Managing the New FGD Wastewater Regulations

Technology Options for Biological Treatment:
Maximum Treatment Reliability with Lowest Lifecycle Cost

Table of Contents

Introduction

The U.S. Environmental Protection Agency's recent update of the Steam Electric Power Generating Effluent Guidelines (commonly called effluent limitation guidelines or ELGs) has far reaching consequences on how coal-fired power plants will operate and, in particular, manage their wastewater in the future. One of the most complex and demanding segments on of the new ELGs concerns managing Flue Gas Desulfurization (FGD) wastewater. The ELGs set a host of new numerical limits for total dissolved solids, arsenic, mercury, selenium, and nitrate/nitrite for FGD wastewater.

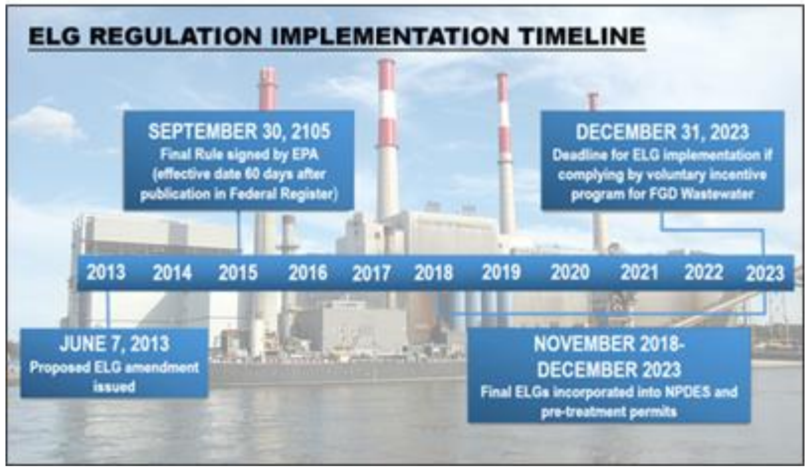
The ELGs are technology-based regulations, which means the limitations set by the EPA under this rule are established based on what is achievable given the implementation of a certain treatment technology the agency selects as a basis for consideration. A number of different technologies have been suggested by the EPA as 'trusted', and while each of these exhibits efficacy in addressing some portion of the wastewater treatment challenge, many have substantial limitations based on the nature of the wastewater stream, their ability to treat a broad range of the contaminants in question – reliably, and their cost. This has been particularly shown to be the case in meeting selenium discharge requirements, where biological treatment systems have been shown to offer superior treatment efficacy as well as other benefits.

Top-performing technology

Today, Envirogen Technologies offers the most reliable biological technology for treating FGD wastewater: The Fluidized Bed Reactor (FBR). In addition to delivering the most consistent removal of selenium and other metals, the FBR technology offers the benefits of greater system reliability and significantly lower costs than other commercially-available technologies. Envirogen has the broadest background and installation-base of biological treatment systems for both selenium and other oxyanions in the environmental industry. This track record of designing, building and operating biological systems offers the engineering community and power utilities a strong partner in developing reliable, least-cost solutions to managing FGD wastewater treatment operations under the new ELGs.

The New Regulatory Environment

FIGURE 1:



While impacting around 1,000 facilities throughout the United States, the segment of the new ELGs rule that regulates FGD wastewater will have the greatest impact on fewer than 500 (generating capacity greater than 50MW) of these power plants that are coal-fired units that discharge to a surface water body via a National Pollutant Discharge Elimination System (NPDES) permit (direct dischargers) or discharge to a publicly owned treatment works (POTW) via a pretreatment permit (indirect dischargers). The rule creates more stringent effluent limitations on arsenic, mercury, selenium, and nitrate/nitrite for flue gas desulfurization waste streams and ash transport water.

Under these new rules (Figure 1), the EPA wants compliance "as soon as possible" beginning on November 1, 2018, but no later than December 31, 2023, with further delays in implementation currently under consideration by the EPA. According to EPA's technical development document, the flexibility considerations include "time to expeditiously plan (including to raise capital), design, procure, and install equipment to comply with the requirements," timing of the plant's NPDES permit renewal, and any competing/additional changes being made at the plant to satisfy other standards and regulations.

For existing facilities, the new ELGs consider two 'tracks' for compliance – a wastewater treatment/discharge track and a zero-liquid discharge (ZLD)/disposal track. For the ZLD/disposal track,

TABLE 1: Treatment Options

	Current Rule	New Rule BAT/PSES *(Existing Sources)*	New Rule NSPS/PSNS *(New Sources)*
FGD Wastewater	Impoundment Included as low volume waste	Chemical precipitation + biological treatment Hg, As, Se, NO_2 + NO_3 Limits	Evaporation Hg, As, Se, TDS limits

the EPA offers an incentive that extends the ELG compliance deadline to December 31, 2023, regardless of permit renewal date for any existing FGD wastewater generators who voluntarily accept a more stringent technology basis for treatment of FGD wastewater—vapor-compression evaporation—and agree to be subjected to numerical limits for mercury, arsenic, selenium, and TDS commensurate with this treatment technology. For the wastewater treatment / discharge track, treatment and discharge of the wastewater are regulated as described in the Effluent Guidelines. An advantage of this track is that it is has the potential to be significantly less expensive. On the downside, the discharge limits for the wastewater treatment track are very stringent and future amendments to discharge limits are possible.

