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# Evaluation of the Hanford 200 West Groundwater Treatment System: Fluidized Bed Bioreactor

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May 12, 2017

SRNL-STI-2017-0163

Revision 0

**Cover phtograph: Anaerobic fluidized bed bioreactor systems at Hanford 200W water treatment facility located at the Department of Energy Hanford reservation near Richland WA**



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# Evaluation of the Hanford 200 West Groundwater Treatment System: Fluidized Bed Bioreactor

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# Acronyms and Abbreviations

| | |
|---|---|
| AOP | advanced oxidation processes |
| BTEX | benzene and related compounds |
| COD | Chemical Oxidant Demand |
| COV | coefficient of variation |
| cu ft, cu m, cu yd | cubic feet, cubic meter, cubic yard |
| DOE | U.S. Department of Energy |
| DOE-EM | DOE Office of Environmental Management |
| DOE-RL | DOE Richland Operations Office |
| EPA | U.S. Environmental Protection Agency |
| FBR | fluidized bed reactor |
| ft | foot (or feet) |
| FY | fiscal year |
| GAC | Granular activated carbon |
| gal, gpm, gpd, gpy | gallon(s), gallons per minute, gallons per day, gallons per year |
| g, mg, µg, kg | gram, milligram, microgram, kilogram |
| L, mL | liter, milliliter |
| lb | pound |
| MCL | maximum contaminant level |
| m | meter |
| mg/Kg, mg/L | Milligrams per kilogram, milligrams per liter |
| O&M | operations and maintenance |
| orp | oxidation-reduction potential |
| PNNL | Pacific Northwest National Laboratory |
| PRC | CH2M Hill Plateau Remediation Company |
| RCRA | Resource Conservation and Recovery Act |
| SRNL | Savannah River National Laboratory |
| sq ft, sq m, sq yd | square feet, square meter, square yard |
| TRL | Technology Readiness Level |
| µg/kg, µg/L | micrograms per kilogram, micrograms per liter |
| US | United States |
| UV | ultraviolet |
| WA | State of Washington |
| yr | year |
| 200W | 200 West |

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# Evaluation of the Hanford 200 West Groundwater Treatment System: Fluidized Bed Bioreactor

## Executive Summary

A fluidized bed reactor (FBR) in the 200W water treatment facility at Hanford is removing nitrate from groundwater as part of the overall pump-treat-reinject process. Control of the FBR bed solids has proven challenging, impacting equipment, increasing operations and maintenance (O&M), and limiting the throughput of the facility. In response to the operational challenges, the Department of Energy Richland Office (DOE-RL) commissioned a technical assistance team to facilitate a system engineering evaluation and provide focused support recommendations to the Hanford Team. The DOE Environmental Management (EM) technical assistance process is structured to identify and triage technologies and strategies that address the target problem(s). The process encourages brainstorming and dialog and allows rapid identification and prioritization of possible options.

Recognizing that continuous operation of a large-scale FBR is complex, requiring careful attention to system monitoring data and changing conditions, the technical assistance process focused on explicit identification of the available control parameters ("knobs"), how these parameters interact and impact the FBR system, and how these can be adjusted under different scenarios to achieve operational goals. The technical assistance triage process was performed in collaboration with the Hanford team. The participants identified and evaluated a number of technologies and strategies that were grouped in the following categories:

- Improving Bed Solids Separation and Control in the Fluidized Bed Reactor Vessel:
  - Bed-Solids Cleaning
  - Bed-Solids ("Core") Substrate
  - Electron Donor (Liquid Carbon Substrate)
  - Microbial Nutrients and FBR Geochemistry
  - Fluidized Bed Vessel Design and Hydraulics
  - Monitoring
- Improving Bed-Solids Separation and Control in the Bed-Solids Separator:
  - Bed-Solids Separator Design
  - Bed-Solids Pretreatment
- Overall FBR Related Collateral Impacts to 200W Treatment System
  - Post-Treatment Options to Support Reinjection
  - Nitrate Treatment Goals and Alternatives

Each technology or strategy was evaluated and assigned to one of four summary assessment bins: 1) viable and recommended, 2) viable and conditionally recommended, 3) viable but not recommended, and 4) not viable. If a technology was designated as viable and conditionally recommended, then the summary also includes a description of the associated conditions. The resulting tables (and backup evaluations) are a resource to support planning and crafting a solution set.

