Startup and Commissioning of a Full-Scale Selenium Treatment Facility for Mine Water Treatment

Rangesh Srinivasan[1*], Kar Munirathinam[2], Phil Facer[2] and Tom A. Sandy[3]

[1] CH2M HILL Cincinnati, OH
[2] CH2M HILL, Pittsburgh, PA
[3] CH2M HILL, Denver, CO

* Email: Rangesh.Srinivasan@CH2M.com

ABSTRACT

A 4 MGD (2,800 gpm) biological fluidized bed reactor (FBR) based water treatment plant (WTP) was commissioned at a confidential North American mine facility in 2013 to meet effluent discharge limits for selenium and other conventional parameters. This water treatment plant is the first of its kind for selenium removal from mine water. Mine waters from three (3) different sources with varying selenium and nitrate loadings are combined prior to treatment at this plant. The primary process train consisted of FBRs for facilitating anoxic/anaerobic reduction of selenite/selenate to elemental selenium followed by ballasted sand clarifiers for the removal of solids from the FBR effluent including elemental selenium and the biomass. The next step in the process is an aerobic moving bed biofilm reactor (MBBR) for removal of residual organics and to increase the dissolved oxygen (DO) prior to discharge. Once stable operations were reached during startup, the plant was able to consistently meet the selenium limit. An analysis of the plant performance along with challenges faced during startup and commissioning of this plant are discussed.

KEYWORDS: Selenium, fluidized bed reactor, anoxic/anaerobic biological treatment, mine water, chemical oxygen demand (COD), coagulation, treatment plant

INTRODUCTION

Selenium treatment in wastewater has become a major challenge for a wide range of industries including oil and gas, agriculture and mining. Mining operations release selenium that is naturally present in the rocks and soils into the environment primarily through surface runoff over the waste rocks and tailings. Selenium laden mine water comprised of surface runoff and groundwater contacting the waste rock areas is typically collected in sedimentation ponds for solids removal prior to discharge.

This study focuses on a full-scale water treatment plant (WTP) that was constructed and commissioned at a confidential North American mine facility to address some of the issues associated with meeting compliance for selenium. In the past, effluent from the sedimentation ponds at the facility was discharged to a surface water of the state as permitted by National Pollutant Discharge Elimination System (NPDES) permits issued by the state regulator. In 2006, total recoverable selenium limits (average monthly limit of 4.7 µg/L and a daily maximum limit of 8.2 µg/L for total selenium) were included as a permit requirement in the facility's permit (Table 1). Since the mine water effluent selenium is typically in the 10 – 50 µg/L range, the facility had exceeded these limits at times and had to evaluate options to ensure compliance with these limits.

Table 1. NPDES Permit Effluent Limits

Parameter	Units	Monthly Average	Daily Maximum	Sampling Frequency
Selenium, Total	µg/L	4.70	8.20	Semi-monthly
Manganese, Total	mg/L	2.00	3.47	Semi-monthly
Iron, Total	mg/L	1.57	2.73	Semi-monthly
Aluminum, Total	mg/L	1.88	3.27	Semi-monthly
Total Suspended Solids (TSS)	mg/L	35	70	Semi-monthly
pH	s.u.	6.0 – 9.0		Semi-monthly

A conceptual treatment alternatives evaluation was conducted to compare selenium treatment alternatives for the site NPDES outfalls including evaluation of multiple biological and physical-chemical treatment technologies. The conceptual evaluation identified the FBR to be a more cost effective technology for selenium removal from the mine water and recommended that pilot testing be conducted to confirm selenium treatment at this mine site. Pilot testing performed subsequently as a proof of concept demonstrated compliance for selenium with the required limits and also helped understanding of key design parameters. Results of the pilot testing performed by CH2M HILL were presented elsewhere (Munirathinam *et al*., 2011). Flow monitoring was conducted in parallel to develop a design basis for the WTP including more accurate determination of dry and wet weather flows.

CH2M HILL supported the design, construction and startup of the full-scale 2,800 gpm (4 MGD) FBR based selenium removal WTP. Construction was completed in early 2013 and the plant became fully operational in January 2013. This treatment plant is the first of its kind for selenium removal from mine water. The WTP has been operational for over a year and has generally been in compliance meeting the low effluent discharge limits for selenium and other parameters. An analysis of the plant performance over the past year are presented in this paper. Some of the key challenges faced during startup and commissioning of this plant are also discussed.

MATERIALS AND METHODS

A process flow diagram (PFD) depicting the WTP is shown in Figure 1 and a picture of the overall WTP layout is shown in Figure 2. The basis for the process design was established based on results from pilot testing, mine water characterization, and a discharge flow evaluation performed during the engineering phase. The regulated discharges requiring treatment under NPDES permits at this facility included three (3) individual outlets shown as sources 1 through 3 in the PFD.

Treatment Design Basis

Prior to design of the WTP, sampling, chemical analysis, and flow characterization activities were undertaken to characterize the discharges for the purpose of developing a basis for design. This design basis (Table 2) created the foundation for a WTP design to treat selenium to meet the discharge limits. Historical flow and water characterization data at the three outlets was also utilized for development of the mine water design basis. The design basis for the WTP includes design average and maximum flows of 1,885 gpm and 2,800 gpm, respectively.

WTP Process Description

Pretreatment

Flows from the respective ponds for the three sources are pumped and conveyed through pipelines to the head of the WTP where they combine in the blend tank. The 225,000 gallon capacity blend tank provides a hydraulic retention time (HRT) of two (2) hours at the average flow rate. Since the pH of the feed stream ranges from 7.5 to 9.0, there is provision to add hydrochloric acid if needed ahead of the blend tank to control potential scaling in the heat exchangers. From the blend tank, water is pumped through a set of self-cleaning screens (1/8-inch mesh) for removal of any leaves and debris and a portion of the clay materials (through coating the screen mesh). Flow continues to the influent flow meter and during the winter through heat exchangers to maintain a relatively constant minimum feed flow water temperature of 10 ± 1°C (50 °F) required to sustain biological activity in the FBR for selenium reduction. Two (2) 400 HP propane fired steam boilers are used to supply the heat exchangers with necessary steam to heat the influent water in winter.

FBR System

FRB feed pumps convey the pretreated water to the FBR system. In a FBR system, water to be treated is passed through a granular solid media (e.g., granular activated carbon (GAC), or sand) at high enough velocities to suspend the media and cause it to behave as though it were a fluid. The granular solid media provides surface for the biomass to attach and grow. Fluidization keeps the media with attached biomass in suspension and expanded in depth to provide efficient contact of the water requiring treatment with biomass for effective treatment. The process uses facultative heterotrophic bacteria, which reduce the selenate to selenite and selenite to elemental selenium. These bacteria use the DO, nitrate, selenite, and selenate in this order as electron acceptors and organic carbon as an electron donor for energy and new cell synthesis.