The 2015 ELGs update focuses on six power plant wastewater streams:

- ■ Flue gas mercury control (FGMC) system wastewater
- ■ Bottom ash transport waters
- ■ Fly ash transport waters
- ■ Flue gas desulfurization (FGD) wastewater
- ■ Coal combustion residuals (CCR) leachate
- ■ Integrated Gasification Combined Cycle (IGCC) wastewater

FGD wastewater is defined by the EPA to include “any process wastewater generated specifically from the wet flue gas desulfurization scrubber system, including any solids separation or solids dewatering processes”

TABLE 2:

Numerical Limits

Flue Gas Desulfurization Wastewater *(Existing Sources)*		Flue Gas Desulfurization Wastewater *(New Sources + Incentive Program)*	
Arsenic, ppb		**Arsenic, ppb**	
30-Day Average:	8	30-Day Average:	N/A
Daily Maximum:	11	Daily Maximum:	4
Mercury, ppt		**Mercury, ppt**	
30-Day Average:	356	30-Day Average:	24
Daily Maximum:	788	Daily Maximum:	39
Selenium, ppb		**Selenium, ppb**	
30-Day Average:	12	30-Day Average:	N/A
Daily Maximum:	23	Daily Maximum:	5
Nitrite-Nitrate, ppm as N		**Total Dissolved Solids, ppm**	
30-Day Average:	4.4	30-Day Average:	24
Daily Maximum:	17	Daily Maximum:	50

This paper will focus on the most complex section of the new rule – FGD wastewater. Industry experts agree that this area will demand the greatest level of engineering, design, planning and investment in treatment systems – with the longest lead times to successful project completion.

Characterizing FGD Wastewater

FGD wastewater poses a challenge to treat because of high concentrations of TDS and TSS, supersaturation in sulfates, high temperatures, potentially high organic concentrations, ammonia, nitrate/nitrites and heavy metals and trace constituents. Numerous studies have shown that FGD wastewater composition varies significantly from facility to facility and even within a single facility over time. The wastewater flowrate and characterization are affected by a number of factors, including the coal burn rate, scrubber equilibrium chloride concentrations, effectiveness of fly ash removal, the gypsum dewatering system, type of FGD process, and composition of the coal, limestone and make-up water. The purge rate required to maintain a target equilibrium chloride concentration is directly dependent on the coal chloride content and coal burn rate.

TABLE 3:

Average Pollutant Concentrations in Untreated FGD Wastewater

Analyte	Unit	Average Total Concentration	Average Dissolved Concentration a
Classicals			
Ammonia as Nitrogen	mg/L	13.1	NA
Nitrate-Nitrite as N	mg/L	91.4	NA
Nitrogen, Kjeldahl	mg/L	34.9	NA
Biochemical Oxygen Demand	mg/L	8.18	NA
Chemical Oxygen Demand	mg/L	345	NA
Chloride	mg/L	7,180	NA
Sulfate	mg/L	13,300	NA
Cyanide, Total	mg/L	0.733	NA
Total Dissolved Solids	mg/L	33,300	NA
Total Suspended Solids	mg/L	14,500	NA
Phosphorus, Total	mg/L	4.02	NA
Metals, Metalloids, and other Nonmetals			
Aluminum	ug/L	331,000	1,470
Antimony	ug/L	28.9	3.87
Arsenic	ug/L	507	7.07
Barium	ug/L	2,750	284
Beryllium	ug/L	17.5	2
Boron	ug/L	242,000	266,000
Cadmium	ug/L	127	128
Calcium	ug/L	3,290,000	2,050,000
Chromium	ug/L	1,270	4.17
Hexavalent Chromium	ug/L	NA	4.76
Cobalt	ug/L	245	206
Copper	ug/L	673	20.1
Iron	ug/L	566,000	100
Lead	ug/L	315	1.00
Magnesium	ug/L	3,250,000	3,370,000
Manganese	ug/L	85,700	106,000
Mercury	ug/L	289	7.19
Molybdenum	ug/L	273	136
Nickel	ug/L	1,490	973
Selenium	ug/L	3,130	1,130
Silver	ug/L	8.18	1.00
Sodium	ug/L	2,520,000	276,000
Thallium	ug/L	22.1	15.1
Tin	ug/L	164	100
Titanium	ug/L	4,300	10
Vanadium	ug/L	1,300	13.4
Zinc	ug/L	4,110	1,580

Source: Steam Electric Analytical Database for the Final Rule [ERG, 2015d].

NA - Not applicable. Samples were not analyzed for this particular analyte.

Note: Concentrations are rounded to three significant figures.

a – EPA calculated the average concentrations based on various data sets available for untreated FGD wastewater (as described in Section 3). As a result of using various data sets, the average dissolved concentrations presented in the table may be higher than the total concentrations; however, the pollutant concentrations for untreated FGD wastewater are not used in EPA's loadings calculations.

FGD wastewater may contain as much as 7% suspended solids (if primary hydrocyclone overflow is used) or as little as 30 mg/L of suspended solids (when using thickener or stacking pond overflow). Moreover, because it is common for a plant to change coal and limestone suppliers, the wastewater constituents will change over time during operation of the FGD system.

FGD wastewater can contain high levels of selenium, mercury, hexavalent chrome, cadmium, copper, and zinc – in various phases of speciation. An emerging body of study points to the oxidation state of FGD wastewaters – as measured by oxidation reduction potential (ORP) - as a key factor in the treatability of metals and the attainment of low discharge levels directed by the ELGs. For many metals, both concentration and solubility are a function of the oxidation state. As swings in condition of the FGD wastewater occur, ORP may produce changes in the dominant state of regulated metals. For example, there is a strong correlation between ORP and Se concentration. As the ORP drops, there is a corresponding drop in the selenium concentration. At ORP levels below about 300 mV, selenium exists predominantly in the +4 oxidation state as selenite. Selenite is easily removed by many wastewater treatment methods, including physical-chemical treatment methods. As slurry ORP increases above about 300 mV, selenium shifts to the +6 oxidation state to form selenate. Selenate is a dissolved species that passes through some wastewater treatment systems, causing concern for compliance with effluent limitations. Similar impacts of ORP in speciation of manganese and mercury have been observed, which directly impact concentrations and treatability.

