APPENDIX B

Selenium Treatment System Conceptual Designs

TABLE OF CONTENTS

1.0 Selenium Treatment 1
2.0 Selenium Removal Mechanisms 2
2.1 Precipitation 2
2.1.1 Selenate (Se+6 or SeO4-2) 3
2.1.2 Selenite (Se+4 or SeO3-2) 3
2.1.3 Elemental Selenium (Se0) 4
2.1.4 Selenide (Se-2) 4
2.2 Extraction 5
2.2.1 Adsorption 5
2.2.2 Ion Exchange 6
2.2.3 Solvent Extraction 6
2.3 Filtration 6
2.3.1 Reverse Osmosis (RO) 6
2.3.2 Nanofiltration 7
2.3.3 Emulsion Liquid Membranes 7
2.4 Volatilization 8
3.0 Selenium Treatment Technologies 9
3.1 Chemical Source Control 9
3.1.1 Smoky Canyon Source Control Treatability Studies 9
3.2 Passive Treatment 11
3.2.1 Smoky Canyon Passive Treatability Studies 11
3.2.2 Constructed Wetlands 12
3.3 Active Treatment 13
3.3.1 Iron Co-precipitation 13
3.3.2 Membrane Filtration 14
3.3.3 Biological Selenium Reduction 14
4.0 Conceptual Treatment Designs 16
4.1 Hoopes Spring Active Water Treatment 16
4.2 Lower Pole Canyon Creek Passive Water Treatment 18
4.3 Seep Passive Water Treatment 18
5.0 References 20

LIST OF FIGURES

Figure	Title
B-1	Eh-pH diagram for selenium for typical conditions at Hoopes Spring
B-2	Eh-distribution diagram for selenium for typical conditions at Hoopes Spring (pH=8)
B-3	Conceptual Design for Hoopes Spring Biological Selenium Reduction Treatment
B-4	Conceptual Design for Passive Seep Treatment

1.0 SELENIUM TREATMENT

This appendix describes the conceptual water treatment system designs used for development and evaluation of EECA alternatives. The conceptual designs (Section 4) represent the most promising treatment technologies for specific settings at the Site (i.e., Hoopes Spring, Pole Canyon Creek and overburden disposal area seeps). The technologies were selected based on a review of general treatment technologies (Section 2) and specific information from work at the Site and at other locations (Section 3).

2.0 SELENIUM REMOVAL MECHANISMS

There are four major removal mechanisms for selenium that can be utilized by treatment systems:

- Precipitation
- Extraction
- Filtration
- Volatilization

Precipitation is controlled by the solubility of crystalline or amorphous minerals. When the concentrations of the elements that compose the mineral reach a given level (the saturation index), the mineral will precipitate from solution.

Extraction can be defined as the removal of the element from the aqueous solution via a solid or immiscible liquid that has a greater affinity for the element than the aqueous solution. Unlike precipitation, the element remains in a dissolved state but is sequestered on the surface of a solid or within an immiscible liquid in contact with the water.

Filtration is the physical removal of the ionic element from the aqueous solution. Removal is accomplished using very small pore spaces (i.e., nanometer-sized openings) in the filtration membrane and high pressures to force small ions and molecules through the pores while retaining larger ions and molecules.

Volatilization is the removal of an aqueous element by converting it to a gaseous phase. In the case of selenium, it is converted to dimethyl selenide via biological mechanisms.

Oxidation or reduction of selenium—via abiotic or biotic mechanisms—plays a critical role in many of the treatment technologies available. For instance, precipitation of selenate minerals does not happen until the concentration of the mineral constituents are very high, but if the selenate can be reduced to elemental selenium it will readily precipitate even at relatively low concentrations.

2.1 Precipitation

Precipitation can further be divided into:

- Selenate (Se^{+6} or SeO_4^{-2})
- Selenite (Se^{+4} or SeO_3^{-2})
- Elemental selenium (Se_0)

- Selenide (Se^{-2} or HSe^{-})

A pH-Eh diagram for selenium is shown in Figure B-1. This type of diagram is useful in understanding the relationship between the species within natural aquatic systems.

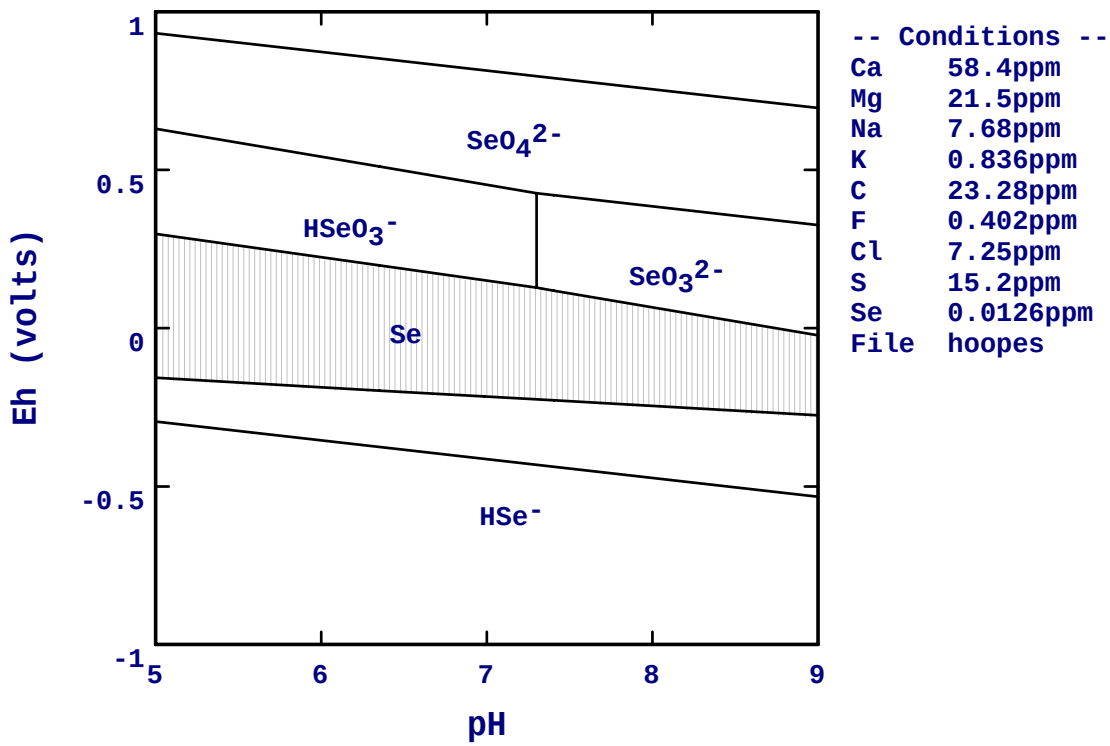

Figure B-1 Eh-pH diagram for selenium for typical conditions at Hoopes Spring.

