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Final Report

Review of Available Technologies for the Removal of Selenium from Water

Prepared for

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CH2MHILL

Tom Sandy, P.E.
CH2M HILL
11301 Carmel Commons Blvd. Suite 304
Charlotte, NC 28226

Cindy DiSante, P.E.
CH2M HILL
1100 112th Avenue NE, Suite 400
Bellevue, WA 98004

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Executive Summary

This document describes industry-specific approaches to prevention, control and removal of selenium in water, with a focus on water treatment approaches for selenium removal. Industries represented in the North American Metals Council - Selenium Work Group (NAMC-SWG) are faced with managing selenium in water from processes that include the mining, agriculture, power generation, and oil and gas industry sectors. Case studies of pilot-scale and full-scale treatment technologies for selenium removal are presented for each industry sector.

The development of low cost, reliable technologies to remove selenium from water is a priority for the industry sectors as environmental standards and criteria applicable to their surface water discharges are currently very low with a potential for them to be even lower given pending guidance by regulatory agencies in North America.

Water treatment for the removal of selenium will likely be a component of a successful selenium management strategy for industry to achieve selenium discharge requirements on the order of 1-5 µg/L. Potential for selenium treatability should be considered in conjunction with water reuse, prevention and source control measures. Prevention of release and source control strategies for selenium may be more or less desirable or feasible depending upon the nature of the industrial process and associated costs compared to end of pipe water treatment. Generally, complete source control will not be possible or practical for process-affected waters from the various industry sectors.

Source control approaches vary by industry sector. Agricultural strategies generally focus on improved irrigation practices and crop selection. Selenium release reduction strategies for mining operations have generally focused around waste rock and tailings management. Power plants can minimize selenium release through design and selection of fly ash handling and flue gas desulfurization systems. For the oil and gas sector, selenium in produced water is a function of the production technology applied, and the resource deposit it is contained in, thereby posing significant challenges to applying source control approaches. Downstream refining source control strategies are generally limited to sour water management, crude washing and crude desalting operations.

Achieving selenium levels on the order of 1-5 µg/L in surface water discharges from the various industry processes poses a challenge given that selenium:

- Removal is limited by the minimum and maximum feasible ranges of design flows that can vary greatly over time;
- Exists in a variety of chemical forms;
- Is relatively dilute in concentration;
- Removal from water is confounded by the water matrix (e.g., temperature, pH and other chemicals);
- Treatment generally results in a concentrated by-product or residual; and,
- Re-release from the residuals can occur.

Significant variation in selenium levels and forms exists among the different industry types, within each industry type, and even sometimes within the same facility over time. This increases the complexity of how to determine applicable selenium removal technologies to a wide variety of industries. Because of the various complexities associated with industry-specific waters, there is no treatment technology that is a "one-size fits all" solution.

Adequate characterization of wastewater or industrial process residuals that captures its seasonal variation and speciation should be performed to determine the applicable technology for removal. Selection of the correct technology is highly dependent on the speciation of selenium and the competing and interfering water chemistry of industry-specific waters. The flows for some discharges vary greatly over the course of time and selection of the best technology will be limited by the minimum and maximum feasible ranges of design flows for a treatment system to function properly.

A variety of physical, chemical and biological treatment technologies have been shown to remove selenium from water. Applying these treatment technologies must consider the aforementioned challenges. This typically means that the treatment technology must be configured as a "system" that includes primary, tertiary and residual treatment processes in addition to the core treatment technology process. Because the performance of each technology is flow based, the system may require flow equalization infrastructure. The end result is a treatment plant that can have significant total installed and operations and maintenance costs.

Costs presented in this document generally were either based on the literature referenced, or developed as part of completion of this document. Careful consideration of the costs and the basis of the estimates should be given in using any cost information. Many references will present costs for treatment systems without providing clear definitions of the basis for the cost estimate. Most documents will only present the capital costs or direct costs for equipment as that is what is typically provided by the equipment supplier. These costs unfortunately are only a fraction of the total installed cost for a water treatment system.

Total installed costs by definition include everything that will be required to install the system. This typically includes the following elements:

- Direct costs - equipment, delivery, taxes, and installation costs
- Indirect costs - engineering, construction, contingency for undefined items, escalation, permitting, startup and commissioning costs

Total installed cost and operation and maintenance cost estimates and associated parametric cost graphs presented in this document are considered Class 5 cost estimates with an estimated accuracy of +100% and -50%.

Tertiary treatment will generally be required to meet both the selenium and other conventional surface water discharge guidelines or criteria (e.g., dissolved oxygen, total suspended solids, biochemical oxygen demand, etc.). Residuals or by-product treatment will be required for most systems. The residuals will contain concentrated levels of selenium that, if disposed of as a solid or liquid waste, will need to comply with other disposal regulations (e.g., USEPA RCRA Hazardous Waste). By-products may require further treatment to ultimately reduce the selenium to a less hazardous form.

Table ES-1 is a summary table of the treatment technologies (arranged alphabetically) discussed in this review. It includes technology description, removal treatment, key design considerations such as flow or concentration limitations or the extent and significance of any confounding factors, main advantages and disadvantages, and capital and operating costs.

While these physical, chemical and biological treatment technologies have the potential to remove selenium, there are very few technologies that have successfully and/or consistently removed selenium in water to less than 5 µg/L at any scale. There are still fewer technologies that have been demonstrated at full-scale to remove selenium to less than 5 µg/L, or have been in full-scale operation for sufficient time to determine the long-term feasibility of the selenium removal technology. No single technology has been demonstrated at full-scale to cost-effectively remove selenium to less than 5 µg/L for waters associated with all industry sectors. Therefore, performance of the technology must be demonstrated on a case-specific basis.

Information exchange among and within industries is necessary to advance technologies for selenium removal. This includes the need to consider process engineering principles applied to both the science behind the physical, chemical, or biological treatment technology, and an overall system configuration for the core treatment technology.