What is important to consider here is the extent to which operation of the FGD system impacts the flow, makeup and treatability of its wastewater. Ultimately, the plant's wastewater treatment system – and its system components - must be flexible enough to handle these varying inputs yet produce a treated stream that meets the plant's wastewater discharge permit requirements

FGD Wastewater Treatment Technologies

For the ELGs, EPA has established Best Available Technology economically achievable (BAT) effluent limitations based on a review of available technologies. The rule identifies treatment using chemical precipitation followed by biological treatment as the BAT technology basis for control of pollutants discharged in FGD wastewater. Specifically, the technology basis for BAT is "a chemical precipitation system that employs hydroxide precipitation, sulfide precipitation (organ sulfide), and iron co-precipitation, followed by an anoxic/anaerobic fixed-film biological treatment system designed to remove heavy metals, selenium, and nitrates". EPA has rejected chemical precipitation alone as BAT for FGD wastewater because the technology is not effective at removing selenium, nitrogen compounds, and certain metals that contribute to high concentrations of TDS in FGD wastewater.

EPA identified several other technologies that have been evaluated for treatment of FGD wastewater, including zero valent iron, iron cementation, reverse osmosis, absorption or adsorption media, ion exchange, and electro-coagulation. Most of these technologies have been evaluated only as pilot-scale studies. Other technologies under laboratory-scale study include polymeric chelates, taconite tailings, and nanoscale iron reagents.

Today, there are two different types of active, fixed-film systems that have received significant pilot and field testing with selenium-containing wastewaters – the fixed-film downflow filter (also known as a 'packed bed reactor' – PBR) and the fluidized bed reactor (FBR). Both of these technologies have been piloted extensively for the coal mining industry for the removal of selenium from coal mining waters. This experience with selenium (one of the key targets of the new ELGs) is instructive in how they will operate in treating selenium in FGD wastewaters.

Treatment of Selenium-Containing Wastewaters

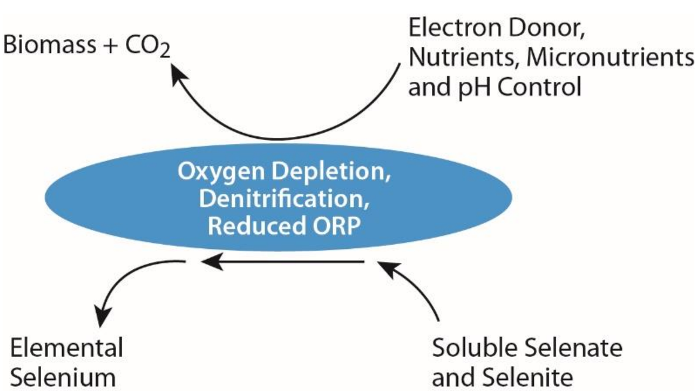
Managing selenium in FGD wastewaters is one of the most important considerations in selecting a treatment approach, because of the difficulty, and ultimately the cost of this activity. It can be said that in most operations, treatment of selenium can be considered the first limiting factor in evaluating a treatment technology.

Biological systems catalyze the reduction of selenium. Selenate can be reduced to selenite, and both selenate and selenite can be reduced to elemental selenium.

$$SeO_4^{2-} + \text{organic carbon} \rightarrow SeO_3^{2-} + \text{organic carbon} \rightarrow Se^0 + CO_2 + H_2O$$

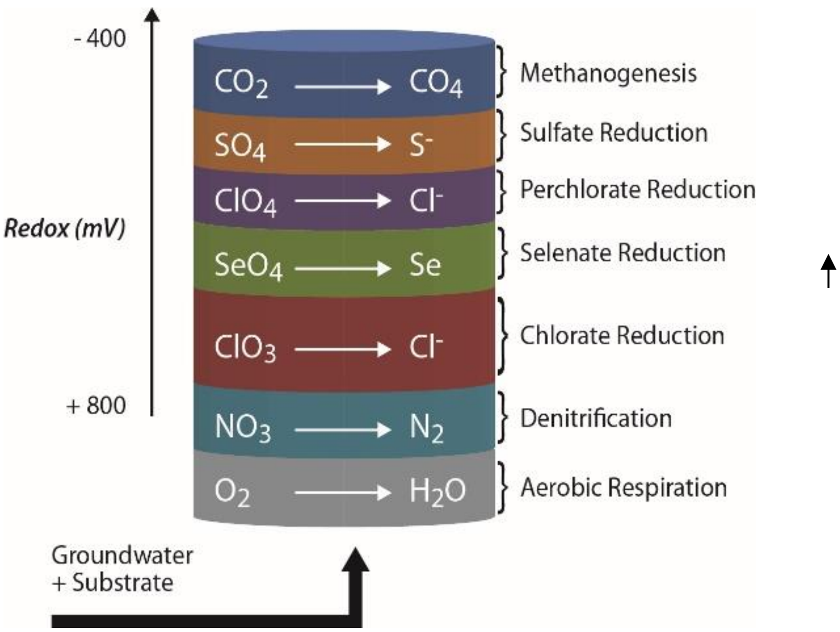
These reactions are desirable because elemental selenium is virtually insoluble and therefore can be removed from the environment through conventional liquid/solid separation and disposal. In biological treatment, the conversion of selenium anions to elemental selenium is accomplished via biologically catalyzed reduction. Selenium-reducing bacteria (Figure 2) are considered heterotrophic. They utilize organic carbon as their electron donor and selenate/selenite as their electron acceptors. Commonly used electron donor materials include methanol, acetate, citric acid and molasses. New ‘designer’ electron donors, generally composed of complex carbohydrates and organic process by-products that have been proven effective for selenium reduction and precipitation, are also available.

Figure 2: Selenium Reduction & Precipitation



One of the major issues in biological treatment of selenium is the presence of other anions in the influent streams. Both oxygen and nitrate are more favorable electron acceptors than oxidized forms of selenium. Figure 3 shows common anions and their order of biological reduction based on ORP. The order of electron acceptor use follows the more energetically favorable reactions first. Also, reduction enzyme systems appear to have evolved such that reduction enzymes are generally inhibited by electron acceptors that are more energetically favorable, particularly if the microorganism contains more than one reduction system.

