ferris Haggarty Mine,
- Standard Mine

- Iron King Mine
- Fran Mine
- Cadillac Mine
- Confidential Site, CA (planned)

The septic infiltration chambers were used successfully at the Iron King Mine and they are included in the detailed design for the confidential site in California.

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ATTACHMENT A
TECHNICAL PAPERS

A PERIODIC TABLE OF PASSIVE TREATMENT FOR MINING INFLUENCED WATER¹

James J. Gusek²

Abstract. The technical community of regulators and engineers that specializes in passive water treatment should be familiar with the passive treatment "decision" tree" that was published by the former US Bureau of Mines about 14 years ago. The decision tree was originally intended to address mining influenced water (MIW) from coal mines. But since then, the breadth of passive treatment has expanded to embrace precious and base metal mines, uranium mines, and even gravel pits. Each MIW has its unique signature, either imposed by the natural geochemical conditions of the ore body and surrounding mine waste, or by resource recovery processes that may include heap leaching or traditional hydrometallurgical technologies. In the context of the elements of the periodic table, the decision tree certainly could be improved as it was originally developed to focus on coal geology derived MIW which typically contains acidity/alkalinity, iron, aluminum and manganese. For example, the expanded decision tree could consider residual ammonia or nitrates from blasting, cyanide from heap leach pad rinsing, trace amounts of selenium, or other parameters that may require passive treatment at a given mine, coal or otherwise. However, developing an individual decision tree for each MIW element or suite of elements and their species would be a daunting task and would probably introduce more confusion where simplicity is desired.

With apologies to Dmitri Ivanovich Mendeleev, a "Periodic Table of Passive Treatment" could become a useful design tool to satisfy the need to embrace a larger range of MIW chemistries. The revised, color-coded table presented in this paper focuses on identifying passive treatment methods that have been observed to work on specific elements or species of elements typically found in MIW that is based on the author's experience or other practitioner's of the technology. The author offers it as a starting point that could be enhanced with further study, to include geochemical modeling and speciation investigations in existing passive treatment systems.

Additional Key Words: MIW, acid rock drainage treatment, metal, coal

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Introduction

The Periodic Table of Elements (PTE) was first introduced by the Russian chemist Dmitri Ivanovich Mendeleev in 1869. Fifty-seven of the elements had been discovered prior to that date, and the rest discovered since then. The scientific and industrial revolution of the 18th and early 19th centuries yielded most of the rest of the elements that Mendeleev categorized. Mendeleev's contribution to science was monumental; he organized the elements into similar groups which we now know are governed by how their atomic structures are arranged. For a more in-depth approach to the PTE from different perspective, the reader is referred to "An Earth Scientist's Periodic Table of the Elements" (Railsback 2004).

The concept of "mining influenced water" was first introduced by Schmiermund and Drozd (1997). It covers the breadth of solutions ranging from what might be termed traditional acid rock drainage (ARD) and neutral mine drainage to the mining process solutions that may be very alkaline such as NaCN solutions used in the recovery of Au or Ag in heap leaching or milling operations. The multiplicity of MIW sources compounds the problems facing engineers charged with designing MIW treatment systems. Consequently, every treatment system, whether active or passive, seems to require some site-specific customization. Before passive treatment approaches to various groups in the PTE can be discussed, it is appropriate to consider the accepted definition of the term "passive treatment". In the past, "constructed wetlands" was in common usage but this term carries much regulatory baggage and is not appropriate for many passive treatment unit processes.

To paraphrase Gusek (2002):

Passive treatment is a process of sequentially removing contaminants and/or acidity in a natural-looking, man-made bio-system that capitalizes on ecological, and/or geochemical reactions coupled with physical sequestration. The process does not require power or chemicals after construction, and lasts for decades with minimal human help.

Passive treatment systems are typically configured as a series of sequential process units because no single treatment cell type works in every situation or with every MIW geochemistry. It is an ecological/geochemical process because most of the reactions (with the exception of limestone dissolution) that occur in passive treatment systems are biologically assisted. Lastly, it is a removal process because the system must involve the filtration or immobilization of the

metal precipitates that are formed. Otherwise, they would be flushed out of the system, and the degree of water quality improvement would be compromised.

