REPORT

State-of-Knowledge on Selenium Treatment Technologies

NAMC–SWG White Paper Addendum

Prepared for:

North American Metals Council – Selenium Working Group (NAMC–SWG)

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This report was prepared out of Golder's Vancouver Office under the technical direction of Tom Rutkowski (P.Eng., P.E., M.Sc. Associate, Senior Engineer).The following Golder technical specialists also contributed to this review: Michelle Xu, Henlo du Preez, Adrian de Bruyn, Michael Bratty, and Paul Pigeon.

Executive Summary

The North American Metals Council - Selenium Working Group (NAMC–SWG) developed a white paper on Selenium Removal Technologies in 2010 (CH2M HILL 2010); a technical addendum – update to the original white paper – was prepared in 2013 (CH2M HILL 2013). The effort contained in this report is the second technical addendum to the 2010 white paper. Since 2013, progress has been made with regard to installation of full-scale systems, and development of new technologies.

This update on the state of selenium treatment includes:

- Providing an overview of the operation and performance of new plants installed since 2007 (including: number of plants, types of technologies, industry sector breakdowns, treatment capacities, selenium removed)
- Describing advancements of technologies (including core selenium removal and pre- and post-treatment processes)
- Describing the importance and strategies for residue management
- Providing a view of technology maturity
- Providing available approximate capital and operating costing information

A survey of end users, vendors, and consultants was developed and distributed in order to collect information on operating treatment plants. Many of the vendors and consultants are affiliates or supporters of the NAMC-SWG effort. The focus of this report is on full-scale systems. Presentation and description of emerging technologies and related bench- and pilot-scale studies are excluded as they have not been proven at full-scale.

Selenium criteria/guidelines and environmental effects monitoring requirements downstream of discharge points have recently been updated by various regulatory agencies in North America. Updates include the finalization of fish tissue-based standards and setting the chronic toxicity-based water quality criteria at 1.5 micrograms per liter (µg/L) in lentic aquatic systems and 3.1 µg/L in lotic aquatic systems based on total recoverable selenium. These changes may have a bearing on the selection of treatment method to meet new criteria. It is important to recognize that these criteria are not end-of-pipe limits, however they can be used to derive individual plant effluent limits. In the US (United States), individual limits are known as water quality-based effluent limits (WQBELs) and these are incorporated into National Pollutant Discharge Elimination System (NPDES) permits. Criteria and guidelines for selenium vary from state to state in the US. Resultant effluent limits for treatment systems can range from less than 5 µg/L to about 20 µg/L. Regulation can also vary by industrial sector. In the US power sector, for instance, a proposed rule from the US Environmental Protection Agency (EPA) would increase selenium limitations on flue gas desulfurization wastewater.

The survey results documented thirty (30) full-scale selenium removal systems have been installed predominantly in North America from 2007 to 2018, with design flow rates ranging from 75 gpm to 2,800 gpm (i.e., 410 m^3/day to 15,260 m^3/day). Selenium removal technologies in these systems vary and include physical/chemical or biological processes, or a combination of the two. Selenium speciation of the influent and effluent water is a key factor for selection of an appropriate technology. Removal of selenite can occur with iron co-precipitation, a conventional physical/chemical process. Selenate removal, on the other hand, is more challenging and cannot be addressed with conventional water treatment technologies. As a result, research and technology development for selenate removal has continued, and numerous full-scale plants have been installed and commissioned. For the period covered by the survey, biological treatment for selenate has emerged as the most prevalent technology, being the core removal process in seventy percent (70%) of the full-scale systems documented herein.

There is an array of biological systems ranging from active to passive, and from tank-based to *in-situ* systems. Although they share a common treatment principle, they differ greatly in level of maturity, cost, and complexity. Active biological systems are the most common type being installed at full scale. Detailed case studies from two such systems indicate the ability to generally achieve high rates of selenium removal, but have experienced occasional bioreactor bed upsets due to backwashing and de-gassing. Variability in influent water quality, site constraints and effluent targets has resulted in the emergence of a variety of biological treatment system components resulting in each installation being rather unique. Operational challenges also differ among systems. Of particular significance is the management of reduced or organic selenium species that can exhibit greater selenium bioaccumulation potential in the effluent vs. the influent to a biological treatment plant. Although the focus of this update was on full-scale systems currently in operation, there are non-biological technologies under development that are not yet operational at full scale. There are full-scale plants currently under construction that use newly-developed technology combining ion exchange with electro-reduction of selenium.

Despite numerous installations, selenium treatment technologies have not reached full maturity and should still be regarded as developmental. In some instances, systems are consistently capable of meeting stringent limits of less than 10 µg/L, for example. However in other instances, this has not been achievable. Capital costs are highly variable and largely driven by site-specific factors and not necessarily by the cost of the core selenium removal technology.

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1.0 INTRODUCTION

The North American Metals Council - Selenium Working Group (NAMC–SWG) developed a white paper on Selenium Removal Technologies in 2010 (CH2M HILL 2010); a technical addendum – update to the original white paper – was prepared in 2013 (CH2M HILL 2013). The effort contained in this report is the second technical addendum to the 2010 white paper. Since 2013, progress has been made with regard to installation of full-scale systems, and development of new technologies.

This report presents an update on the state of selenium treatment technology by:

- Providing an update on the operation and performance of new plants installed over this period (including: the number of treatment plants, type of technologies, industry sector breakdowns, treatment capacities, selenium removed)
- Describing advancements of technologies (including core selenium removal and pre- and post-treatment processes)
- Describing the importance and strategies for residue management
- Providing a view of technology maturity
- Providing available approximate capital and operating costing information

A list of relevant of end users, vendors and consultants was developed, and a survey was prepared and distributed to members and non-members of the NAMC–SWG, in order to collect information on operating plants. The focus of this update is on implementation of full-scale systems ranging from design flow rates of between 75 gpm to 2,800 gpm (i.e., 410 m^3/day to 15,260 m^3/day). The presentation and description of emerging technologies and related bench- and pilot-scale studies are excluded, as this work focuses on technologies implemented at a full scale.

1.1 Regulatory Context

Selenium criteria/guidelines have been recently updated by various regulatory agencies in North America. Updates include the finalization of a fish-tissue based standard and setting the chronic toxicity-based water quality criteria to 1.5 µg/L in lentic aquatic systems and 3.1 µg/L in lotic aquatic systems based on total recoverable selenium (USEPA 2016). While these criteria are not end-of-pipe limits, they can be used to derive individual plant effluent limits which, in the US, are known as water quality-based effluent limits (WQBELs); these are incorporated into National Pollutant Discharge Elimination System (NPDES) permits. Criteria and guidelines for selenium vary from state to state in the US. Resultant effluent limits for treatment systems can range from less than 5 µg/L to about 20 µg/L.

The Canadian Water Quality Guideline (CWQG) for the protection of freshwater aquatic life is 1 µg/L. The CWQG was published in 1987 (CCREM 1987) and has not been updated since (GEI et al. 2018). The most recent provincial water quality guideline revision was British Columbia's freshwater aquatic life selenium guideline of 2 µg/L (BCMOE 2014). Alberta has recently (2018) adopted British Columbia's above-mentioned guideline.

Regulations can also vary by industrial sector. For instance, in the United States (US), the Environmental Protection Agency (USEPA) regulates selenium discharge in flue gas desulfurization wastewater at power generating facilities through a best available technology (BAT) approach. In November 2019, the USEPA issued a proposed rule for Effluent Limitations Guidelines and Standards for Steam Electric Power Generating with selenium daily maximum and monthly average limitations of 76 and 31 µg/L, respectively, for flue gas desulfurization (FGD) wastewater treatment with biological treatment (USEPA 2019). This effluent limitation was derived by BAT approach, which sets limits based on demonstrated performance of treatment technologies deployed for treatment of the FGD wastewater. The BAT for selenium removal is anaerobic biological treatment. The 2019 limitations are a change from those issued in 2015, which included daily maximum and monthly average effluent limitations for FGD of 23 and 12 µg/L, respectively. The increase in limitations is based on an updated evaluation of the performance of biological treatment of FGD wastewaters.

2.0 SELENIUM CHEMISTRY

Selenium is a metalloid found in Group VIA of the periodic table, below sulfur, as used by the Chemical Abstract Service (CAS). It has similar chemical properties to sulfur, due to its analogous electron distribution, which can make it behave similarly, and difficult for treatment processes to differentiate from sulfur species. Selenium is present in the environment in both inorganic and organic forms, and in solid, liquid, and gas phases. Although it can exist in six oxidation states, the II+ state is not known to exist in nature (Lenz 2008). The four most common, naturally-occurring oxidation states include:

- II- H_2Se, HSe^-, $SeCN^-$, metal selenides, alkyl selenides, seleno-amino acids, seleno-proteins
- 0 Se^0 including trigonal (grey) and monoclinic (red) crystalline forms
- IV+ SeO_3^{2-}, $HSeO_3^-$ and H_2SeO_3 (selenite)
- VI+ SeO_4^{2-} and $HSeO_4^-$ (selenate)

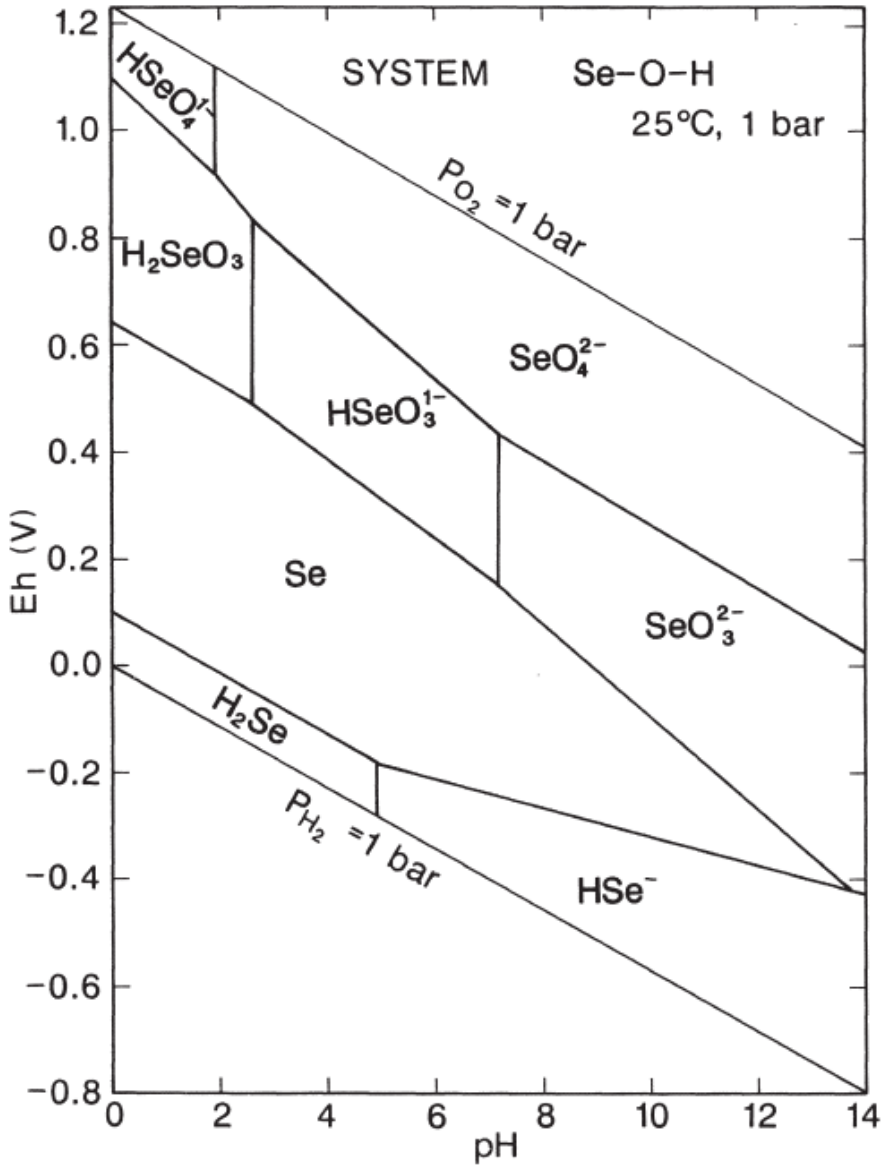
Inorganic forms include: SeO_3^{2-}, SeO_4^{2-}, Se^0, H_2Se, and metal selenides (MeSe). Organic forms include: alkyl selenides such as dimethylselenide (DMSe), dimethyldiselenide (DMDSe), seleno-amino acids, selenocyanate, and selenic-proteins (i.e., selenocysteine and selenomethionine). The latter selenic-proteins are analogues of the sulfur-containing proteins methionine and cysteine, are non-volatile, readily soluble, and highly bioavailable. Both DMSe and DMDSe are volatile, sparingly soluble, and relatively non-toxic, although both are bioavailable (Shrestha et al. 2006). The formation of organic selenium is typically biologically mediated.

Oxidized inorganic forms of selenium exist as highly-soluble oxyanions in aqueous systems. Neither selenate nor selenite anions react with common cations such as calcium or magnesium; therefore, they tend to have a relatively high solubility. Both selenate and selenite are bioavailable and have the potential to bioaccumulate. Selenate and selenite are the predominant selenium species in most industrial waters and impacted groundwaters.

Elemental selenium exists in seven different crystalline forms, and at least three amorphous forms. Elemental selenium is relatively insoluble and not readily bioavailable, making formation of elemental selenium desirable during selenium remediation. Nevertheless, elemental colloidal selenium particles are easily transported through aqueous systems (Haygarth 1994) and may be oxidized, depending on redox potential (Eh) of the solution. Inorganic reduced selenium species include insoluble metal selenides, and the highly toxic hydrogen selenide (H_2Se), an analogue to hydrogen sulfide usually formed under strongly-reducing conditions. Selenocyanate is known to exist in industrial wastewaters emerging from oil and gas (O&G) and mining operations, and has been identified as one of the intermediary products formed during biological treatment (Littlejohn et al. 2017). Hydrogen selenide is highly reactive and can form metal selenides or is substituted into metallic sulfide minerals such as chalcopyrite ($CuFeS_2$) and pyrite (FeS_2).

2.1 Oxidation-Reduction Reactions

Selenium speciation depends upon pH and redox potential (Eh). Knowledge of selenium speciation and its manipulation are essential for successful treatment. A simplified selenium-water system Pourbaix diagram showing major thermodynamically-stable selenium species as a function of pH and Eh is illustrated in Figure 1. This diagram assumes thermodynamic equilibrium; however, selenate and selenite are often observed to be outside their predicted thermodynamically-stable zones (Microbial Technologies 2005). Because selenite is more reactive than selenate, some treatment processes depend on the initial reduction of selenate to selenite. Under certain pH and Eh conditions, this process is energetically favored, but occurs slowly in natural systems.



(Source: Eh-pH Diagrams for Geochemistry 1988)

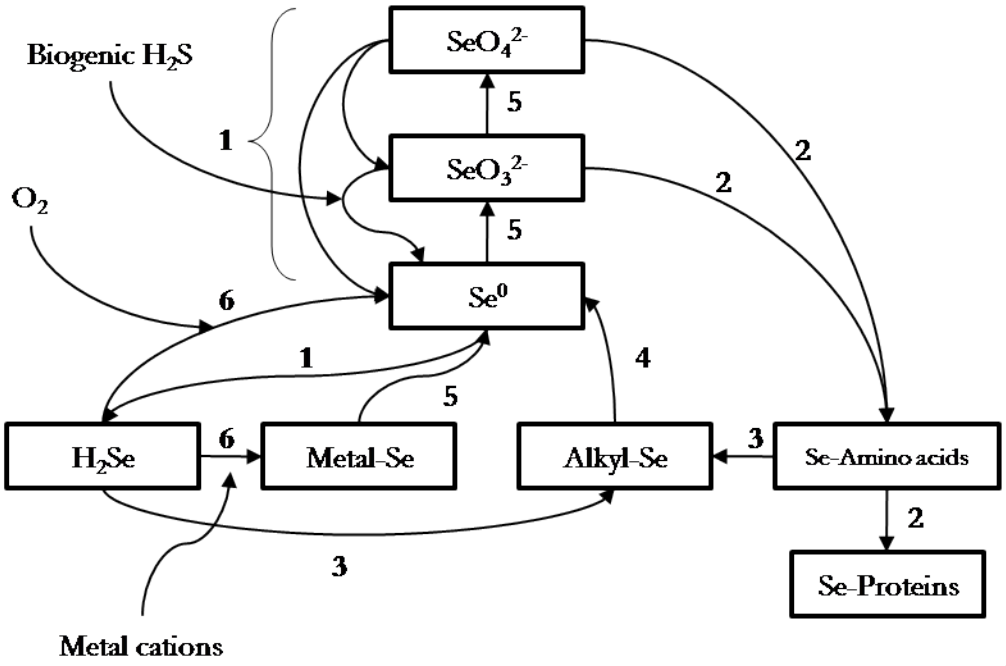
Figure 1: Eh-pH Diagram for the Se-H_2O System

2.2 Biologically-Mediated Reactions of Selenium

Biological systems can assist with the reduction of selenium under typical environmental conditions. Anaerobic-anoxic and aerobic bacteria, algae, fungi, and plants have all been shown to mediate these reactions (Masscheleyn and Patrick 1993). Selenate can be reduced to selenite, and both selenate and selenite can be reduced to elemental selenium or alkyl selenides. These reactions are desirable because elemental selenium is less soluble and therefore less bioavailable and alkyl selenides such as DMSe and DMDSe are highly volatile and sparingly soluble in aqueous systems. At the same time, the production of undesirable reduced organic species that are more bioavailable, such as selenocyanate and selenomethionine, can also take place. Reducing reactions have been encouraged for selenium treatment by creating conditions favorable to microbial growth, such as constructing wetlands, and applying selenium-bearing wastes or waters to plant-soil systems, a process known as phytoremediation (e.g., Zhang and Frankenberger 2003; Azaizeh et al. 2006; Bañuelos et al. 2005). Temperature, pH, moisture, time, selenium concentration and speciation, and the addition of a carbon source all affect these reactions (Masscheleyn and Patrick 1993; Lenz 2008).