2.1.1 Selenate (Se^{+6} or SeO_4^{-2})

Selenate precipitation as a treatment technology is not feasible nor capable of obtaining water quality criteria due to the high solubility of selenates. Selenate precipitation as a key treatment process will not be discussed due to its shortcomings.

2.1.2 Selenite (Se^{+4} or SeO_3^{-2})

Although selenite precipitates are slightly less soluble than selenate precipitates, they are still too soluble to be a viable treatment technology to achieve water quality criteria. For the Smoky Canyon Mine Site where the majority of selenium is present as selenate, chemical or biological reduction from selenate to selenite would need to be an integral part of the treatment system. However, due to the shortcomings of selenite precipitation as a key treatment process, it will not be discussed further.

2.1.3 Elemental Selenium (Se^0)

Elemental selenium is fairly insoluble in neutral pH water given the appropriate reducing environment. The Eh-pH diagram in Figure B-1 shows the 'window' where elemental selenium dominates. Figure B-2 shows a distribution diagram for selenium at a pH of 8 (essentially a cross-section of Figure B-1 at pH=8). Notice that elemental selenium is highly insoluble between an Eh of roughly 0.1V to -0.2V. Chemical or biological reduction of the selenate to elemental selenium would be required as an integral part of the treatment.

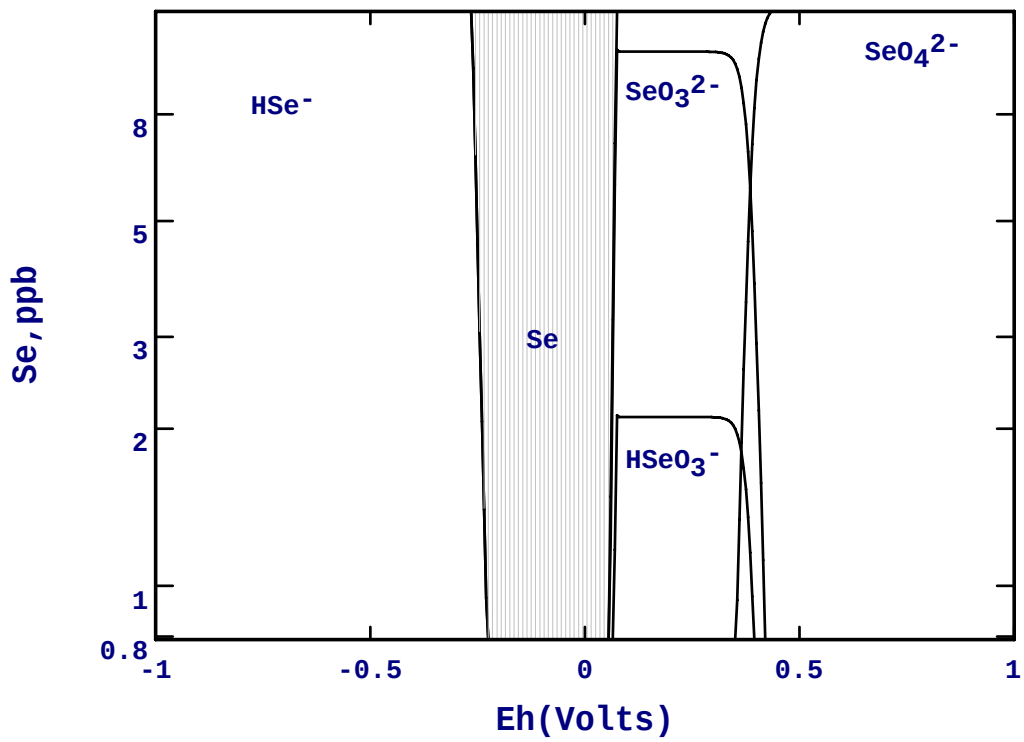

Figure B-2 Eh-distribution diagram for selenium for typical conditions at Hoopes Spring (pH=8).

2.1.4 Selenide (Se^{-2})

Many metal selenides are highly insoluble and follow a similar hierarchy as metal sulfide solubilities. A limiting factor is that in order for this to be a viable treatment option, the metals must be present at high enough concentrations to precipitate the selenide to an acceptable aqueous concentration.

2.2 Extraction

Extraction can be defined as the removal of dissolved selenium via contact of the impacted water with a solid or immiscible liquid that has a greater affinity for the selenium than the aqueous solution. The selenium remains in a dissolved state but is sequestered on the surface of a solid or within an immiscible liquid in contact with the water.

Sequestration of dissolved selenium on the surface of a solid is called adsorption or ion exchange, and sequestration within an immiscible liquid is called solvent extraction. Adsorption, ion exchange, and solvent extraction are discussed in more detail below.

2.2.1 Adsorption

Adsorption is the result of solid-liquid interactions in which dissolved selenium is electrostatically bound to the surface of the solid. The adsorbed selenium ion does not change the surface of the solid and it can be removed or exchanged by other ions (Hem, 1992).

Balistrieri and Chao (1990) studied adsorption of selenium by amorphous iron oxyhydroxides (i.e., ferrihydrite) and manganese dioxide. They found that the iron solid adsorbed more selenium than the manganese solid and that selenite adsorption increases with decreasing pH. They also found that the presence of phosphate and silicate ions reduces the iron oxyhydroxide's effectiveness for adsorbing selenite due to competition for sorption sites.