Certainly, treating some MIW parameters is considered "easy", such as systems that address Fe and hydrogen ion (the basic unit of acidity). These parameters have been the focus of typical coal geology derived MIW treatment since the early 1980's. In comparison, "difficult" parameters such as common anions (e.g., Na, Cl, and Mg and other components of total dissolved solids [(TDS]) are conserved in traditional passive treatment systems; passive treatment is not considered an appropriate technology. Next are the elements associated with traditional metal mining: Fe, Cu, Pb, Zn, Cd, Hg, and As. These elements are typically found in metal mine ores and wastes as sulfides and passive treatment designers typically focus on creating conditions favorable to sulfide precipitation such as those found in biochemical reactors (BCRs). Fortunately, ARD formation involving pyrite evolves sulfate needed in BCRs; but sulfate in and of itself can become an MIW issue. Aluminum and Mn are special cases worthy of focused consideration.

The compounds associated with MIW that do not receive much attention from a passive treatment perspective might include:

- Ammonia and NO₃ sidue from blasting agents),
- Selenium,
- Uranium and Ra
- Cyanide and CN complexes, and
- Thallium.

The definition of MIW may be driven by regulations. Coal mines typically need to meet effluent standards for: pH, Al, Fe, and Mn. However, it has been this author's experience that coal geology derived MIW typically contains other heavy metals including nickel, Cu, Zn, and Co which are usually removed in lime dosing treatment systems installed at active mines but may not be included in the permit limits. The MIW chemistry from the abandoned Fran Coal Mine in Clinton County, Pennsylvania has much in common with the chemistry of the Berkley Pit MIW in Montana. Fortunately for Pennsylvania, the volume of MIW involved at the Fran Mine is many orders of magnitude less. Regardless, in designing a BCR for the Fran Mine, the non-regulatory parameters needed to be considered because the BCR sizing depends on acidity, Al, and Fe *plus* the concentrations of Zn, et al. Placing these parameters in proper perspective

has been a design challenge for the past 20 years. How can parameters be grouped to streamline the design process? Revisiting Mendeleev's Periodic Table of Elements (since revised) might be a good place to start.

Periodic Table of Elements Review and Typical MIW Related Elements

Oriented horizontally, the PTE (Fig. 1) is organized into seven periods or rows of elements and the Lanthanide and Actinide Series (omitted in Fig. 1). Oriented vertically, there are 18 groups or columns of elements. The noble gases are found on the right side of the table; the H and the cations such as Li, Na, and K are found on the left side of the table. The elegance of this organization is that the elements of a single group tend to behave similarly in chemical reactions and that applies to behavior in passive treatment systems as well. Why this happens is typically not a concern to passive treatment system design engineers but the fact that it does may need to be more fully embraced.

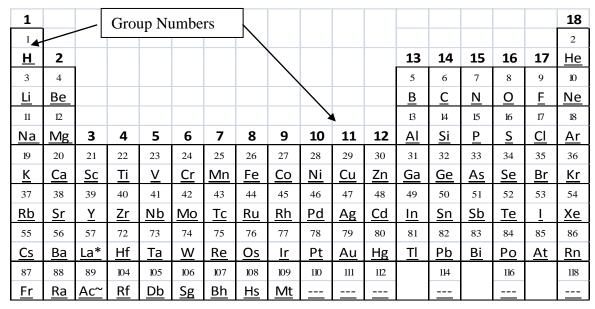


Figure 1 – Simplified Periodic Table of Elements sans Lanthanide and Actinide Series

For the sake of simplicity, the focus of the discussion will be elements and compounds that are problematic or "interesting" ones associated with MIW as summarized in Table 1 below.

Table 1 – Elements and Species of Interest in Passive Treatment Systems

Group	Elements	Common Aqueous Species/Associated Parameters
1	Hydrogen (H), Sodium (Na), and Potassium (K)	TDS, Acidity
2	Magnesium (Mg), Calcium (Ca), Barium (Ba),	TDS, Ra-226
	Radium (Ra)	
3	No traditional MIW elements or compounds	N/A
4	No traditional MIW elements or compounds	N/A
5*	Vanadium (V) and Uranium (U) [*Actinide	V_2O_6, U_3O_8
	Series]	
6	Chromium (Cr), Molybdenum (Mo)	Cr^{+6} , Cr^{+3} , Mo^{+5} , Mo^{+6}
7	Manganese (Mn)	Mn ⁺² , Mn ⁺⁴ , Acidity
8	Iron (Fe)	Fe ⁺² , Fe ⁺³ , Acidity
9	Cobalt (Co)	Co ⁺² , Acidity
10	Nickel (Ni)	Ni ⁺² , Acidity
11	Copper (Cu), Silver (Ag), Gold (Au)	Cu ⁺² , Ag ⁺² , AgCN complex, Au-Chloride?
		AuCN complex, Acidity
12	Zinc (Zn), Cadmium (Cd), Mercury (Hg)	Zn ⁺² , Cd ⁺² , Hg ⁺² , Hg ⁺¹ (organic), Acidity
13	Aluminum (Al), Thallium (Tl)	Al ⁺³ , SO ₄ ⁻² Tl ⁺¹ , Tl ⁺³ , Acidity
14	Carbon (C), Lead (Pb)	HCO ₃ , TOC, BOD ₅ , Pb ⁺² , Pb carbonate
		complex
15	Nitrogen (N), Phosphorous (P), Arsenic (As),	NH_3 , N_2 , NO_2 , NO_3 , PO_4 , As^{+3} , As^{+5} ,
	Antimony (Sb)	multiple As-complexes/ionic species
16	Oxygen (O), Sulfur (S), Selenium (Se)	O ₂ , SO ₄ , Selenite, Selenate
17	Fluorine (F), Chlorine (Cl)	TDS
18	Noble Gases, No traditional MIW elements or compounds	N/A