Figure 3: Redox Profile of Biological Reduction



From a practical standpoint, these relationships are critical. The presence of either oxygen or nitrate will limit selenium reduction. Even in anoxic biological systems, the presence of nitrate is an important consideration in system design and the selection of microorganisms and electron donors. Many FGD wastewaters contain high levels of nitrate that will be preferentially reduced before selenium, and must be removed before effective selenium reduction will occur. Biological systems for FGD treatment must be sized to reduce nitrate levels, and sufficient electron donor material is required to reduce both nitrate and selenium.

Active, fixed-film biological treatment systems have received significant attention from the wastewater treatment community because of their potential to work with a broad range of selenium concentrations in wastewaters – including very dilute streams – and for their ability to reduce selenium to very low levels. These outcomes are due to the fact that the heterotrophic bacteria are retained in the bioreactor for relatively long periods of time, improving the chance that they will come in contact with the contaminants and the ability of these systems to control reaction conditions more precisely. Additionally, because of the tendency of the microbes to attach to the solid media and to form dense biomass films, these reactors can have high biomass concentrations. This is especially the case with the Envirogen FBR technology.

Envirogen Fluidized Bed Reactor Technology

Proven technology with critical advantages for the power industry

Fluidized Bed Reactors have been in operation in North America in environmental applications for over 30 years. In the 1980s and 1990s, Envirogen's work on enhancing biomass control and system automation allowed the FBR to reliably treat large volumes of influent water to low target contaminant levels. Continuing development of this technology has allowed Envirogen to use it to treat a broad range of oxianions (nitrate, perchlorate, selenium, etc.) in diverse applications (industrial, groundwater remediation, potable water treatment) – in systems that have ranged up to 4,000 gpm in size. As such, it is a technology with an excellent track record in being scaled-up and installed – as well as operating successfully over decades in the field. In addition to its on-going work in technology development, Envirogen has substantial experience in operating FBR systems in the field. This operating experience adds to the ability to develop reliable, long-term solutions and gives the company insights on asset life and lifecycle costs.

Envirogen's FBR is an active, fixed-film bioreactor that fosters the growth of microorganisms on a hydraulically fluidized bed of fine media. In this type of reactor, a fluid is passed through a granular solid material at velocities sufficient to suspend or fluidize the solid media.

Media types include sand and activated carbon media that are manufactured to exacting specifications for hardness, shape, size, uniformity, density and impurity levels. The small fluidized media in the FBR provide an extremely large active surface area upon which microorganisms can grow while treating contaminants. A large biomass inventory is produced while maintaining thin films, reducing mass transfer limitations and offering high volumetric efficiency.

Envirogen manufactures both aerobic and anoxic FBR systems. Aerobic systems utilize air or oxygen for removal of organics. Anoxic FBR systems are the technology of choice for inorganic contaminants such as perchlorate, nitrate and selenate/selenite. Other distinguishing features of Envirogen FBRs include patented biomass control systems that are key to retaining media and steady-state operation and plug flow; custom molded parts; proprietary design of internal vessel components and proprietary and patented controls for chemical feed systems.

Base System Design

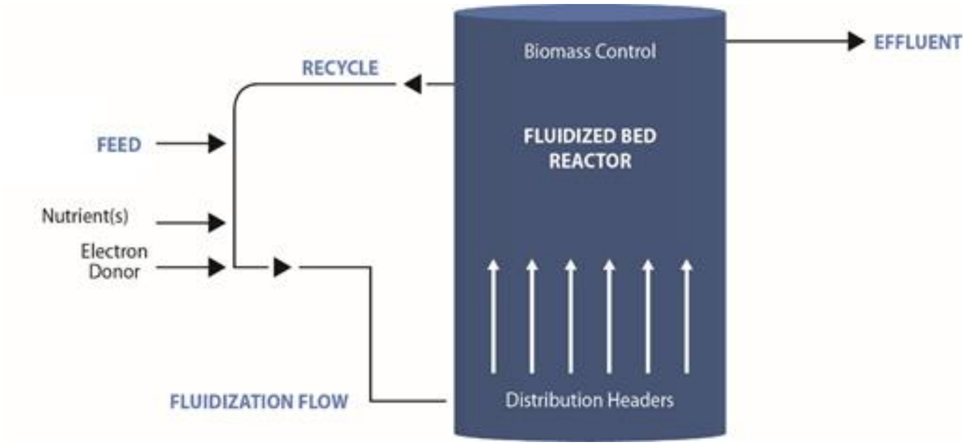
Envirogen FBR installations typically feature one or more vessels in series and/or parallel configurations, depending on influent water characteristics and discharge limits (Figure 4). A range of materials can be used for vessel construction, including stainless steel, fiberglass, lined-carbon steel or concrete. Prefabricated FBR vessels from 2- to 14-feet diameter and up to 30-feet in height are available – offering very deep beds in comparison to other fixed-film technology. This vertical orientation is one of the factors that contribute to the FBR's smaller footprint compared to packed bed reactors or other biological treatment systems. Field-fabricated concrete or metal vessels are also available for very large load applications. Overall system packages are outfitted with fluidization pump(s), piping, valves, chemical feed pumps and controls that may be field assembled or pre-assembled based on client preferences. Most Envirogen FBR systems are equipped with programmable logic control and may be provided with a SCADA package, telemetry and motor controls options.