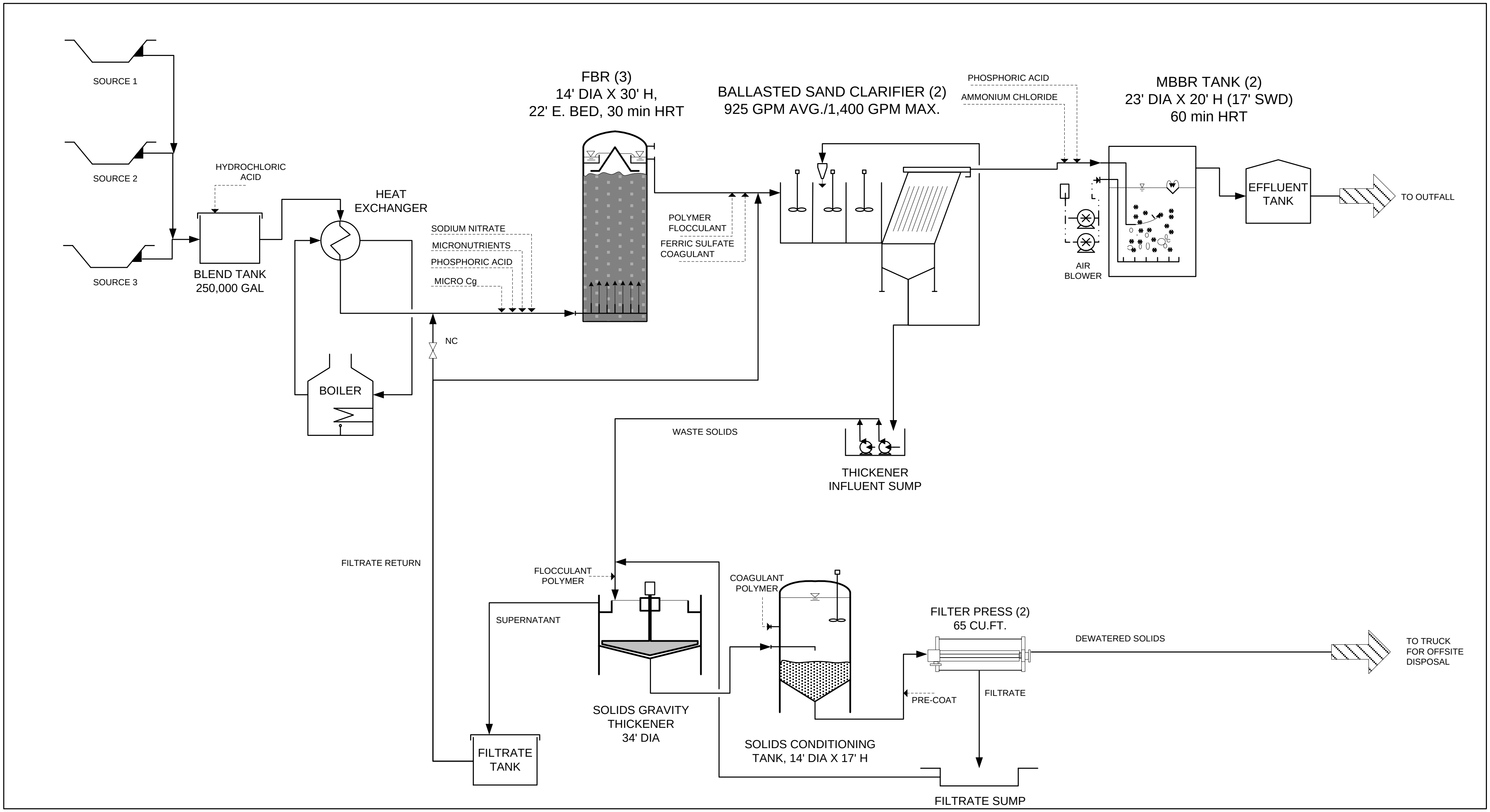

Figure 1. Process Flow Diagram – Selenium WTP

Table 2. WTP - Water Quality Design Basis

Parameter	Units	Source 1		Source 2		Source 3		Combined Influent	
		Avg	Max	Avg	Max	Avg	Max	Avg	Max
Flow	gpm	1,250	1,800	525	800	110	200	1,885	2,800
Nitrate, N	mg/L	3.5	3.8	14	18	2.6	3.8	6.4	7.7
COD	mg/L	5.9	11.2	5.1	9.0	10	25	5.9	11.4
Selenium									
Total	µg/L	13.5	16.7	46	54	8	16	22	27
Selenite (Se (IV))	µg/L	0.68	0.82	0.53	0.66	0.29	0.32	0.62	0.75
Selenate (Se (VI))	µg/L	11.2	12.9	36	39	8.0	12.7	17.9	20.2
Calcium	mg/L	113	116	147	165	121	143	123	131
Magnesium	mg/L	136	143	171	198	79	86	142	155
Iron	mg/L	0.031	0.039	0.016	0.030	0.531	1.02	0.06	0.09
Aluminum	mg/L	0.006	0.001	0.014	0.023	0.017	0.022	0.009	0.015
Chloride	mg/L	5.4	6.3	6.8	7.7	7.0	9.5	5.9	6.9
Sulfate	mg/L	536	627	723	822	406	458	581	671
TDS	mg/L	1,091	1,250	1,480	1,650	875	914	1,187	1,342
TSS	mg/L	0.6	0.6	0.6	0.6	1.5	3.2	0.7	0.8
Temperature	ºF	-	-	-	-	-	-	32 - 89	
pH	s.u.	-	-	-	-	-	-	7.0 – 9.0	

Figure 2. Overall Plant Layout – Selenium WTP

The FBR system consists of three (3) fiber reinforced plastic (FRP) columns, 14 feet (4.3 m) diameter by 30 feet (9.1 m) high with a design target expanded bed height of 21.8 feet (6.6 m) in order to provide a minimum HRT of 25 to 30 minutes. Based on pilot testing results, this is the HRT required for desired reduction of selenate and selenite to elemental selenium. Each column is filled with 64,000 lbs (29,000 kg) of GAC media. The major equipment associated with the each FBR vessel include a fluidization pump to maintain desired bed expansion and an integral fluidization distribution and effluent collection system to enhance uniform flow distribution. FBR effluent is monitored via online analyzers for ORP, temperature, and pH so as to maintain optimal treatment conditions. The expansion of the GAC bed is controlled by the biomass separator, which sloughs off excess biomass growth with the effluent using instrument air at the top of the expanded bed. Excess biomass is also removed by the in-bed cleaning system. This system consists of an end suction centrifugal pump that draws suction from the FBR recycle line and re-circulates a small portion of water through the FBR at a high pressure to dislodge any solids accumulated at the bottom and mid-section of the reactor. This maintenance procedure is required to maintain the fluidization flow and bed height at the design conditions and prevent excessive solids accumulation in the reactor.

Since the influent mine water is low in nutrients and degradable organics (biochemical oxygen demand [BOD]), both nutrients and carbon substrate are added to the FBR to maintain biomass growth. Carbon substrate (as *MicroCg*), phosphorus (as phosphoric acid), and micronutrients are added based on forward flow via chemical metering pumps upstream of the FBR. There are provisions in place to dose sodium nitrate in the event that the influent water nitrate concentration is too low (<3.0 mg/L NO_3-N) to maintain the required biomass concentration in the FBR. There are also provisions to dose sodium hydroxide if necessary, for pH adjustment to maintain a minimum FBR liquid pH of 6.8.