Predominant Treatment Mechanisms in Passive Systems

The following treatment mechanisms have been thought to prevail in passive systems addressing "traditional" acidic and alkaline MIW.

- Biological sulfate reduction with accompanying alkalinity improvement
- Metal sulfide formation
- Oxidation
- Carbonate dissolution
- Organic complexation
- Plant uptake
- Adsorption

Conventional wisdom and much research has shown that micro-biologically facilitated reduction and oxidation reactions and carbonate dissolution are the most important removal mechanisms and organic complexation, plant uptake and adsorption play minor and/or temporary

roles. The microbiology of passive treatment has become better understood in the past five years and perhaps a "periodic table of microbial activity" might be a logical extension of this paper. Such a paper would link the microbial communities most responsible for the removal of parameters of interest in passive treatment system components.

Periodic Table of Passive Treatment for MIW

From a passive treatment system designer's perspective, there are several basic components available "off-the-shelf" as shown on the traditional passive treatment "decision tree" as shown in Fig. 2.

- Sulfate reducing bioreactors,
- Aerobic wetlands,
- Anoxic limestone drains,
- Aeration & Settling ponds,
- Successive alkalinity producing systems (SAPS), and
- Open limestone channels & limestone beds (not shown).

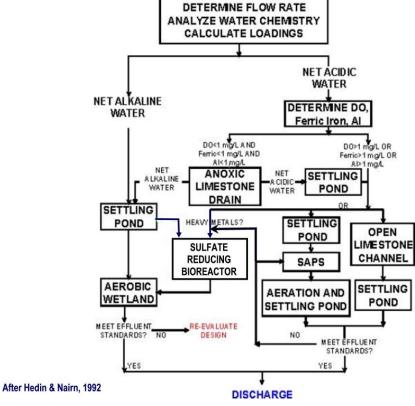


Figure 2 – Traditional Passive Treatment Decision Tree

Recently, the SO_4^{2-} reducing bioreactor has evolved into a more universal MIW passive treatment role. The evolution of the name for this specialized passive treatment unit has included over the years:

- Compost wetland,
- Anaerobic cell or wetland,
- Sulfate reducing bioreactor (SRB or SRBR),
- Vertical flow pond, and most recently,
- Biochemical reactor (BCR).

Many practitioners agree that the "BCR" moniker captures many facets of the technology because it acknowledges both the biotic and abiotic processes involved. BCRs have been known to treat MIW and similar waters for a wide range of contaminants to include the typical suite of heavy metals, and CN, NO₃, SO₄², Se, and several radionuclides. References to guide the interested reader in how these behave in BCRs are provided in Table 3.

The pH of the MIW will control the formation of metal precipitates; some metal species are almost fully pH-dependent; Al is an example as it can precipitate in both oxidizing and reducing conditions. Attempting to fully understand the variety of competing reactions, biological activity, and metal and ionic removal phenomena can be a very daunting task, and may require modeling using geochemical software. While these models typically do not include biological inputs, some can generate pH-Eh diagrams that can be quite useful. In an attempt to simplify matters to a level that will fit the proposed Periodic Table of Passive Treatment, it is assumed that the oxidation reduction potential (ORP) conditions prevailing in the off-the-shelf components will typically control the bio-geochemical reactions that occur there.

Oxides and hydroxides will form typically in aerobic zones and reducing conditions are favorable for the formation of oxides (e.g., U), hydroxides (e.g., Cr and Al), and other reduced species such as sulfides. Table 2 characterizes each component with respect to prevailing ORP conditions. The color coding, when applied to the periodic table, should show at a glance how various elements and groups of elements might be treated passively.