Historically, these biologically-mediated reactions have been poorly understood, but recent advances, such as monitoring technology for microbes, have increased our understanding of these processes. Figure 2 illustrates the biochemical cycling of selenium in the environment by bacteria (adapted from Lenz 2008). Selenate and selenite can be reduced to elemental selenium, a process known as dissimilatory metal reduction, by anaerobic-anoxic selenium respiration and non-specific selenium reduction by nitrate and sulfate reducers, and *Archaea*. Influent nitrate concentration is known to play an important role in the oxidation and attenuation of selenium in mine wastes through biogeochemical mechanisms (Dockrey et al. 2015). Lenz (2008) suggests that inhibition and competition with other anions, such as nitrate (which limits the reduction of selenium in their presence) can be overcome by including anaerobic-anoxic selenium respirers in the microbial community. Selenium respirers will selectively reduce only selenium and are not affected by competing anions. This process, termed bioaugmentation, occurs when specific bacteria are added to an existing microbial population or biostimulation when conditions are manipulated to promote the growth of targeted microbial populations. In natural ecosystems, the oxidation or reduction of selenium can occur as a function of redox potential (i.e., Eh and pH). The following are a few examples:

- Oxidation of elemental selenium back to soluble oxyanions can be mediated by bacteria under oxidizing conditions. Generally, rates of re-oxidation are three to four orders of magnitude slower than microbial reduction (Tokunaga et al. 1994).
- Solubilization of selenium can occur when elemental selenium is reduced to selenides; however, selenides readily react with metal cations, forming microbiologically-induced metal selenide precipitates.
- Microorganisms can also re-oxidize metal selenides; however, in selenium treatment systems, the goal is to control the reactions, such that insoluble forms of selenium are produced.



Adapted from Lenz 2008.

Figure 2: Biochemical Selenium Cycling with 1) Dissimilatory Reduction, 2) Assimilatory Reduction, 3) Alkylation, 4) Dealkylation, 5) Oxidation, and 6) Bio-induced Precipitation

Biological treatment systems are designed to facilitate the reduction of selenate and selenite to elemental selenium as highlighted in the following reactions:

Selenate Reduction:

$$\frac{1}{6}SeO_4^{2-} + \frac{4}{3}H^+ + e^- \rightarrow \frac{1}{6}Se_{(s)} + \frac{2}{3}H_2O$$

Selenite Reduction:

$$\frac{1}{4}SeO_3^{2-} + \frac{3}{2}H^+ + e^- \rightarrow \frac{1}{4}Se_{(s)} + \frac{3}{4}H_2O$$

Temperature impacts to biological reduction can be expressed by the Arrhenius equation, with different activation energies for selenate and selenite reduction.

3.0 IMPLEMENTATION OF SELENIUM TREATMENT SYSTEMS

A review of selenium treatment systems was conducted, taking into consideration operational constraints (e.g., temperature, flow) and water quality constituents (e.g., total suspended solids [TSS], total dissolved solids [TDS], sulfate, nitrate, and/or alkalinity). There are a wide variety of sources for which treatment systems are being used, including:

- Groundwater seeps
- Industrial effluents (mining, petroleum refining and power generation)
- Pump-and-treat systems
- Agricultural systems
- Other systems

Although there is progress in the advancements of selenium treatment technology, in many instances progress is limited, and the results are highly variable. Selection of treatment technology is site-specific and depends on several factors, including:

- The influent and effluent target selenium concentrations and speciation, as dictated by the discharge permit limit or effluent water quality guideline (WQG).
- The removal performance of the applied biological, chemical and physical technologies as they operate with a defined removal performance range that dictates the general water chemistry, as well as achievable discharge selenium concentration.
- The other constituents present and their concentrations and variability in the influent (as listed earlier in this section).
- The flow rate and variability of the influent stream.
- The type and amount of residue produced and waste residue management approaches.

3.1 Survey Methodology for Full-Scale Selenium Treatment Systems

A survey was conducted pertaining to full-scale treatment systems completed and made operational since 2007. The year 2007 was selected as a starting date for the survey in order to focus on relatively recent full-scale operating systems designed specifically for selenium. While the original white paper report (CH2M HILL 2010) and the subsequent addendum (CH2M HILL 2013) also reported on full-scale implementations, the intent of this survey and addendum is to capture data on as many full-scale systems as possible. Some of the systems included in survey results were also included in the original white paper and subsequent addendum. Some applications (e.g., membranes, and evaporation) remove other additional constituents, and are excluded because selenium-specific technologies are typically more cost effective than those. For instance, thermal evaporation applications used in the power industry for effluent treatment are not included, because those treatment applications are not targeting selenium removal as the main constituent of concern, but indiscriminately remove a range of constituents of concern. Similarly, membrane applications were excluded, except where they are combined with another treatment technology that specifically targets selenium removal.

Due to the unique nature of each application, every selenium treatment project is different. In some cases, a selenium treatment project starts with a demonstration- or pilotscale system that is then expanded to a full-scale operation. However, the sizes of demonstration-scale plants and full-scale plants are variable across industries. For instance, due to the magnitude of operations in the mining industry, demonstration-scale plants may be larger than full-scale treatment plants in the power industry.

To conduct the survey, Golder developed information request questionnaires in two formats: (1) a main survey that was distributed to NAMC–SWG members and associates/consultants, and to industrial selenium treatment plant owners that were not NAMC–SWG members; and, (2) a shortened vendor survey requesting that vendors provide a list of operating systems, pilots and client contacts. The survey was sent out to 65 recipients, with responses providing data for 30 full-scale systems and 70 systems in total (i.e., including full-scale and pilot-scale plants). This report focuses on the 30 full-scale plants. Duplicate responses were received for some systems from the vendor and the end user. In those instances, the information supplied by the end user was prioritized.

For reference, template copies of the main and vendor surveys are attached to this report (see Attachments A and B).

Figure 3 illustrates the total number of responses received and the breakdown of plant data provided.

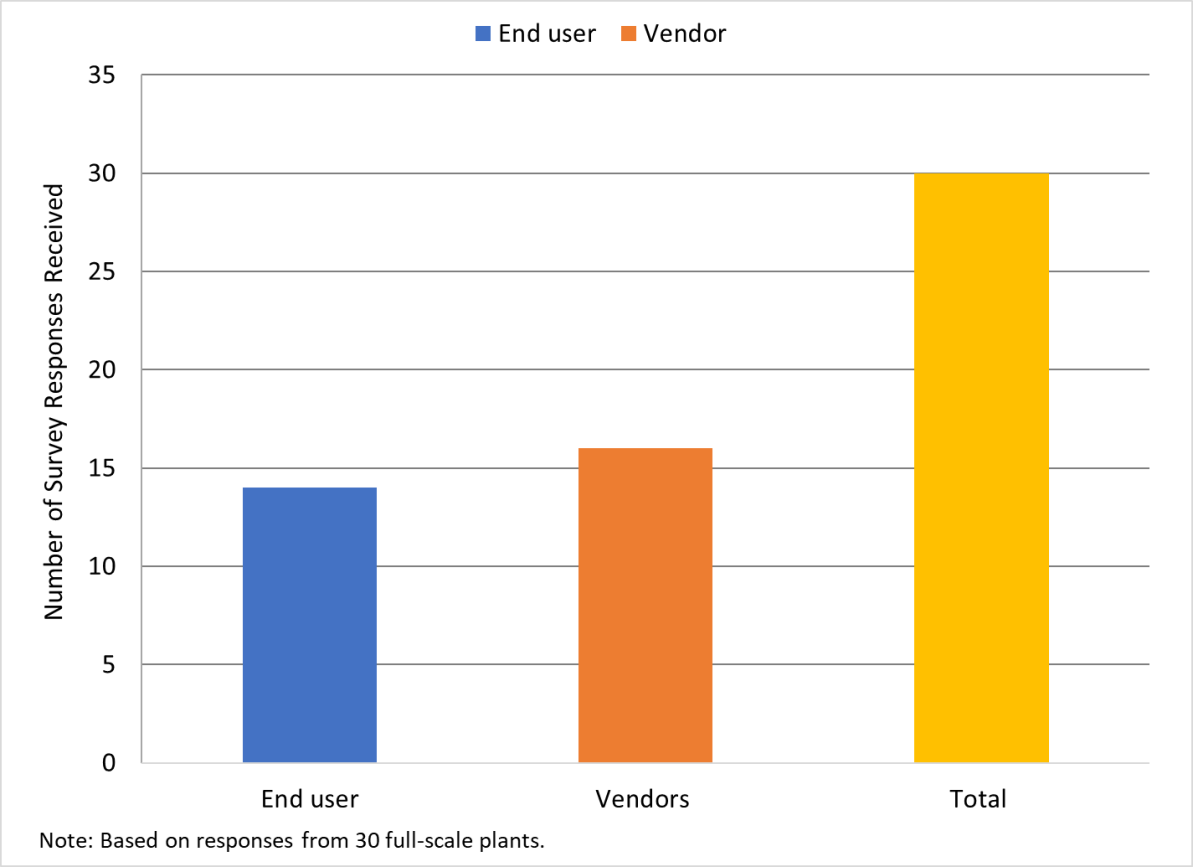


Figure 3: Survey Responses Received by End Users and Vendors

3.2 Survey Results

Survey results presented herein are limited to full-scale systems that became operational since 2007. Some of the systems reported herein were presented in the 2010 white paper (CH2M HILL 2010) and the associated addendum (CH2M HILL 2013). Systems currently in the process of being designed or constructed with anticipated completion dates of 2019 or beyond, are not included, due to uncertainties related to costs and performance. For ease of comparison, survey results presented in this section are also presented on a single page in Appendix C. Section 8.0 contains the cost information obtained from the survey.

Figure 4 illustrates the number of biological, physical/chemical, and combined biological and physical/chemical treatment systems installed per year from 2007 to 2018, for the 30 treatment plants identified in the survey. The number of active biological systems exceeded the number of physical/chemical and combined systems installed for selenium treatment. Figure 5 illustrates the number of treatment systems installed annually across six industry sectors, with mining and power sectors contributing the most. Figure 6 illustrates the total combined new treatment capacity annually. From 2016 to 2018, the total combined new capacity added has remained steady with a range between 3,000 gpm and 3,300 gpm (i.e., 16,500 m^3/day and 18,000 m^3/day). Figure 7 provides the total amount of selenium removed annually by the new facilities. From 2016 to 2018, these new facilities added removal capacity ranging between 1.0 and 1.8 metric tons (MT) per year (t/yr). When comparing results from Figure 6 and Figure 7 between 2016 and 2018, the selenium mass removal is not linearly related to the treatment capacity. This is because the selenium mass removed is not only dependent on the flow rate of the treatment plants, but also on influent selenium concentrations.

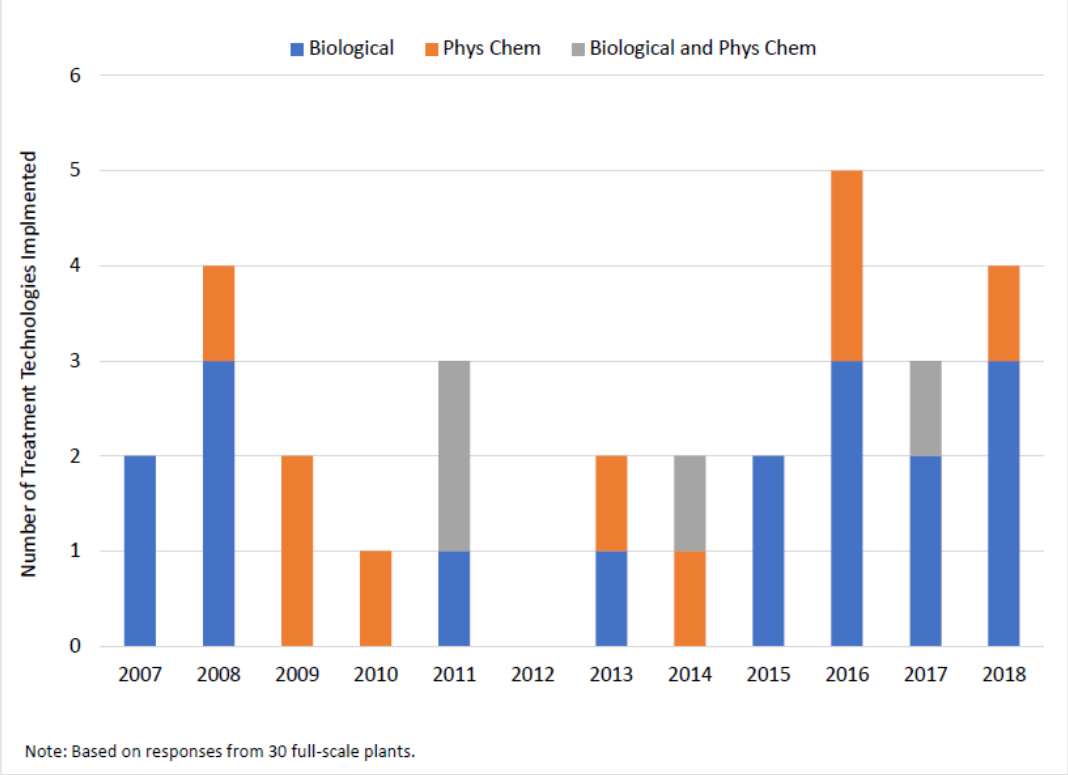


Figure 4: Number of Full-Scale Treatment Technologies Implemented Annually (2007–2018)

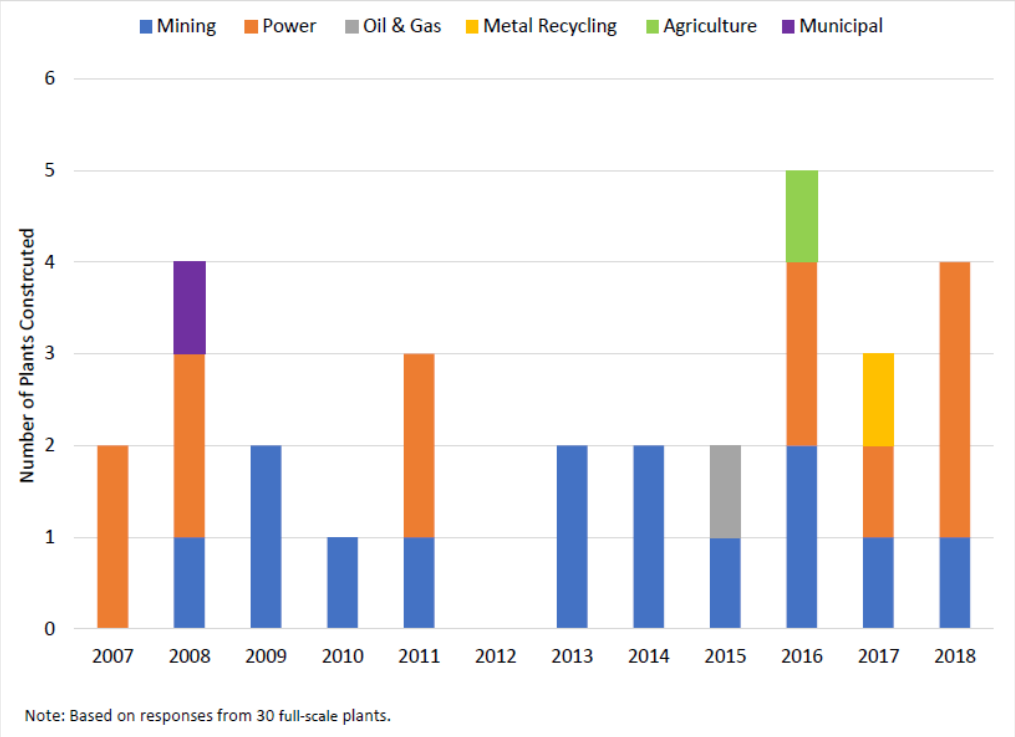


Figure 5: Full-Scale Treatment Plants Constructed Annually (2007–2018) – by Sector

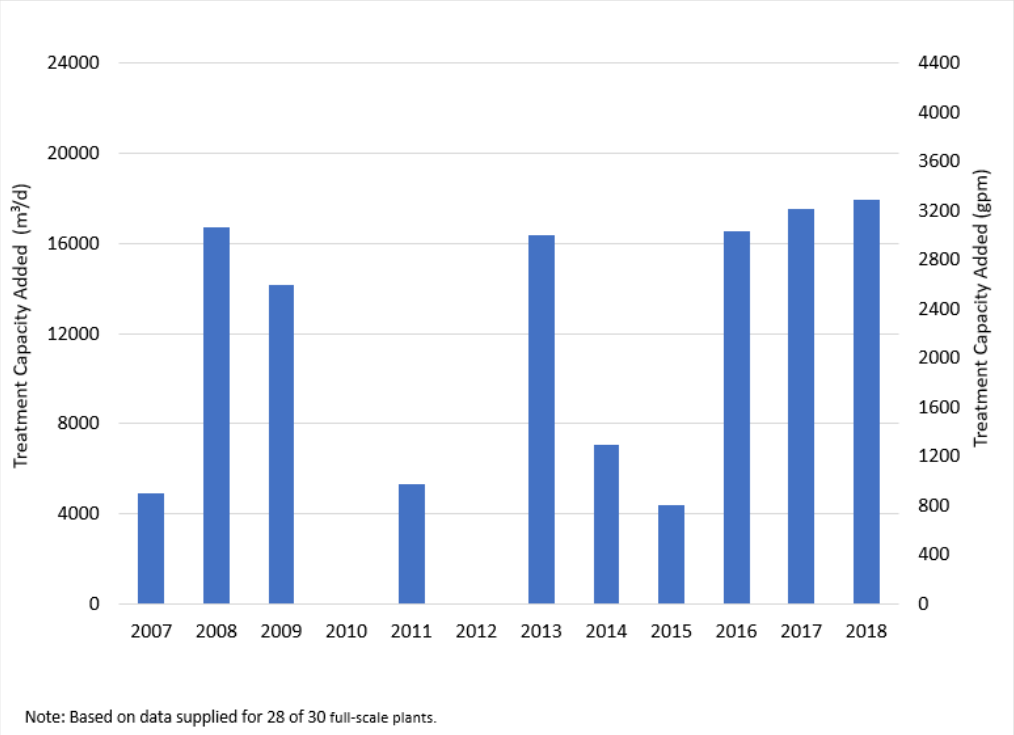


Figure 6: Treatment Capacity Added Annually (2007–2018)

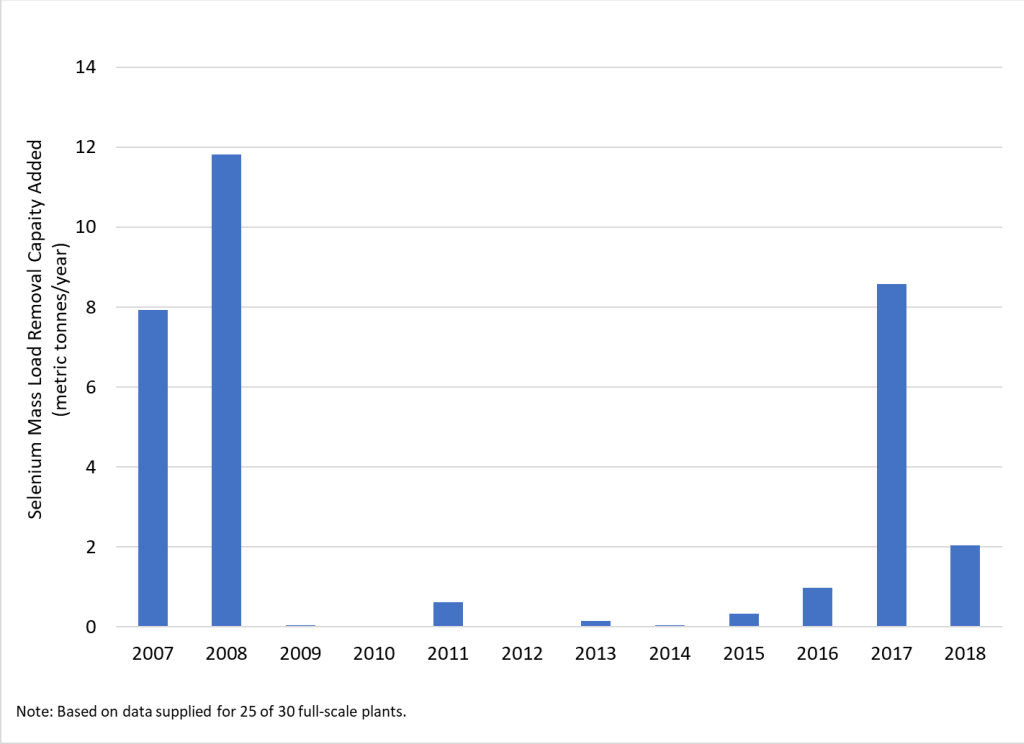


Figure 7: Selenium Mass Load Removal Capacity Added Annually (2007–2018)

A summary of key survey results for the 30 full-scale selenium treatment systems is provided in Table 1.