Figure 3. FBR Vessels

Ballasted Sand Clarifier System

Following reduction of nitrate-nitrogen to nitrogen gas, and selenite and selenate to elemental selenium, effluent from the FBR system is sent to a ballasted sand clarifier for removal of the elemental selenium as insoluble solids and the biomass. Ballasted sand clarifiers are high-rate gravity settling systems that increase the terminal settling velocity of biological flocs, thereby minimizing system footprint. The clarifiers are used to remove TSS from the FBR effluent, which contains both excess (i.e., sloughed) biological solids and particulate selenium. The water is split evenly between two (2) units, each rated for 1,400 gpm (50% of maximum design flow). In each unit, the water flows through a series of chambers for coagulation, flocculation, maturation and settling.

Figure 4. Ballasted Sand Clarifier

As the FBR effluent enters the first chamber a coagulant is added and rapidly mixed to enhance particle agglomeration. The water then overflows to a second chamber – the flocculant tank. Microsand and a flocculant are added to enhance particle attachment to microsand. The tank is also rapidly mixed to allow even dispersion of the microsand and the flocculant. The microsand serves as ballast for the chemically conditioned biological solids and particulate selenium. The water then flows to a third chamber where the water is gently mixed thereby allowing the particles to floc and grow in size. Finally the water flows into the fourth tank, which contains tube gravity settler. The clarified water overflows to a collection trough and flows by gravity to the MBBR. The ballasted particles that settled at the bottom of the clarifier are pumped to a hydrocyclone where the microsand is separated from the biological solids and the particulate selenium. The microsand is recycled back to the system (i.e. into the flocculation chamber) and the mixture of biological solids and particulate selenium is sent to the solids handling system (gravity thickener). The ballasted sand clarifier chemicals include ferric sulfate (coagulant), poly aluminum chloride and polymer (flocculant), which are both flow paced based on forward flow.

MBBR System

Following solids removal, the clarifier effluent flows by gravity to a MBBR system for removal of residual BOD from the FBR process and also to raise the DO of the effluent prior to discharge.

Figure 5. MBBR Tanks

MBBR system is a fixed film biological treatment system. Typically, the MBBR consist of a tank with neutrally buoyant media for attached growth, screen and a blower to provide the required aeration. The media consists of plastic carrier elements that offer adequate surface area for bacteria to attach and grow, and aerobically degrade the organics. BOD removal occurs on the biofilm that develops on the carrier elements. In addition to DO, aeration also supplies mixing energy to cause the carriers to be dispersed throughout the liquid and completely mixed.

The MBBR system consists of two (2) 75,000 gallon carbon steel tanks in parallel that provide an HRT of 1 hour at average flow conditions. The MBBR tanks are filled to approximately 47% of the total tank volume with plastic media of various diameters. The plastic media provide sufficient surface area for fixed film growth. The water and submerged media are aerated and agitated together via two (2) common positive displacement blowers. Adequate oxygen is supplied so that carbon oxidation can occur in the reactor through a series of diffusers. Each MBBR is equipped with a DO probe. Phosphoric acid if needed and ammonium chloride are added to the MBBR reactors to help ensure balanced microbial growth. From the MBBR system, effluent flows by gravity to the MBBR effluent tank and then pumped to the common outlet for discharge.

Solids Handling System

Solids from the ballasted sand clarifier and screen backwash are sent to a solids gravity thickener to further concentrate the solids prior to dewatering. The thickener has a 100,000 gallon volume and provides 3 days of solids storage capacity. The thickener supernatant then flows by gravity to the filtrate collection tank and is pumped back into the process feed stream either to the FBRs or the ballasted sand clarifiers. The thickener underflow is manually pumped to the solids conditioning tank. A flocculant polymer is added to the thickener to enhance solids settling and thickening through a liquid polymer feed system.

The solids conditioning tank has a capacity of 20,000 gallons, and is equipped with a mixer. A coagulant polymer is prepared in a polymer blending unit similar to the one described for the ballasted sand clarifier and is added in the solids conditioning tank. The conditioned solids are transferred to the filter press for dewatering by filter press feed pumps.

Two (2) 65 ft^3 plate and frame filter presses are provided to process batch loads of conditioned solids twice a day (4-hour cycle) during the weekdays, for a total of 10 times per week during average flow conditions and three times a day during the weekdays during peak flow conditions. A precoat system is provided to trap the elemental selenium in the solids, preventing it from passing through the cloth in the beginning of the sludge feed. It also improves the dewatering performance of the press. The precoat system consists of a tank and a pump to transfer the solution of precoat material to the press to cover the entire filtering area with an even thickness of filter aid prior to starting each solids processing cycle. The dewatered solids cake consisting of approximately 20 - 25% solids are collected and hauled off to a landfill by truck. The filtrate is pumped to the gravity thickener.

WTP Startup and Operation

The WTP startup and commissioning was performed once construction was complete. Temperatures during the startup period in winter of 2013 routinely dropped well below freezing and freeze protection of the exposed equipment including pumps and instrumentation, external piping, and any “wet” items were incorporated.

Key samples collected and analyzed to confirm WTP performance and selenium removal were plant influent, FBR effluent, ballasted sand clarifier effluent and MBBR effluent. Onsite analysis was performed to monitor pH, Temperature, DO, conductivity, oxidation reduction potential (ORP), sulfide, ammonia-nitrogen, nitrate-nitrogen (NO_3-N), total suspended solids (TSS) and COD, whereas samples were sent offsite for analysis of selenium (total and filtered), BOD, iron, aluminum, sulfate, phosphate, total dissolved solids (TDS) and hardness. Samples of the filter press solids were also collected routinely for toxicity characteristic leaching procedure (TCLP) analysis to determine if the solids would be classified a characteristic hazardous waste.

RESULTS AND DISCUSSION

Influent Water Quality

Table 3 summarizes WTP influent water quality for some of the key parameters based on over a year of operational data. Key observations are summarized and discussed in this section.

Table 3. Influent Water Quality Summary

Parameter	Units	Minimum	Average	Maximum
WTP Flow	gpm	270	2,100	2,800
Selenium, Total	µg/L	6.6	17.5	25.8
Nitrate-N	mg/L	0.5	3.1	4.5
TSS	mg/L	0	18	80
Temperature	°F	43.5	60.5	72.5

Average WTP influent flow has been higher than the average design flow. The observed average flow is around 2,100 gpm when compared to the design flow of 1,850 gpm (Figure 6). This shows that the WTP has been operating at the maximum flow conditions at a higher frequency than anticipated. This is primarily as a result of a wetter/colder than average winter and spring in 2013. Higher flows can impact the operations/performance of certain unit operations as discussed later in the operational challenges section.