The challenges of the 200W FBR system are complex and inter-related. Therefore, a combination of actions will be needed to move toward more stable and robust operations. We recommend assembling a portfolio of compatible technologies from the viable and baseline bins. A portfolio of combined technologies provides the best option to optimize and improve the FBR performance and to mitigate underperformance. Alternative portfolios have different levels of cost and risk. Possible portfolios range from relatively low cost (likely to improve performance but with a lower level of confidence) to very high cost options (likely to substantially improve performance with a high level of confidence). Several examples of portfolios are provided – in general these include actions to improve and/or change the bed solids, improve bed solids separations, and better prepare the treated water for reinjection. The most robust options – toward meeting the DOE goal of operational stability and confidence – include expansion of the bed-solids separator capacity (i.e., adding an additional bed-solids separator). Some innovative concepts were proposed for consideration including supplemental magnetic separation in the bed-solids separator. Strongly advocated technologies include straightforward ideas such as elimination of phosphate containing antiscalants in the air stripper, and several methods for improved bed solids cleaning and control.

Specifically, based on low costs and potential effectiveness, our team recommends incorporation of several key items in any near-term and mid-term technology portfolio; these include: substitution or elimination of the phosphate antiscalant in the air stripper, improving bed solids cleaning within the FBR vessel using an integral inlet eductor (and consider using a booster pump to provide FBR inlet water as a motive fluid for all of the eductors throughout the FBR), and inclusion of a static inline mixer for pretreatment of fluids entering the bed-solid separator. Other items for near-term consideration include evaluation of alternative bed-solid substrates, implementation of a continuous anticlogging system in the bed-solids separator, and implemention of supplemental actions to improve the performance of the aerobic membrane bioreactor. A prudent near term path forward would be to phase-in key actions from the low cost portfolio and determine performance and effectiveness. Implementation of the higher cost portfolio options could be considered as a follow-on if needed.

A primary goal of the technical assistance process is a rapid and efficient evaluation. This is a key reason that the output is partitioned into broad bins. This allows the Site engineers, managers and other experts to further vet the options and develop a plan that is most consistent with local conditions. As technologies are more formally selected for implementation, additional engineering evaluations will need to be performed and formal designs developed.

## 1.0 Introduction

At the U.S. Department of Energy's Hanford Site, CH2M HILL Plateau Remediation Company (PRC) operates several groundwater pump and treat systems which are engineered to treat radiological and chemical contaminants in groundwater that result from the site's former radionuclide production activities. In the 200 West (200W) pump and treat process, a FBR is used to remove nitrate, metals, and volatile organic compounds.

The focus of this activity is the 200W groundwater treatment system's fluidized-bed bioreactor (FBR) which is designed to remove nitrate, as well as hexavalent chromium and carbon tetrachloride:

- The FBR contains granular activated carbon and an active microbial community
- Key inputs to the FBR are contaminated groundwater, a supplemental carbon substrate and macro-nutrients
- Outputs from the FBR system include treated water, off gas, and waste sludge/solids.

Initial operational data indicated that the FBR is generally effective in reducing target contaminant(s) to required cleanup level(s). However, ongoing operational experience with FBR also identified challenges including: carbon carry-over in the treated effluent and over production of microbial extracellular polymeric substances (biofilms). Continuous operation of a large-scale FBR is complex, requiring careful attention to system monitoring data and changing conditions (e.g., flow rates or feed streams) and developing a set of associated technically-based operational paradigms. Key to successful and stable operation is the explicit identification of the available control parameters ("knobs"), how these parameters interact and impact the FBR system, and how these can be adjusted under different scenarios to achieve operational goals.

In March 2017, representatives from the Department of Energy Richland Site Office (DOE-RL) requested assistance from the Savannah River National Laboratory (SRNL) to provide an independent technical assessment to evaluate operational challenges associated with operation of the fluidized bed reactor. SRNL technical personnel visited the site, were briefed by key contractor personnel from CH2MHill PRC, as well as a representative from Envirogen, the contractor responsible for initial installation the treatment system. Our team would like to acknowledge the support of the Hanford Team (DOE-RL and PRC), including provision of: key design information, operational experiences, operating data, current process engineering and control strategies, descriptions of emerging actions, and technical brainstorming.