Table 1: Summary of Survey Results for 30 Full-Scale Selenium Treatment Systems (2007–2018)

Year of Construction	Treatment Technology	Industry Sector	Geographic Location	Flow Rate (gpm)	Flow Rate (m^3/day)	Selenium Removal Capacity (kg/year)
2007	Biological	Power Generation	North Carolina	640	3,490	5,080
2007	Biological	Power Generation	North Carolina	260	1,420	2,840
2008	Biological	Power Generation	North Carolina	1,400	7,630	8,320
2008	Biological	Power Generation	North Carolina	440	2,400	3,490
2008	Physical/Chemical	Mining	New Zealand	1,100	6,000	not available[1]
2008	Biological	Municipal	California	130	700	10
2009	Physical/Chemical	Mining	Saskatchewan	1,760	9,600	10
2009	Physical/Chemical	Mining	Saskatchewan	830	4,540	30
2010	Physical/Chemical	Mining	Saskatchewan	not available	not available	not available[1]
2011	Biological and Physical/Chemical	Power Generation	West Virginia	600	3,270	350
2011	Biological and Physical/Chemical	Power Generation	Pennsylvania	300	1,640	260
2011	Biological	Mining	West Virginia	80	410	not available[1]
2013	Biological	Mining	West Virginia	2,800	15,260	140
2013	Physical/Chemical	Mining	West Virginia	200	1,090	10
2014	Biological and Physical/Chemical	Mining	California	1,300	7,090	40
2014	Physical/Chemical	Mining	Saskatchewan	not available	not available	not available[1]
2015	Biological	Mining	Utah	200	1,090	310
2015	Biological	Oil & Gas	Wyoming	600	3,270	not available[1]
2016	Biological	Mining	British Columbia	1,380	7,500	640
2016	Biological	Mining	British Columbia	380	2,070	90
2016	Biological	Agriculture	California	200	1,090	80
2016	Physical/Chemical	Power Generation	North Carolina	80	410	120
2016	Physical/Chemical	Power Generation	Mid-Atlantic	1,000	5,450	40
2017	Biological and Physical/Chemical	Mining	Idaho	2,000	10,900	500
2017	Biological	Power Generation	Maryland	200	1,090	20
2017	Biological	Metal Recycling	Belgium	1,010	5,520	8,050
2018	Biological	Power Generation	North Carolina	550	3,000	1,080
2018	Biological	Power Generation	Florida	300	1,640	590
2018	Physical/Chemical	Power Generation	Virginia	600	3,270	70
2018	Biological	Mining	British Columbia	1,830	10,000	300

Note 1: Not enough data provided in the survey response to calculate.

4.0 ADVANCEMENTS IN SELENIUM REMOVAL TECHNOLOGY

This section describes advancements in selenium removal technologies since the last addendum (CH2M HILL 2013). Advancement descriptions are grouped by type of treatment technology; physical/chemical, or biological. Importantly, selenium treatment systems often include multiple unit processes, or a treatment train, including: flow equalization, pre-treatment, a core selenium removal technology, post-treatment, and residual management; this train is illustrated in Figure 8. Although the focus is typically placed on the core selenium removal technology, the entire train needs to be selected, designed, and operated properly in order to achieve successful operations. Case studies received from vendors, consultants and end users are included for selected technologies described in this section when they were provided to us. In general, case studies do not include selenium speciation data.

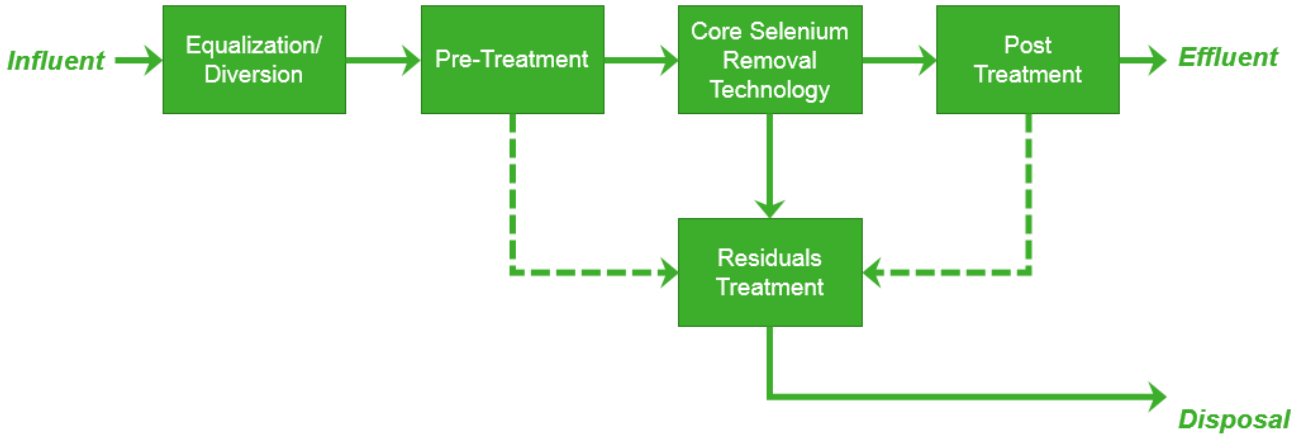


Figure 8: Selenium Treatment Block Flow Diagram, adapted from NAMC White Paper Report Addendum (CH2M HILL, 2013; Figure ES-1)

4.1 Physical/Chemical Treatment Advances

Physical/chemical treatment technologies include membrane treatment (e.g., reverse osmosis, and nanofiltration), co-precipitation, ion exchange, electrocoagulation, and evaporation. Most of these technologies are well understood and have been applied so as to result in selenium removal. An overview of the main physical/chemical treatment technologies and recent advances is provided in this section.

4.1.1 Reverse Osmosis and Nanofiltration

Reverse osmosis (RO) is effective for both selenate and selenite removal, while nanofiltration (NF) is more effective for the removal of selenate than selenite.

RO technology has been adopted into selenium treatment systems on multiple sites. RO will effectively remove selenium and other compounds into the reject, or brine stream, and generate a permeate stream with low levels of selenium. The brine stream must then be treated for selenium removal and disposal. RO alone does not create a sink for selenium, but is rather used primarily as a concentration or flow management tool, thereby reducing the size of the selenium removal and disposal process. In cold climates, RO can reduce energy inputs needed to heat water for biological selenium removal processes.

At sites with highly variable flow rates, an RO system can be ramped up or down to treat a range of influent flows, while maintaining a consistent flow to the selenium removal process. In some cases, permeate from the RO process requires post-treatment stabilization (e.g., recarbonation). At some sites, membrane treatment is combined with biological treatment in which the RO brine is treated in a bioreactor for selenium removal after which time it is recombined with the permeate prior to discharge. Combining these technologies can decrease the overall footprint of a treatment system and reduce capital costs. The case studies described in Section 4.2.6 serve as examples for which membrane and biological treatment technologies are combined.

In addition to RO, NF membranes have been successfully used in selenium treatment systems. NF membranes operate at lower pressures than RO and allow for the passage of monovalent ions (e.g., sodium, chloride, fluoride) into the permeate; while non-monovalent ions (including selenium species) are retained in the reject stream. This allows for the selective increase of selenium concentrations in the reject over other mono-valent species with lower energy requirements.

4.1.2 Ion Exchange and Electro-reduction

Many treatment technologies depend on the reactivity of selenite, which often requires a step to reduce selenate to selenite. This is not the case for ion exchange, where the selenate oxyanion can be removed from solution with an anion exchange resin. Although the reduced selenite form is also anionic, it is a weaker acid and is more difficult to remove by means of ion exchange than the selenate form. For ion exchange, removal can be improved by either ferric co-precipitation of selenite or oxidation of the selenite to selenate in a pre-treatment step.

BQE Water's Selen-IX™ system combines ion exchange, which concentrates selenium in the eluate, with an electrochemical step used for treatment of the eluate, and production of a residue for disposal. In this technology, a sodium sulfate solution is used to regenerate loaded resin. The sulfate cycle has been shown to selectively remove trace selenium concentrations from a sulfate-dominant water matrix. The spent regenerant solution from the ion exchange columns is sent through an electrochemical selenium reduction step, using iron anodes to form a high-density, iron-selenium sludge. The process concentrates the selenium into a sludge, which is removed from the circuit. Electrochemical reduction of selenium allows the spent regenerant solution to be recycled, and eliminates the volume of the regenerant waste stream. Although there are no Selen-IX™ plants in operation yet, pilot programs have been described (Littlejohn et al. 2017) and there are currently two full-scale Selen-IX™ plants under construction: the first is expected to start commissioning in Q2 2020, the second is expected to begin commissioning in Q1 2021 (see Figure 9).

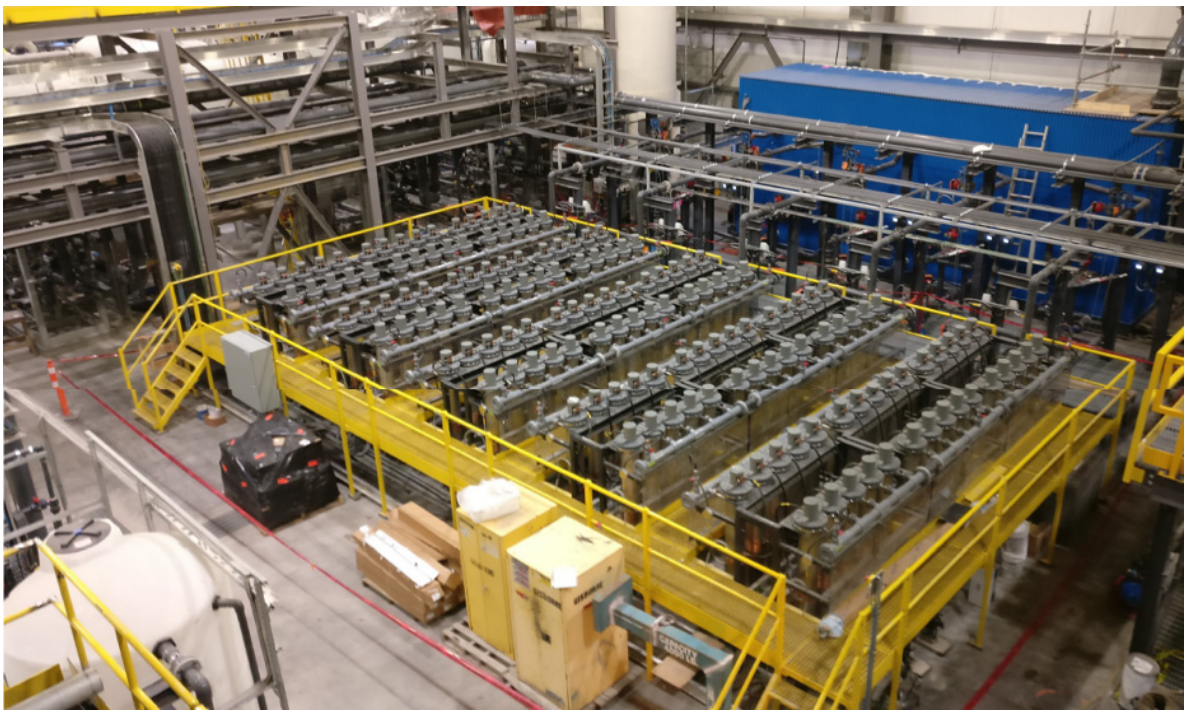


Figure 9: A Full-scale Plant Currently Under Construction that Uses the BQE Water Selen-IX™ Technology

4.1.3 Zero Valent Iron (ZVI) and Co-precipitation

Some physical physical/chemical technologies involve reduction of selenate to selenite or elemental selenium, adsorption of selenite, and precipitation of sorbed and elemental species.

There are many examples of treatment systems in which ZVI has been installed. The influent nitrate concentration plays an important role in ZVI treatment of selenium, because the ZVI process reduces nitrate to nitrite (NO_2^-) and ammonium, which may be unwanted. It may also produce other unwanted, reduced selenium compounds. Earlier versions of this technology made use of granular or steel wool ZVI as the source contained within a reactor. These ZVI reactors require long retention times and lose reactivity through passivation, which causes plugging of the reactor columns. There is little control over the iron content in the effluent, while spent ZVI has to be removed, disposed of, and replaced. Since then, several iterations of advancements in the ZVI-based technology have taken place.

An example of one of these advancements is the Pironox® system by Evoqua, which is described as an advanced reactive media system that relies on inorganic oxidation/reduction chemistry in which the driving force is catalytic reduction using an iron-bearing medium that reduces metals under carefully controlled conditions. Process schematics of the Pironox® system are provided in Figure 10.

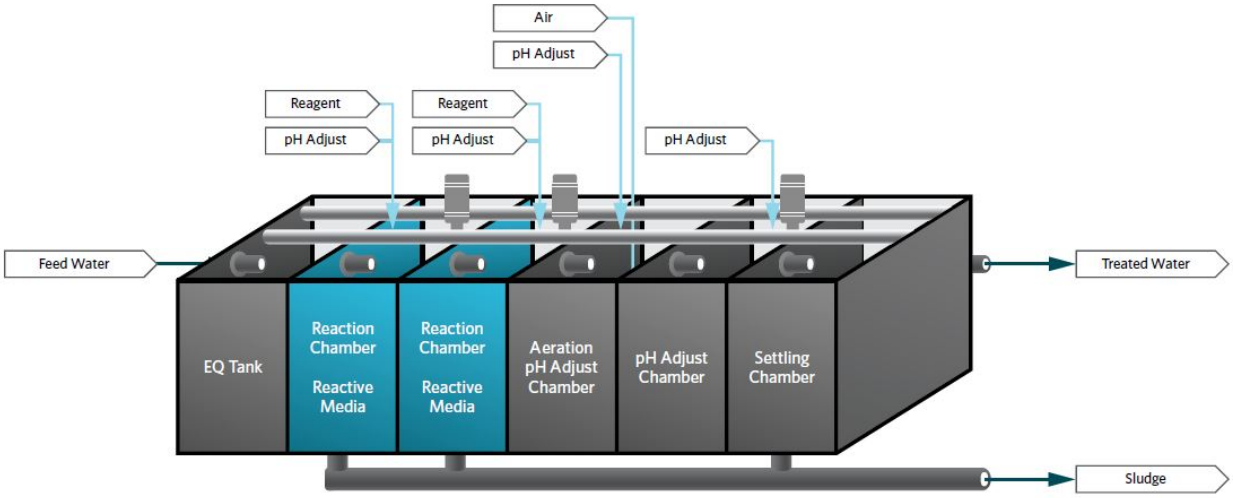


Figure 10: Simplified Process Flow Diagram: Pironox® Advanced Reactive Media System (Reproduced with permission from Evoqua Water Technologies LLC)

The Pironox® advanced reactive media act as an electron source to chemically reduce soluble metal cations and oxyanions to insoluble forms. During the reaction, the treated contaminants are removed by surface adsorption and chemical incorporation into the iron oxidation products. The media are contained in the reaction chambers by means of circular tanks with an inner draft tube and agitator to keep the media suspended.

Specific improvements over earlier versions of ZVI technology are the addition of an anti-passivation chemical to prevent passivation, and the introduction of continuous stirred tank reactors (CSTR) for better process control.

Case Study 1: Sulfur Modified Iron (Confidential Site)

SMI (sulfur-modified iron) is an industrial-grade granular medium that has been reported to be an effective technology to remove selenate. Its removal mechanism consists of adsorption and chemical transformation of the selenium species (i.e., selenate and selenite) through reduction. SMI has a smaller particle size than conventional ZVI, so it yields faster reaction rates. The technology was tested by Evoqua to target the removal of selenate at a coal combustion residuals (CCR) treatment facility. Column tests that compared ZVI, SMI and a barium chloride/activated alumina process indicated that all three had similar removal rates; however, SMI had superior bed life. Data from a 400 gpm to 600 gpm (i.e., 2,200 m^3/day to 3,300 m^3/day) selenium treatment system that was implemented as a polishing unit for selenate removal post-enhanced water treatment process is provided in Figure 11. The figure illustrates an influent selenium concentration ranging between 4 µg/L and 12 µg/L, and that by using SMI for selenium removal the effluent selenium target of 6.5 µg/L was met for all but two instances at 19 mmgal and 33 mmgal when the target was exceeded.