Su and Suarez (2000) determined that amorphous ferrihydrite can adsorb more selenate and selenite than crystalline goethite with the selenite adsorption edge between pH 9-11 and selenate adsorption edge between pH 5-8 (ferrihydrite) and pH 3-6 (goethite). Selenate adsorption was greatly influenced by ionic strength. Increasing ionic strength decreased the pH of the selenate adsorption edge.

Ferrihydrite adsorption of selenium has been identified by the EPA as the Best Demonstrated Available Technology for selenium removal (Rosengrant, et al.; 1990). However, this report may be antiquated because it does not include technologies that have emerged in the past 15 years.

Alumina adsorption of selenium has been evaluated at the laboratory and pilot scales. Activated alumina is more effective at adsorbing selenite than selenate but is not as effective as ferrihydrite adsorption. The pH range for alumina to be effective at adsorbing selenite is between 3 and 7, with decreasing effectiveness with increasing pH. Phosphate, silicate, sulfate, and bicarbonate have all been shown to be inhibitors to selenite/selenate adsorption (Montana Tech and MSE, 1999).

2.2.2 Ion Exchange

Ion exchange is in effect adsorption, but the sorption sites are occupied by loosely bound ions that are replaced by ions from the solution that have a greater affinity for the sorption media (Ramalho, 1983).

Ion exchange is a natural process that occurs within many aquifers that contain clay minerals or high levels of humic material (Drever, 1997; Hem, 1992). Synthetic resins have been in use for treating waste water since the 1940s (Ramalho, 1983).

Natural and synthetic ion exchange materials work under the same principle—they retain divalent ions (Ca^{+2}, SeO_4^{-2}) and exchange out monovalent ions (Na^+, Cl^-). There are specific resins for cation exchange and anion exchange and these resins can be regenerated when the exchange capacity is reached.

2.2.3 Solvent Extraction

Solvent extraction involves two immiscible liquid phases in contact with each other (i.e. water/oil) in which the aqueous selenium has an affinity for the oil phase. This removes the selenium from the water and concentrates it in the oil phase.

For the removal of selenium, this technology has not been tested beyond the pilot scale (Montana Tech and MSE, 1999).

2.3 Filtration

The direct removal of dissolved selenium via filtration is accomplished using membranes with pores small enough to exclude the selenium ions. The major filtration method is reverse osmosis (RO), but nanofiltration and liquid emulsions have also been tested as filtration methods for dissolved selenium (Montana Tech and MSE, 1999).

2.3.1 Reverse Osmosis (RO)

Reverse osmosis (RO) is the process of separating water from a solution (i.e., water + cations/anions) by forcing the water through a semi-permeable membrane that does not allow the passage of most ions. Separation is achieved by applying a pressure on the solution greater than the osmotic pressure (Ramalho, 1983). The effluent from an RO system is split into two streams—the permeate and the reject. The permeate stream is water with little to no ions while the reject stream is the concentrated ions. The ratio of the permeate stream to the reject stream is dependent on the total dissolved solids (TDS) in the influent water, the applied

pressure, and the pore size of the semi-permeable membrane. In general, higher TDS concentrations equate to proportionately larger reject streams.

RO systems are susceptible to fouling resulting in a higher rejection rate or an increased operating pressure. Fouling can be caused by suspended solids coming in contact with the membrane, mineral scaling due to the increased concentration of salts in contact with the membrane, or biological growth on the membrane (Ramalho, 1983).

While RO systems have be shown effective treatment systems they still produce a reject stream with concentrated selenium that will require treatment such as evaporation or other treatment technologies listed herein.

2.3.2 Nanofiltration

Nanofiltration is essentially RO with a more permeable membrane allowing more ions to pass through. The required operating pressures are lower than RO, but the contaminant concentration in the permeate will be higher. A nanofiltration membrane is slightly different than a RO membrane in that it has a hydrophobic component that allows monovalent salts (Na^+, Cl^-) to pass through but divalent salts (Ca^{+2}, SeO_4^{-2}) to be rejected (Sobolewski, 2005).

Nanofiltration systems are susceptible to the same fouling mechanisms as RO, but because the reject stream is not as concentrated, fouling occurs at a slower rate.

Since a reject stream is created with a nanofiltration system, there would be a need for secondary treatment of the selenium concentrated in the reject stream.

2.3.3 Emulsion Liquid Membranes

Emulsion liquid membranes utilize an emulsified organic liquid in contact with the impacted water to extract the dissolved selenium. Within the organic liquid droplets, there are emulsified droplets of an aqueous phase. The selenium passes from the bulk phase into the organic liquid and is ultimately accumulated in the internal aqueous phase. The selenium-enriched immiscible organic liquid is separated from the mixture, it is demulsified, and the internal aqueous phase containing the selenium is extracted.

Emulsion liquid membranes have only been tested for selenium removal at the laboratory and pilot scales (Montana Tech and MSE, 1999). Although this type of technology was effective at the pilot scale, it is still too under-developed to be discussed further or considered a viable treatment option for the Site.

2.4 Volatilization

Selenium can be volatilized, via microbial or phytological processes, from an aqueous solution. This process permanently removes selenium from soil and water under aerobic conditions. It is thought that microbes and plants use this process to avoid selenium toxicity. The process basically converts selenate/selenite to dimethylselenide (DMSe) via biomethylation then the DMSe is volatilized to the atmosphere (Frankenberger and Benson, 1994).

Soil temperature has been found to be an important factor in the rate of selenium volatilization with higher rates occurring at warmer temperatures. At a seasonal level, higher rates were observed in spring and summer; whereas at a diurnal level, higher rate were observed during mid-afternoon (Frankenberger and Benson, 1994).

The majority of research completed with respect to selenium volatilization has occurred within natural and constructed wetlands (Lin and Terry, 2003; Gao, et al., 2003; Zhang and Moore, 1997). Gao et al. (2003) determined that approximately 2% of the selenium in the influent is volatilized in a constructed wetland. However, microalgal isolates have been shown to be capable of removing upwards of 90% of the influent selenate via accumulation/volatilization (Neumann, et al., 2003).

3.0 SELENIUM TREATMENT TECHNOLOGIES

This section describes the treatment technologies that have been evaluated for selenium removal or source control at various sites as well as treatability studies completed at the Smoky Canyon Mine.