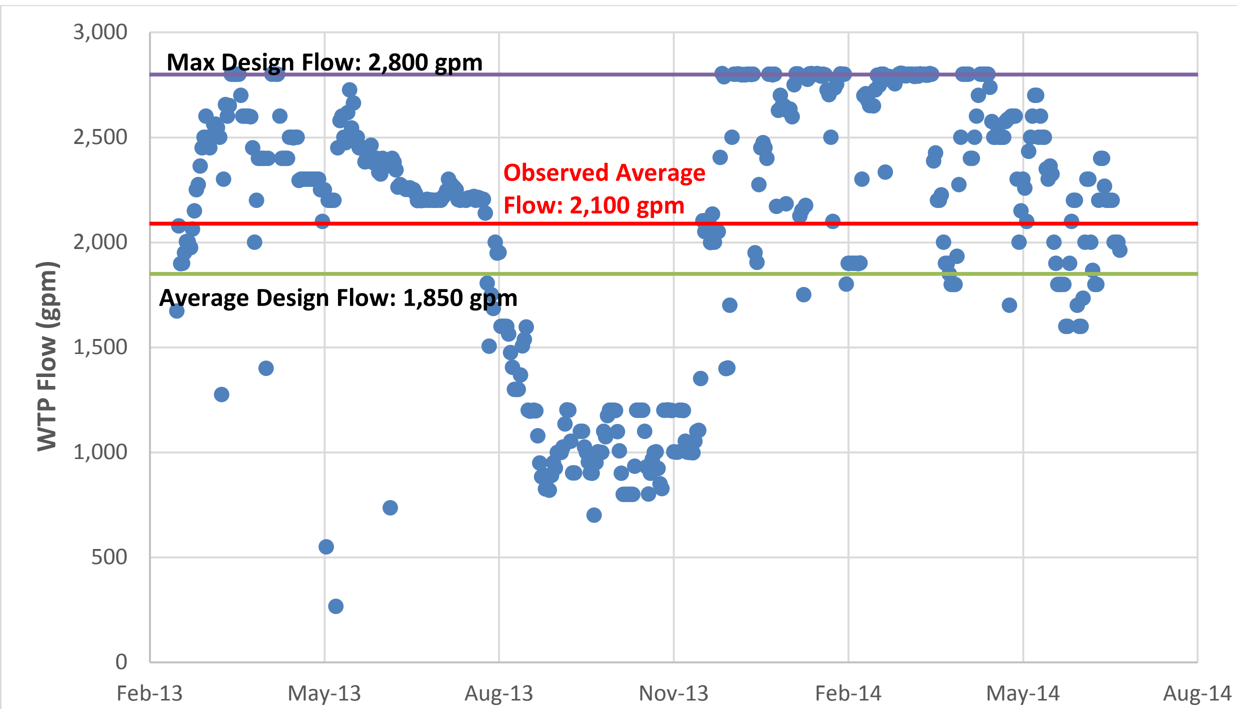

Figure 6. WTP Influent Flow

The nitrate loading to the WTP was observed to be lower than the design as shown in Figure 7. This could be attributed to higher flows being drawn from Source 1 and lower flows being drawn from Source 2 when compared to the design. Source 2 has significantly higher nitrate loading when compared to Source 1 (Table 2). Lower nitrate loading could also be as a result of higher than average flows from all sources providing a dilution effect. Since nitrate loading exerts a significant demand on the carbon source as all the nitrate has be removed (reduced to nitrogen gas) before any selenium reduction occurs in the FBR, influent nitrate concentration can have a significant effect on the process as discussed later in the operational challenges section.

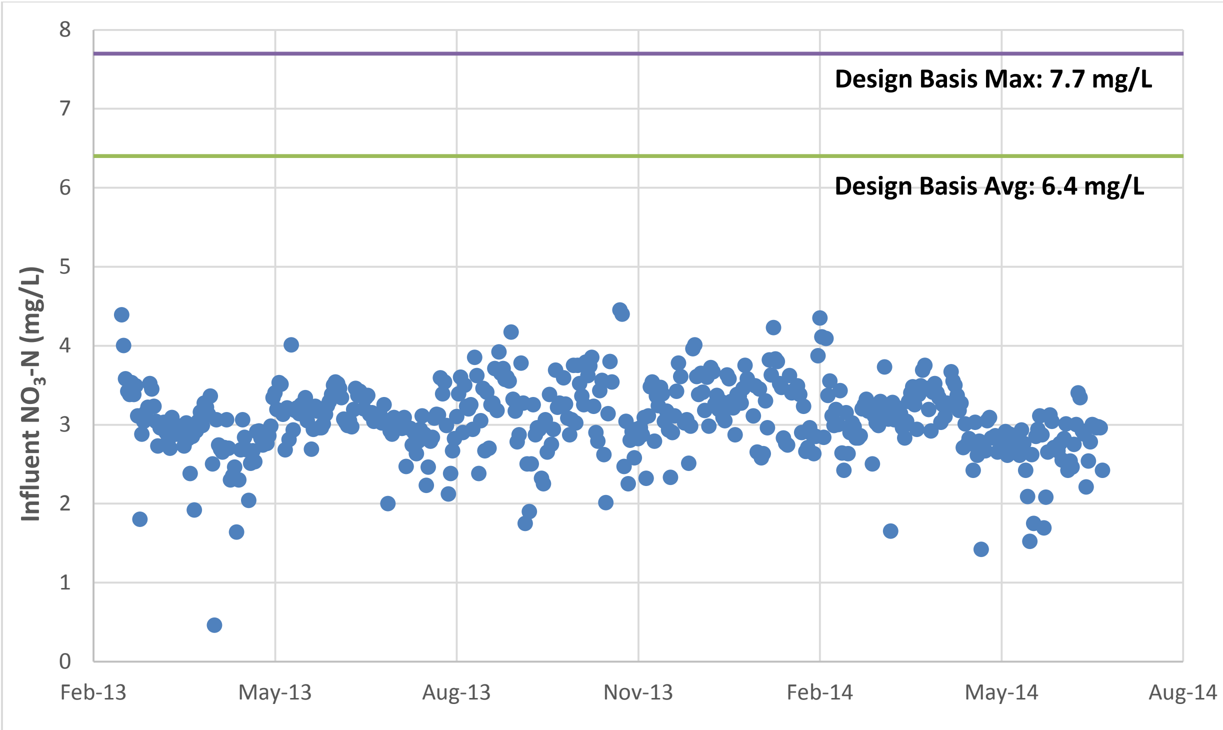

Figure 7. WTP Influent Nitrate-N

Influent TSS concentrations were significantly higher than in the design basis as shown in Figure 8. TSS, especially the fine silt/clay type particles associated with mine water runoffs could be a concern for downstream unit processes. Some of these impacts are discussed later in the operational challenges section.