Table ES-1
Technology Summary

Technology	Section Reference in Text	Technology Description	Development Stage for Selenium Removal	Key Design Considerations	Advantages[1]	Disadvantages[1]	Capital and Operating Costs[2]
ABMet®	4.4.2.2	The ABMet® system is a bioreactor that is an attached growth (comprised of a biofilm, or a layer of microorganisms that grow on the surface of a solid phase media) downflow granular activated carbon bed filter.	Full Scale	1. <u>Flow equalization/diversion</u> required as part of the treatment train. 2. <u>Pretreatment</u> a. pH adjustment may be required. b. Suspended solids to be removed to prevent clogging of granular activated carbon media. 3. <u>Core Technology</u> a. Competing ions and oxyanions. b. Addition of carbon in proportion to oxyanions to prevent sulfate reduction. c. Temperature in mesophilic range (15°C to 40°C). d. Addition of other macronutrients and micronutrients as well. e. Mass transfer driven technology. f. Hydraulic retention time is an important design parameter as selenium removal can be limited by kinetics. 4. <u>Post-Treatment</u> a. Possibly pH adjustment. b. Re-aeration to increase dissolved oxygen and remove biochemical oxygen demand. c. Media filtration for suspended solids and particulate selenium removal. 5. <u>Residuals Treatment</u> a. Treatment of backwash. b. Sludge generated that will require handling and disposal.	• Commercially available technology that has been demonstrated to remove selenium to low levels (e.g., less than 5 µg/L) in pilot-scale and full-scale applications. • Process uses naturally occurring microbes and molasses-based nutrient feed to maintain biomass. • Biologically reduced elemental selenium is in an insoluble form as nanoparticles integral to the biological solids.	• Potential need for pre-treatment to remove suspended solids. • Backwash water required to periodically slough off excess microbial growth, prevent short-circuiting of flow and for de-gassing. • Large footprint required given the low hydraulic loading rate (e.g., 2-4 gpm/ft^2 or 81-162 Lpm/m^2) requirements and high minimum hydraulic residence requirements (4-6 hours). • Presence of an excessive amount of nitrates will require proportional amount of carbon or energy source. This excess carbon source will also generate some additional biomass. • External carbon source is required if soluble influent organic content or COD is insufficient. • Wasted biomass residuals contain elemental selenium that may be hazardous depending upon the TCLP results. • Media replacement may be required over the life of the system. • Biological residuals will need to be thickened and dewatered for landfill disposal.	• Section 4.4.2.2 contains parametric cost curves for capital and operating costs, process flow diagram and assumptions for development of costs. • Total installed cost for 1 million U.S. gallons per day system is estimated as $30 million (2010 USD) (+100%/-50%). • Annual operation and maintenance cost for 1 U.S. million gallons per day system is estimated as $3 million (2010 USD) (+100%/-50%).
Activated Alumina	4.3.2.4	Activated alumina is a general term for various granular, porous oxides and hydroxides of aluminum that have been exposed to sodium hydroxide at high temperature and have a high surface area that has the	Laboratory	Further research and optimization are needed to determine the feasibility of using activated alumina in applications to remove selenium from water.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available

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Technology	Section Reference in Text	Technology Description	Development Stage for Selenium Removal	Key Design Considerations	Advantages[1]	Disadvantages[1]	Capital and Operating Costs[2]
		properties to provide physical adsorption of selenium similar to ferrihydrite.					
Activated Carbon	4.3.2.3	An adsorption process using activated carbon (e.g., granular or powdered) that by design has a high surface area for potential adsorption.	Laboratory	Not effective for selenium removal.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available
Adsorption to Peanut Shells	4.3.2.6	Peanut shells are treated with strong sulfuric acid to carbonize the shells, oxidizing the cellulose and hemicelluloses and fragmenting the lignin. After treatment, the carbonized peanut shells will physically adsorb selenium.	Laboratory	Further research and optimization are needed to determine the feasibility of using treated peanut shells in applications to remove selenium from water.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available
Algal Assimilation	4.4.4.3	Significant amount of selenium is assimilated by algae, particularly in proteins, where selenomethionine is the dominant form (Frankenberger et al., 2004).	Laboratory	Further research and optimization are needed to determine the feasibility in applications to remove selenium from water.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available
Algal-Bacterial Selenium Removal	4.4.4.1	Algal-bacterial selenium removal (ABSR) is a process in which bacterial growth is stimulated by the addition of algae as a food source (NSMP, 2007).	Pilot	<u>Core Technology</u> a. Seasonally limited with treatment affected by duration of solar light and ambient temperatures.	• Potentially low cost-treatment approach. • Results in some direct volatilization of selenium out of the water column. • Can be applied as an *in situ* approach to selenium treatment. • Possibilities for future research include harvest of algae and bacteria as a source of protein and selenium to supplement cattle feed and harvest of algae for biofuel.	• Requires excess nutrients that can create eutrophic conditions in receiving streams. • Seasonally limited with treatment affected by duration of solar light and ambient temperatures. • Difficult to separate algae from water, requiring further treatment with coagulants and flocculants. • Effluent contains more bioavailable forms of selenium that have resulted in higher selenium levels in invertebrates compared to those exposed to untreated	Algal treatments have generally low cost (e.g., $.0008 USD per U.S. gallon) (NSMP, 2007). However, high cost can be associated with the land needed for the ABSR pond (e.g., $200 USD per acre-foot) (NSMP, 2007), as well as the need for separation of the high-rate and reduction ponds (Lenz and Lens, 2009).