Selenium treatment technologies can be divided into three groups based on the objective of the technology:

- Source control
- Passive treatment
- Active treatment

Source control technologies target limiting or preventing the release of selenium from the original source (i.e. overburden within the disposal area). Passive treatment technologies target treating selenium in water but do so in such a manner as to require the least amount of operation/control of the treatment system. Active treatment technologies also target treating selenium in water but require much more operator intervention and process controls than passive systems. These three groups will be discussed in greater detail in the text below.

3.1 Chemical Source Control

Source control technologies are defined as technologies designed to limit or prevent the release of selenium from the overburden. These types of technologies target stopping or minimizing the mechanisms responsible for selenium release (e.g., oxidation) within the overburden and selenium transport from the overburden.

The effective implementation of source control technologies can create a long-term disposal setting without the need for perpetual secondary treatment systems.

3.1.1 Smoky Canyon Source Control Treatability Studies

Source control treatability studies were completed at a bench-scale and on the Pole ODA to determine the effectiveness of amendments to the surface of the ODA or the shallow subsurface of the ODA for reducing the rate of selenium release from the overburden. Effectiveness of amendments added to the Pole ODA was determined by collecting and analyzing pore water via lysimeters installed immediately below the amendment layer.

At a bench-scale, Bond (2000) evaluated the effectiveness of source control via soluble amendments and solid amendments. The soluble amendments tested were Amisorb, ferric

iron, and ferric iron + Amisorb. The test results indicated that the reduction in selenium released is directly related to the addition rate. The largest reduction (in comparison to the control) was approximately 80% with the ferric amendment, while the ferric + Amisorb amendment was more effective than Amisorb alone. Ten different solid amendments were also tested: a sulfate reducing bacteria inoculum (SRB), colloidal iron, scrap iron, scrap iron + SRB, potato starch (PS), PS + SRB, ferric + Amisorb, ferric + Amisorb + SRB, potato waste (PW), and PW + SRB. After four weeks of testing these amendments in a saturated soil paste, all but colloidal iron and SRB reduced the amount of selenium released by greater than 98%. The addition of SRB with the various amendments had no significant effect.

Munkers (2000) completed bench-scale testing of two more solid amendments—cheese whey and cheese whey + colloidal iron—using the same approach as Bond with results indicating between 85% and 99% reduction in selenium released. The greatest reduction occurred with the cheese whey + colloidal iron amendment. Additionally, Munkers tested these solid amendments within saturated, closed batch-reactors over a period of about 12 days. All reactors, including the control, showed a reduction in redox potential and substantially reduced selenium concentrations to less than 0.5 µM (<40 µg/L) within the 12 day test. To determine if the reactors could return to anaerobic conditions after the introduction of oxygen, the iron amended reactor was pumped with air then resealed and within the next 12 days returned to essentially the same redox potential as before the air introduction.

Field studies were completed on the Pole ODA by Munkers (2000) using cheese whey and granular iron as overburden amendments during the spring and summer of 1999. This study included three test fields (30m long by 8 m wide), with 3 lysimeters placed in each test field at a depth of 1m. The surface of the first test field was amended with cheese whey, the second was amended with iron granules, while the third was an untreated control. There was a marked difference in pore water selenium concentrations measured in the lysimeters between the control and the two amended areas during the first sampling, but as the summer progressed, the difference in pore water selenium concentrations diminished. The author hypothesized that this was due to the snowpack and spring precipitation pushing last summer's oxidized selenium further into the subsurface. Since this was not seen in the amended areas, the author inferred that the amendments prevent migration of selenium from the surface into the subsurface.

Munkers (2000) also amended the subsurface of the Pole ODA with granular iron, potato waste, and a mixture of both amendments during the spring of 1999. A large trench was dug within the spoil pile (60m long x 15 m wide x 5.5 m deep) and divided into four equal sections (roughly 56m^2 each). Four pan lysimeters were installed in each treatment section at a depth of approximately 12 feet below ground surface (BGS) with the amendments placed at approximately 10 feet BGS. Overall, the three amendments all reduced the selenium concentration of the pore water, as measured via the lysimeters, with the most effective amendment being the granular iron + potato waste (>80% reduction in comparison to the control).

In addition, Moller reportedly installed a trench just above the toe of the ODA and infiltrated 10,000 gallons per day of cheese whey for approximately one week. Concentrations of selenium in Pole Canyon Creek water exiting the ODA reportedly dropped to approximately 50 µg/L, although no data have been formally documented. Selenium concentrations in lower Pole Canyon Creek quickly rebounded once addition of whey ceased.

3.2 Passive Treatment

Passive treatment technologies are defined as technologies designed to remove aqueous selenium from surface water or groundwater with minimal amounts of O&M required. These types of technologies utilize gravity, long-term reagent/nutrient sources, and enhanced natural settings to minimize the need for operator intervention or complex treatment controls.

3.2.1 Smoky Canyon Passive Treatability Studies

Passive treatment treatability studies were completed at both bench-scale and pilot scale using lower Pole Canyon Creek and D-Panel ODA seep water, respectively.

Bond (2000) completed a bench-scale study on Pole Canyon Creek water collected from the toe of the ODA. The water was treated by:

1. Addition of ferric iron (5, 10, and 25 mg/L),
2. Addition of ferric iron (10 mg/L) with the addition of a corrosion inhibitor (thermal polyaspartate [Amisorb]),
3. alumina (1 and 10 g/L),
4. zero-valent iron (0.1%, 1%, and 10%), and
5. activated carbon (1 and 10 g/L).

In summary, the results indicated that zero-valent iron was the most effective at selenate removal followed by activated carbon. Treatment effectiveness was highly dose-dependent. For example, the initial selenium concentration was 680 µg/L and the zero-valent iron dosages of 0.1wt%, 1.0wt%, and 10wt% resulted in selenium concentrations of 490, 135, and 2 µg/L, respectively. Only the 10wt% dosage would provide water that meets the removal action goal for routine water use (50 µg/L), while both the 1.0wt% and 10wt% dosage would provide water meeting the removal action goal for transient water use (201 µg/L).