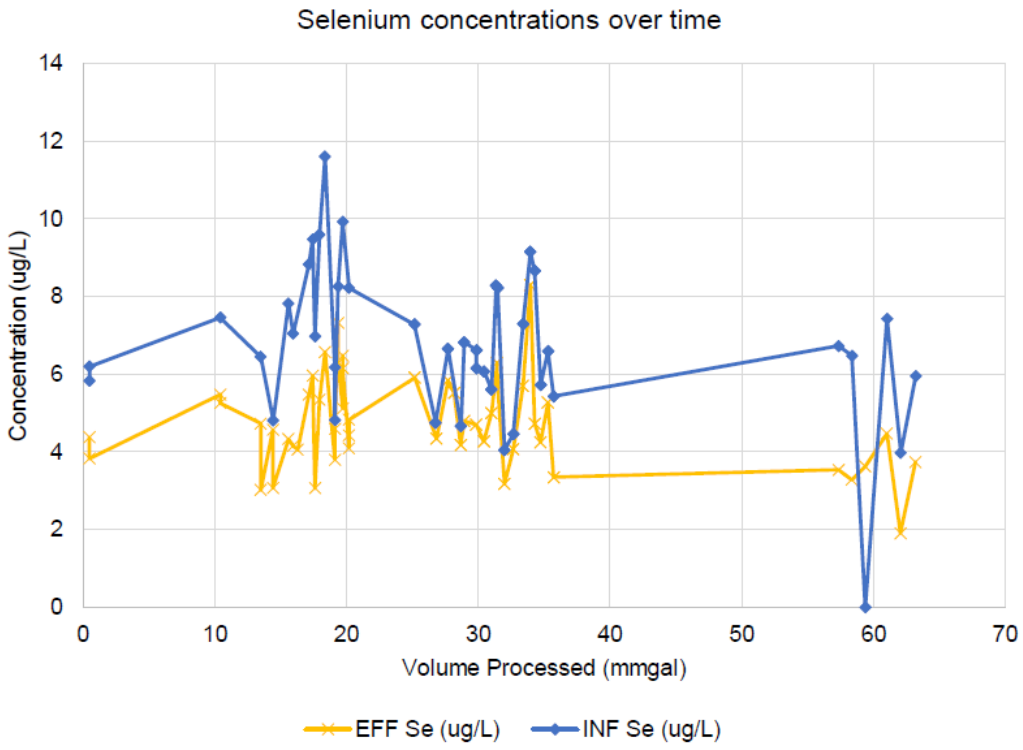


Figure 11: SMI Selenium Treatment Performance Data

Case Study 2: Iron Co-precipitation (Confidential Site)

A mining company (confidential) has an 830 gpm (i.e., 4,540 m^3/day) treatment plant that uses a co-precipitation process to remove selenium. Ferric sulfate is added to precipitated arsenic, molybdenum and selenium (in the selenite form). The effluent of the reaction tanks flows to a clarifier, where a coagulant is added to enhance precipitation. The overflow from the clarifier flows to monitoring ponds and sludge from the clarifiers is handled separately. Selenium concentrations (total) decrease (on average) from 18.5 µg/L to 3 µg/L.

4.2 Biological Treatment Systems

Biological treatment systems include active, passive and *in situ* technologies. As evidenced by the number of full-scale plants constructed since 2007, significant progress and learning about these technologies has occurred in recent years. New commercial biological treatment systems have been introduced and implemented, and progress has also been made on passive and *in situ* technologies and hybrid passive-active treatment approaches. Significant pre- and post-treatment processes can be necessary for biological treatment systems. The large number of biological technology providers, coupled with an even larger variety of pre- and post-treatment processes has resulted in a variety of unique process trains being implemented in biological treatment systems. Most biologically-based technologies rely on a similar anaerobic-anoxic removal mechanism, in which oxidized forms of selenium are largely reduced to particulate, elemental selenium by facultative heterotrophic bacteria such as denitrifying and selenium-reducing bacteria. Biological treatment is effective for removal of both selenite and selenate species.

Influent nitrate concentrations also play an important role in the oxidation and attenuation of selenium in mine wastes and in biological treatment of selenium. Because nitrate provides a higher energy yield than selenium species to microorganisms that are active in biological treatment systems, denitrification generally precedes or runs in parallel with selenium reduction in biological treatment systems. Biological denitrification can be accomplished by attached and suspended growth (activated sludge) systems. Where there is nitrate loading in feed water, the denitrification reaction produces nitrogen and carbon dioxide, both of which are released in the gaseous form. In some biological treatment applications, the formation of the nitrogen and carbon dioxide can cause gas lock problems. The biological denitrification process also produces biomass as a waste residue. Section 6.0 describes the management of waste residues in more detail.

4.2.1 Active Biological Treatment

Active biological treatment systems have received a lot of attention from vendors over the last twelve years; this is mainly so as to optimize systems, including decreasing empty bed contact times (EBCT) and increasing hydraulic loading rates. Active biological treatment systems are fixed-film reactors and include packed beds, fluidized beds and combination fluidized bed/packed bed systems. Detailed descriptions of these reactor types and definitions were provided in the NAMC 2010 white paper (CH2M HILL 2010).

In packed bed reactors, elemental selenium particles are largely retained in the reactor on the media and can be periodically removed by backwashing or agitation of the media. Although the biological reduction reaction has been characterized by numerous studies, the retention and management of particulate elemental selenium in the bioreactor can be equally important in terms of removal efficiencies. Retention of selenium particles is largely a physical process and is dependent on factors such as biofilm thickness and age. In fluidized bed reactors, elemental selenium is not entirely retained in the reactor itself and can require downstream processes for selenium particle removal and management. Successful operation of packed or fluidized bed reactors can depend not only on the biological reduction reactions, but also on the retention of precipitated selenium particles. Suez's ABMet™ packed bed and Envirogen's fluidized bed reactor (FBR) systems have been implemented at numerous sites and are described in greater detail in the NAMC 2010 white paper (CH2M HILL 2010) and the NAMC 2013 addendum (CH2M HILL 2013).

Proper evaluation and design of biological treatment has typically relied upon treatability studies to determine design and operating parameters such as: removal rates, retention times, nutrient dosing and backwashing frequency. Treatability testing for these biological technologies can be lengthy and costly.

Vendors have experimented with different nutrient-dosing sources, and consequently some are moving away from using molasses as carbon source. There are different types of carbon sources used for denitrification that can be employed for selenium reduction. In a review of carbon sources used for biological denitrification, Sapavatu and Yelamarthi (2012) listed a wide variety of diverse sources, including: ethanol, methanol, acetic acid, acetate, methane, propionate, glucose, sawdust, succinic acid, hydrolyzed rice, newspaper, cotton, rice husk, and molasses. Although cost is an important factor in carbon source selection, other factors to consider include: selenium reduction and denitrification rates, the development and types of denitrifying microorganisms, the quantity of carbon source required, the biodegradability of organic residuals, and ease of handling. For instance, although molasses may be the most economical option, it can be difficult to handle and pump, when used in the undiluted form due to its high viscosity. Even though this can be overcome by using the diluted form, diluted molasses is susceptible to biofouling in the feed solution and the injection system, requiring regular monitoring and cleaning. Different carbon sources can also impact the bacterial community which, in turn, can impact selenium removal performance. The addition of phosphorous, nitrogen, and micro-nutrients need to be considered on a site-by-site basis.

Advancements in active biological treatment since the NAMC 2013 addendum (CH2M HILL 2013) include Frontier's SeHAWK™ system which has a dual-stage process configuration, combining an FBR with a downflow packed bed reactor. The suspended bed in the upflow FBR relies on surface contact biofilm growth (attached growth) to create reducing conditions necessary for reduction of selenate to elemental selenium. Particulates in the FBR effluent are then filtered with a downflow granular activated carbon (GAC) packed bed reactor.

Another advancement is the fixed bed electro-biochemical reactor (EBR) developed by Inotec; this reactor uses a direct current voltage to provide a low-voltage electron gradient across the bioreactor. By supplying an electron source directly to the bioreactor, the vendor states that the nutrient feed and biosolid residues can be reduced in comparison to conventional bioreactors. Refer to Section 4.2.6 for more detailed active biological treatment case studies.

4.2.2 Passive Biological Treatment

For the purposes of this report, a passive biological treatment system is a bioreactor system that does not require a deliberate continuous nutrient feed and can operate with minimal or no electrical equipment and operator attention. These systems are commonly referred to as biochemical reactors (BCRs) or compost reactors; the reactor media are a mixture of organic media such as wood chips, hay, or sawdust with inorganic media such as fine-grained limestone. Organic media are degraded by various categories of bacteria (i.e., cellulose-degraders, fermenters) into short-chained organic carbon molecules which, in turn, are utilized by denitrifying and selenium-reducing bacteria for selenium reduction. A technological advantage to these systems is low operating costs; disadvantages include low hydraulic loading rates and large area requirements, lack of control over organic media degradation which drives selenium removal, and potential for high levels of residual nutrients (i.e., organic carbon, ammonia, phosphorus) in the effluent, especially during start-up.

Case Study – Arch Coal's Coal-Mac Mine, West Virginia

A full-scale passive treatment system is currently in operation at the Arch Coal Coal-Mac Mine site, which is meeting a stringent discharge/effluent limit of 4.7 µg/L (monthly average). This integrated passive treatment system consists of an aerobic BCR, followed by an anaerobic-anoxic upflow peat filter, then a horizontal subsurface flow gravel media bed, completed by an open surface flow wetland. This system has been operational since 2011 and treats influent flows ranging from 10 gpm (i.e., 55 m^3/day) in summer months to 75 gpm (i.e., 410 m^3/day) during spring. At the end of the system's operating life, the BCR media will be left in place and will function as a natural wetland.

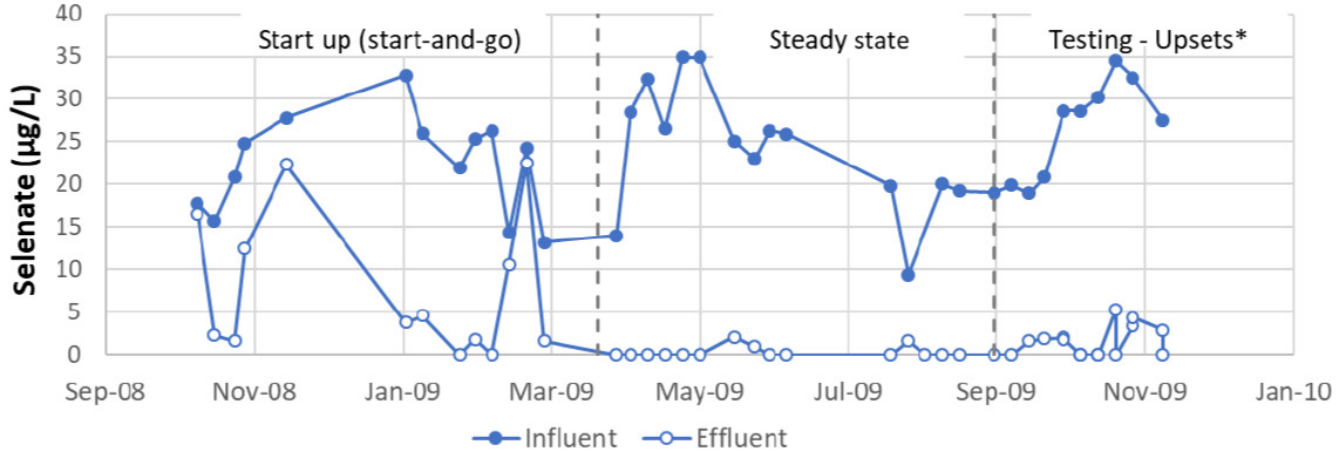
4.2.3 Hybrid Biological – Gravel Bed Reactor

A gravel bed reactor is an example of a hybrid system and is a packed bed reactor of gravel media through which water containing constituents of concern is passed and treated. For anaerobic-anoxic biological treatment, required amendments, such as electron donors and nutrients, are added to the water at the inlet of the reactor to promote the growth and activity of natural microbes capable of reducing the inorganics and sequentially immobilizing the metals/metalloids in the gravel bed. Gravel bed reactors can be constructed in geomembrane-lined cells and require mainly civil construction methods. The top and bottom of the treatment zone are lined using synthetic membranes to prevent water loss / influx, creating hydraulic isolation from the surrounding environment (Mancini et al. 2019).

Case Study – Cienaga Filtration Project, Irvine, California

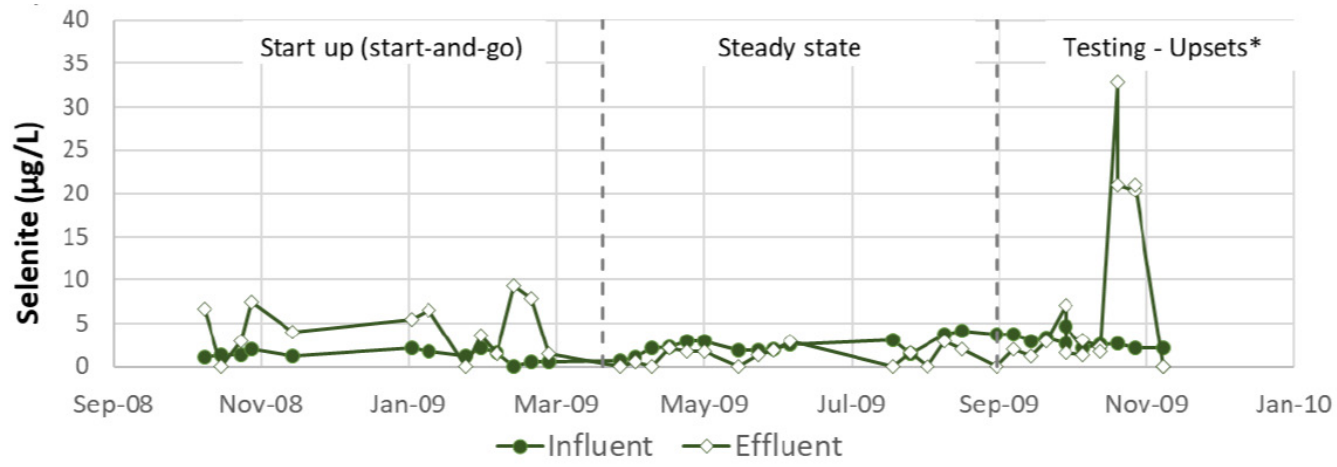
A gravel bed reactor was installed to remove selenium and nitrate from surface water in Peter's Canyon Wash in the City of Irvine, California. The source water selenium concentrations ranged from 20 µg/L to 40 µg/L and nitrate concentrations ranged from 5 mg/L to 15 mg/L (as N). The gravel bed reactor system was assessed between 2008 and 2009, and operated for another 6 years at a flow rate of 130 gpm to 230 gpm (i.e., 730 m^3/day to 1,250 m^3/day). Effluent selenium concentrations ranged between 2.3 µg/L and 1.2 µg/L , while nitrate was <8 mg/L (as N). System upset testing was conducted that involved intentionally shocking the gravel bed reactor system with hydrogen peroxide to assess immobilized selenate and selenite release in the effluent.

Figures 12 and 13 below show selenate and selenite results, respectively, during the assessment period, which consisted of start-up, steady state, and testing-upset phases.



*System upset testing.

Figure 12: Selenate Concentrations (influent and effluent) during the Assessment Period, Cienaga Filtration Project, Irvine, California



*System upset testing.

Figure 13: Selenite Concentrations (influent and effluent) during the Assessment Period, Cienaga Filtration Project, Irvine, California

4.2.4 *In Situ* Biological Treatment

Various *in situ* treatment methods have been demonstrated, including *in situ* pit lakes, saturated rock fills (SRFs), and permeable reactive barriers (PRBs). These systems are defined as *in situ* systems because the treatment process is carried out *in situ* (in place) and does not require construction of a typical treatment plant building.

The SRF technology has been developed and implemented at full scale at a mine site in British Columbia. The technology utilizes a backfilled mine pit as a bioreactor. Mine water and nutrients are injected into the backfill, then flows horizontally through backfill, and the treated water is pumped out of the backfill for polishing treatment and discharge. The backfilled pit serves a similar function to an anaerobic-anoxic packed bed reactor where denitrification and selenium reduction occur. The SRF technology, due to its size, is inherently slow to respond to process inputs, such as nutrient and carbon source changes. Therefore, control of pH, Eh, carbon source side reactions are uncertain. On the other hand, since the process is slow, operators have more time to identify and respond to abnormal or upset conditions than in an active system with much shorter residence times.

Several instances of *in situ* pit lake treatment have demonstrated effective selenium removal (Harrington 2002; Harrington et al. 2004; Paulson et al. 2004).

Case Study – Pit Lake (Confidential Site)

A research program conducted by Golder for a mining client, included bench-, pilot- and demonstration-scale treatment. Selenium concentrations differed by lake layer, but all layers exhibited decreases over the course of the test period. The largest decrease in total selenium occurred in the hypolimnion, with a maximum concentration of 84 µg/L and a minimum concentration of 1.4 µg/L in March 2013. The smallest decrease occurred in the epilimnion, with a maximum concentration of 51 µg/L and a minimum concentration of 17.4 µg/L. Characterization and understanding of pit lake limnology such as chemoclines, thermoclines, and turnover regimes are important for successful implementation. Successful treatment occurred over cold winter months when ice cover functioned as a successful oxygen barrier and the entire water column was rendered anoxic. During summer months, oxygen intrusion at the water surface impeded anoxia and selenium reduction near the surface, also known as the epilimnion. The pit lake was not a fish-bearing water body.

4.2.5 Biological Treatment Comparison

Although biological treatment technologies all rely on the same selenium reduction reaction, there are significant differences among technologies. Table 2 below provides a high-level comparison of technologies based on various factors. One attribute, mechanism (e.g., backwash), which allows management of precipitated selenium as a separate waste stream, is an important differentiator. Active treatment systems are equipped with backwash capabilities or media agitation systems that allow for precipitated selenium and biomass to be periodically removed from the BCR, and subsequently managed with a solids/liquids separation and dewatering process, which results in solid waste residual formation (discussed further in Section 6.0). The passive, hybrid and *in situ* biological technologies lack this attribute and typically continue to remove selenium in the same reactor for the entire operating period, or lifespan, of the system. This can present a few risks/uncertainties: 1) in the event of an upset condition, high selenium concentrations, in excess of influent concentrations may be released; and, 2) the selenium remains on site or in the environment and cannot be disposed of in an engineered disposal facility. In the case of *in situ* pit lake treatment, for example, the precipitated selenium accumulated at the bottom of the pit lake could be mobilized by changing redox conditions in the lake or if the pit is eventually re-mined.