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Technology	Section Reference in Text	Technology Description	Development Stage for Selenium Removal	Key Design Considerations	Advantages[1]	Disadvantages[1]	Capital and Operating Costs[2]
						water. - Has not been demonstrated to treat to low levels of selenium (less than 5 µg/L). - High residence time required for treatment. - Large footprint required as algae growth limited to the upper surface of the water due to light penetration limits.	
Algal Volatilization	4.4.4.2	Algal volatilization occurs when selenium is methylated and converted to a gaseous form (Frankenberger et al., 2004). Algal volatilization treatment involves the removal of selenium from wastewater by selenium biomethylation and further volatilization (Golder, 2009a,b).	Pilot	<u>Core Technology</u> a. Seasonally limited with treatment affected by duration of solar light and ambient temperatures.	- Potentially a lower cost treatment approach. - Can be applied as an *in situ* approach to selenium treatment. - Possibilities for future research include algal harvesting as a source of protein and selenium to supplement cattle feed and for biofuel.	- Requires excess nutrients that can create eutrophic conditions in receiving streams. - Seasonally limited with treatment affected by duration of solar light and ambient temperatures. - Difficult to separate algae from water, thereby requiring coagulants and flocculants. - Effluent contains more bioavailable forms of selenium that have resulted in higher selenium levels in invertebrates compared to those exposed to untreated water. - Has not been demonstrated to treat to low levels of selenium (less than 5 µg/L). - High residence time required for treatment. - Large footprint required as algae growth limited to the upper surface of the water due to light penetration limits.	Similar to the algal-bacterial treatments, this treatment has low costs (Golder, 2009a). However, treatment cost can increase depending on land requirements (e.g., $104 to $272 USD per acre-foot treated) (USBR, 2002b).
BioSolve®	4.4.2.4	The BioSolve® technology system, developed by Calcon using the Hall reactor, consists of a continuously stirred tank reactor with plastic sponge media used as a surface for biofilm development	Laboratory	Further research and optimization are needed to determine the feasibility in applications to remove selenium from water.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available

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Technology	Section Reference in Text	Technology Description	Development Stage for Selenium Removal	Key Design Considerations	Advantages^1	Disadvantages^1	Capital and Operating Costs^2
		(Nurdogan et al., 2009).					
Capacitive Deionization Process (SeClear™)	4.3.2.8	The Capacitive Deionization Process (SeClear™) is a direct current driven ion exchange technology with an electrostatic charging system that operates like a capacitor.	Laboratory	Further research and optimization are needed to determine the feasibility in applications to remove selenium from water.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available
Catalyzed Reduction (Cementation)	4.3.3.2	The addition of copper or nickel to a zero valent iron treatment process has been demonstrated to catalyze the reduction of selenium by creating a greater electrochemical potential between the elemental iron and soluble selenium.	Pilot	Design and operational considerations for catalyzed cementation are similar to the zero valent iron technology, including the potential need for pretreatment, and the presence of interfering anions such as nitrate, sulfate, etc.	• Basic technology is demonstrated in laboratory studies to remove selenate and selenite to low concentrations.	• Technology has not been proven in full-scale treatment. • Potential for long residence times. • Spent media must be removed, disposed of and replaced. May require disposal as hazardous waste. • Sludge disposal may be significant cost. • Media replacement may be a significant cost. • Other potential issues with copper and nickel discharges.	Reagent consumption of this technology is estimated to be $8.11 (USD) per 1,000 U.S. gallons treated. Design, equipment purchase, construction, and startup costs for a 300 U.S. gpm system were estimated as $1,083,285 (2001 USD) (MSE, 2001); annual O&M costs for a 300 U.S. gpm system were estimated as $1,165,358 (2001 USD) (MSE, 2001).
Constructed Wetlands	4.4.3.1	Engineered wetlands are designed and constructed to use vegetation, soil, rock and other civil structures to promote the appropriate microbial and plant activity to provide selenium treatment. They can be designed in vertical upflow, subsurface horizontal and surface flow configurations depending upon selenium ecological requirements.	Full Scale	1. <u>Flow equalization/diversion</u> required as part of the treatment train. 2. <u>Pretreatment</u> a. pH adjustment may be required. b. Service water addition may be required if concentrations of other parameters such as chlorides or boron could cause adverse effects in the wetlands plants. c. Suspended solids removal required. 3. <u>Core Technology</u> a. Control of stoichiometry is limited because it is a natural treatment process. b. The rate of flow, strength of influent, and target effluent criteria influence the design size of the wetland. c. Typical retention times for passive treatment systems can be several days or more. d. Due to the large retention time required, the footprint of constructed wetlands is generally large and can be several acres. e. The performance of a wetland can be	• Basic technology is reasonably demonstrated to remove selenium at low concentrations. • Process requires minimal operator supervision. • Process can operate passively without energy or chemicals. • Subsurface flow wetlands can operate in cold climates with installations in Northern Europe and Canada. • Able to treat large volumes of water.	• Potential for long residence time. • Large and flat footprint is required. • Uncertainties relating to consistently meeting very low selenium discharge limits (less than 5 µg/L). • Performance of surface flow wetlands is affected by temperature. Selenium removal is greater in summer months during warmer period. • Monitoring may be required to assess ecological risk from bioaccumulation of selenium, including toxicity to aquatic life and animals (nesting birds); if significant, exclusion measures may be required. • Potential for groundwater	• Section 4.4.3.1 contains parametric cost curves for capital and operating costs, process flow diagram and assumptions for development of costs for subsurface flow wetland. • Total installed cost for 1 million U.S. gallons per day system is estimated as $17 million (2010 USD) (+100%/-50%). • Annual operation and maintenance cost for 1 million U.S. gallons per day system is estimated as $150,000 (2010 USD) (+100%/-50%).