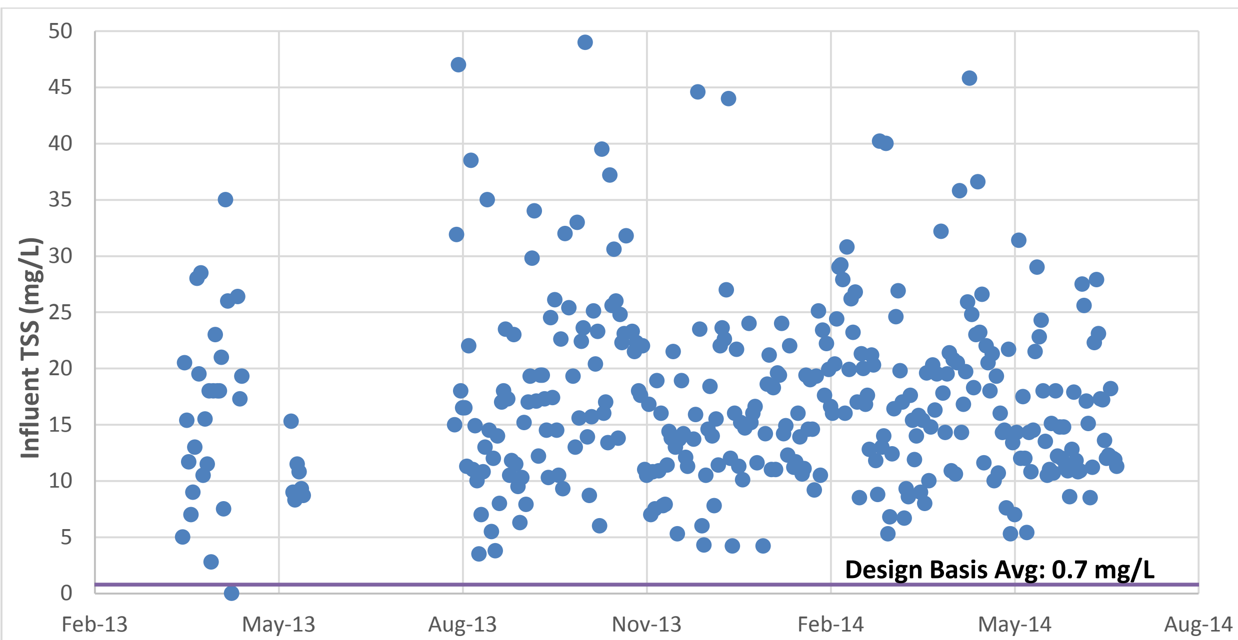

Figure 8. WTP Influent TSS

Startup and Initial Operations

The acclimation phase for the FBR lasted approximately eight (8) weeks and the operational parameters were adjusted based on process performance during this time period allowing the system to stabilize and reach stable operation. The FBR effluent contained reduced elemental selenium in colloidal form with biomass due to the nature (fluidized media with attached biomass sloughing off in the effluent) of FBR technology. The reduced elemental selenium is removed with biomass in the downstream ballasted sand clarifier units with coagulant and flocculant chemicals addition.

Figure 9 shows the performance of the plant for selenium removal over the initial five (5) month duration. During the acclimation phase, effluent selenium concentrations exceeded the limits on a few samples primarily due to, among other issues, process upsets as a result of changing influent conditions. Once stable operations were reached, the plant was able to consistently meet the selenium limit with the effluent selenium concentrations generally staying at or below the average value of 4.7 µg/L except for a few samples, which were still below the 8.2 µg/L monthly maximum limit.

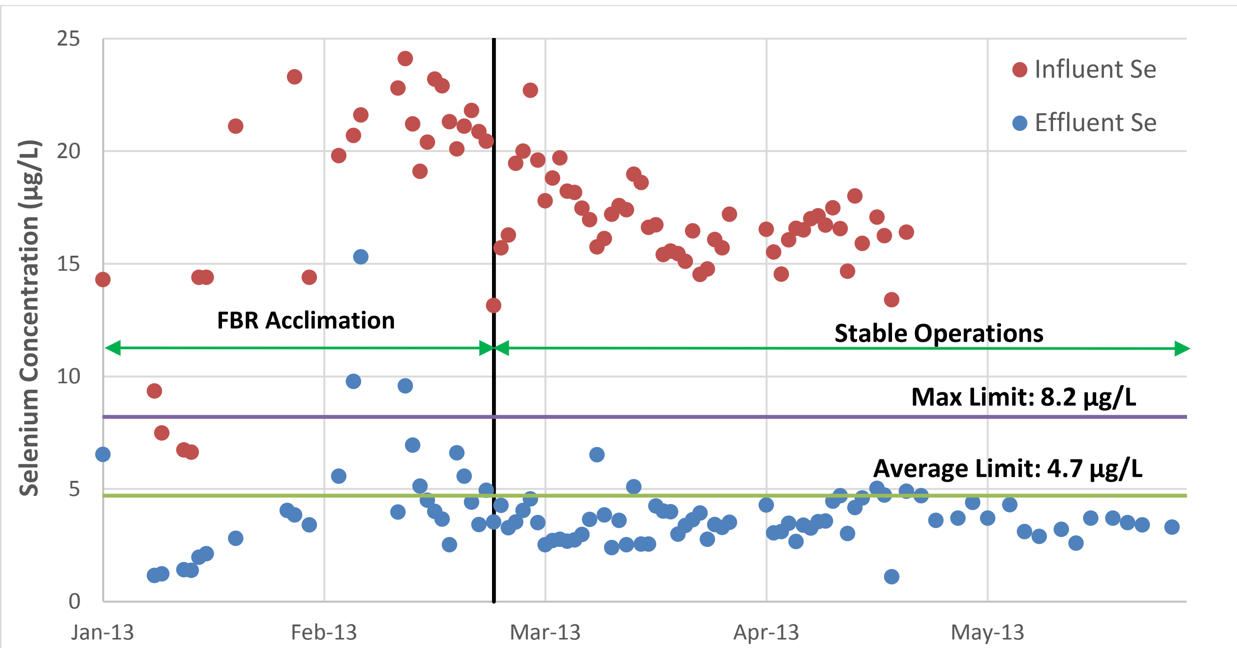

Figure 9. WTP Initial Operations - Selenium Data

In order to maintain anoxic/anaerobic conditions conducive for biological selenium reduction, the FBRs were operated at an oxidation reduction potential (ORP) range of -150 to -200 mV. The *MicroC* dosage was adjusted to maintain the required ORP and also to control the FBR effluent sulfide concentration in the range of 0.5 to 1.0 mg/L. Due to varying influent nitrate-nitrogen loadings, resulting from changes in the influent blending ratios, the sulfide concentrations at times exceeded the 1.0 mg/L maximum value in the FBR effluent. This excess sulfide resulted in the formation of iron sulfide (FeS) solids in the ballasted clarifier where ferric sulfate is used as a coagulant. Some of these fine FeS solids were difficult to remove and were carried over in the clarifier effluent on a few occasions, as reflected in the total iron concentrations measured in the final effluent from the plant. Due to the low iron limits in the discharge permit, it was decided to use an aluminum based coagulant also in the clarifier by reducing iron dosage to alleviate issues with compliance for iron. Figure 10 shows the observed effluent iron and aluminum concentrations as a result of the changes in the clarifier coagulation chemistry. A combination of iron and aluminum coagulants seemed to perform well with the plant being able to maintain concentrations well below the discharge limits.