Table 2: Attribute Comparison of Biological Treatment Technologies

Attribute	Active (i.e., packed bed, fluidized bed, combination packed/fluidized)	Hybrid Gravel Bed Reactor	Passive Biochemical Reactor	*In situ* (e.g., pit lake, saturated rock fill, permeable reactive barrier)
Typical EBCT	20 min to 6 hours	12 hours to 2 days	12 hours to 12 days	days to months
Mechanism (e.g., backwash) which allows for management of precipitated selenium as a separate waste stream	Yes	Maybe	No	No
Footprint	Small	Medium – Large	Medium - Large	Medium – Large
Level of Development	> 30 full-scale installation > 1,000 gpm (i.e., 5,500 m^3/day)	Bench- and pilot-scale testing 1-4 full-scale installations > 75 gpm (i.e., 410 m^3/day)	Bench- and pilot-scale testing 1-5 full-scale installations > 200 gpm (i.e., 1,100 m^3/day)	1 – 10 full-scale installations (variable installations)[1]
CAPEX	High	Medium	Medium	Low
Complexity	High	Low – Medium	Low	Low
Maintenance Requirements	High	Low – Medium	Low	Low
Commercialized	Yes	No	No	No

Note 1: Flow rates for *in situ* systems vary widely from *in situ* pit lakes which may not have consistent influent or effluent to permeable reactive barriers treating low groundwater flows to high flow SRF systems. The maximum reported flow rate for an *in situ* system is 1,835 gpm (i.e., 10,000 m^3/day) for an SRF system.

4.2.6 Detailed Case Studies of Biological Systems

Detailed case studies are provided below for two biological systems including influent and effluent selenium data for a multi-year period. The first case study describes a system treating agricultural drain water in California, the second one describes a mine water treatment system in Idaho.

Detailed Case Study 1 – Central Valley, California

A demonstration treatment plant designed for selenium removal from agricultural drainage water has been constructed in Central Valley of California and is currently operating. The original process flow was ultrafiltration as a pre-treatment followed by RO, where RO concentrate was the influent to a packed bed bioreactor. There are two parallel packed bed bioreactor trains, each consisting of two downflow reactors, operating in parallel with even flow distribution. The design EBCT was 12 hours when being fed RO concentrate. The system configuration was altered due to scale generated in the RO process, which scaled the downstream bioreactor. The process was reconfigured to implement the bioreactor as the first unit operation in the demonstration treatment plant, which would be the influent to downstream ultrafiltration and RO processes. The current packed bed reactor EBCT is 6 hours. Given that two bioreactors operate in series for each train, the EBCT in each bioreactor is three hours. Influent and effluent total selenium concentrations are provided in Figure 14. This case study is notable for a few reasons: EBCTs have decreased since this system was constructed as vendors have gained experience and learned more about removal mechanisms and rates of removal. Regarding the performance data, the data are limited to influent and effluent from the bioreactors and do not include removal associated with the ultra-filtration (UF) or RO. Periodic elevated effluent concentrations in 2017 and 2018 are probably likely related to backwashes and or de-gassing, which can cause selenium release from the reactor bed.

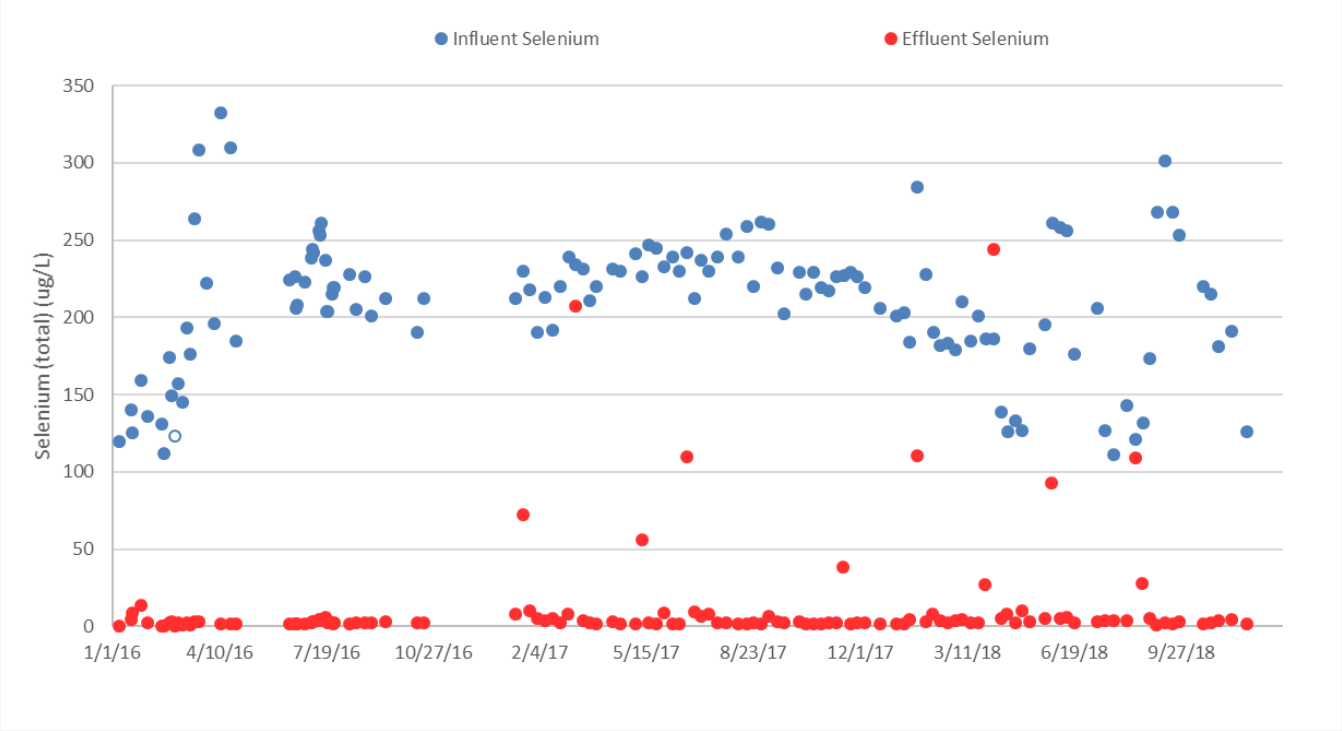
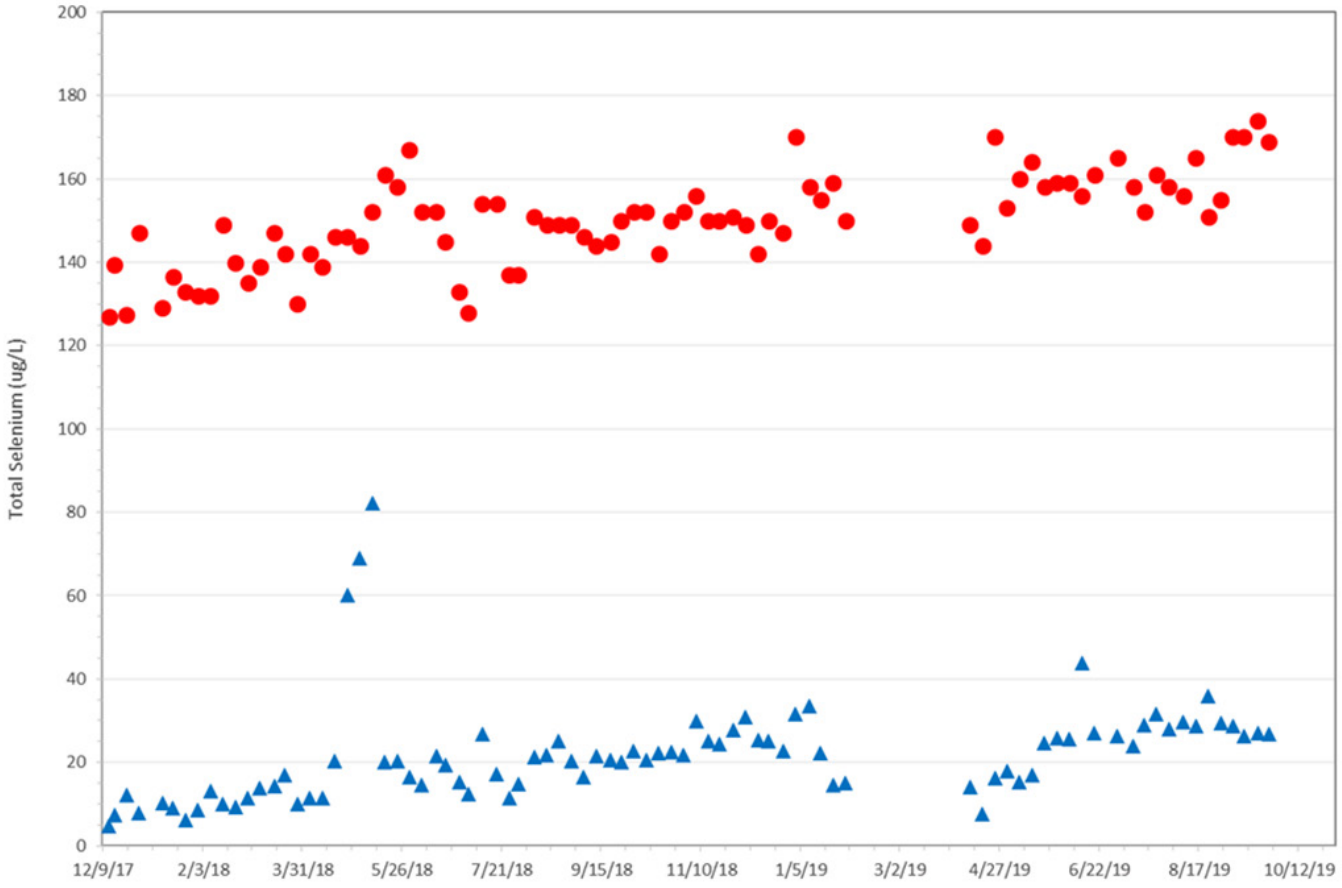


Figure 14: Central Valley Operational Data for Selenium Concentrations - Influent and Effluent

Detailed Case Study 2 – Hoopes Pilot, Smokey Canyon Mine, Idaho (J.R. Simplot)

The J.R. Simplot company constructed the Hoopes Selenium Treatment Study Pilot (Hoopes TSP) at their Smoky Canyon Mine in Idaho. The Hoopes TSP combines physical and biological processes that concentrate water-soluble selenium with RO prior to biological reduction and solids removal. The unit processes applied include UF, RO, anaerobic-anoxic biological, aerobic biological, and tertiary filtration. Biosolids are dewatered with a centrifuge and disposed off-site. Operational data from December 2017 to October 2019 are presented in Figure 15. Outlier effluent values are associated with interruptions in the nutrient feed. An operational observation is that backwash and de-gassing events lead to decreased selenium removal (Witt et al. 2019).



*Note that red dots represent total selenium concentration in the influent and blue triangles represent final effluent from the treatment system.

Figure 15: Hoopes Pilot Operational Data for Selenium Concentrations - Influent and Effluent

4.2.7 Operational Challenges of Biological Treatment Systems

Operation of biological systems for selenium treatment can be challenging due to inherent challenges with any biological system such as: nutrient control, impact of temperature, and maintaining a viable biomass. Those challenges, coupled with selenium-specific considerations such as rapidly-varying influent nitrate and selenium concentrations and achieving very low, part per billion, effluent limits require precise control over redox conditions and adept management of the bioreactor bed (e.g., backwash, de-gassing). For many industrial sites, operating a biological selenium removal system presents an unfamiliar challenge for staff. A few important considerations include:

- Management of influent solids and higher nitrate loads can lead to bioreactor plugging of some bioreactor designs and need for frequent backwashing or de-gassing for fixed-bed designs. Proper consideration of influent solids during design and potential inclusion of pre-filtration can mitigate this issue. FBRs have been reported to handle higher solids and nitrate concentrations due to media fluidization and complete disengagement of nitrogen gas.
- Management of fluctuations in feed flow and/or loading, including interruptions in flow and power.
- Maintaining proper redox control—nutrient demand is driven by the combined load of electron acceptors including dissolved oxygen, nitrate, and selenium. As influent selenium and nitrate concentrations increase, nutrient demand will change. If the nutrient feed is not adjusted, then the redox potential can increase to a higher level than desired, resulting in a decrease in selenium removal. Conversely, if influent concentrations decrease, then a lower than optimum redox potential can occur, causing production of hydrogen sulfide and the potential for production of additional reduced selenium species. Nutrient feed can be automated based on influent flow rate or oxidation-reduction potential, both of which can have drawbacks. Control of side reactions that consume reagents (such as methanogenesis) can also be a concern.
- Backwash—in a packed bed reactor, occasional backwashing is necessary to remove biomass and selenium and maintain bed permeability. The intent of backwashing is to exert a shear force on bioreactor media in order to remove biomass and associated precipitated selenium. Once the backwash cycle is complete and flow reverts to downflow, it is not uncommon for effluent selenium concentrations to increase because of incomplete removal of selenium precipitates during backwash. Visual observations of a pilot media bed surface after backwash indicate red selenium precipitates that have been stripped from the biomass - but not entirely removed from the bioreactor - into the backwash waste system.
- De-gassing—in packed bed reactors, de-gassing typically resembles a short-duration backwash and is intended to remove any gas buildup that can reduce hydraulic permeability. Carbon dioxide, nitrogen, and hydrogen sulfide gases can all accumulate in the bed. Similar to a backwash, a de-gas cycle can liberate selenium particles from the bed, which can lead to elevated effluent selenium concentrations after the completion of the de-gas cycle.
- Discharge of anoxic water—bioreactor effluent is anoxic and contains nutrients, and residual biochemical oxygen demand, and can contain hydrogen sulfide. Direct discharge of bioreactor effluent to the environment can cause oxygen deficiency and related negative impacts to aquatic ecosystems. Post-treatment processes such as aeration or chemical oxidation followed by clarification or filtration can polish bioreactor effluent before discharge.

- Selenium limits for discharge from sites range from nominally around 5 µg/L up to 20 or 30 µg/L. The ability of biological technologies to meet stringent limits depends on many factors, including influent selenium and nitrate concentrations and water temperature. Some sites have been able to meet stringent limits of 5 µg/L with biological treatment (refer to Case Study 1 in Section 4.2.6, Rutkowski et al. 2014) and other sites have effluent concentrations in the 10 to 30 µg/L range (refer to Case Study 2 in Section 4.2.6). For a coal mine site in the eastern US with influent selenium concentrations in the tens of micrograms per liter and negligible nitrate concentrations, treatment to stringent limits is feasible. At a coal mine site in Canada with selenium concentrations potentially in the hundreds of micrograms per liter and elevated nitrate concentrations, treatment to stringent limits below 10 µg/L, for instance, is challenging.

4.2.8 Selenium Speciation Measurement

Dissolved and total selenium concentrations are not directly related to toxicity because: 1) the bioavailability and toxicity of different selenium species varies; 2) there is potential for modifying effects of constituents (e.g., sulfate) in the sample matrix can modify effects on selenium bioaccumulation; and, 3) selenium species conversions to more bioavailable forms may occur. Selenium risk can be more effectively evaluated if selenium speciation is measured to evaluate selenium bioaccumulation as a function of the receiving environment, selenium species present, and factors that modify the uptake of each species.

Total and dissolved selenium is typically measured through inductively coupled plasma-mass spectrometry (ICP-MS)-based methods, which have high sensitivity and fast throughput. For selenium speciation analyses, other methods are used; while non-chromatographic analytical methods can differentiate among selenate, selenite and reduced selenium species, they are not as reliable as chromatographic methods that can directly quantify each individual selenium species. Direct quantification is useful when monitoring the performance of bioreactors because the presence of certain types of selenium species can be indicative of specific process issues. By adjusting the operation of the bioreactors, the treatment efficiency could be improved, and the production of bioavailable, reduced selenium species in the effluent could be reduced.

Standard analytical methods are not sufficient for speciation measurement because some selenium species are volatile and need to be converted to a non-volatile form before being measured, while other reduced species can degrade upon acidification and/or be adsorbed onto container surfaces. Another common problem is that colloidal selenium can pass through a 0.45 µm filter. These challenges can be overcome by adapting standard methods for the collection, preservation and digestion of samples being tested for selenium (Wozniak 2018).

4.2.9 Selenium Bioavailability

Selenium toxicity is related to selenium concentrations bioaccumulated by sensitive biota such as fish and aquatic birds (Chapman et al. 2010). This is generally expressed in the offspring of exposed biota (e.g., eggs, larvae, hatchlings). The magnitude of bioaccumulation depends on many factors, including selenium concentration and speciation (e.g., DeForest et al. 2016), modifying factors that affect uptake of each species (e.g., Riedel and Sanders 1996; Lo 2014; Van Geest et al. 2016; Vriens et al. 2016), the structure and composition of biological communities in the receiving environment (Baines et al. 2001; Presser and Luoma 2010),and the type of periphyton impacts on trophic transfer (Friesen et al. 2017). Selenium speciation appears to be a particularly important factor, with algal uptake studies reporting orders-of-magnitude greater bioaccumulation of organo-selenium species compared to inorganic oxyanions (Kiffney and Knight 1990; Riedel et al. 1991; Besser et al. 1993; Baines et al. 2001; Fournier et al. 2006). These results highlight the importance of understanding not only how treatment processes change total or dissolved selenium concentration, but also how they change selenium speciation.

The potential for treatment to change selenium bioaccumulation potential is illustrated by the following case studies:

- In one biological system, monitoring demonstrated that treatment was removing most of the selenium from influent water, resulting in approximately a 50% reduction in total selenium concentrations in receiving waters. Despite these reductions in aqueous concentrations, biological monitoring indicated that near-stream benthic invertebrate selenium concentrations increased up to 7-fold compared to before treatment. The observed increase in bioaccumulation was attributed to the production of low concentrations (< 1 µg/L) of organo-selenium species within the treatment system. The end user subsequently added an oxidation step to the facility to convert reduced species back to selenate, and more recent monitoring has indicated that near-stream benthic invertebrate selenium concentrations returning to pre-treatment levels.
- In another example (Amweg et al. 2003), algal-bacterial selenium reduction (ABSR) is a treatment technology that showed promise for reducing selenium in agricultural drainage. Selenium speciation of influent and effluent ABSR samples were compared while the treatment effects on invertebrate tissue were studied over a period of two years. Results demonstrated that the ABSR was removing up to 80% of total influent selenium, but that the microbial and algal activity produced selenite and organic selenium species (more bioavailable relative to selenate) with a combined concentration that increased 8-fold through treatment. The net effect led to greater selenium exposure due to higher bioavailability in the treated water (2 to 10 times greater than in the influent).