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				affected by the density of plant growth. Plant detritus is used as organic substrate for microbial reduction of selenium. If there is insufficient plant cover within a wetland, an additional organic substrate may be used to improve selenium removal.		contamination.	
Electrocoagulation	4.3.2.5	A physical adsorption process where ferrous iron is produced by applying direct electrical current to the water where an iron anode oxidizes to form ferrous iron that can reduce selenate and the resultant ferric iron can co-precipitate selenite.	Laboratory	Further research and optimization are needed to determine the feasibility of using electrocoagulation in applications to remove selenium from water.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available
Enhanced Evaporation System	4.2.2.2	An enhanced evaporation system is similar to an evaporation pond but with a mechanical device added to increase the evaporation rate of water through aspirating or spraying the water into the air.	Full scale for salt management, not implemented specifically for selenium management.	1. <u>Core Technology</u> a. Only applicable for areas with favorable climates (where evaporation rate exceeds precipitation rate). b. Mechanical aspiration/spraying of the pond results in increasing the surface area of the water exposed to air thereby resulting in enhanced evaporation. c. Realized enhanced evaporation potential a function of the spray equipment's ability to discharge above the water saturated vapor headspace of the pond. d. Can result in suspended particulate drift. e. The volume of the pond is reduced due to the increased efficiency of evaporation using mechanical sprayer equipment. f. Scaling potential for mechanical equipment as the dissolved solids increase.	• Lower costs because the technology relies on solar radiation for evaporation. • Can potentially be disposed of in place with proper design and permitting. • Increased evaporation efficiency over evaporation ponds due to mechanical spraying. • Requires a slightly smaller footprint than conventional evaporation ponds.	• Large space requirements due to efficiency decline as the total dissolved solids increases. • Generally will not result in a completely dry residual, which limits disposal alternatives. • Ineffective in areas with cold wet climate. A dry climate in which evaporation greatly exceeds precipitation is required. Alternate treatment is needed during cold weather. • Risk of infiltration to groundwater (depending on liner type) could occur. • Evaporation results in a net loss of water that may be a concern to areas with scarce water resources. • May pose risk to wildlife. An ecological risk assessment should be performed prior to implementation. • Higher operation and maintenance costs considering the mechanical aspiration/spraying.	The cost for an enhanced evaporation system in the San Joaquin Valley was $480 (2005 USD) per acre-foot (Salton Sea Ecosystem Restoration Program, 2005).

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Technology	Section Reference in Text	Technology Description	Development Stage for Selenium Removal	Key Design Considerations	Advantages[1]	Disadvantages[1]	Capital and Operating Costs[2]
						• Potential corrosion and scale issues with the mechanical aspiration/spraying equipment as the salinity increases.	
Enhanced *in situ* microbial reduction	4.4.3.4	Enhanced *in situ* microbial reduction of oxidized forms of selenium is accomplished by addition of organic amendments, nutrients or inoculated micro-organisms. Selenium removal with this technology is based on the presence of microorganisms to remove selenium.	Pilot	Anoxic conditions are required for *in situ* microbial reduction of selenate and selenite to occur. Microcosm testing can be performed to determine the available microbial populations and whether treatment may be effective for selenium reduction prior to implementation.	• Lower cost alternative for remediation of large volumes of water. • Low maintenance.	• Long retention times required. • Anoxic water may require aeration/settling as post-treatment prior to discharge to receiving water.	Less than USD $1.00/1,000 U.S. gallons, due to low capital costs (Sobolewski, 2005).
Enzymatic Selenium Reduction	4.4.2.5	An enzyme is a protein that can bring about digestion (breakdown) of molecules into smaller units and greatly speed up chemical reactions. Enzyme extracts were tested from microbes that were previously demonstrated to treat selenium.	Laboratory	Further research and optimization are needed to determine the feasibility in applications to remove selenium from water.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available
Evaporation Pond	4.2.2.1	Concentrates dissolved salts by natural evaporation of water to various levels of salinity based on the prevailing climate conditions.	Full scale for salt management, not implemented specifically for selenium management.	1. Core Technology a. Efficiency declines as total dissolved solids increases, requiring large footprint. b. Only applicable for areas with favorable climates (where evaporation rate exceeds precipitation rate).	• Lower costs because the technology relies on solar radiation for evaporation. • Simple operation. • Can potentially be disposed of in place with proper design and permitting.	• Large space requirements due to efficiency decline as the total dissolved solids increases. • Generally will not result in a completely dry residual, which limits disposal alternatives. • Ineffective in areas with cold wet climate. A dry climate in which evaporation greatly exceeds precipitation is required. Alternate treatment is needed during cold weather. • Risk of infiltration to	Evaporation pond treatment in the San Joaquin Valley cost $630 USD per acre-foot of treated water with $2.8 million/year (USD) for O&M (Salton Sea Ecosystem Restoration Program, 2005).