## 2.0 Background and Target Problem

The focus of this technical assistance activity is an evaluation of the 200 West Area groundwater treatment systems FBR. The initial operational data show that the FBR is generally effective in reducing targeted contaminants to required cleanup levels. However, operational experience with FBR also identified significant operational challenges that include:

- Carryover of bed-solids (granular carbon) from the FBR to downstream systems
- Over production of microbial biofilms
- The presence of “high” chemical oxygen demand (COD) levels in the treated effluent

The collateral impacts of these challenges on the 200W treatment system are significant and include:

- Biological and mineral fouling of injection wells
- Adverse impacts of particles on equipment
- FBR limits overall throughput of overall 200W treatment
- Disproportionate O&M requirements (e.g., manual removal and handling of carbon particles)
- General lack or robustness in performance

The observations and recommendation of the technical assistance team are documented in the following discussion. It should be emphasized that this evaluation is cursory in nature and represents the good faith recommendations of the technical team to provide useful and actionable options that can be considered to improve the operation of the treatment system.

## 3.0 Framework

### 3.1 Overview and Objectives

Development of technical frameworks is a key strategy to apply basic science to an applied field problem. When directed toward understanding complex real-world environmental remediation challenges, frameworks are tools that support practical identification and incorporation of the key-controlling scientific processes and principles. Frameworks can also be used to minimize technical risks, encourage efficiency and effectiveness, and provide the basis for innovative and creative solutions. The overall technical framework for this activity is summarized below:

> Continuous operation of a large-scale FBR is complex, requiring careful attention to system monitoring data and changing conditions (e.g., flow rates or feed streams) and developing a set of associated technically-based operational paradigms. Key to successful and stable operation is the explicit identification of the available control parameters ("knobs"), how these parameters interact and impact the FBR system, and how these can be adjusted under different scenarios to achieve operational goals.

Consistent with this framework, the overarching goal for this activity is as follows:

> The technical assistance team will collaborate with the Hanford team to identify a range of options for the FBR and related systems to improve 200W treatment system performance and robustness, to reduce the potential for FBR underperformance, and to reduce FBR related collateral impacts throughout the 200W treatment system.

Careful matching of technologies and technical approaches to complex challenges is critical for long-term success. The matching process facilitates selection of technologies with particular strengths that align with real-world needs and constraints, encourages strategic use of multiple or combined approaches, and supports transitioning technologies over time as the treatment system is modified and expanded.

Several specific technical areas were identified as important to improve the operation of the FBR and will be developed further in this report. These include: bed-solids separation and control, electron donor and nutrient optimization, monitoring, post treatment technologies, and an evaluation of nitrate treatment goals/alternatives. Each of these technical areas is addressed and discussed in sections that are arranged to align logically with the sequence of sub-processes within and around the FBR system. The evaluations are followed by a table providing a synopsis of the specific technologies and strategies relative to the specific goal listed above. In the evaluation tables, remedies will be evaluated in terms of expected performance, potential benefits, implementability/cost, and overall advantages/disadvantages. The final team consensus is organized into the following categories: baseline, viable & recommended, viable & conditionally recommended, and not recommended.

### 3.2 Technical Synopsis

To date, one of the most significant challenges in operating the 200W treatment process has been separation and control of the particles that serve as the solid substrate for the biomass in the FBR.

Figure 1 illustrates that the bed solids consist of a core material (currently carbon) covered by an active film of biomass – biological reactions in the biofilm are responsible for the removal of nitrate and other contaminants. The overall FBR system consists of two inter-related subunits; the fluidized bed bioreactor and a bed solids separator (Figure 2).