At a pilot scale, a field study was completed during the summer of 2001 that evaluated the efficacy of using subsurface bioreactors to treat seepage from the D-panel (Moller, 2002). The bioreactor had a 4,000-gallon capacity and was loaded with approximately 100 lbs of seep sediment for a bacteria source, 400 lbs of powdered iron (powdered instead of granular to get a

higher surface area to mass ratio), and filled with plastic bio-rings. The residence time of the seep water in this reactor was roughly 5 days. During the first 3 months of operation, cheese whey was used as a carbon source while compost was used during the latter 3 months. Cheese whey achieved roughly 75% reduction of selenium in seep water while the compost achieved greater than 90% reduction.

3.2.2 Constructed Wetlands

Constructed wetlands have been studied at the laboratory, pilot-study scale and full-scale for a number of years (ITRC, 2003). This type of treatment system works by multiple mechanisms but is more effective if the selenium is in the selenite form versus the selenate form. Numerous studies have identified the fate of the selenium entering the constructed wetland (Zhang et al., 2004; Lin & Terry, 2003; Gao et al., 2003) and the effectiveness of the various removal mechanisms (Zhang et al., 1997; de Souza et al., 1999; Carvalho & Martin, 2001).

There are basically two types of constructed wetlands—surface flow and subsurface flow (ITRC, 2003). Subsurface constructed wetlands are roughly 60% more costly to construct and operate than surface wetlands (Halverson, 2004; USEPA, 2000a; USEPA, 2000b). The major reason a subsurface wetland would be used over a surface wetland would be the potential for the contaminant(s) of concern to bioaccumulate to toxic concentrations within the plants and animals using the wetland (ITRC, 2003).

A variety of factors affect the cost of a constructed wetland (ITRC, 2003):

- Detention time (influenced by climate)
- Treatment goals
- Media type
- Pretreatment type
- Number of treatment cells required (more cells equate to more hydraulic control structures, etc.)
- Source and availability of gravel media
- Terrain

The average construction cost of a surface flow wetland is $22,000/acre and a subsurface flow wetland is $87,000/acre (ITRC, 2003).

A petroleum refinery in Richmond, California utilizes a constructed wetland to treat effluent containing 10-30 µg/L selenium at 1,000 gpm. They've had to do many modifications to the original design to limit bird access to the wetland because of an increased rate of deformities amongst young birds. Sobolewski (2005) estimated that this system cost $1-3 million to design

and construct, $50-100K in O&M, and could be capable of removing 80-95% of the influent selenium concentration.

It is noted that climate is a factor in the effectiveness of passive systems. The relatively cold winters at the Smoky Canyon Mine Site would make operation difficult.

3.3 Active Treatment

Active treatment technologies are defined as technologies designed to remove aqueous selenium from surface water or groundwater within a highly controllable treatment plant. They require more operator control than passive treatment systems, but in return offer greater selenium removal efficiency and process controllability.

The most common types of active treatment systems implemented for selenium removal include iron coprecipitation, membrane filtration, and biological selenium reduction (Sobolewski, 2005).

3.3.1 Iron Co-precipitation

Iron co-precipitation is listed by EPA as the Best Demonstrated Available Technology (BDAT) for the removal of selenium (Rosengrant et al., 1990). This type of active treatment plant has been implemented at two mines in South Dakota and one in Idaho (Sobolewski, 2005). At the Richmond Hill Mine in Lead, SD, the iron co-precipitation plant was installed in 1994, it took over three years to optimize, and the best effluent selenium concentrations ranged from 12-22 µg/L. This type of active treatment system has also been implemented at the Homestake Mine in Lead, SD, and the Dry Valley Mine, ID. These two latter treatment systems utilize pre-treatment with zinc powder to reduce the selenate to selenite prior to iron co-precipitation.

No associated costs were available for the treatment plants discussed above, however, costs were generated during a treatability study completed at the Kennecott Utah Copper Corporation's Garfield Wetlands-Kessler Springs (MSE, 2001). In this study, they treated selenium-impacted water (2,000 µg/L) using iron co-precipitation and projected the costs for a full-scale treatment plant operating at 300 gpm to be $1M in capital costs and $2M in annual O&M. These costs equate to roughly $14 per 1,000 gallons treated. An earlier pilot study referenced by Sobolewski (2005) and completed in 1986 indicated that to treat a selenium-impacted water (40-60 µg/L) the per unit cost would be roughly $0.50 per 1,000 gallons treated, however, Sobolewski indicated that these costs were very optimistic.

Additionally, this technology has been applied in conjunction with an active sand filter that has the potential to make this technology more effective at selenium removal and reduce the volume of sludge produced. This joining of technologies is still in its infancy but may be a viable method of employing iron co-precipitation in a more cost-effective manner.

3.3.2 Membrane Filtration

Sobolewski (2005) summarized membrane filtration costs for the Richmond Hill Mine near Lead, SD. This reverse osmosis system treats effluent from an iron precipitation plant that does not remove selenium to discharge levels. Their RO system is a secondary treatment system that reduces the selenium concentration from 12-22 µg/L to < 2 µg/L. The influent to this system is roughly 200 gpm and the permeate is only half of this flow (100 gpm) with the remainder being the reject which is recycled back to the iron precipitation plant. This treatment plant has a filtration pre-treatment step to reduce the TSS load on the membranes, and they have been contemplating the addition of a softening pre-treatment to reduce the fouling of the membranes due to calcium precipitation. During the winter months, the water must be heated to 15 ^{o}C to prevent cold-induced precipitation on the membranes.

An RO treatment system similar to the one implemented by the Richmond Hill Mine (200 gpm) would have a capital cost of roughly $1.4 million (including the pre-filtration unit) with annual O&M costs of roughly $0.6 million (Sobolewski, 2005). These costs do not include the disposal of the brine (i.e., reject) which was roughly half of the influent flow rate (100 gpm) at the Richmond Hill Mine.

Nanofiltration is potentially less costly because it runs at lower operating pressures and is subjected to less fouling, but there have been no full scale applications of nanofiltration at mine sites (Sobolewski, 2005).