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Technology	Section Reference in Text	Technology Description	Development Stage for Selenium Removal	Key Design Considerations	Advantages[1]	Disadvantages[1]	Capital and Operating Costs[2]
						groundwater (depending on liner type) could occur. • Evaporation results in a net loss of water that may be a concern to areas with scarce water resources. • May pose risk to wildlife. An ecological risk assessment should be performed prior to implementation.	
Ferrihydrite Adsorption or Iron Co-Precipitation	4.3.2.2	Ferrihydrite adsorption is a two step physical adsorption process in which a ferric salt is added to the water source at proper conditions such that a ferric hydroxide and ferrihydrite precipitate results in concurrent adsorption of selenium on the surface; also known as iron co-precipitation.	Full Scale	1. Flow equalization/diversion required as part of the treatment train. 2. Pretreatment a. pH adjustment may be required, optimal pH for treatment is between 4 to 6. 3. Core Technology a. Only applicable for selenite, very little selenate removal. b. Staged mixing generally required for coagulation and flocculation of iron precipitation solids. c. Gravity sedimentation required to separate iron solids and adsorbed selenium from water matrix. 4. Tertiary Treatment a. Media filtration and pH adjustment may be required. 5. Residuals Management a. Iron residuals with adsorbed selenium will require thickening and dewatering for disposal as solid waste in a landfill. b. Will require toxicity characteristic leaching procedure (TCLP) testing to determine whether sludge should be disposed as hazardous waste.	• Widely implemented at full-scale throughout the industry • Established by US EPA as best demonstrated available technology for selenium (e.g., selenite) removal. • Relatively simple and low cost chemical adsorption technology.	• Selenium removal not proven to low µg/L (less than 5 µg/L). • Produces relatively large quantities of sludge that may need to be disposed as a hazardous waste depending upon outcome of TCLP testing. • Iron co-precipitation is pH dependent with optimal conditions in the range of pH 4 to 6. • Not able to remove selenate. Requires oxidation of selenocyanate to selenite prior to removal. • Potential release of selenium from ferrihydrite residuals.	• Section 4.3.2.2 contains parametric cost curves for capital and operating costs, process flow diagram and assumptions for development of costs. • Total installed cost for 1 million U.S. gallons per day system is estimated as $11 million (2010 USD) (+100%/-50%). • Annual operation and maintenance cost for 1 million U.S. gallons per day system is estimated as $4 million (2010 USD) (+100%/-50%).
Ferrous Hydroxide	4.3.3.3	A two step reduction oxidation and physical adsorption process where ferrous iron is added resulting in the reduction of selenate to selenite and the subsequent physical adsorption or co-precipitation of selenite by ferrihydrite or ferric	Full Scale	Similar design considerations for ferrihydrite adsorption or iron co-precipitation. Reduction and subsequent adsorption are best accomplished under reducing conditions at a pH of approximately 8-9 (Twidwell et al., 2009).	• Widely implemented at full-scale throughout the industry. • Relatively simple and low cost reduction oxidation and physical adsorption technology.	• Selenium removal not proven to low µg/L (less than 5 µg/L). • Large quantities of sludge may need to be disposed as a hazardous waste. • Reduction and subsequent adsorption is pH dependent with optimal conditions in the range of pH 8 to 9. • Not as effective at the reduction of selenate to	Costs were reported for a 300 U.S. gpm FGD water treatment plant as $15 million (2000 USD); annual O&M cost of $1.5 to $2 million (2000 USD).

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		hydroxide.				selenite as zero valent iron.	
Fluidized bed reactor	4.4.2.3	In a fluidized bed reactor, water containing selenium is passed through a granular solid media (e.g., sand or granular activated carbon) at high enough velocities to suspend, or fluidize the media creating a completely mixed reactor configuration for attached biological growth or biofilm.	Pilot	1. Flow equalization/diversion required as part of the treatment train. 2. Pretreatment a. pH adjustment may be required. 3. Core Technology a. Competing ions and oxyanions. b. Addition of carbon in proportion to oxyanions to prevent sulfate reduction. c. Temperature in mesophilic range (15ºC to 40ºC). d. Addition of other macronutrients and micronutrients. e. Mass transfer driven technology. f. Hydraulic residence time is an important design parameter as selenium removal can be limited by kinetics. 4. Post-Treatment a. pH adjustment may be needed. b. Re-aeration to increase dissolved oxygen and remove biochemical oxygen demand (BOD). c. Media filtration for suspended solids.	• Process uses naturally occurring microbes and biodegradable carbon sources to maintain biomass. • Biologically reduced elemental selenium is in an insoluble form as nanoparticles integral to the biological solids. • Smaller footprint given completely mixed reactor configuration resulting in lower total installed costs. • Requires little to no pretreatment for suspended solids. • No backwash water required. Biomass separated from centrifugal separator on reactor effluent.	• Presence of an excessive amount of nitrates will require proportional amount of carbon or energy source. This excess carbon source will also generate some additional biomass. • Commercially available technology operating in similar full scale applications (e.g., nitrate and perchlorate removal) but no full scale selenium treatment for fluidized bed reactor is currently utilized. • External carbon source is required if soluble influent organic content or chemical oxygen demand (COD) is insufficient. • Wasted biomass sludge contains elemental selenium that may be hazardous depending upon the TCLP results. • Media replacement required periodically. • Biological residuals will need to be thickened and dewatered for landfill disposal.	• Section 4.4.2.3 contains parametric cost curves for capital and operating costs, process flow diagram and assumptions for development of costs. • Total installed cost for 1 million U.S. gallons per day system is estimated as $11 million (2010 USD) (+100%/-50%). • Annual operation and maintenance cost for 1 million U.S. gallons per day system is estimated as $3 million (2010 USD) (+100%/-50%).
Hydrogen-Based Membrane Biofilm Reactor	4.4.2.6	Hydrogen is used as an alternative electron donor to the carbon-based electron donors used in other reactors cited. The membrane is used within this treatment system to directly supply dissolved gas to a biofilm growing on the membrane surface.	Laboratory	Further research and optimization are needed to determine the feasibility in applications to remove selenium from water.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available
Ion Exchange	4.3.2.1	An adsorption process where undesirable ions in the water are exchanged for like charged ions by	Pilot	1. Flow equalization/diversion required as part of the treatment train. 2. Pretreatment • a. Suspended solids removal is required to reduce fouling potential	• Generally greater than 90% recovery rates given resin specificity for target constituent and regenerant and back wash requirements.	• Uncertainty regarding performance for selenium removal to low levels (e.g., less than 5 µg/L) given small amount of test data in literature.	• Section 4.3.2.1 contains parametric cost curves for capital and operating costs, process flow diagram and