5.0 ADVANCEMENTS IN PRE- AND POST POST-TREATMENT TECHNOLOGY

5.1 Pre-Treatment

For mining systems, pre-treatment typically consists of some form of flow equalization and measures to remove or control suspended solids from the influent to protect against downstream fouling or plugging of media/beds. For RO treatment systems, ultrafiltration is often used as a pre-treatment step to protect the downstream RO membranes. In the power industry, physical/chemical pre-treatment is used for systems that treat flue gas desulfurization (FGD) wastewater. In most cases, the provision of a pre-treatment step provides an opportunity for pH adjustment, if needed.

5.2 Post-Treatment

Post-treatment processes are generally implemented to increase selenium removal or remove the residual biochemical oxygen demand and nutrients in the bioreactor effluent. Regarding increased selenium removal, some post-treatment processes are geared towards selenium removal in the solid phase, after conversion or removal from the aqueous phase in the bioreactor. Depending on the type of core treatment, this could be in the form of a ballasted clarifier or micro/ultrafiltration to improve the total selenium removal efficiency.

Other post-treatment technologies are implemented in order to address constituents in bioreactor effluent such as elevated biochemical oxygen demand (BOD) or phosphorus. Technologies implemented for BOD removal include moving bed bioreactors (MBBR), aeration, or activated sludge. Iron co-precipitation has been implemented for phosphorus removal and media filtration is also sometimes necessary. BOD concentrations in bioreactor effluent are variable and can be too low to maintain aerobic bacterial populations in activated sludge systems and can also lead to filamentous bacterial growth. Filamentous bacteria can cause operational issues due to poor settling and can negatively impact media filtration processes. An additional nutrient feed to these polishing systems is sometimes required to mitigate these concerns.

Another post-treatment process is chemical oxidation for removal of hydrogen sulfide or reduced selenium species. In one treatment system, an advanced oxidation process (AOP) has been implemented to significantly oxidize trace concentrations of reduced selenium species to selenate, which is bioavailable (Davidson 2019). The AOP process generates hydroxyl or other radicals that are highly oxidizing by combining reagents such as ozone, hydrogen peroxide, and/or UV light. Other examples of oxidative processes include ferrate and Caro’s Acid.

6.0 RESIDUE MANAGEMENT

Most selenium treatment technologies produce waste residues. For some technologies, selenium is concentrated in a waste stream that requires disposal or further treatment at high capital and operational costs. Others may require dewatering of the waste and disposal as a solid waste.

In physical/chemical treatment systems, large quantities of iron sludge can be generated. In biological systems, sludge generation is lower than in physical/chemical systems and is affected by selenium and nitrate content in the influent water as well as nutrient dosing. To reduce nitrate and selenium concentrations, an external carbon source is required to act as an electron donor. The biomass growth rate (i.e., the measure of biomass produced) is not only dependent on the oxygen, selenium and nitrate in the feed, but also on the type of carbon source used for the biological removal of nitrate and selenium. For municipal wastewater denitrification systems, the carbon source demand and biomass yields can be calculated empirically from stoichiometric equations and observed biomass yields as described in the USEPA's Nitrogen Control Process Design Manual (Scheible et al. 1993). For these denitrification systems, biomass yield ranges from 0.4 to 0.9 mg volatile suspended solids (VSS) per mg NO_3—N removed (Metcalf and Eddy, Inc. 1991).

Based on the survey results of full-scale treatment systems conducted for this update, Table 3 contains residue information for seven treatment plants:

Table 3: Residue Survey Response Data

Year of Construction	Treatment Technology	Treatment Plant Capacity (gpm)	Treatment Plant Capacity (m^3/day)	Residue Production (m^3/year)	Residue Production (metric tons/ year)	Residue % Solids
2016	Biological	1,375	7,500	550	N/A	40%
2017	Biological and Physical/Chemical	2,000	10,902	183	N/A	20%
2020	Biological	400	2,180	N/A	N/A	25–30%
2009	Physical/Chemical	1,760	9,600	283,941	N/A	35%
2010	Physical/Chemical	N/A	N/A	274	N/A	60%
2009	Physical/Chemical	830	4,536	N/A	8,165	35%
2014	Physical/Chemical	N/A	N/A	11,604	N/A	20%

N/A = not available.

Residue production varies, and physical/chemical systems can produce significantly more sludge per unit of water treated than biological systems. There can also be significant variability in the consistency of residue produced, which could be in the form of a filter backwash effluent, or a sludge cake produced by a dewatering system that makes use of centrifuges, filter presses, or sludge-thickening tanks.

Passive and *in situ* systems do not create a residual waste stream for dewatering and disposal. In these systems, the precipitated selenium is retained in the bioreactor in the case of passive, or in the *in situ* system. In the long term, the fate of the precipitated selenium may cause on-going issues with these systems.

In some cases, on-site disposal is possible, which may require disposal system infrastructure, while in other cases the sludge is tucked away for off-site disposal. In the power sector, the backwash effluents from power plants are often discharged into huge sedimentation ponds, although the use of these ponds is waning because of the Federal CCR regulatory program.

In most jurisdictions, there are hazardous characteristics standards (e.g., Toxicity Characteristic Leaching Procedure – TCLP) for the selenium content in the waste residue. Pilot results indicate that, in some cases, the sludge is classified as hazardous, while in other cases it is not. The physical-chemical characteristics of selenium residues and the conditions to which the residues are exposed in storage, determines the stability and fate of selenium-containing residues over time. Management of selenium-containing residues should include the steps taken to minimize selenium release from these residues.

Case Study – Residue Production (Confidential End User)

Using survey data provided by a confidential end user, Golder compared the theoretical biomass yield against the actual residue production. The calculations are based on mine water that has an influent nitrate concentration of 19 mg/L NO_3 (as N) and assumes that the selenium concentration is negligible compared to that of nitrate, and methanol is used as the carbon source. The theoretical biomass yield of total residual solids was calculated to be 1.2 mg VSS per mg NO_3 (as N), while the actual residue generated was 5.3 mg per mg NO_3 (as N) of total residual solids. While the theoretical biomass yield calculation considered only the contribution from a denitrification process, the water treatment system also included waste streams from other treatment processes, such as iron co-precipitation, aerobic biological process, and media filtration. Due to the challenges associated with the removal of insoluble and some soluble selenium from bioreactors, a relatively large quantity of residue can be generated to remove a relatively small amount of selenium.

Case Study – Residuals Landfill, Line Creek Operations (Teck Coal)

Management of selenium treatment residue at Teck's Line Creek Operations (LCO) in British Columbia's Elk Valley is described in a Mines Inspector report prepared by the British Columbia Ministry of Energy, Mines & Petroleum Resources (BCMEMPR 2017). Based on this report, waste filter cake from the selenium treatment plant is disposed of for permanent storage in a landfill. The facility is double-lined and has an installed leachate collection system that returns leachate generated back to the treatment plant. Groundwater wells are installed around the facility to detect leaks. The landfill site operators are equipped with personal gas meters and a standard operating procedure is in place to address health and safety hazards. The process mixes the filter cake with soil sourced from an adjacent borrow site. The residuals facility has a design capacity that provides enough storage to last for several decades.

7.0 TECHNOLOGY MATURITY

When a new technology is introduced, the technology's performance typically improves as more resources are expended on it, and/or as time passes. This progression of technology maturity can be generically presented by an S-curve(Figure 16), with technology phases that can be classified as follows (adapted from MITRE 2019):

i) New Phase: Through research and development, new technologies are identified, but with little improvement in performance. In this phase, the technology has only just reached the first tipping point in the s-curve of technology maturity.

ii) Improving Phase: Technology is improving or emerging as continued investment starts to bear fruit and more is learned about the technology through bench- or pilot-scale testing. This is within the exponential development stage of the curve after the first tipping point and before the second tipping point.

iii) Mature Phase: Mature technology is when performance improves through practical experience as the technology is more widely adopted. This leads to the second tipping point before the curve starts to trend downwards.

iv) Aging Phase: In some instances, a technology is unable to remain competitive when performance limits are being pushed higher and the technology starts to lose its competitive advantage. This is depicted as an aging technology on the downward tail.

Results from the selenium water treatment technology survey – conducted for support of this report – shows that members of various industry sectors are investing in selenium treatment technology and making progress in performance. Some technologies have multiple successful full-scale installations and are improving design by developing or refining process models, evaluating their technologies with industrial wastewaters that vary significantly from site to site and sector to sector, and targeting lower and lower effluent targets. Other technologies are at an earlier stage of the curve and focused on establishing a treatment process and implementing pilot-scale studies, and an initial full-scale implementation.

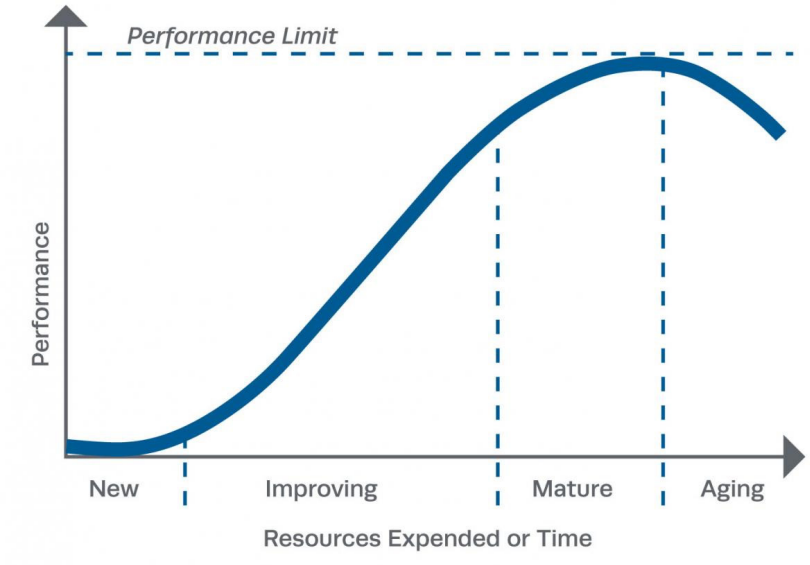


Figure 16: Technology Maturity S-curve (Reproduced from MITRE Systems Engineering Guide (MITRE 2019))

8.0 COST CURVE UPDATES

The survey covered capital and operating costs for selenium treatment systems, including pre- and post-treatment as well as costs associated with residue management. Costing information presented in this section focuses on systems that have been constructed and are currently in operation. Cost information was provided by relatively few respondents.

Capital and operating cost curves presented in Sections 8.2 and 8.3 are based on information in survey responses adjusted for inflation to 2019 values using the Engineering News Record's Construction Cost Indexes (ENR 2020) to account for time value because not all systems were installed in the same year. Where applicable, a Canadian dollar to US dollar conversion rate of 0.7 was applied. For each data set, a curve is fitted to estimate the cost over a range of treatment capacities. Curves were not fitted for data sets where only two data points are available. Similar to the NAMC white paper addendum (CH2M HILL 2013), Class 5 estimate ranges are applied to the cost curves to provide estimates with +100% and -50% accuracy ranges, indicated as ranges on the curves. In some cases, there was not enough costing data available to present it graphically. These include operating costs for chemical-physical treatment systems.

8.1 Capital Cost Breakdowns

Total capital costs to construct a selenium treatment facility consist several components. For a typical installation, costs include the supply and installation of the selenium treatment technology itself and other pre- and post-treatment equipment; engineering, procurement, and construction management (EPCM); and owner's costs such as power infrastructure and civil site work. Figure 17 provides an illustrative example for a particular case study of the capital cost breakdown of these components relative to each other for a biological system. The selenium removal equipment itself is often not the biggest cost contributor to the treatment plant's capital cost.

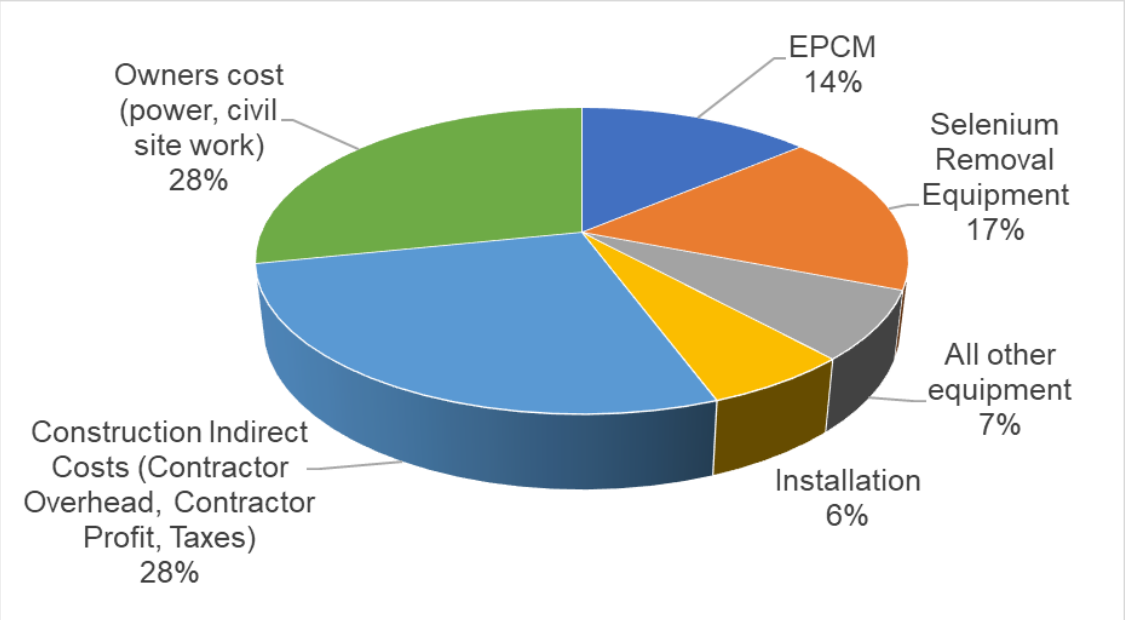


Figure 17: Capital Cost Breakdown (example)

8.2 Capital Cost Curves for Survey Results

Total capital costs include the treatment plant direct costs, direct costs of related infrastructure that falls outside the treatment plant itself, engineering fees and owner's costs.

Figure 18 shows the total capital cost curve for a chemical-physical treatment (ZVI and co-precipitation systems).

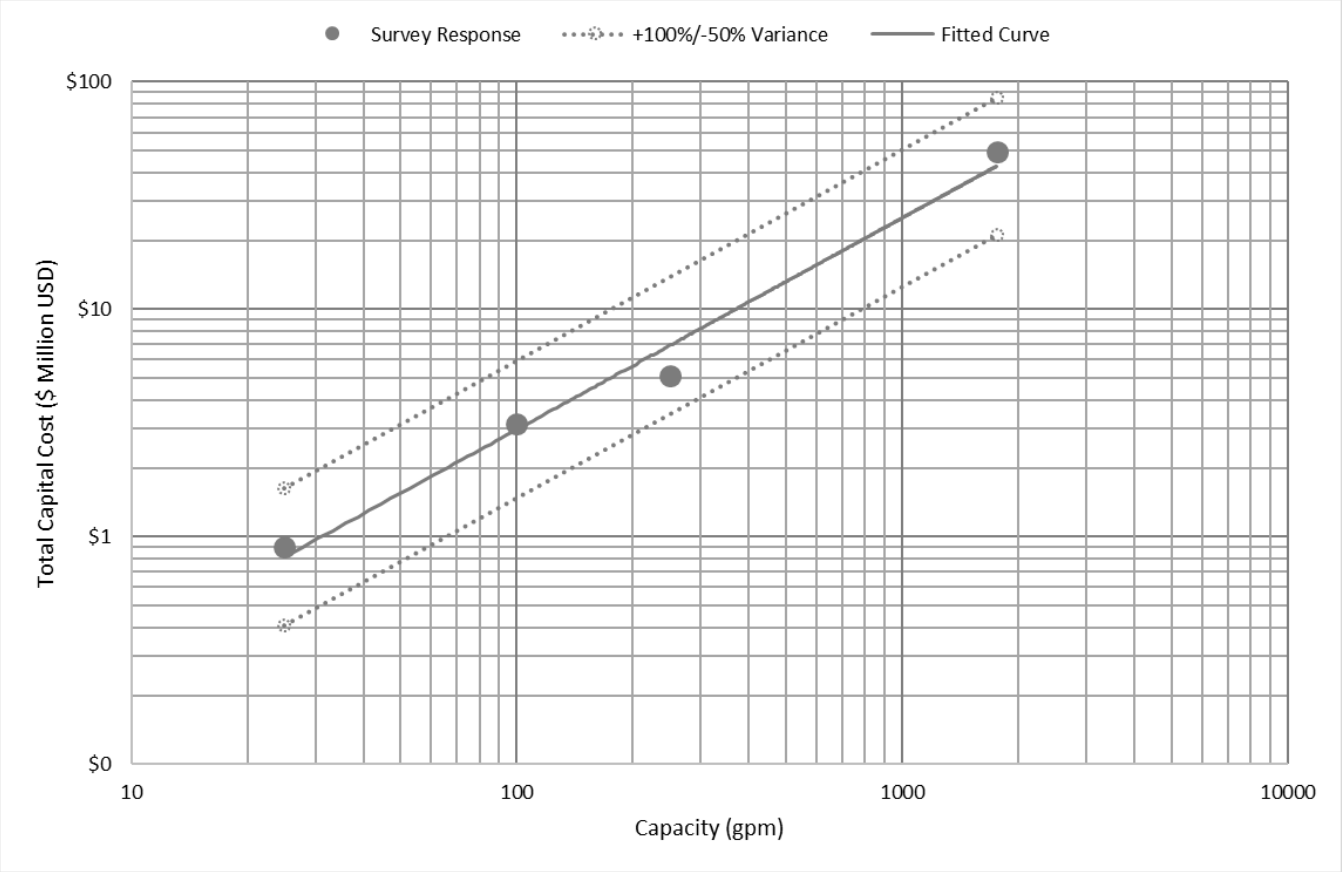


Figure 18: Total Capital Cost for Chemical-Physical Treatment Systems

Figure 19 shows the total capital and operating costs for installing active biological treatment systems.