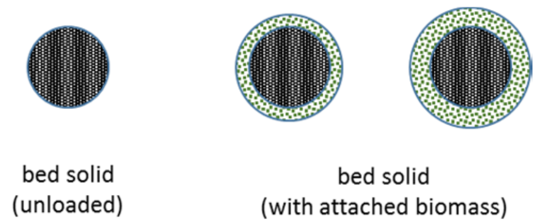



Figure 1. Simplified diagram of unloaded and loaded FBR bed-solid particles

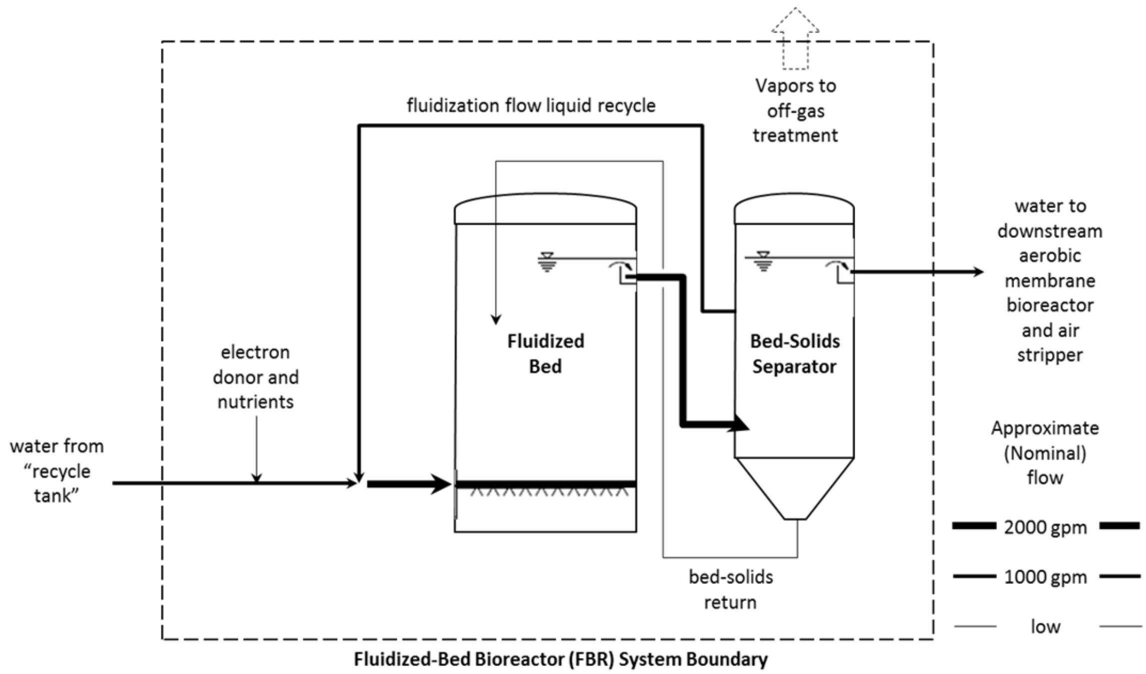



Figure 2. Simplified depiction of the overall FBR System showing key subunits and nominal flows

The primary input to the overall FBR system consists of inlet water from the "recycle tank" (water that was previously treated to remove radionuclides as needed). The principal function of the FBR system is to remove nitrate from the inlet water (approximately 35 mg/L as N, with periods of higher input depending on the nature of the groundwater area(s) being treated), and to reduce concentrations to meet the 200W treatment goal for nitrate (<10 mg/L as N). The primary output from the FBR system is effluent water that feeds into downstream processes (aerobic membrane bioreactors and air strippers prior to re-injection).

Within the FBR system, additional process inputs include electron donor (liquid carbon substrate) and required macro- and micro- nutrients. Internally, the flow rate in the fluidized bed reactor is about twice the system inlet and outlet flows (this maintains the desired fluidized bed expansion) – the higher internal flow is maintained by continuous recycle of water from the bed-solids separator back to the fluidized bed vessel.  As shown, the internal FBR system "high" flow rate enters the bed-solids separator. Near the top of the bed-solid separator, about half of the flow is recycled back to the fluidized bed and about half is discharged to downstream 200W processes.

Underperformance issues related to bed solids are occurring in both the fluidized bed vessel and in the bed solids separator, specifically: a) excessive bed solids are exiting the fluidized bed, and b) the bed-solids separator is not effectively/sufficiently collecting solids material for sidestream return to the fluidized bed vessel. In the bed-solid separator, any particulates that are not immediately collected by cyclonic action are effectively entrained in the upward flow and then into the liquid being recycled to the fluidized bed vessel or into the FBR system effluent. These entrained solids have a significant impact on operations and maintenance, specifically; these particles cause abrasion and erosion of pump components and nozzles used for distribution of liquid in the bottom of the fluidized bed. During recycle process, the solids are subject to breakdown (e.g., in the fluidization pumps) reducing particle size and exacerbating subsequent potential for bed solids carryover. Bed solids that exit the overall FBR system collect in the splitter inlet system to the aerobic membrane bioreactor, necessitating costly manual removal, staging and material recycle/disposition.

A number of mechanisms have been identified as “responsible” for the observed transfer of bed-solids (currently carbon and biomass) to downstream portions of the 200W process. Within the fluidized bed, these mechanisms include high biomass loading on particles in the upper zone of the FBR, localized hydrodynamics, abrasion and particle breakdown/agglomeration, particle-gas interactions, and other types of entrainment. Within the bed-solids separator, the system design has significant weaknesses (discussed below) related to system sizing and hydraulics.