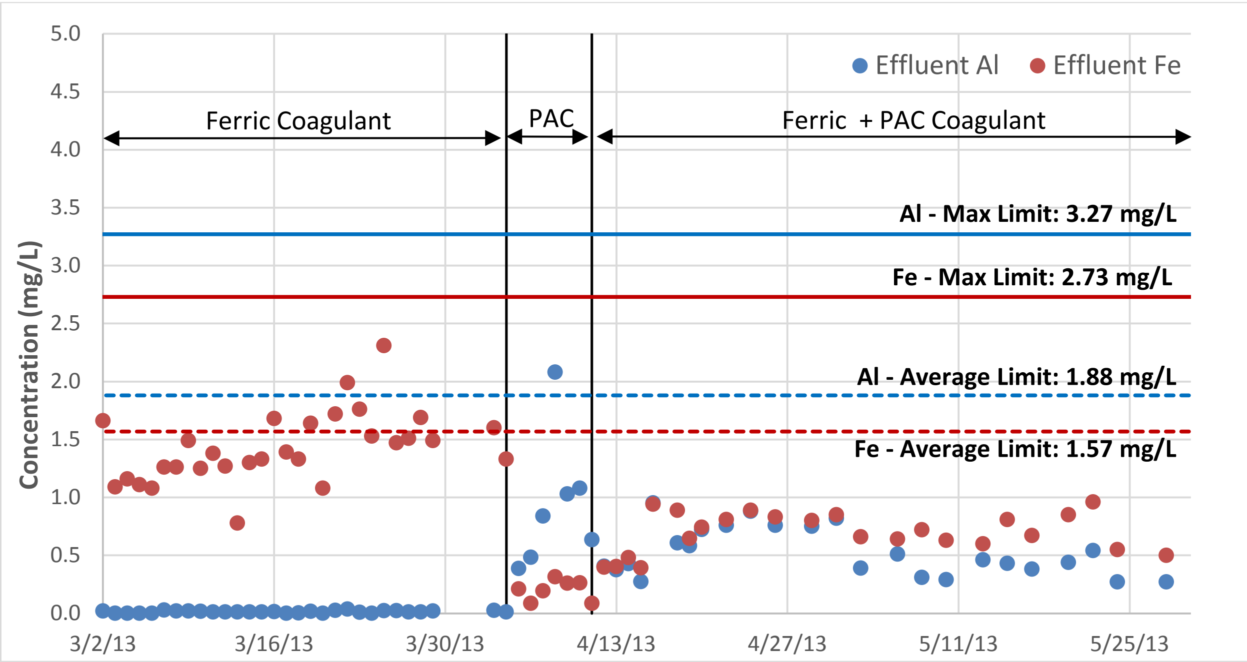

Figure 10. WTP Initial Operations – Effluent Iron, Aluminum Data

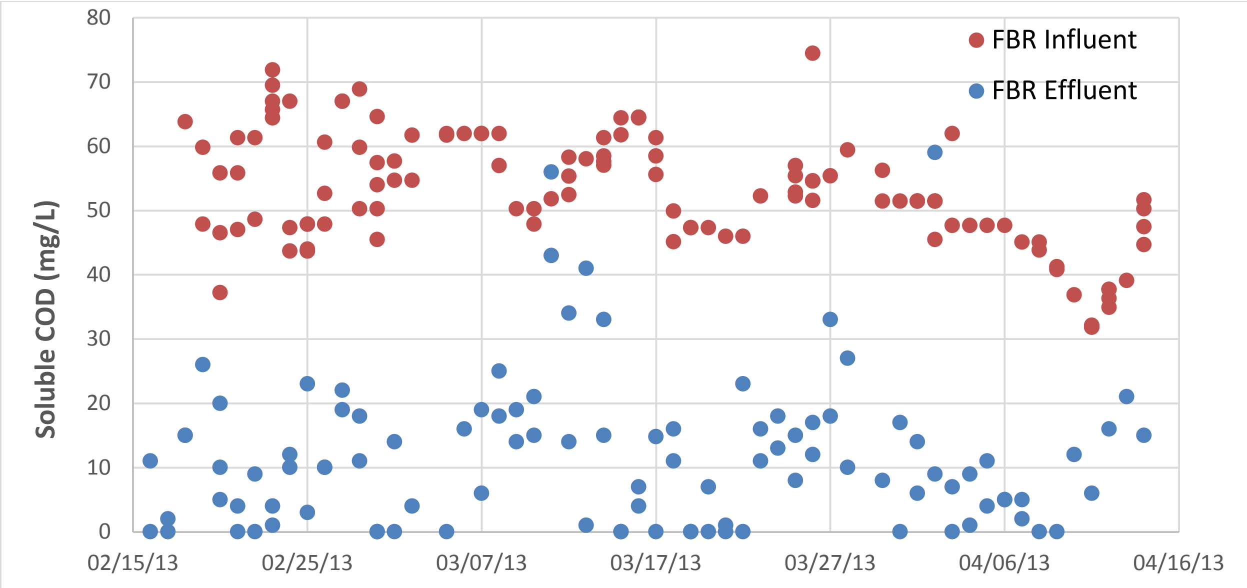

Figure 11. WTP Initial Operations – FBR COD Data

In addition to aeration of the plant effluent prior to discharge, the function of the aerobic MBBRs was to polish of the excess COD in the FBR effluent that was added to drive the biological process to selenium reduction. Figure 11 shows the FBR influent with *MicroC* addition and FBR effluent COD concentrations.

TCLP analysis of the filter press cake solids showed a TLCP Se concentration of less than the 1.0 mg/L limit to classify the solids as hazardous. As a result, the dewatered solids are being sent to a solids waste landfill as nonhazardous waste.

WTP Long-Term Operation and Performance

The WTP was required to be in compliance by March 1, 2013 and has been continuing full-scale operations since then. Figure 12 shows the WTP effluent selenium data over the past year. The plant has been able to consistently meet the selenium limit with the effluent selenium concentrations generally staying at or below the monthly average value of 4.7 µg/L. A few samples exceeded the monthly average limit but were still within the 8.2 µg/L daily maximum limit. The influent selenium concentrations have been in the 15 to 20 µg/L range.