3.3.3 Biological Selenium Reduction

Active biological selenium reduction (BSR) treatment plants have been implemented at two mines—Wharf Resources Mine in Lead, SD and Zortman-Landusky Mine in north central Montana (Sobolewski, 2005), and evaluated at a pilot-scale side-by-side with iron co-precipitation at the Kennecott Utah Copper Corporation's (KUCC) Garfield Wetlands-Kessler Spring (MSE, 2001).

Basically, a BSR treatment plant is an anaerobic bio-reactor filled with activated carbon, plastic bio-rings, or gravel where the attached bacteria reduce selenate/selenite to elemental selenium. Nutrients and organic carbon are added to the influent to sustain the bacteria while pH and oxidation-reduction potential are tightly controlled.

BSRs are susceptible to fouling and short-circuiting due to accumulation of extracellular biological material, mineral precipitation (e.g., CaCO3), and elemental selenium. Sobolewski (2005) states that these potential problems could be addressed in a pilot-study.

The Wharf full-scale system and the pilot-scale testing completed at KUCC were effective at removing the selenium and discharging water containing less than 2 µg/L selenium. However,

neither system addresses the excess organic carbon in the effluent contributing to biological oxygen demand (BOD). In the winter months, the influent water temperature at the Wharf mine is between 1.5 – 4°C and to achieve the desired selenium reduction additional nutrients and carbon are added. This increased nutrient and carbon loading causes the bioreactor to reach lower oxidation-reduction potentials which establishes an environment conducive to ammonia and sulfide production (Sobolewski, 2005).

Sobolewski (2005) summarized the capital and O&M costs for the Wharf and Zortman-Landusky BSR treatment plants. The Wharf BSR treatment plant operates at flow rates of 40-300 gpm with an influent selenium concentration of 15 µg/L (selenate). The Wharf BSR's capital cost was <$1M with an annual O&M cost of $40-60K. The Zortman-Landusky BSR treatment plant operates at flow rates of 75-300 gpm with an influent selenium concentration of 500-700 µg/L, and an effluent selenium concentration of 100 µg/L (discharge does not meet surface water criteria and the effluent is land applied). The Zortman-Landusky BSR's capital cost was $3M with an annual O&M cost of $250K. MSE (2001) estimated the capital and annual O&M costs for a BSR, operating at 300 gpm, to treat the KUCC spring (1,600 µg/L selenium). The capital cost of the system was estimated to be $0.6M (utilizing existing tanks) and the annual O&M costs were estimated to be $135K.

None of the BSR treatment plant costs listed above include secondary treatment (aeration) for consuming BOD and removing ammonia. It may be necessary to include a secondary treatment such as a conventional activated sludge system, a sequencing batch reactor, or a constructed wetland to re-oxygenate the effluent and consume the excess BOD/ammonia before discharging to the receiving stream. The size of this secondary treatment system is dependent on the BOD loading rate from the effluent of the BSR. It is estimated that the secondary treatment system could increase the capital and O&M costs by 70% (Frigon, 2005 pers. comm.).

4.0 CONCEPTUAL TREATMENT DESIGNS

This section describes the conceptual treatment designs for the removal or attenuation of selenium from surface water that are used in the EECA alternatives and evaluation. Specifically, the following text describes the conceptual treatment designs for Hoopes Spring, seeps emanating from various overburden disposal areas, and lower Pole Canyon Creek where it emerges from the toe of the Pole Canyon Creek overburden disposal area. The technologies have been selected based on the information provided in Section 3 as showing the most promise for each setting. It is noted that any treatment system would need to be pilot tested to verify that it could be implemented effectively for specific Site conditions.

4.1 Hoopes Spring Active Water Treatment

The conceptual design of the Hoopes Spring active water treatment plant is based on biological reduction of selenate/selenite to elemental selenium (Lortie et al., 1992; MSE, 2001; Montana Tech and MSE, 1999; Sobolewski, 2005; Cantafio et al., 1996), and is shown in Figure B-3. This technology was chosen because of the proven effectiveness at various mine sites with similar selenium concentrations and discharge limits, its lower cost, and its lower waste stream production.

In short, specific types of bacteria reduce oxidized forms of selenium (selenate and selenite) to elemental selenium which then precipitates from solution. The elemental selenium is flocculated, settled, and removed from the treatment system as sludge via a filter press or clarifier. The treated water is re-oxidized to consume excess biological oxygen demand (BOD) and to bring the dissolved oxygen concentration to within acceptable limits for surface water. The treated water would be discharged back to the Hoopes Spring drainage.

This active treatment plant design requires that the influent be amended with nutrients and dissolved organic carbon to enable the microbial community within the treatment bioreactor to thrive. The nutrients required for optimal bacterial growth and selenium reduction include nitrate and phosphate. The nutrient and carbon dosing rates are highly dependent on the amount of nutrients in the influent water, the selenium concentration and oxidation state, the dissolved oxygen concentration, and the concentration of other constituents (e.g., iron and manganese) that may act as barriers to reaching the desired oxidation-reduction potential (ORP) for elemental selenium precipitation. A pilot study would be required to determine the most effective carbon and nutrient dosing rates. Additionally, various sources of carbon have been shown to be effective but the carbon unit costs vary significantly with more costly carbon sources providing higher carbon utilization efficiency.

Biological selenium reduction efficiency is sensitive to the pH within the bioreactor and the dominate strain of selenium reducing bacteria. Cantafio et al. (1996) found that selenium reduction efficiency for *Thauera selenatis* was only obtained when the influent pH was lowered from 7.0 to 6.5, whereas *Pseudomonas stutzeri* achieve effective selenium reduction between a pH of 7 to 9 (Lortie et al., 1992). In practice, the bacterial community within the bioreactor will depend on the carbon source, the bacterial inoculation source, and the bacteria within the influent water. The results of the pilot study would be used to determine the optimal pH range for the bioreactor.