Table 2 – Oxidation Reduction Conditions Prevalent in Conventional Passive Treatment System Components

Passive System Component	Aerobic (ORP > zero mV) Oxidizing Conditions	Anaerobic (ORP < zero mV) Reducing Conditions
Biochemical bioreactors	X (upper 1-2 cm)	X (most of the cell mass)
Aerobic wetlands	X	
Oxidation & settling ponds	X	
Anoxic limestone drains		X
Reducing Cell (RAPS) component in a Successive Alkalinity Producing System (SAPS)	X (upper 1-2 cm)	X (most of the cell mass)
Open limestone channels and limestone beds	X	

Note: Table 2 above does not include emerging technologies that hold promise but may still be under development. Also, while an anoxic limestone drain may exhibit mildly reducing conditions, it is sole design goal is to add alkalinity, not remove metals. Thus it should not be inferred that ALD's are appropriate for the precipitation of certain metals beyond their ability to remove Al and Fe. ORP values assume standard hydrogen electrode.

When the general ORP categories introduced in Table 2 are applied to the PTE based on the author's experience and the available literature, the following guideline results:

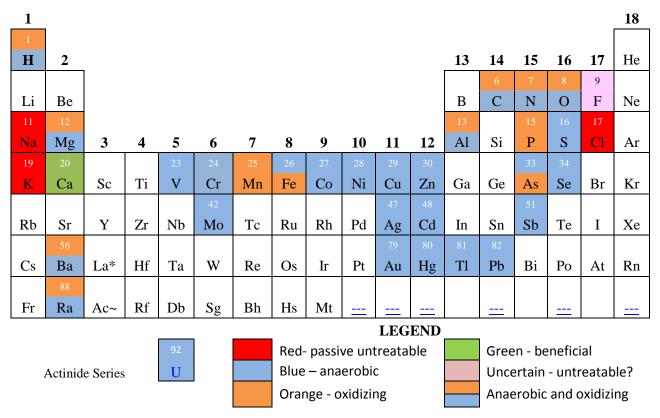


Figure 3 – Proposed Periodic Table for Passive Treatment of MIW

Discussion

In Fig. 3, the red-shaded elements (Na, K, Cl), which may be associated with elevated TDS, are not affected by the off-the-shelf passive treatment processes. Calcium, which is also conserved or involved in the generation of hardness, is a beneficial ion and it is therefore color coded in green. There are specialized situations where elevated fluorine (as F) has been a component of MIW. Being a halide immediately above Cl, passive F removal is not straightforward. In acidic MIW, F solubility is known to be sensitive to pH, but a solid precipitate can be formed only in a very restricted pH range. This condition may be difficult to maintain in a passive treatment system; fluorine is thus color coded a shade of pink.

The discussion will now progress through the elements remaining in the various groups as shown in Table 3. The references are provided to provide guidance for cursory additional research and are not intended to be all-inclusive.

Table 3 – Passive Treatment of Typical Elements and Species in MIW

Group	Element or Species	Suspected or Documented Mechanisms & Passive System Components	Reference
1	Hydrogen ion	H ⁺ can be addressed aerobically and anaerobically: limestone dissolution in ALDs, OLCs, BCRs and SAPS and microbial bicarbonate alkalinity in BCRs or SAPS	Conventional Wisdom (multiple refs)
2	Magnesium	Mg has been observed being removed by the replacement of calcium in limestone to form suspected dolomitic limestone in a pilot BCR in Slovakia; this may occur aerobically as well	Gusek, et al. 2000
2	Barium	Dissolved barium can be precipitated aerobically or anaerobically as the insoluble barium sulfate by comingling with slightly-elevated sulfate bearing MIW	Conventional Wisdom
2	Radium	Ra 226 was observed being removed in a BCR pilot in 1993, probably as RaSO ₄ with barite	Unpublished BCR data & Wanty et al. 1999
5	Vanadium & Uranium	V and U occur naturally in uranium roll front deposits which form in reducing conditions prevalent in BCRs	Whitmer and Saunders 2000
6	Chromium	Reduction to Cr ⁺³ with hydrolysis/ precipitation of chromium hydroxide in BCRs	Ozawa et al. 1995
6	Molybdenum	Molybdenum removal in a pilot BCR was observed in 1994 Precipitation of MnO ₂ facilitated by bacteria and algae;	Unpublished data Conventional
7	Manganese	oxidizing conditions required; presence of limestone is recommended but not required; MnCO ₃ (<i>rhodochrosite</i>) formation suspected in over-loaded BCRs	Wisdom, Robbins & Ziemkiewicz 1999, & other refs
8	Iron	Fe precipitation as ferric oxy-hydroxide in aerobic wetlands, OLCs, oxidation ponds, and the surface zone of BCRs; iron sulfide (FeS) precipitation in BCRs and reducing zone of SAPS	Conventional Wisdom (multiple refs)
9	Cobalt	Cobalt sulfide formation in BCRs	Eger 1992
10	Nickel	Nickel sulfide formation in BCRs	Hammack and Edenborn 1991
11	Copper	Copper sulfide formation in BCRs	Wildeman et al., 1990