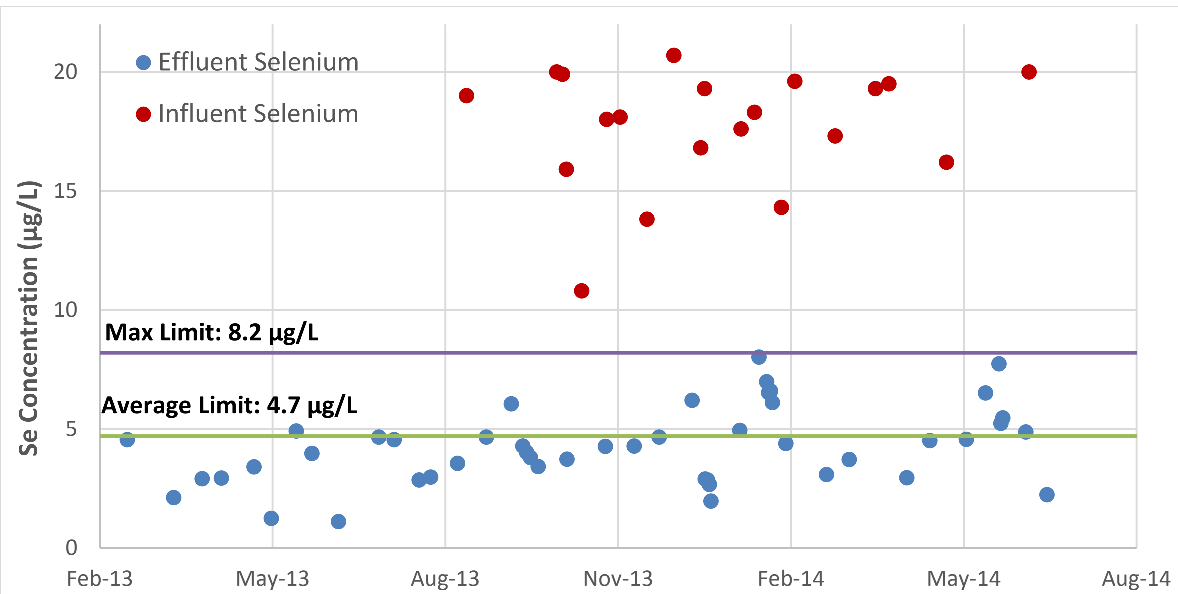

Figure 12. WTP Selenium Removal Performance

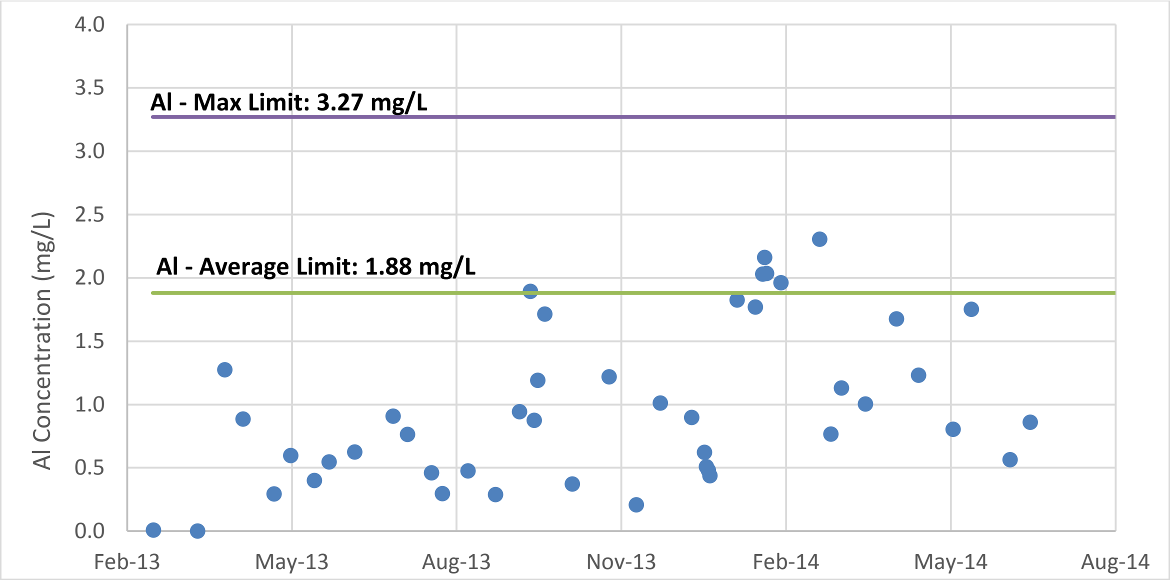

Figure 13. WTP Effluent Aluminum

From Figures 13 and 14, it can be seen that the WTP has been able to meet compliance for both aluminum and iron. Modifications undertaken in the clarifier coagulation chemistry during startup by using a combination of iron and aluminum coagulants in the ballasted sand clarifier seemed to perform well with the plant being able to maintain effluent concentrations generally at or below the average limits.

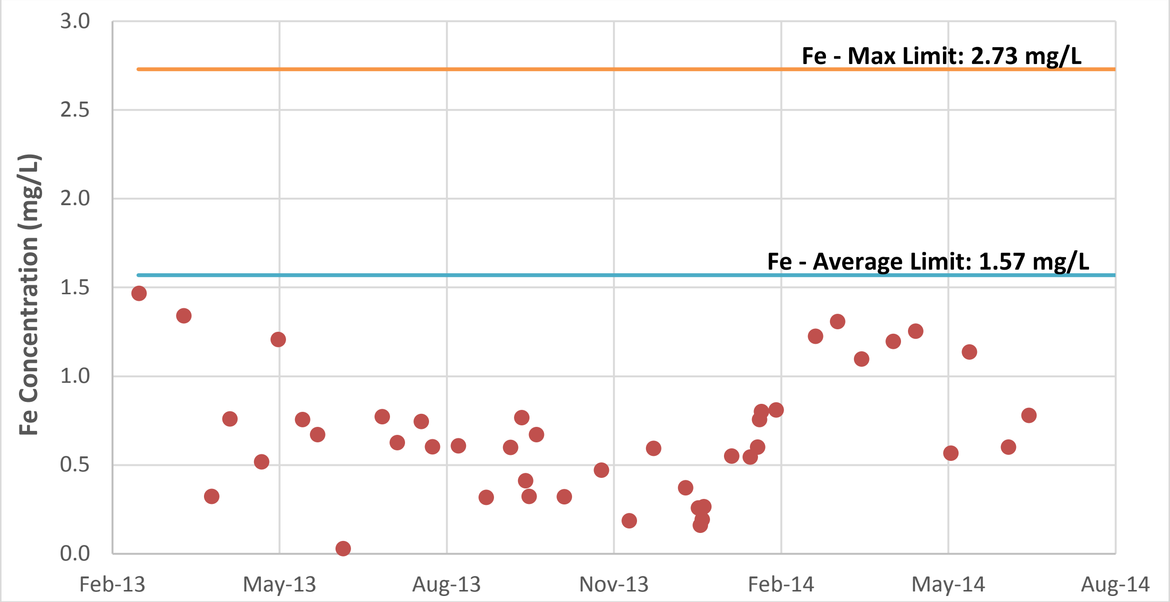

Figure 14. WTP Effluent Iron

The WTP has been consistently meeting compliance for TSS and pH as well as shown in Figures 15 and 16. Majority of the selenium laden biosolids are removed at the ballasted sand clarifier with some additional solids polishing in the MBBR tanks through settling thereby meeting compliance for not only TSS but also total selenium at the final discharge location.