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Technology	Section Reference in Text	Technology Description	Development Stage for Selenium Removal	Key Design Considerations	Advantages[1]	Disadvantages[1]	Capital and Operating Costs[2]
		electrostatic attraction to sites of opposite charge on the surface of granular chemicals known as ion exchange resins.		of membrane. - b. pH adjustment may be needed. - c. Potential scale removal to prevent resin fouling. 3. Core Technology a. The resin type (e.g., weak or strong base), the volume and type of regenerant, backwash water source, backwash quantities, pre-filtration for solids, pH adjustment before and after ion exchange, column configuration, mode of operation, and cycle length are all considerations for operations of an ion exchange system. b. Configuration of ion exchange columns- requires potentially lead- lag-lag serial column configuration with full caustic regeneration to minimize leakage. 4. Residuals Management a. Concentrated regenerant to be treated with core selenium removal technology and/or concentrated and disposed.	- In the right application, capable of treating to potentially low levels (e.g., 5 µg/L or less) with proper resin selection and system design with consideration to competing water chemistry. This same technology has been applied to perchlorate in similar water matrices. - Concentrates the selenium reducing the volume for treatment.	- Ion exchange capacity for selenium can be greatly reduced by competing anions (e.g., sulfates, nitrates). - Resin may need to be disposed if it cannot be regenerated, meaning high disposal costs. - Concentrated regenerant stream requires treatment and/or disposal.	assumptions for development of costs. - Total installed cost for 1 million U.S. gallons per day system is estimated as $28 million (2010 USD) (+100%/-50%). - Annual operation and maintenance cost for 1 million U.S. gallons per day system is estimated as $4 million (2010 USD) (+100%/-50%).
Katchall Filtration Systems, LLC Media	4.3.2.9	An adsorbent media that is called "Heavy Metals Removal Media" that consists of coarse and fine-granular materials loaded into an enclosed vessel through which water is passed for treatment. Metals are removed by chemical bonding onto organic molecules (media), producing a discharge with low metal concentrations (NSMP, 2007).	Laboratory	Further research and optimization are needed to determine the feasibility in applications to remove selenium from water.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available
Mechanical Evaporation/ Crystallization	4.2.2.4	Provides an external heat source, mechanical mixing, and/or pressure or vacuum to enhance the evaporation potential of water resulting in brine concentration and crystallization.	Full Scale for industrial applications, has not been implemented specifically for selenium management.	1. Flow equalization/diversion required as part of treatment train. 2. Pretreatment a. Because of the high cost of treatment, wastewater is usually pre-concentrated with nanofiltration, reverse osmosis, ion exchange, or other concentrating technology to reduce the volume for treatment by mechanical	- Provides a high level of treatment producing a concentrated selenium salt cake and pure water distillate. - Generally would be effective at reducing the volume of pre-concentrated streams of selenium from reverse osmosis and ion	- Disposal of solid waste stream could be hazardous and may be large in quantity, depending on the wastewater volume and characteristics. - Pretreatment can be required depending upon the water quality.	- Section 4.2.2.4 contains parametric cost curves for capital and operating costs, process flow diagram and assumptions for development of costs. - Total installed cost

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Technology	Section Reference in Text	Technology Description	Development Stage for Selenium Removal	Key Design Considerations	Advantages^1	Disadvantages^1	Capital and Operating Costs^2
				evaporator/crystallizer. 3. <u>Core Technology</u> a. Scale, corrosion, and high ionic strength must be considered during design and selection of materials of construction. b. Flow limitations- although there are no limitations, it is recommended to treat a reduced volume that has been pretreated due to expense of treatment. 4. <u>Tertiary Treatment</u> a. Distillate may need to be recombined with other streams prior to discharge. 5. <u>Residuals Management</u> a. The crystallizer system concentrates the dissolved solids in the brine from the evaporator further resulting in up to 90% total solids residual that may require further dewatering. The solid requires disposal and may be hazardous: toxicity characteristic leach procedure (TCLP) testing needs to be performed to characterize the residual.	exchange technologies. • Concentrates the selenium reducing the volume for treatment.	• Requires electric, steam and cooling water utilities. • Distillate will require blending to reconstitute with minerals depending upon the discharge requirements. • Redundancy requirements given maintenance outages. • High capital and operation and maintenance cost.	for 1 million U.S. gallons per day system is estimated as $70 million (2010 USD) (+100%/-50%). • Annual operation and maintenance cost for 1 million U.S. gallons per day system is estimated as $8 million (2010 USD) (+100%/-50%).
Nanofiltration	4.2.1.3	Nanofiltration is a pressure driven membrane process similar to reverse osmosis that retains selenium and other dissolved salts between 0.001 and 0.01 microns but is operated at pressures approximately one-third of reverse osmosis.	Pilot	Design considerations are similar to reverse osmosis. However, unlike reverse osmosis, nanofiltration is limited by the pore size being in the molecular weight cutoff range that is similar to the size of the selenite and selenate oxyanions. Therefore, depending upon the exact cutoff, performance may not be as effective as reverse osmosis.	• Operates at one-third of the pressure requirement of reverse osmosis technology. • Small space requirements, modular type construction, and easy expansion. • Can offer improved recoveries by rejecting a smaller portion of the salts including selenium, thereby reducing scale potential. • Concentrates the selenium reducing the volume for ultimate reduction treatment.	• Not tested at full-scale for selenium removal. No actual performance data are available yet for selenium removal. • Requirements for pretreatment and chemical addition (micro filter, mixed media filter) to reduce scaling/fouling. • Frequent membrane monitoring and maintenance. • Pressure, temperature, and pH requirements to meet membrane tolerances. • Requires treatment and disposal of the reject stream. • Temperature operating issues due to viscosity effects at extreme low and high temperatures.	• Total installed cost and operations and maintenance costs are similar to reverse osmosis cost estimates. • Total installed cost for 1 million U.S. gallons per day system is estimated as $40 million (2010 USD) (+100%/-50%). • Annual operation and maintenance cost for 1 million U.S. gallons per day system is estimated as $3 million (2010 USD) (+100%/-50%).
Octolig® system	4.3.2.7	Octolig® system consists of an organic ligand that	Laboratory	Further research and optimization are needed to determine the feasibility of using the Octolig® system in applications	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-	Not available