Figure 4: Envirogen FBR for Perchlorate Removal

System Operation

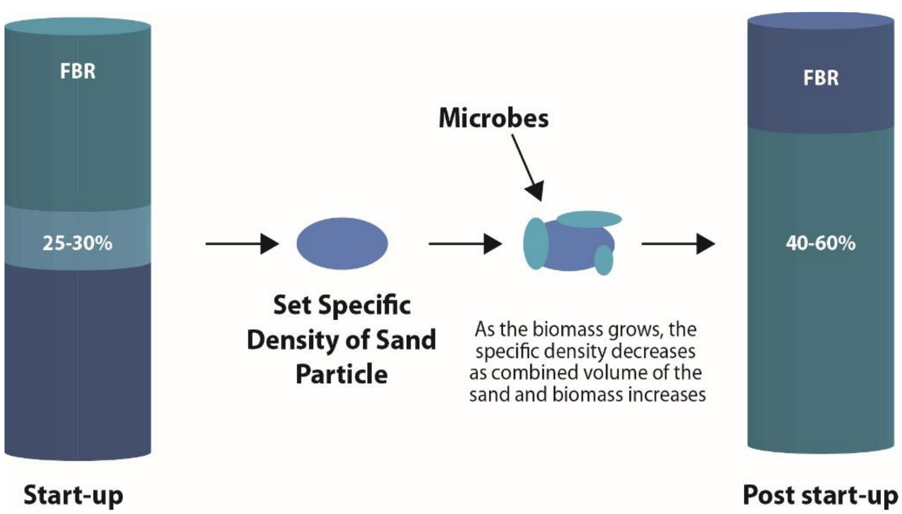
During start-up, the FBR is seeded with heterotrophic bacteria that are suited for nitrate and selenium removal (Figure 5). Electron donor materials and nutrients are pumped into the FBR to promote microbial growth.

Figure 5: Start-up of FBR system



Selenium-containing wastewater is pumped from a feed tank into the FBR in an upflow direction to suspend the media. As microorganisms envelope the media, the fluidized bed height expands (Figure 6).

Figure 6: Fluidization of FBR media



With time, a biofilm develops on the media surface. Nitrate and selenate/selenite reduction occur on this biofilm. Treated water from the FBR system is discharged to a downstream liquid/solid separation system where the biological solids and elemental selenium are separated. Thickened or dewatered bio-solids and elemental selenium are disposed.

One of the key features of operation is the technology used to fluidize the media bed and to uniformly distribute fluidization flow to the system. This is accomplished with the design and placement of the distribution nozzles and the sizing and arrangement of the header-lateral distributors. Uniformity of flow is critical to establishing steady-state plug flow conditions and the associated optimized performance.

Another key feature of these FBR systems is Envirogen's proprietary technology for biomass control. In all properly functioning biological systems some of the energy that is derived from the consumption of electron donor is used by the microbes for biomass growth. This results in the production of excess biomass or "yield" that must be removed from the bioreactor. In packed bed reactors this is accomplished with periodic backwash operations that remove large quantities of biomass using very high backwash rates – creating turbulence and shear to separate and wash out accumulated biomass.

In Envirogen's FBR systems biomass is removed in a steady-state manner with Envirogen's patented biomass control devices. These systems allow the FBR to operate with an optimized and consistently high biomass concentration, resulting in reliably high performance.

Limitations inherent in packed bed reactors render them incapable of handling high feed nitrate, selenium and suspended solids concentrations. This is due to problems of rapid plugging, nitrogen gas binding, channeling and high backwash requirements. With Envirogen's patented biomass controls, FBRs effectively handle feed loads that are greater than an order of magnitude higher then packed bed reactors.

The Fluidized Bed Reactor Advantage

The following issues highlight the Envirogen FBR systems' performance advantages compared to packed bed bioreactor technology.

Optimization of microorganism efficiency

One of the key advantages of FBR technology over packed bed reactors is the lack of 'channeling' that occurs in FBR systems. Packed bed reactors tend to develop preferential pathways for flow due to solids build-up in the bed and nitrogen gas binding caused by conversion of nitrate to nitrogen gas. This can cause pressure drop in the typical fixed-film system as well as short-circuiting or partial flow by-passing. These deviations from steady state plug flow conditions result in reduced performance because not all the biomass in the vessel is in contact with the wastewater. In the fluidized bed reactor, because the bed is expanded, no channeling occurs, resulting in an even distribution of flow. Therefore, all of the biomass within the bioreactor is utilized – meaning increased treatment efficiency. These issues directly affect the hydraulic residence time (HRT) required and explain why the footprints for Envirogen FBR systems are so much smaller than competitive packed bed bioreactors for the treatment of nitrate and selenium.

Smaller overall footprint

FBR systems have a smaller site footprint than other biological treatment systems. The key contributors to this feature are the vertical orientation of the FBR vessels and the efficiency of treatment (lower HRTs). Treatment efficacy is affected by a high concentration of biomass and the tall beds. This smaller footprint has a dramatic effect on construction and installation costs and schedules.

Steady-state operation

Envirogen FBR systems are designed to be operated continuously – meaning they do not require cyclical backwash operations. Packed bed reactors require periodic backwashing to slough off excess microbial growth, to eliminate channeling and to remove nitrogen gas pockets that have built up during the running part of the packed bed reactor operating cycle. Frequency of backwashing is related to the loading of contaminants in the influent stream and requires large pumps and intermittent operation. In addition to increased energy costs, backwashing limits the flow of wastewater through the entire system since it is necessary to remove the backwashed unit from service, recover, clarify and recycle the dirty backwash suspension. Recycled backwash water adds to the feed loading and thereby limits net throughput. Perhaps more importantly, the biomass in the system requires time to regrow following a backwash, further increasing the required HRT. With higher loadings of feed nitrate, selenium and/or suspended solids, the backwashing requirements can become so excessive as to render the packed bed bioreactor ineffective or completely impractical.

Dramatically lower hydraulic residence times

Despite having a smaller overall footprint, field studies have shown that FBR systems can achieve required performance with dramatically shorter HRTs than packed bed systems. This is due primarily to deep beds and steady-state plug flow operation. HRTs for typical FBR systems used in selenium treatment are 1/3 to 1/10 those required for packed bed reactors.

Robustness of the system

Envirogen FBR systems have a proven history over the past 30 years, operating effectively over a wide range of feed flow rates and influent types. The systems are tolerant of high feed concentrations of total suspended solids (TSS) and metals. In addition, these systems have the ability to recover quickly from upsets such as power outages and loss of chemical feeds.