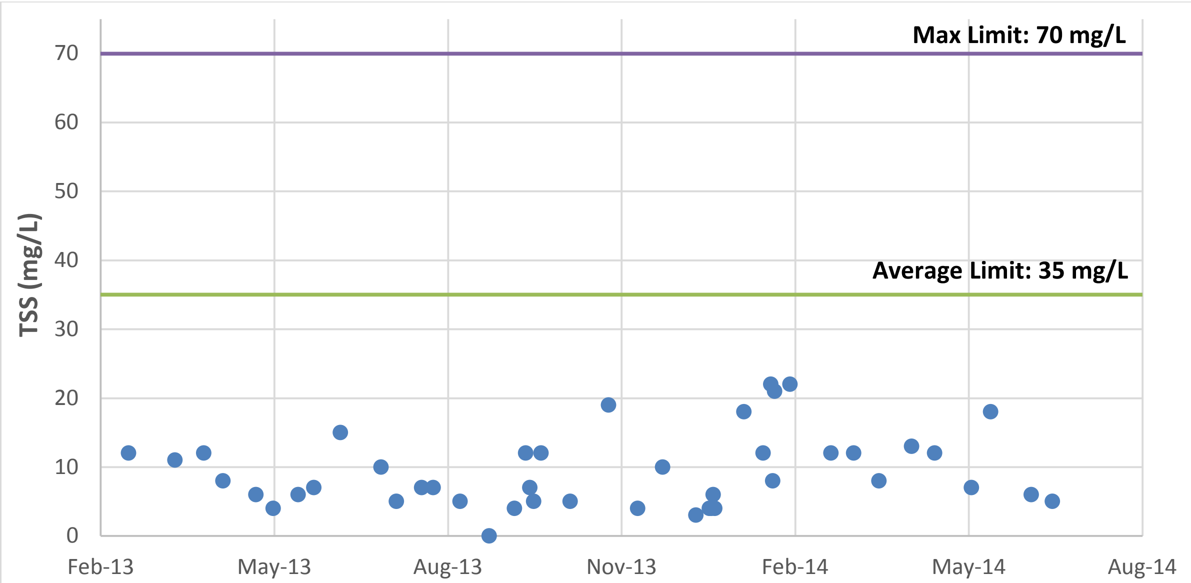

Figure 15. WTP Effluent TSS

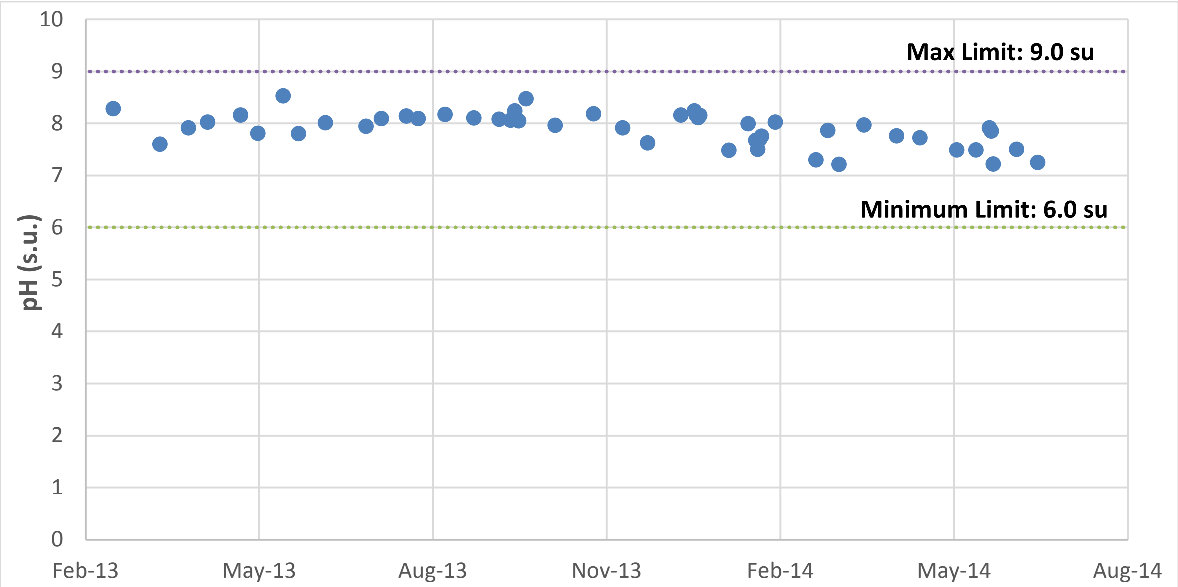

Figure 16. WTP Effluent pH

Operational Challenges

The key challenges with the startup and initial operations of the WTP are listed in Table 4. The reasons for these issues and remedies undertaken to address them are also discussed.

Table 4. Major Operational Challenges Observed During Startup

Issue	Description	Reason	Remedy
FBR bed height control	Bed heights in the FBR were challenging to control in order to maintain the desired expansion, and this was affecting the FBR performance for selenium removal	Accumulation of the fine silt/clay solids in the FBR beds	Daily monitoring of the bed heights and establishing a new in-bed cleaning schedule with more frequent cleanings and for longer duration than originally proposed
Performance issues with heat exchangers and magnetic (mag) flow meters	It was challenging to maintain the minimum required temperature in the FBR influent during winter and also operational issues were observed with the mag meters	Scaling on the heat exchanger surfaces and on mag meters from the fine silt/clay solids and mineral deposits in the mine water	More frequent cleaning of these units was added to the preventive maintenance plan
MicroC dosing pump control	It was challenging to control dosing with changes in flows and blending ratios especially since the required dosages were much below the estimated dosages during design. Operator intervention was required to constantly adjust pump speed and stroke to get to the low flow rates	Lower nitrate loadings in the influent as well as lower COD requirement of the full-scale FBR resulted in dosages being much lower than the design. The *MicroC* dosing pumps did not have VFDs and required a lot of manual adjustment	Better control was achieved with addition of VFDs on these pumps
Clarifier polymer dosing	Fish eyes and lumps were observed in the made up polymer solution	Inadequate mixing with the service water was the primary reason for this and affected the polymer dosage to the clarifier	An in-line water heater was added to the service water resulting in a more uniformly mixed polymer solution

CONCLUSIONS AND RECOMMENDATIONS

A 4 MGD (2,800 gpm) WTP was commissioned at a confidential North American mine facility in 2013 to meet compliance for selenium. This treatment plant uses the biological FBR based process for selenium removal and is the first of its kind for selenium treatment in mine water. An analysis of the plant performance during startup and full-scale operations over the past year were presented in this paper.

The primary process train consisted of FBRs for facilitating anoxic/anaerobic reduction of selenite/selenate to elemental selenium followed by ballasted sand clarifiers for the removal of the elemental selenium and the biomass. The next step in the process is an aerobic moving bed biofilm reactor (MBBR) for removal of residual organics and to increase the dissolved oxygen (DO) prior to discharge.

The main findings and conclusions from the study are listed below.

- The WTP has been operational for over a year and has been able to consistently meet the low selenium limit (4.7 µg/L monthly average and 8.2 µg/L daily maximum). The WTP has been in compliance meeting the low effluent discharge limits for other parameters as well.
- Like any plant startup, there were operational challenges during startup and commissioning of this plant. Steps taken to address these issues have been instrumental in successful operation of the plant over the past year.
- The WTP receives mine waters from three (3) different sources with varying selenium and nitrate loadings that are combined prior to treatment at this plant. The biggest operational challenge has been to control the carbon addition to maintain the required COD at the FBR to control biological activity with constant changes in the flows and blending ratios.
- The full-scale FBR system has been able to replicate the pilot system performance by demonstrating sufficient dissolved selenium removal to meet the average discharge limit of 4.7 µg/L for total selenium. The full-scale FBRs with the deeper beds are significantly more efficient than the pilot unit in terms of the COD required for the desired selenium removal. This has resulted in significant chemical and associated cost savings for the electron donor used for COD addition at the FBR.
- The ballasted sand clarifiers have been effective in removal of solids containing the particulate elemental selenium, which is a critical step in order to meet the selenium limit at the discharge point. Modifications in clarifier coagulation chemistry were required to overcome some of the operational and performance issues observed during startup and initial operations.
- Lower levels of COD in the FBR effluent that initially anticipated have allowed the MBBRs to be used for reaeration instead of COD polishing. The MBBRs have been effective in raising the DO in the effluent to the desired levels ($\geq$ 6 mg/L) prior to discharge.
- The dewatered biosolids containing elemental selenium have consistently shown a TCLP selenium concentration of less than the 1.0 mg/L. Therefore, the biosolids are being sent to a solids waste landfill for disposal as nonhazardous waste.

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