Group	Element or Species	Suspected or Documented Mechanisms & Passive System Components	Reference
11	Silver	Silver sulfide formation in BCRs	Conventional Wisdom
11	Gold	Native gold precip. in BCRs is possible but undocumented	?
12	Zinc	Precipitation of sphalerite (ZnS), also sorbs to ochre	Wildeman, et al. 1990.
12	Cadmium	Cd removal in a pilot BCR suspected to be as <i>greenockite</i> (CdS) observed in 1994	Unpublished data
12	Mercury	<i>Meta-Cinnabar</i> (HgS) in BCRs – some uncertainty of Hg methylation in BCRs	Unpublished data
13	Aluminum	Al hydroxide (<i>gibbsite</i>) precipitates at pH >5 in well-buffered MIW in aerobic wetlands, OLCs, SAPS, ALDs; aluminum hydroxysulfate precipitation in BCRs	Conventional Wisdom & Thomas 2002
13	Thallium	Tl sulfide co-precipitation with FeS in BCRs	Blumenstein, et al. 2008
14	Cyanide	CN degradation anaerobically in BCRs	Cellan, et al. 1997
14	Cyanide	CN degradation aerobically by UV light in aerobic wetland	Wildeman, et al. 1994
14	Biochemical Oxygen Demand (BOD)	By-product of BCRs – polished with aerobic wetlands	Conventional wisdom (multiple refs)
14	Lead	PbS (galena) precipitation in BCRs	Wildeman, et al. 1993
15	Ammonia	NH ₃ is oxidized to nitrate in aerobic wetlands and is also utilized by plants	EPA 1988
15	Nitrate/ Nitrite	NO_3 and NO_2 are denitrified in BCRs to N_2	EPA 1988
15	Phosphate	Plant uptake in aerobic wetlands	EPA 1988
15	Arsenic	Removal in aerobic conditions adsorbing to iron oxy-hydroxide and anaerobic (BCR) conditions as sulfide	Wildeman et al. 1994
15	Antimony	Stibnite (Sb ₂ S ₃) formation in hot springs environments may be similar to conditions in a BCR – removal data lacking	?
16	Oxygen	Depressed dissolved oxygen from BCRs is polished with aerobic wetlands; oxygen is required in aerobic wetlands and other situations to precipitate iron.	Conventional wisdom (multiple refs) Conventional
16	Sulfate	Sulfate is removed by microbial conversion to sulfide in a BCR	wisdom (multiple refs)
16	Sulfide	Sulfide is scavenged by sacrificial metals such as zero valent iron	Conventional wisdom (multiple refs)
16	Selenium	Selenium is removed by microbial conversion to elemental selenium or iron selenide precipitates in a BCR	Conventional wisdom (multiple refs)

Summary

The proposed Periodic Table of Passive Treatment (PT²) offers another view of the sometimes complicated picture of conflicting priorities in treating MIW passively. In some instances, the author has no specific experience with a particular element (e.g., Sb) and was not successful in finding a reference in the over 3,000 technical papers found in the combined

proceedings of the American Society of Mining and Reclamation (ASMR), International Conference on Acid Rock Drainage (ICARD), the West Virginia Acid Mine Drainage Task Force Symposia, and the Tailings and Mine Waste Conferences.

As suggested earlier, the proposed PT² is a starting point to a more complete understanding of the complicated bio-geochemistry behind the passive treatment design process. It should be considered a logical expansion of the former USBM passive treatment decision tree and like Mendeleev's original work over 130 years ago, should be the focus of future enhancement. This might consist of geochemical modeling, investigations into the speciation of precipitate formation in different passive treatment cell types or zones within those types, and studies that might identify specific microbiological suites associated with or that have adapted to given elements.

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