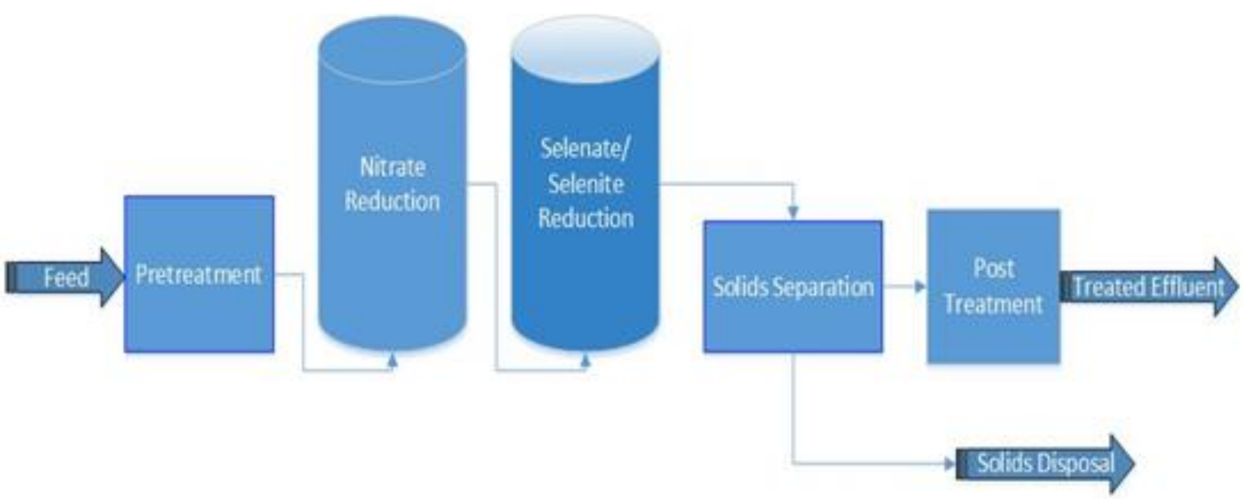
Lower costs

One of the major advantages of employing an FBR in a selenium treatment application is a considerable cost advantage in system design and installation compared with other commercially available technologies. This is primarily due to smaller system footprints as well as the ability to manage issues such as suspended solids and waste disposal in a much more effective fashion, over a broad range of influent flow rates. A 2010 analysis performed for the North American Mining Council showed that initial capital costs for an FBR system can be 1/3 or less the cost of a packed bed reactor system designed for similar treatment requirements.

Solids Management: Field Systems and Pilot Testing Experience

One of the critical areas of learning for selenium treatment from operating experience at coal mining sites and pilot studies conducted on power industry FGD wastewater has been in the application of alternative liquid/solid separation technologies, as they relate to feed water quality and meeting final effluent requirements. In some early tests, it was observed that, despite the biological treatment performing as designed in the conversion of selenate and selenite to elemental selenium, total selenium removal targets were not being met in instances where influent levels of selenium were high (> 500 ug/L).

FIGURE 8: Se Biotreatment Simplified PFD



It was determined that, in order to meet treatment targets, it was necessary to provide a means of liquid/solid separation that included removal of colloidal selenium, or simply small selenium particles that break away from the biomass, with particle sizes less than a micron in size. In another study, it was found that in influent streams with as little as 100 µg/L Se, selenium colloids were present in a variable size range, depending on seasonal and environmental conditions. Control of coagulant chemicals and polymers, as well as control of sulfide in the biological system effluent, were operationally challenging and resulted in sporadic spikes in effluent Se concentrations above treatment targets of 5 µg/L or 10 µg/L.

These observations called for a fresh look at the liquid/solid separation technologies accompanying biological treatment of selenium. Recent work has been conducted that utilizes membranes as a liquid/solid separation step, with positive results. The combination of an FBR with membrane separation has been under evaluation through a series of pilot programs. While the addition of membranes can add to capital costs, it is also possible that they offer benefits in the treatment of FGD wastewater that include:

- Positive retention of reduced Se
- Biological polishing of the FBR effluent with reduction of trace Se residuals
- Elimination of the coagulant chemicals and polymers required with conventional clarification and filtration technologies
- Substantial reduction in waste solids generation due to elimination of coagulant chemicals and polymers and due to lower biosolids yield as a consequence of longer solids residence times
- Elimination of the need to thicken filter backwash of clarifier reject streams since membrane solids are discharged at a high enough concentration to allow efficient filter press dewatering without the need for pre-thickening.
- Possible treatment of other regulated contaminants such as metals (Zn, Cr, Hg, Cd, etc.).
- Smaller footprint

This is not to say, however, that stringent effluent limits on selenium cannot be met by the FBR without membrane filtration. The deployment of large FBR-based treatment systems in Canada for mining wastewater have demonstrated in the field that significant selenium reduction below 12 µg/L levels are reliably achieved using conventional ballasted sand clarification (BSC) and filtration technology.

Dual-stage Multimedia Filtration (MMF) is another option being tested by Envirogen for removal of the suspended solids (biosolids and particulate selenium) exiting in the FBR effluent. It is expected that an even greater level of particulate selenium removal can be achieved versus the BSC at lower cost with a continuous backwash dual-stage granular multimedia filter approach employing a combination of anthracite, sand and garnet.

Pilot Study Shows ELG Compliance

A pilot study was completed on Flue Gas Desulfurization (FGD) wastewater at a coal fired power generating station located in the Southeast US to assess the FBR's ability to meet established effluent limitation guidelines (ELGs). The scrubbing of flue gas during seasonal coal combustion at this facility generates a wastewater with a wide range of constituents including arsenic, mercury, selenium and nitrate/nitrite. Treatment of the FGD wastewater involved physical-chemical precipitation pretreatment to remove arsenic, mercury, and other heavy metals prior to advanced treatment for the removal of selenium oxyanions and nitrate/nitrite.