In addition to bed-solids control issues, the FBR system is experiencing related challenges such as the carryover of relatively significant quantities of COD (liquid carbon electron donor and biomass) to the downstream processes, difficulties in monitoring of the fluidized bed height, and the overall performance and robustness. Also, FBR-related issues are causing adverse collateral impacts to other key activities throughout the 200W treatment process. A notable example is the impact residual electron donor (i.e., COD) and nutrients on the re-injection wells, leading to biofouling of these wells which is primary limitation on the overall water processing rate of the 200W treatment system.

To aid in a logical conceptual flow, the following sections address the underperformance of the FBR system sequentially by topic. For bed-solids control and separation, each of the major FBR subprocesses is addressed in turn: first the fluidized bed vessel and then the bed-solids separator. In each section, the conceptual framework and key challenges are described followed by a topical assessment of a range of possible technology/strategy options for further analysis and consideration. The technical assistance team similarly evaluated other key FBR related issues – topics where underperformance of the FBR system manifests as underperformance in other areas of the overall 200W treatment. The resulting organization of the technical evaluation tasks is summarized below:

- Improving Bed Solids Separation and Control in the Fluidized Bed Reactor Vessel:
    - Bed-Solids Cleaning
    - Bed-Solids (“Core”) Substrate
    - Electron Donor (Liquid Carbon Substrate)
    - Microbial Nutrients and FBR Geochemistry
    - Fluidized Bed Vessel Design and Hydraulics
    - Monitoring
- Improving Bed-Solids Separation and Control in the Bed-Solids Separator:
    - Bed-Solids Separator Design
    - Bed-Solids Pretreatment
- Overall FBR Related Collateral Impacts to 200W Treatment System
    - Post-Treatment Options to Support Reinjection
    - Nitrate Treatment Goals and Alternatives

## 4.0 Technical Evaluation

4.1 Improving Bed Solids Separation and Control in the Fluidized Bed Reactor Vessel

Conceptually, the composite bed-solids in an operating anaerobic FBR vessel (with a cylindrical configuration) segregate into design-basis zones (Figure 3 left). In the 200W FBR vessels these are a "settled media" zone that is circa 12 feet thick overlain by an "expanded media" zone that is circa 8 feet thick (circa 20 feet total bed height) overlain by circa 7 feet of treated water that is collected in a perforated pipe for transfer to the bed-solids separator.