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Technology	Section Reference in Text	Technology Description	Development Stage for Selenium Removal	Key Design Considerations	Advantages[1]	Disadvantages[1]	Capital and Operating Costs[2]
		has been chemically immobilized onto a silica gel substrate. The Octolig® media is used in a flow-through column arrangement similar to an ion exchange system.		to remove selenium from water.		scale only.	
Passive biochemical reactor	4.4.3.2	Passive biochemical reactors consist of an excavated lined area that has been filled with an organic substrate. They are generally operated in a gravity down-flow mode, although up-flow mode is also a possible configuration.	Full Scale	1. <u>Flow equalization/diversion</u> can be part of treatment train. 2. <u>Pretreatment</u> a. Suspended solids removal as pretreatment can increase lifespan of passive biochemical reactor. 3. <u>Core Technology</u> a. Hydraulic retention time is a key design parameter.	• Low capital and operations and maintenance costs, including low cost of organic substrate; local materials can be used for organic substrate. • Process requires minimal operator supervision. • Process can operate passively without energy or chemicals. • Subsurface design means that system can operate in cold climates.	• Uncertainty regarding potential re-mobilization of selenium. • Large footprint required. • Uncertainty in consistently meeting very low selenium discharge limits (less than 5 µg/L). • Organic substrate degrades over time and may require replacement.	The design and construction cost of the first module of the Montana gold mine passive treatment system was approximately $200,000 (2007 USD). A total of three modules are planned to treat a total of 20 US gpm (75 Lpm), with annual operating costs estimated at $0.95 per thousand gallons (Golder, 2009a).
Permeable Reactive Barriers	4.4.3.3	Permeable reactive barriers are a type of passive, *in situ* treatment for shallow groundwater (generally employed at depths less than 50 to 70 feet) (USEPA, 1998) and can be employed for source zone treatment.	Full Scale	Zero valent iron is often used as the reactive media in implementation of permeable reactive barriers. The corrosion of zero valent iron causes an increase in pH values and a decrease in oxidation state. Monitoring of pH and oxidation reduction potential can be used to help evaluate the performance of permeable reactive barriers.	• Lower cost alternative than other technologies. • Low maintenance. • Can be used as a source control measure to mitigate exposure to downgradient receptors.	• Finite life span. • Potential to be clogged due to precipitation of secondary metals. • Has not been fully demonstrated to achieve low µg/L levels in the effluent (less than 5 µg/L).	$24 per 1,000 U.S. gallons (2004 USD) (USDOE, 2004).
Photoreduction	4.3.3.4	Photoreduction is a chemical reduction and adsorption technology. Photoreduction uses irradiation of ultraviolet light at a certain wavelength and in the presence of titanium dioxide to convert selenate and selenite to elemental selenium (Shamas et al., 2009).	Laboratory	Further research and optimization are needed to determine the feasibility in applications to remove selenium from water.	Advantages are not provided for technology demonstrated at laboratory-scale only.	Disadvantages are not provided for technology demonstrated at laboratory-scale only.	Not available
Reverse Osmosis	4.2.1.2	Reverse osmosis is a membrane	Full Scale	1. <u>Flow equalization/ diversion</u> required	• Demonstrated at full scale to remove selenium	• Higher capital cost to purchase, install, and	• Section 4.2.1.2 contains parametric

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Technology	Section Reference in Text	Technology Description	Development Stage for Selenium Removal	Key Design Considerations	Advantages^1	Disadvantages^1	Capital and Operating Costs^2
		separation process that uses high pressure to force a solution through a membrane that retains the soluble selenium (e.g., selenite and selenate) and other dissolved salts less than 0.001 microns on the reject side of the membrane and allows the purified water pass to the permeate side.		as part of the treatment train. 2. Pretreatment a. Suspended solids removal to reduce fouling potential of membrane to a silt density index of less than 5. b. May require temperature control at low and high temperatures to minimize viscosity effects. c. pH adjustment may be required. d. Antiscalant addition to prevent membrane fouling may be required. 3. Core Technology a. Can remove high levels of total dissolved solids (TDS), but not practical above 10,000 mg/L TDS. b. Scale-forming ions will irreversibly foul the membranes and create selenium removal issues by allowing leakage. c. A heuristic approach for osmotic pressure requirements is to assume that 10 pounds per square inch gauge of osmotic pressure is exerted for every 1,000 mg/L TDS. 4. Tertiary Treatment a. Effluent blending of the reverse osmosis and the crystallizer distillate. b. Effluent may need to be re-constituted as ions may need to be added to discharge prior to receiving water. 5. Residuals Management a. Brine concentrates require treatment with core selenium removal technology and/ or further concentrated for disposal.	(selenite or selenate) to less than 5 µg/L. • Can remove high levels of TDS, approximately 90 to 98% removal. • Produces a high water quality with relatively high recoveries as a function of scale treatment. • Small space requirements, modular type construction and easy expansion. • Concentrates the selenium reducing the volume for ultimate reduction treatment.	operate than other membrane separation processes. • Requirements for pretreatment and chemical addition (microfilter, mixed media filter) to reduce scaling/fouling. • Pressure, temperature, and pH requirements to meet membrane tolerances. • Frequent membrane monitoring and maintenance. • Requires treatment and disposal of the brine (reverse osmosis reject stream). • Reverse osmosis permeate stream will require treatment (pH and TDS buffering) prior to discharge to receiving waters to meet aquatic toxicity test. • Operating issues will result from viscosity changes at extreme low and high temperatures.	cost curves for capital and operating costs, process flow diagram and assumptions for development of costs. • Total installed cost for 1 million U.S. gallons per day system is estimated as $40 million (2010 USD) (+100%/-50%). • Annual operation and maintenance cost for 1 million U.S. gallons per day system is estimated as $3 million (2010 USD) (+100%/-50%).
Salinity Gradient Solar Pond	4.2.2.3	Salinity gradient solar ponds are deep bodies of saline water that develop a temperature gradient from top to bottom and utilize trapped solar radiation with mechanical circulation to enhance evaporation.	Full scale for salt management, not implemented specifically for selenium management.	1. Core Technology a. Enhances performance of an atmospheric evaporation pond by utilizing stratification due to salinity gradients within the pond to more effectively trap heat from solar radiation or other heat inputs within the pond.	• Takes advantage of solar radiation and climate to provide a less expensive mechanical evaporator. • Relatively simple to construct. • Improved performance compared to evaporation ponds with and without mechanical enhancements.	• Requires relatively large footprint with a relatively deep side depth. • The fate of selenium is unknown within salinity gradient solar ponds as they have not been used for selenium treatment. • Potential corrosion and scale issues with the mechanical equipment.	Costs for solar gradient ponds can range up to $6,100 (USD) per acre-foot (NSMP, 2007). Operation and maintenance costs can be about 10 times greater than an evaporation pond (NSMP, 2007).
Upflow anaerobic sludge blanket (UASB) bioreactor	4.4.2.1	In a UASB bioreactor, the wastewater flows upward through the granular sludge at a high enough velocity	Pilot	1. Flow equalization/diversion required as part of the treatment train. 2. Pretreatment a. pH adjustment may be required.	• Requires no attached growth media and therefore no media replacement. • Process uses naturally occurring microbes and biodegradable nutrient to	• Commercially available technology typically applied to high strength organic wastewater. • Long hydraulic residence (e.g., > 6 hours) and solid	The total cost for a 1 million U.S. gallons per day (4000 cubic meter per day (m^3/day) system is estimated at $0.36 to $0.42/ m^3 of water