Data collected during the six-month validation study conducted from August 2016 to February 2017, demonstrates the efficacy of the two stage Fluidized Bed Reactor (FBR) treatment system for biological reduction of the selenium oxyanions and nitrate/nitrite concentrations followed by ultrafiltration (UF) membranes for the removal of the reduced, insoluble selenium and other particulate.

Specific objectives of the validation study were the following:

1. Demonstrate compliance of treatment system effluent with ELGs. This includes the demonstration of effective biological reduction of selenium and nitrates through the FBRs, effective removal of selenium by reduction in the FBR and subsequent removal with ultrafiltration to below 12 µg/L monthly average and 23 µg/L daily maximum, and consistent compliance of all constituents after the UF membranes with regulatory targets.
2. Maximize system flux. This includes demonstration of an expanded bed contact time (EBCT), or hydraulic residence time (HRT), of up to two hours for the two stage FBR system and assessment of membrane flux rates for varying influent conditions.

3. Define full-scale design parameters. This includes the definition of ideal residence time based on the pilot plant results and knowledge of pilot to full scale transitions at other facilities; and the estimation of chemical usage requirements.

The pilot system operated for a duration of six months and consisted of four distinct phases:

Phase I goal was system optimization for consistently available flow rates.

Phase II targeted a forty-five day proof of successful biological reduction and removal of selenium and nitrate through the proprietary FBR system and ultrafiltration.

Phase III addressed the hydraulic objective of the pilot by incrementally increasing feed flow rate dependent on available FGD wastewater from the pretreatment system.

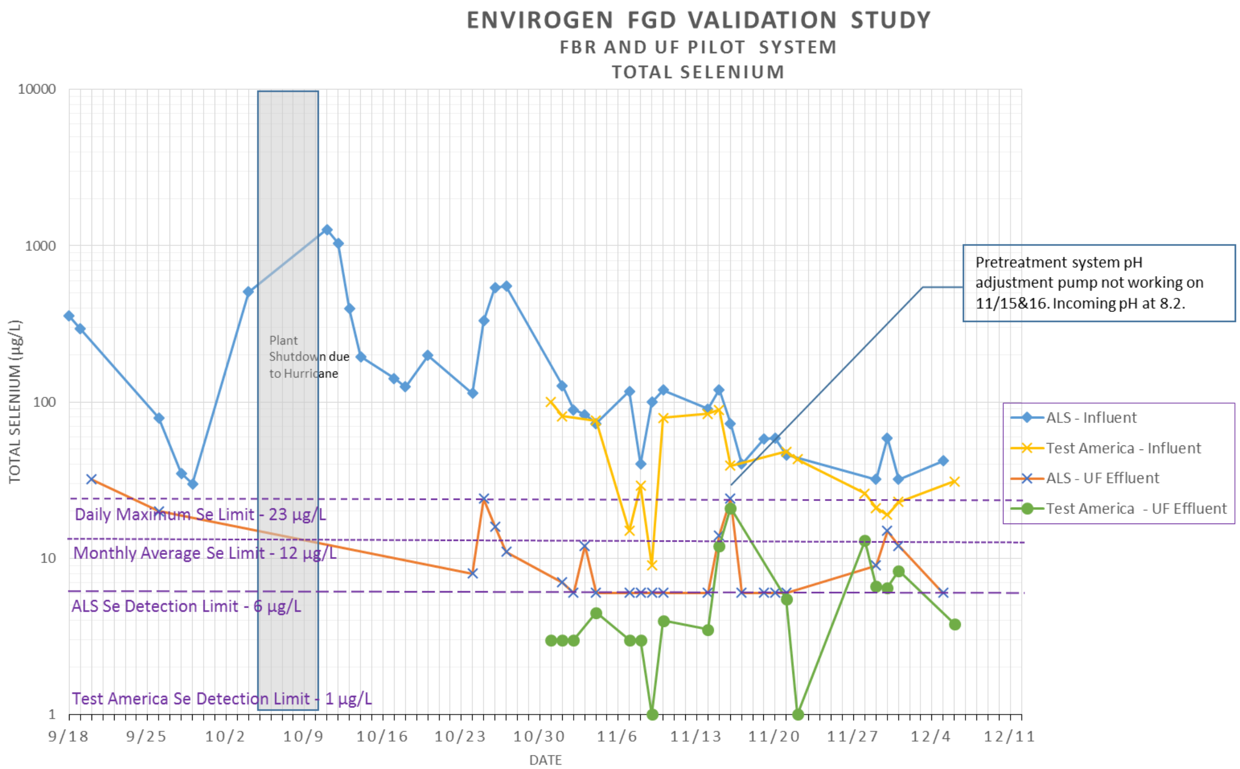
Phase IV challenged the limitations of system design in terms of hydraulic capacity and influent feed concentrations to determine the extent of the system capabilities.

Following system optimization, Phase II commenced and the FBR pilot system was validated to meet expectations regarding ELG compliance. The influent total selenium and nitrate/nitrite-N concentrations to the pilot systems varied over a wide range due to the intermittent operation of the generating units and FGD scrubber, which are typical for a peak load plant.

The physical/chemical pretreatment system removed up to 75 percent of the selenium from the FGD wastewater prior to the FBR pilot, reducing the selenium load. The average *influent* selenium concentration to the FBR pilot averaged 181 µg/L, and the pilot system achieved an average *effluent* total selenium concentration of less than 12 micrograms per liter (µg/L), the Monthly Average ELG, with a residence time between 1 and 3 hrs.

The system also achieved consistent load removal in excess of 90 percent throughout all testing phases. Figure 9 demonstrates the data from the Phase II prove out test. The nitrate/nitrite-N was below detection limits in the treated effluent and consistently met the ELG limits.

Figure 9:



Phase III of the validation program focused on the achievement of hydraulic parameters and system improvements required to meet these parameters. In addition, several investigations were conducted to provide the data needed to optimize the system design for best performance on the full scale, and to determine the optimum cleaning regimen for the UF membranes.