The bioreactor design would consist of a sealed vessel filled with a medium for bacterial growth and attachment. Various types of bioreactor media have been tested including gravel, granular activated carbon, and plastic rings/spheres/saddles with costs increasing as the effective surface area increases. Gravel is the least expensive medium with the lowest effective surface area, but has the highest potential for plugging due to bacterial extracellular material and/or inorganic precipitates (e.g., calcium carbonate, calcium sulfate, elemental selenium). A gravel-filled bioreactor would need to be oversized—in comparison to using other media—to retain the same retention time. Plastic rings/spheres/saddles are the most expensive medium and have the highest effective surface area. A bioreactor filled with this medium can be substantially smaller—in comparison to other media—and there should be little to no problems with bioreactor plugging due to the high void volume of the medium.

The bioreactor effluent will contain particulate elemental selenium, biological particulate (detached biofilms), and potentially carbonate/sulfate mineral precipitates that will need to be extracted from the effluent via flocculation/clarification or filtration. The results of the pilot study would be used to determine the most appropriate particulate extraction method. The most effective extraction method will depend on many factors including the mineral precipitation rate, the settling characteristics of the floc, backflush requirements, etc. Since the resulting sludge will contain a significant amount of concentrated selenium, it may need to be handled and disposed. Information has not been identified for sludge management for the Wharf plant. It is likely that the system could be operated to generate sludge that is not a characteristic hazardous waste, however, this would need to be verified by pilot scale treatability testing. The filtrate will contain excess organic carbon that will need to be consumed prior to discharge. Aeration and carbon consumption can be accomplished using either an active system such as an aerobic digester or a passive system consisting of a series of ponds, riffles, and drop structures. An active system would have a smaller footprint and aeration rates can be controlled more precisely. The size of the aeration system would depend on the excess carbon concentration in the effluent, the water temperature, and the results of the pilot study could be used to appropriately size this system. Further treatment to remove ammonia may also be necessary.

4.2 Lower Pole Canyon Creek Passive Water Treatment

The conceptual design for the lower Pole Canyon Creek passive water treatment is based on biological reduction of selenate/selenite to elemental selenium (Lortie et al., 1992; MSE, 2001; Montana Tech and MSE, 1999; Sobolewski, 2005; Cantafio et al., 1996) enhanced by the addition of powdered zero-valent iron (Zhang et al, 2005). The conceptual design is shown in Figure 5-4 (in EECA text).

Moller (2005) completed a treatability study at the toe of the Pole Canyon overburden disposal area in August 1999 in which a 200-ft long trench was placed slightly up-gradient from the emergence of lower Pole Canyon Creek. The trench was lined with powdered zero-valent iron, and then 10,000 gallons of cheese whey was added daily for a week. The result was substantially lower selenium concentrations in lower Pole Canyon Creek. However, the effectiveness of this treatment system is contingent on the continuous addition of cheese whey to the trench. The results of the treatability study showed that the selenium removal effectiveness quickly diminishes once the addition of cheese whey stops. This indicates that a continuous carbon source is necessary to maintain reducing conditions needed for biological reduction of selenate/selenite to elemental selenium. Additionally, if reducing conditions are not maintained, the immobilized elemental selenium can re-oxidize and be released to Lower Pole Canyon Creek.

In short, the Lower Pole Canyon Creek passive water treatment system conceptual design consists of a trench dug within the toe of the Pole overburden disposal area intersecting all of Pole Canyon Creek flow above the surface of the native alluvial material. The trench will be loaded with zero-valent iron and continuously dosed with cheese whey.

4.3 Seep Passive Water Treatment

The conceptual design of the seep passive water treatment system is based on biological reduction of selenate/selenite to elemental selenium enhanced by the addition of zero-valent iron and is shown in Figure B-4. Numerous studies have documented the effectiveness of biological reduction (Lortie et al, 1992; MSE, 2001; Montana Tech and MSE, 1999; Sobolewski, 2005; Cantafio et al, 1996) and zero-valent iron (Zhang et al, 2005) while treatability studies have been completed at Smoky Canyon Mine merging both technologies into a single design (Munkers, 2000; Moller, 2002). This technology was chosen because its effectiveness has been proven at the Site, it can be designed to minimize O&M requirements, and because it is subsurface will not attract wildlife to selenium-enriched water.

In short, the seep water is collected and directed into a subsurface bioreactor where it comes in contact with zero-valent iron and a carbon source (e.g., whey). After a retention time in the bioreactor of roughly 5 days, the effluent is infiltrated.

The seep treatment system basically consists of either a single subsurface bioreactor or a series of subsurface bioreactors. The bioreactors are filled with a high void medium such as plastic rings/spheres/saddles for bacterial growth and attachment. Other media types (gravel, granular activated carbon, etc.) could be used but they would require a larger bioreactor due to the lower void space of these media.

Zero-valent iron and whey are added discretely. The treatability study completed by Moller (2002) between May 2001 and November 2001 used two discrete additions of powdered iron, weekly additions of carbon—cheese whey—for the first four months, and a single addition of carbon—compost—for the final three months.

Accumulation of spent iron, carbon, precipitated elemental selenium, and other precipitated minerals will need to be removed from the bioreactor when the minimum retention time cannot be maintained, the effectiveness decreases substantially, or the bioreactor plugs. This will be a mixed media waste that could be separated to reuse bio rings or managed as a waste. It is anticipated that the waste would not be characteristic hazardous, however this would need to be evaluated by treatability testing.