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		to keep the sludge suspended without washout. The upper part of the bioreactor contains a gas/solids separator to allow gases produced to be vented and solids entrained by the gases to be recovered.		3. <u>Core Technology</u> a. Competing ions and oxyanions may exist in water matrix. b. Addition of carbon in proportion to oxyanions is required. c. Temperature required is in the mesophilic range (15 °C to 40 °C).	maintain biomass. • Biologically reduced elemental selenium is in insoluble form as nanoparticles integral to the biological solids. • Requires little to no pretreatment for suspended solids.	residence (e.g., > 10 days) time requirements result in larger reactor sizes and footprint. • No full scale proof of concept. • Presence of an excessive amount of nitrates will require proportional amounts of carbon or energy source. This excess carbon source will also generate some additional biomass. • External carbon source is required if soluble influent organic content or chemical oxygen demand is insufficient. • Prone to washout conditions given very low nitrate, nitrite and/or selenium concentrations coupled with poor liquid solids separation, thereby requiring concentration of these through ion exchange or reverse osmosis. • Long periods of time for startup to acclimate the seed given washout and difficulty in controlling the solids residence time. • Requires granulating solids to perform at a high removal rate and minimize solids washout. • Biological residuals will need to be thickened and dewatered for landfill disposal.	treated, with operating costs representing \$0.28 to \$0.34/ m^3 (Frankenberger et al., 2004). The cost for the organic carbon that is added to the water accounts for 5 to 25% of the operating costs if methanol is used (Frankenberger et al., 2004).
Zero Valent Iron (ZVI)	4.3.3.1	ZVI chemically reduces the oxidized forms of selenium: selenate and selenite. ZVI media can be in powder, granular or fibrous forms.	Pilot-Scale	1. <u>Flow equalization/diversion</u> required as part of the treatment train. 2. <u>Pretreatment</u> a. pH adjustment may be required. 3. <u>Core Technology</u> a. Mass transfer driven technology. b. Hydraulic residence time is a key design parameter. c. pH control at pH 4 to 5 is key to green rust formation for reduction..	• Basic technology is demonstrated in laboratory studies to remove selenate and selenite at low concentrations. • Provides two reduction mechanisms for selenium including: green rust for reduction of selenate to selenite and selenite to elemental selenium; and ferrous iron for reduction of	• ZVI technology has not been proven in full-scale treatment and at higher selenium concentrations. • Potential for long residence times. • Spent ZVI must be removed, disposed of and replaced. • Dissolved oxygen and other oxyanions can oxidize the ZVI at certain	• Section 4.3.3.1 contains parametric cost curves for capital and operating costs, process flow diagram and assumptions for development of costs for a column-based (using steel wool) system and a stirred-tank based

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				d. Presence of other oxyanions (e.g., carbonate, sulfate, nitrates, phosphates) can interfere with reduction. 4. Tertiary Treatment a. Due to iron content and reducing environment, aeration followed by clarification is recommended to remove iron. 5. Residuals Management a. Media requires periodic replacement and disposal. b. Iron residuals with adsorbed selenium will require thickening and dewatering for disposal as solid waste in a landfill. c. Will require TCLP testing to determine whether sludge should be disposed as hazardous waste.	selenate to selenite. - Provides ferric iron for ferrihydrite adsorption of selenite.	conditions. - Sludge disposal may be significant cost. - ZVI treatment is temperature and pH dependent.	system (using granular ZVI). For Column-Based System (Using Steel Wool) - Total installed cost for 1 million U.S. gallons per day system is estimated as $13 million (2010 USD) (+100%/-50%). - Annual operation and maintenance cost for 1 million U.S. gallons per day system is estimated as $3 million (2010 USD) (+100%/-50%). For Stirred-Tank Based System (Using Granular ZVI) - Total installed cost for 1 million U.S. gallons per day system is estimated as $11 million (2010 USD) (+100%/-50%) - Annual operation and maintenance cost for 1 million U.S. gallons per day system is estimated as $3 million (2010 USD) (+100%/-50%).

Notes:

[1] Advantages and disadvantages are not presented within this table for technologies that have been demonstrated at laboratory-scale only, because further research and optimization are needed to determine the feasibility in applications to remove selenium from water.

[2] Capital and operations and maintenance cost assumptions associated with costs developed as part of this document are provided within the section text for specific technologies. Costs developed for this document are defined by the American Association of Cost Engineers International as Class 5 with an accuracy of +100% and -50%. This estimate is prepared based on limited information, where little more than proposed plant type and the capacity are known. These estimates were prepared to provide guidance in evaluation of each of the technologies. They are based solely on the information available at the time of the estimate. Actual final costs will depend on the actual labor and material costs, competitive market conditions, location and site conditions, final project scope, implementation schedule, and other variable factors. As a result, the final total installed cost will vary from the total installed cost and operations and maintenance costs prepared.