Phase IV of testing served to identify the maximum achievable hydraulic and concentration parameters of the test system to bracket the design parameters of the full-scale design. The test was performed by increasing flow rate and spiking influent concentrations using sodium selenate and sodium selenite to the point of system failure to simulate either high load or pretreatment excursions. The results of the challenge test confirmed, with influent selenium concentrations of up to 1,500 µg/L, and a residence time (EBCT) of 1 hour, a 90 percent load reduction was achieved, but was not sufficient to meet monthly average ELGs. This data, where the system was pushed to the point of failure, proved crucial to effective design of the full-scale system via mathematical modeling of the pilot Phase IV data.

Selenium removal effectiveness

The average pretreated feed to the Envirogen FBR system contained an influent total selenium concentration of 200 µg/L. During Phase II, the average effluent UF membrane selenium concentration was 7.8 µg/L. Similarly, during Phase III from January 16 through February 22 at the start of Phase IV, the filtered effluent selenium concentration averaged 9.3 µg/L. These results demonstrate the effectiveness of the Envirogen FBR over varying concentrations and FBR system feed flows.

During phase IV, additional selenite and selenate were fed to the system to increase the selenium concentration in the influent to 300 µg/L. Simultaneously, the feed FGD wastewater flow was increased from 8 to 10 GPM. During this spiking event, the effluent selenium concentration increased above daily and monthly limits showing that a 60-minute residence time would be inadequate at high selenium loads. These excursions provided valuable guidance leading to the proposed residence time and number of FBR stages needed to handle rapid increases in selenium and flow during FGD scrubber startup.

Membrane selection

Based on evaluation of both external tubular and submerged ultrafiltration membranes, for the ultimate removal of the residual particulate downstream of the FBRs, it was determined that the most cost effective and functional solution is the submerged UF membrane for the full-scale system.

System effectiveness

The testing conducted allowed a full understanding and validation of the optimum system design parameters including hydraulic residence time in the FBR beds, chemical and nutrient feed rates, testing and monitoring to enable prompt adjustments to variations in feed conditions (flow and concentration), and planned membrane cleaning to assure continued effectiveness and flux. This validation study shows that the FBR system is a cost-effective treatment technology that will meet reliability and treatment needs for FGD wastewater and ultimately deliver ELG compliance for selenium and nitrate removal.

Choosing a Way Forward: Performance, Flexibility and Track Record

While it is still early in the development of technology solutions for managing FGD wastewater, analysis to date make several things clear. FGD wastewater is highly variable – both between different power generating facilities and within the normal on-going operation of a single FGD wastewater treatment operation. This points to the need for technologies that allow significant flexibility – with the ability to successfully treat ELG-listed contaminants even under the most difficult circumstances as well as under less extreme conditions. To date, it has been biological treatment – and specifically the FBR technology – that has performed best at the top end of the difficulty range. This approach offers the added benefit of being significantly less costly and possessing a smaller equipment footprint than the Packed Bed Biofilter. All of these factors recommend the FBR as the technology of choice for further study and piloting toward developing a solution that will help power companies begin meeting the ELG limits as their NPDES permits come up for renewal staring in 2018.

Envirogen Technologies has been at the forefront of anoxic biological treatment technology for oxyanions since the 1990s, with over 75 installations throughout North America – treating oxyanions such as perchlorate/chlorate, selenate/selenite and nitrate/nitrate. Envirogen has designed, installed, started-up and even operated some of the world's largest oxyanion treatment projects – some of which have been in operation for over a decade. Today, Envirogen FBR systems are at work in the field treating selenium in coal mining water applications with success. In the area of selenium treatment for the coal industry, Envirogen has treated more water and conducted more pilot studies than any other company in the industry. Envirogen offers the best solution for meeting FGD wastewater challenges that addresses a broad range of issues – from specific wastewater characterizations and treatability to operating environments, space limitations and of course cost.

Envirogen's unique combination of technology development, process design, system construction and operating experience, makes the company an ideal partner for developing the tailored solutions that will be required to help power generating companies meet the ELGs – reliably and cost-effectively into the future.

Afterword: About Envirogen in the Power Industry

Envirogen Technologies, Inc. is an environmental technology and process solutions provider that combines experience in water and air treatment with process development and O&M expertise - delivering long-term, guaranteed solutions for a broad range of treatment and process-related applications. We pride ourselves in delivering superior 'lifecycle performance' by offering long-term, guaranteed, pay-for-performance contracts that produce the lowest total cost over the lifetime of an installation. The company conducts business throughout the United States, with locations in Texas, Southern California, New Jersey and Tennessee.

For the Power industry, Envirogen offers solutions for FGD wastewater treatment as well as the challenges now faced over Coal Combustion Residuals (CCR) management.

Envirogen offers two highly effective treatment technologies for meeting the new nitrate and selenium ELGs: (1) the Fluidized Bed Reactor, and (2) engineered iron based sorbent material.

In the area of CCR management, Envirogen offers a modularized solution for meeting water discharge requirements during coal ash dewatering and pond closure projects. In particular, our "drop in" Advanced Metals Removal System (AMRS) featuring Zero Valent Iron technology can enhance traditional physical/ chemical metals removal systems by adding the capability of removing selenium downstream. A recent validation study conducted on coal ash pond water demonstrated the performance of the AMRS to remove selenate from 200-250 µg/l down to below 1 µg/l. For sites where the aquifer has been impacted, Envirogen offers groundwater extraction and treatment systems for hydraulic control, removal of arsenic and other metals, O&M services and groundwater monitoring. For landfill leachate projects, Envirogen combines our metals treatment expertise with our FGD solutions to create a complete package for this often complex water. Envirogen has extensive experience treating selenium, arsenic, mercury, chromium, lead, thallium, iron, manganese, aluminum, vanadium, cadmium, copper and other metals.

Envirogen has over 20 years of turnkey design, installation and O&M experience with dewatering and groundwater remediation projects at more than 100 sites. Our integrated O&M offering includes engineering and technical services as important components. This commitment of technical expertise in support of O&M allows us to adapt to changing conditions for maximum reliability.

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