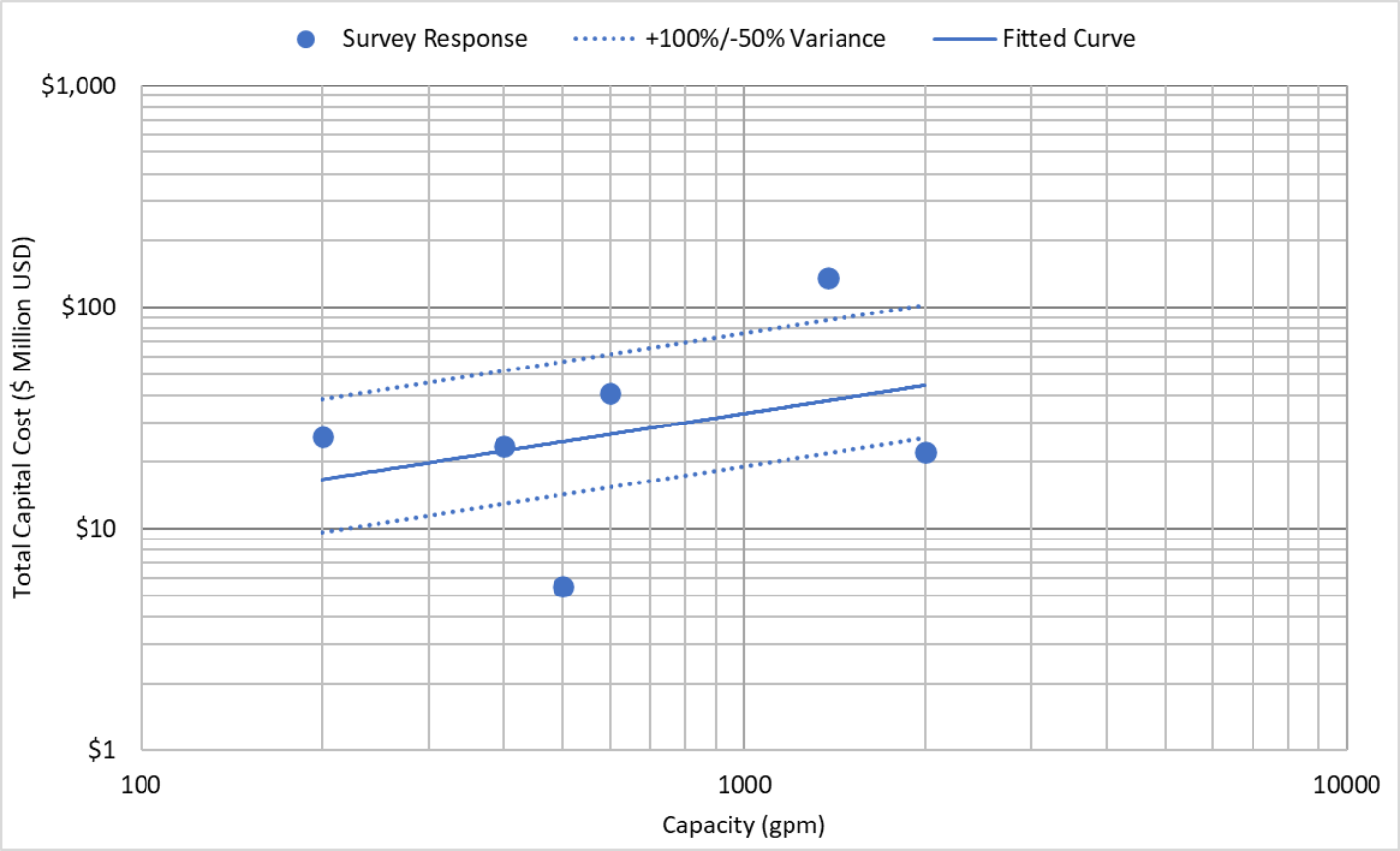


Figure 19: Total Capital Cost for Active Biological Treatment Systems

Figure 20 shows the total capital and operating costs for installing in situ biological treatment systems.

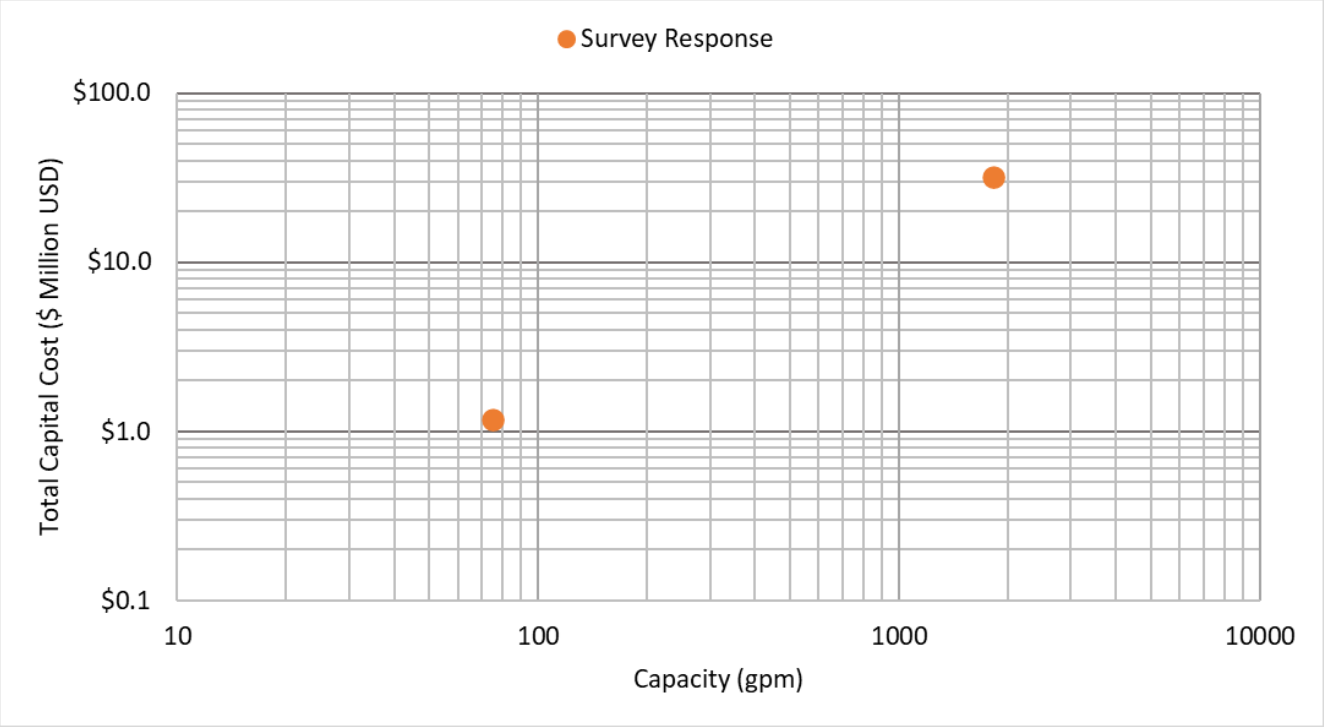


Figure 20: Total Capital Cost for In Situ Biological Treatment Systems

Figure 21 shows the total capital costs for biological and chemical treatment systems on the same graph. Based on costing information received, active biological systems are generally the most expensive to install at treatment capacity below 1,000 gpm (5,500 m^3/day). Passive biological systems are typically the least expensive to install and chemical systems are typically somewhere in between passive biological and active biological systems.

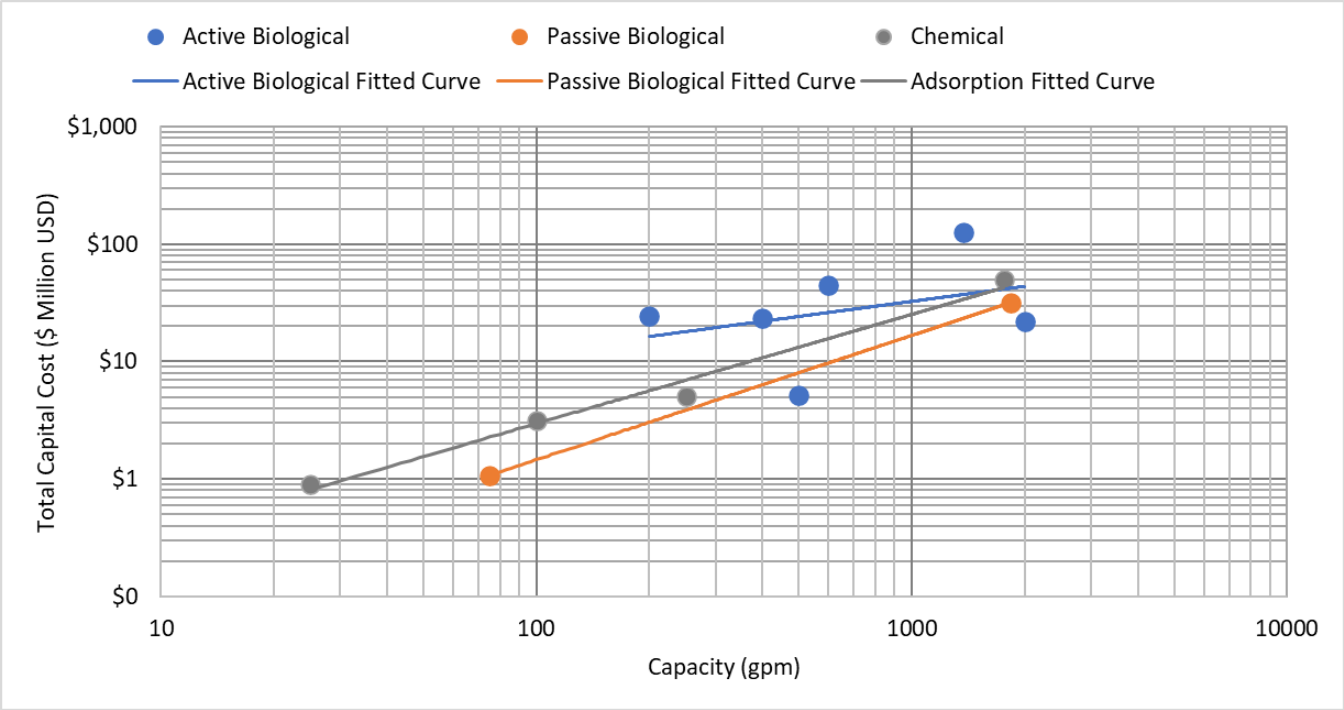


Figure 21: Total Capital Cost for Biological and Chemical-physical Systems

8.3 Operating Cost Curves

Total operating costs include treatment plant operating costs, costs of management and disposal of treatment residuals, and sampling and monitoring costs.

Figure 22 shows the total operating costs for active biological treatment systems.

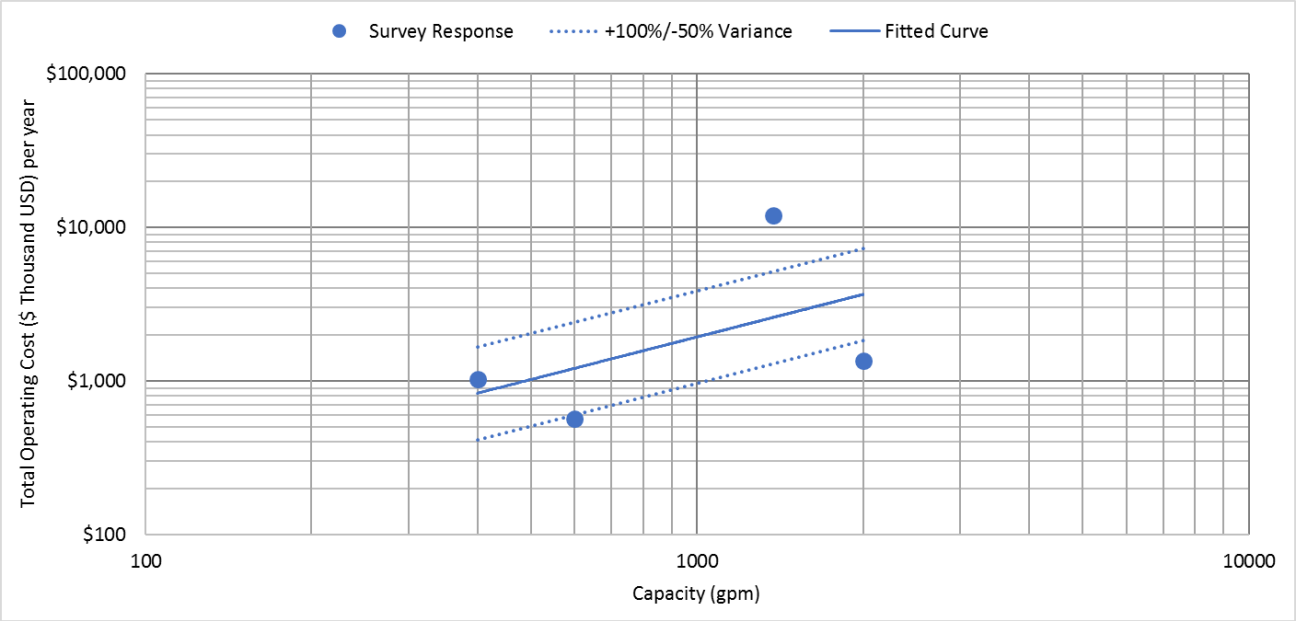


Figure 22: Total Annual Operating Cost for Active Biological Systems

Figure 23 shows the total operating costs for passive biological treatment systems.

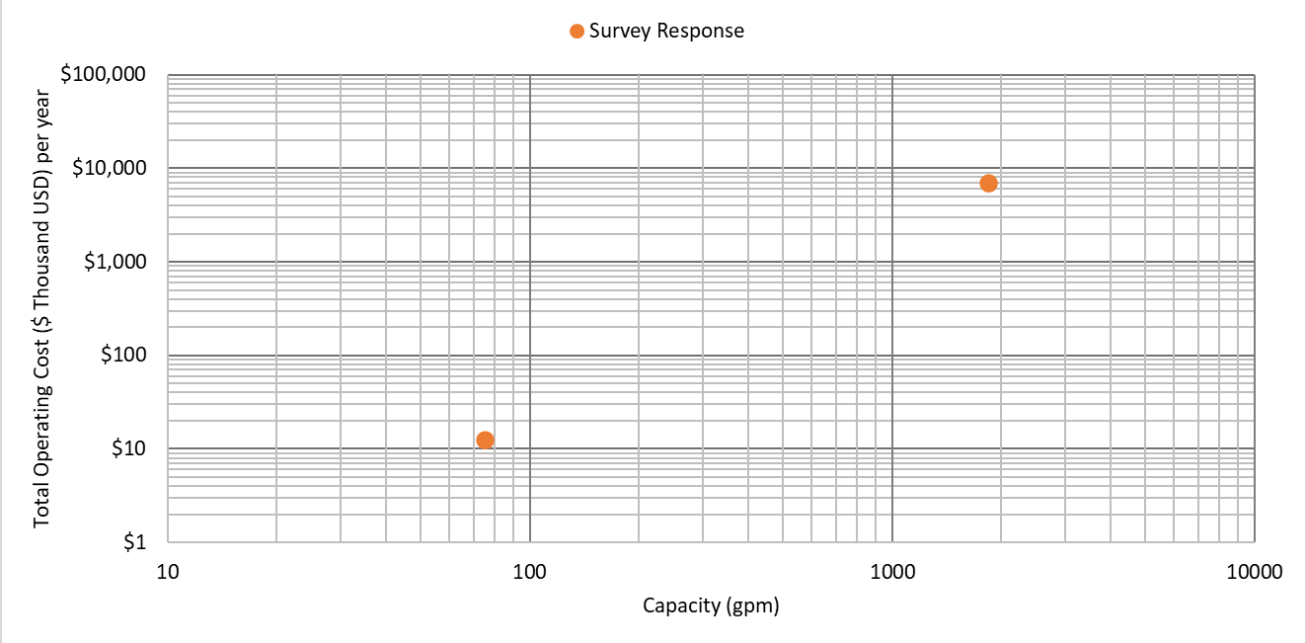


Figure 23: Total Annual Operating Cost for Passive Biological Systems

9.0 CONCLUSIONS

Survey results were received for 30 full-scale selenium removal systems that have been installed since 2007. The core selenium removal technologies in these systems vary and include physical/chemical processes or biological processes, or a combination of the two. Selenium speciation is important to consider when comparing technologies. Removal of selenite can occur with iron co-precipitation, a conventional technology or process, although meeting stringent, part per billion effluent limits using this technology may not be possible. Selenate removal, on the other hand, is typically not feasible using conventional physical/chemical technologies. Thus, technology development for selenate removal has been progressing over the past two decades. Since 2007, biological treatment for selenate has emerged as the most prevalent technology being implemented in 70% of the systems documented. In some instances, membrane technology has been implemented to concentrate selenium prior to biological treatment.

There is an array of biological systems ranging from active to passive, and from tank-based to *in-situ* systems. Although they share a common treatment principle, they differ greatly in level of maturity, cost, and complexity. Active biological systems are the most common type being installed at full scale. Detailed case studies from two such systems indicate the ability to generally achieve high rates of selenium removal, but have experienced occasional bioreactor bed upsets due to backwashing and de-gassing. Variability in influent water quality, site constraints and effluent targets have resulted in the emergence of a variety of biological treatment system components resulting in each installation being rather unique. Operational challenges also differ among systems.

Of particular significance is the management of reduced or organic selenium species that can exhibit greater selenium bioaccumulation potential in the effluent vs. the influent to a biological treatment plant. Although the focus of this update was on full-scale systems currently in operation, there are non-biological technologies under development and not yet operational at full scale. There are full-scale plants currently under construction that use newly-developed technology combining ion exchange with electro-reduction of selenium.

Despite numerous installations, selenium treatment technologies have not reached full maturity and should still be regarded as developmental. In some instances, systems are consistently capable of meeting stringent limits of less than 10 µg/L, for example. However in other instances, this has not been achievable. Capital costs are highly variable and largely driven by site-specific factors and not necessarily by the cost of the core selenium removal technology.