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FIGURES

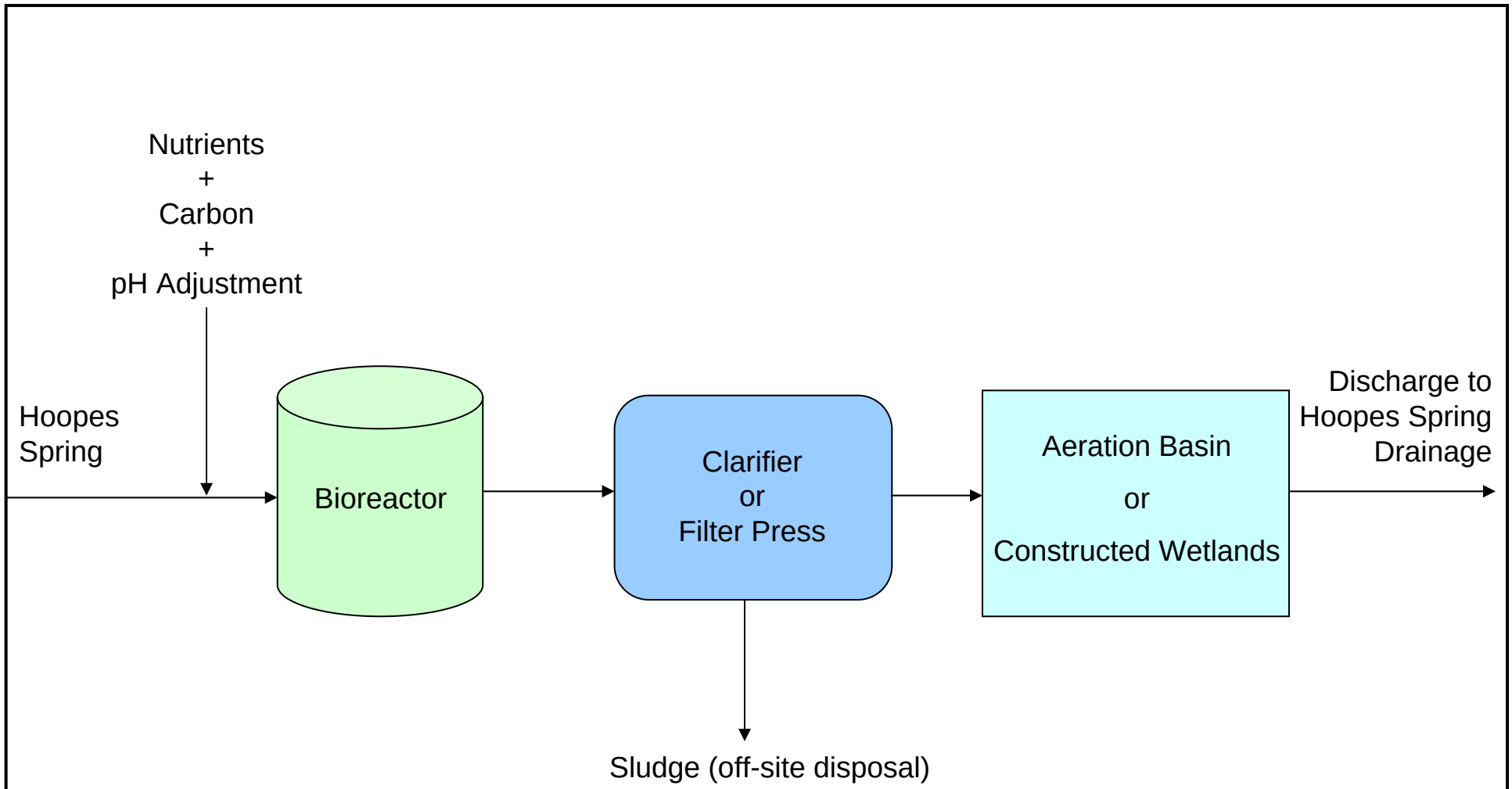

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FIGURE B-3

Conceptual Design for Hoopes Spring Biological Selenium Reduction Treatment

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NEWFIELDS

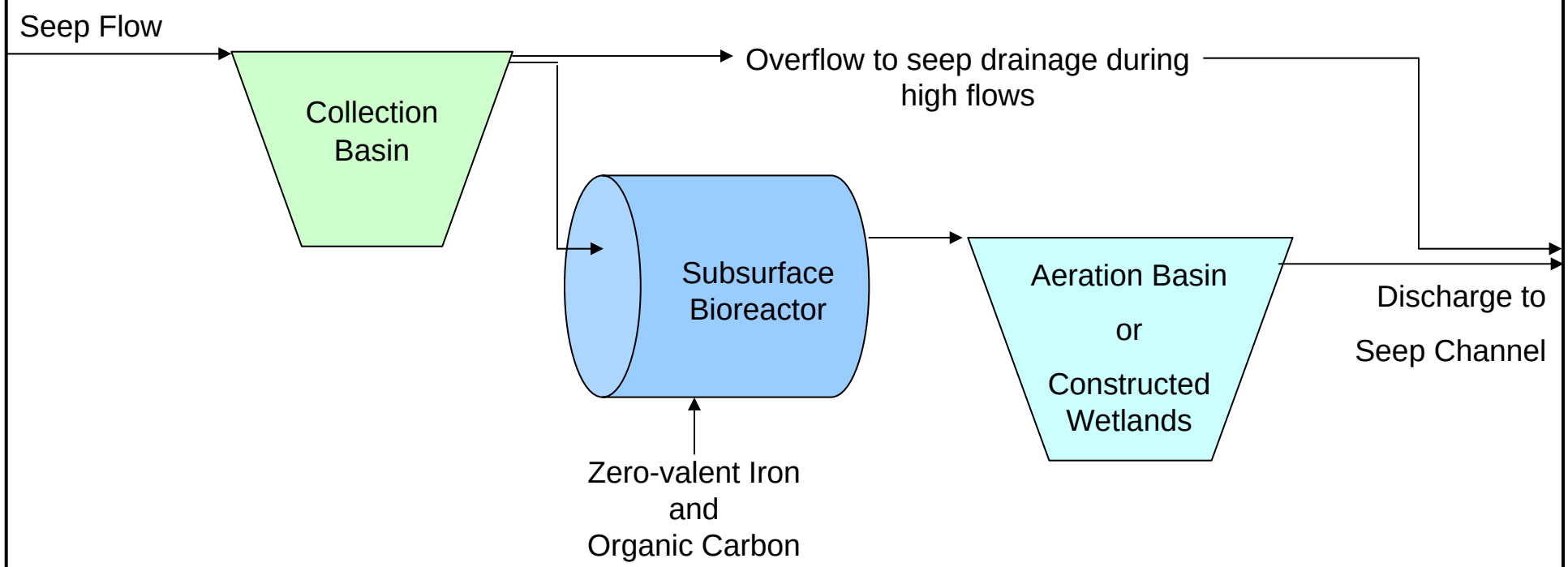

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FIGURE B-4

Conceptual Design for Passive Seep Treatment

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