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APPENDIX A

Main Survey

Confidentiality

The purpose of this survey is to inform a white paper update on the current state-of-knowledge on selenium treatment technologies. The report will be made public and is expected to be read by regulators, industry personnel, consultants, and interested citizens. The survey therefore contains certain confidential fields (i.e., company name, plant location) marked with an asterisk (*) in the survey, and these fields will not be shared in the report, ***unless the participant gives permission to do so****. If there are additional survey fields that should not be shared in the report, please specify this in the comments section at end of the survey.*

A. Contact Details

Date		**Company Name (*)**		**Affiliation**	
Contact Name		**Contact Email**		**Contact Phone Number**	

Responses

1. Can the company name be shared in the updated white paper?

B. Treatment System

1. Do you have and/or have you designed a selenium treatment system?

If No, please complete sections in the survey you see fit and add any other contacts you have who might have information on a selenium treatment system or technology in the comments section at the end of the survey.

If Yes, what is the operational scale of the selected selenium treatment plant?

If this is a pilot facility (i.e., not demonstration or full-scale), please ignore the costing section (Section H)

2. Which industry sector(s) was the water treatment system completed for? (select multiple if needed)

If other is selected, please specify.

3. What is the source(s) of selenium impacted water? (select multiple if needed)

If other is selected, please specify.

4a. Which type(s) of selenium treatment technology is implemented at the water treatment plant? (select multiple if needed)

If other is selected, please specify.

4b. For the treatment system(s) selected, do you heat the water as part of the treatment system?

4c. If you have selected biological treatment, what is the typical hydraulic retention time in the reductive reactor?

4d. For the selected selenium treatment technologies, please name the vendor(s) if able to do so

5. When was the plant constructed (year of construction)? For pilot systems, when were they operated?

6. How long is the treatment facility expected to be operational (number of years from construction)?

7a. Location of selenium treatment system (*)

i. Country

ii. States/Provinces/Territories

7b. Can the location be shared in the updated white paper?

7c. What is the design flow rate of the plant/pilot system?

C. Pre-treatment

1. Have you installed any flow equalization system upstream of the selenium treatment system?

2. Have you installed any additional system(s) upstream of the selenium treatment system? (e.g., solid removal, pH adjustment, softening)

If Yes, please specify.

D. Post-treatment

1. Have you installed any system(s) downstream of the selenium treatment system? (e.g., aeration, solids/liquids separation, oxidation, filtration)

If Yes, please specify.

2. Does the system include a solids dewatering process such as a filter press, centrifuge or settling pond to manage residues/sludges?

If Yes, please specify.

3. What is the removal efficiency (weight percent solids of final product)? %

E. Treatment Efficiency

Please fill in the influent and effluent water quality ranges in *Table 1* on the next page.

Table 1. Influent and Effluent Water Quality

Item	Parameters	Unit	Influent Water Quality (Minimum to Maximum Range)	Influent Water Quality (Average)	Effluent Water Quality (Minimum to Maximum Range)	Effluent Water Quality (Average)
1	Water Temperature	°C				
2	pH	S.U.				
3	Total Selenium Concentration	mg/L				
4	Dissolved Selenium Concentration	mg/L				
5	Speciation of selenium (Selenite, Selenate, Organo-selenium, Seleno-cyanate, Particulate Se)	N/A				
6	Total Suspended Solids	mg/L				
7	Total Dissolved Solids	mg/L				
8	Sulfate	mg/L				
9	Nitrate	mg/L				
10	Alkalinity, Total	mg/L				
11	Total Iron	mg/L				
12	Dissolved Iron	mg/L				

1. Does the treatment plant experience major seasonal variations in flow and influent/effluent qualities?

If Yes, please describe.

2. Optional: Please highlight any water quality considerations

F. Toxicity

1. Is effluent regulated for toxicity requirement? (e.g., acute lethality with rainbow trout, Daphnia or chronic toxicity with fathead minnow, Ceriodaphnia dubia)

If Yes, please specify the toxicity requirement (e.g., acute lethality with rainbow trout, Daphnia, or chronic toxicity with fathead minnow, Ceriodaphnia dubia).

2. Has it consistently met the toxicity requirement?

If Yes, please specify.

3. Is the effluent regulated for selenium bioaccumulation in receiving environment (e.g., "is selenium concentration in biota tissue monitored?")?

If Yes, please specify the receiving environment parameter (e.g., selenium concentration in biota tissue).

4. Has it consistently met the selenium bioaccumulation requirement?

If Yes, please specify.

G. Residue Management

1. What type(s) of residue is generated by the treatment process? (e.g., backwash solids, brine, sludge)

2a. Does the site dispose of residuals on site?

If Yes, please answer 2b below:

2b. Is leachate generated from residuals management?

If Yes, how is leachate from disposed residuals managed?

If available, please provide typical leachate water quality for key parameters below (or in a separate attachment)

Parameters	Unit	Value

3. What is the annual residuals volume and/or mass?
4. What is the average % solids of residuals? %
5. Has residual stability/characterization testing been conducted, e.g. TCLP, SPLT?
If Yes, please specify what type of testing has been performed and provide the residuals testing results, if able to do so.

6. Are the residues hazardous under jurisdictions/regulations?
E.g., EPA has defined hazardous wastes as " waste with properties that make it dangerous or capable of having a harmful effect on human health or the environment " on their website.
<https://www.epa.gov/hw/learn-basics-hazardous-waste>

If Yes, please specify under which parameter(s) and jurisdiction/regulation.

H. Costing (demonstration or full-scale system only)

Please fill out the costing information in *Table 2* and *Table 3*.

Table 2. Capital of treatment System

Item	Parameters	Units	Description	Value
1	Treatment plant direct costs	USD	The battery limits are the treatment plant (including pre- and post-treatment, dewatering equipment) . If possible, please exclude costs from outside plant battery limits (e.g., bringing utilities to the plant, major water conveyance and discharge structures)	
2	Outside Battery Limit Direct Costs	USD	(e.g., utilities, water conveyance and discharge)	
3	Engineering Fees	USD	Engineering fees associated with engineering, procurement, construction	
4	Owner's Costs	USD	Owner's team costs directly associated with the treatment system	
5	Total Capital Cost	USD	Sum of item 1 to 4	

Table 3. Annual Operating Cost of Treatment System

Item	Parameters	Unit	Description	Value
1	Treatment plant Operating Costs	USD/ year	Cost for consumables, utilities, labor and maintenances (including pre- and post treatment)	
2	Management/ disposal of treatment residuals	USD/ year	Cost of transporting and disposing of residue	
3	Sampling and monitoring costs	USD/ year	-	
4	Total Operating Cost	USD/ year	Sum of item 1 to 3	

I. System Performance Limitations

1. Has this system experienced any major upsets?

If Yes, please describe.

J. Regulatory

1. Is the effluent regulated by a permit?
2. If Yes, please fill out *Table 4* with the regulated selenium (and other) parameters with their corresponding limits.

Table 4. Regulated Parameters and permit limits

Regulated Parameters	Units	Discharge Limits	Type of monitoring period (e.g. daily maximum, monthly average)
Total Selenium	mg/L		
Dissolved Selenium	mg/L		

3. If the treatment plant is not specifically regulated by a permit, what is the treatment target for selenium?
4. Has the treatment plant consistently achieved the discharge limits/treatment target?
5. If No, what percentage of time does the plant fail to meet the limit/target? %

General Comments (Please provide any additional information or clarification that may provide useful in preparing the white paper. E.g., details of non-NAMC contacts that might also have information on selenium treatment operations/technologies.)

-END-

APPENDIX B

Vendor Survey

Confidentiality

The purpose of this survey is to inform a white paper update on the current state-of-knowledge on selenium treatment technologies. The report will be made public and is expected to be read by regulators, industry personnel, consultants, and interested citizens. The survey therefore contains certain confidential fields (i.e., company name, plant location) marked with an asterisk in the survey, and these fields will not be shared in the report, unless the participant gives permission to do so. If there are additional survey fields that should not be shared in the report, please specify this in the comments section at end of the survey.

A. Contact details

Date		**Company Name (*)**		**Affiliation**	
Contact Name		**Contact Email**		**Contact Phone Number**	

Responses

1. Can the company name be shared in the updated white paper?

B. Treatment System

1. Do you supply and/or design selenium treatment system?

If No, please add any other contacts you have who might have information on selenium treatment in the comments section at the end of the survey. If Yes, please continue with the survey.

2. Which industry sector(s) do you supply/provide service to? (select multiple if needed)

If other is selected, please specify.

3a. Please specify the types of treatment technology you supply (e.g., reverse osmosis, ion exchange, zero valent iron, fixed bed adsorption, biological treatment, co-precipitation)

b. what is the number of full-scale installations?
c. what is the number of demonstration-scale installations?
d. what is the number of pilot-scale installation?

C. System Performance

Please provide case studies in Table 1.

Table 1. System Performance

Item	Parameters	Treatment Systems						
		Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7
1	Treatment Technology							
2	Operational scale of system							
3	Year of Construction							
4	Location of System (States/Provinces) (*)							
5	System Capacity (i.e., design flow rate)							
6	Concentration (mg/L)							
7	Influent Selenium Speciation							
8	Selenium							
9	Client Name (*)							
10	(i.e., name and email							

We are asking for client name to prevent presenting duplicated data in the update. The client name and location would be kept confidential.

1. Please provide any additional performance data that could be helpful to our study in the comments section below or as a separate attachment.

General Comments

-END-

APPENDIX C

Figures from Section 3.0 Implementation of Selenium Treatment System

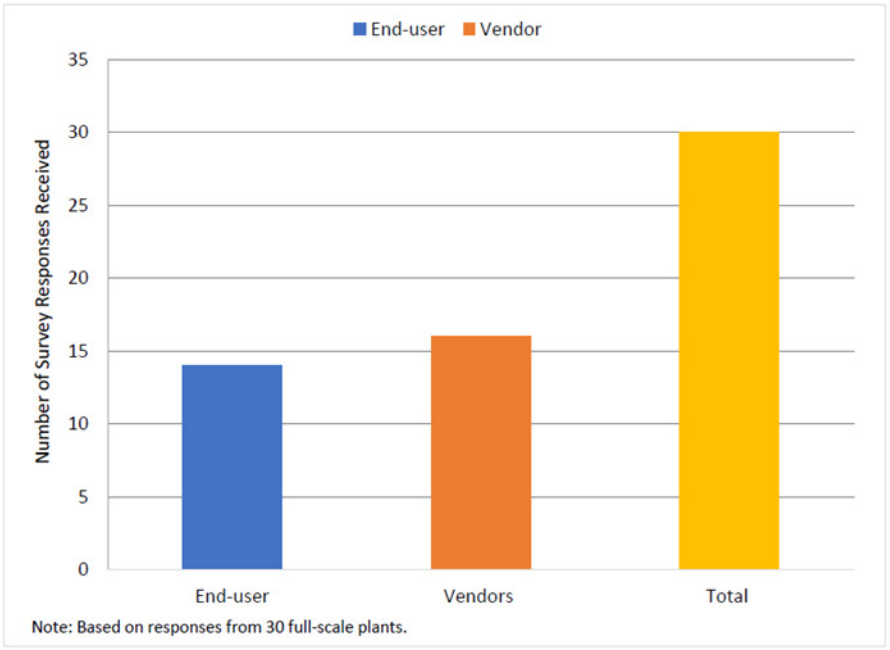

Figure C1: Breakdown of Survey Responses

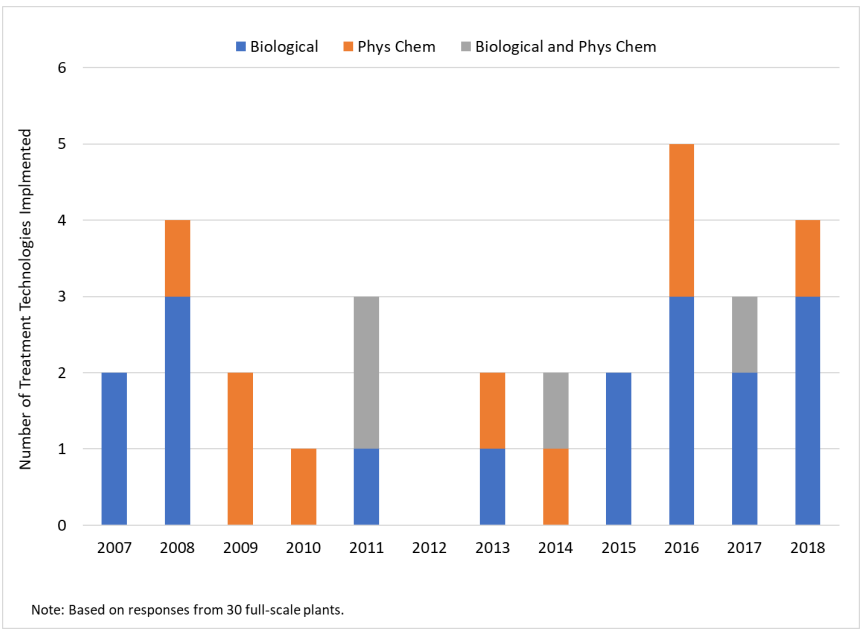

Figure C2: Number of Full-Scale Treatment Technologies Implemented per Year

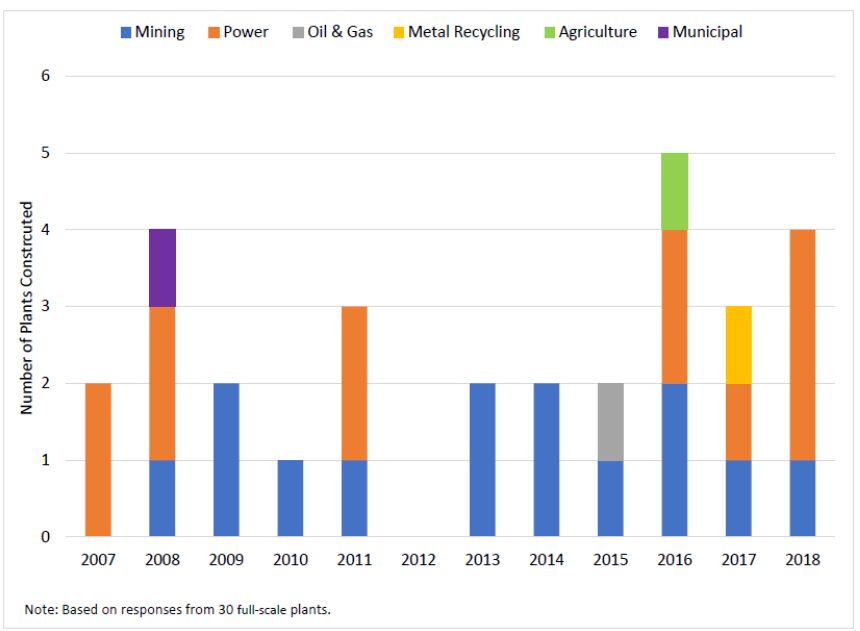

Figure C3: Full-Scale Treatment Plants Constructed per Year

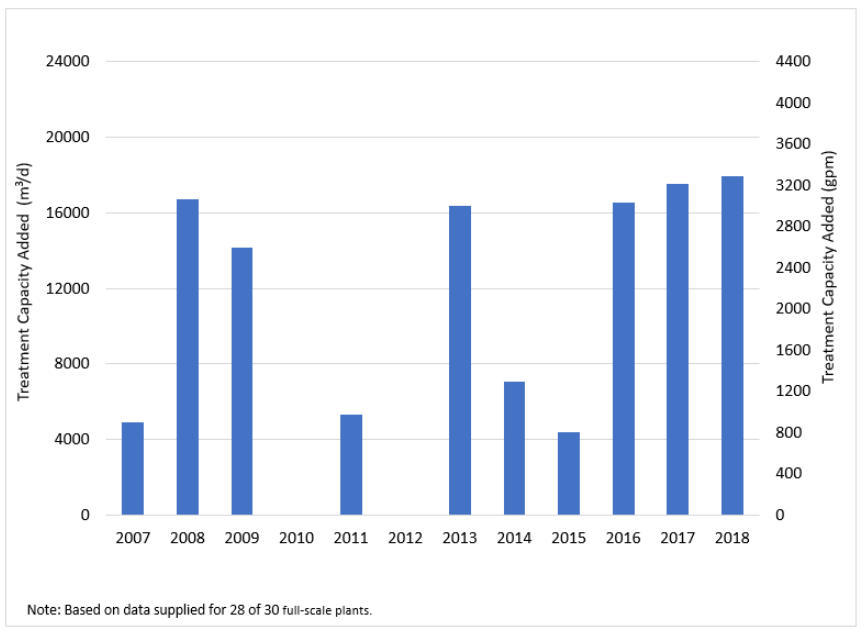

Figure C4: Treatment Capacity Added per Year Sector per Year

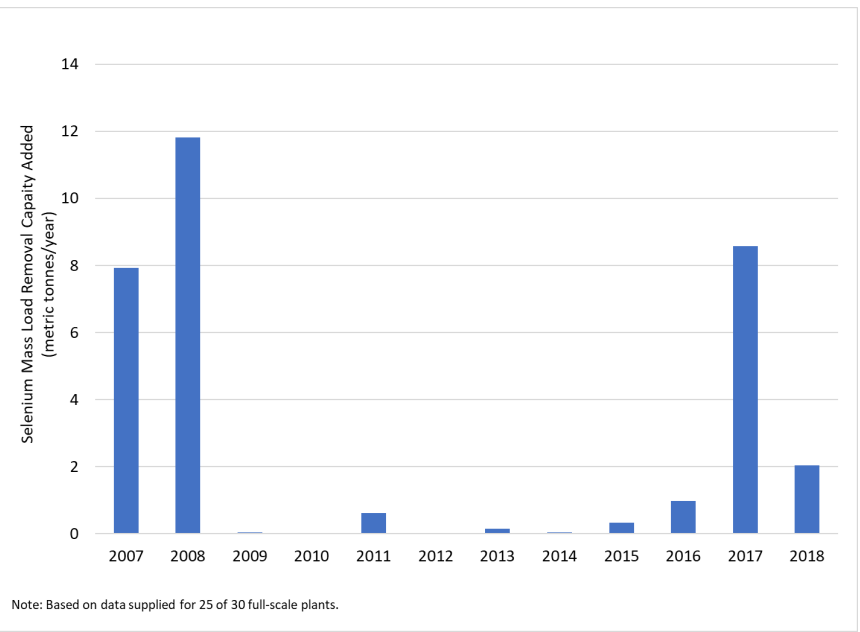

Figure C5: Selenium Mass Load Removal Capacity Added per Year

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