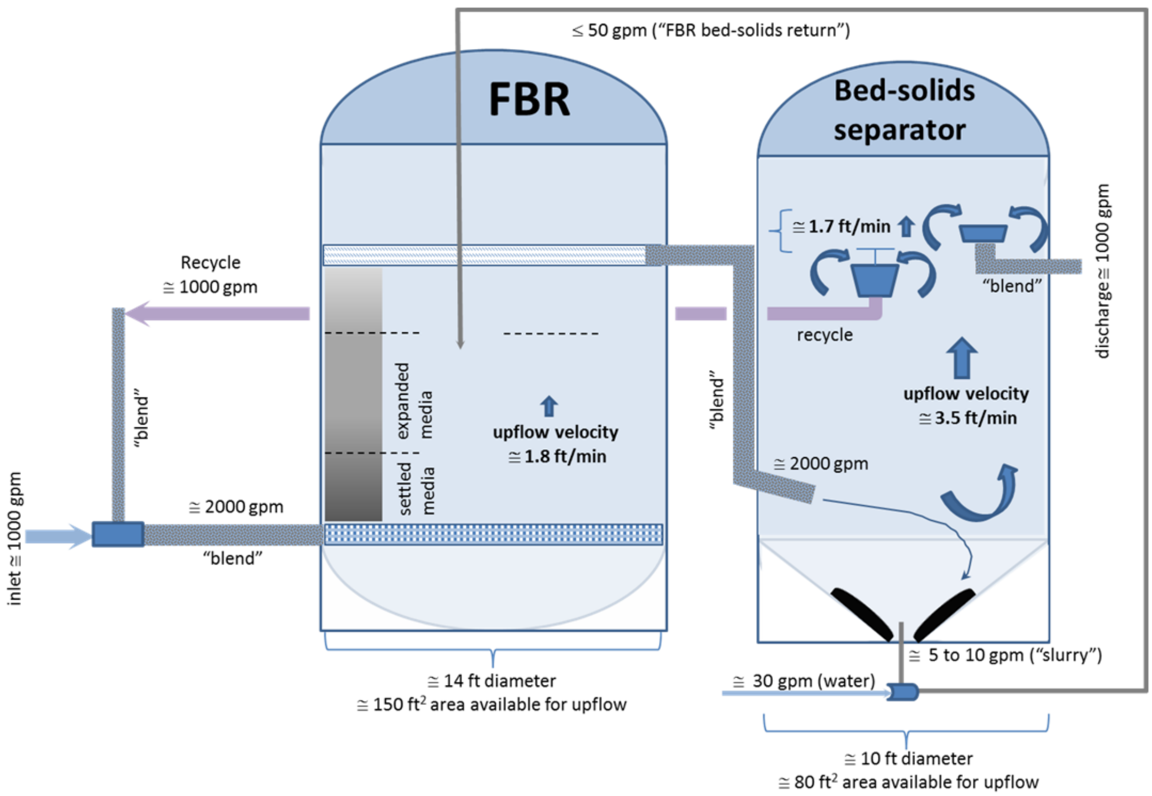



Figure 3. Simplified Schematic of FBR System showing design basis zones in the fluidized bed, key flowrates and bulk fluid velocities, and notations of entrained bed-solids ("blend")

As water flows upward from the bottom, stratification of the fluidized bed results from the varying particle bulk densities. The unloaded bed-solids serve as a substrate/core for the growth of the biomass needed for water treatment (Figure 1-left). Many "core" materials have been used for bed-solids including: sand, granulated activated carbon, coal, ion exchange resins, PVC, glass, garnet, sintered metal, and minerals such as vermiculite. Typical unloaded particle diameters range from <0.1 to a few mm (with the selected diameter based on desired flow rates, target biomass film thickness, and fluidization behavior). FBR bed solids that are loaded with biomass have a lower bulk density than unloaded bed solids. As biomass builds up on the bed-solids, the total bed volume increases and the fluidized bed expands upward. The particles with the highest biomass loading (Figure 1-right) occupy the upper portion of the FBR. Stable operation requires the particles to achieve a pseudo-steady-state that is controlled by biomass shedding that result from agitation and physical shearing in the FBR. If excessive biomass builds up on the particles, then downstream transfer of bed-solids will increase (see section on bed-solids cleaning). Note that there are a number of up-front design strategies and operational paradigm modification that have the potential to provide more robust solids control, such as: using a bed-solid substrate that is denser than carbon, modifying the electron donor or nutrient algorithm, increasing the upper vessel diameter near the design basis total bed height to reduce upflow velocity, and alternative monitoring systems.

Controlling FBR systems and bed-solids is an active area of research an innovation (see Table of FBR Patents in Appendix A for a partial listing) – numerous vessel designs and configurations are available that aide in maintaining the bed height and preventing loss of media. For application to 200W, many of the tabulated approaches would require extensive modification of the existing reactor vessels or outright replacement. Other approaches rely on operational process controls. The following sections evaluate a range of selected alternatives and/or technologies for improving bed-solids separation and control (and related issues) within in the FBR.

#### *4.1.1 Bed-Solids Cleaning for Biomass Control and Maintenance*

During the operation of the 200W FBR, growth of excessive biomass has been observed. As described above, much of the impact results from changes in the bulk density (specific gravity) of composite bed-solids, specifically the specific gravity of the particles decrease as excess biomass accumulates. As the specific gravity of the particles decrease, the particles are subject to entrainment in the fluid and can be carried out of the FBR. Further, the presence of excess biomass may contribute to continued "float" and carry-over through the carbon separator and into the membrane tank splitter structure.

> Key Points:
>
> Three bed-solids cleaning technologies were identified as possible alternatives to the baseline manual eductor system. These include conituous or semi-continuous use of: 1) recirculating diaphragm pumps, 2) integral inlet eductors, or 3) in-tank sonication. All technologies appear to be technically viable. Of the alternatives, the integral eductor and diaphragm pump have a higher maturity level and are recommended if performance is confirmed by pilot testing.

A key control mechanism to reduce the FBR biomass is removal of excess biofilm by hydraulic shear and mechanical abrasion. Currently, eductor pumps have been installed in the FBR's to aid in the removal of excessive biomass from the bed solids (baseline system). In operation, pressurized liquid enters the eductor through the pressure nozzle and produces a high velocity jet. This jet action creates a vacuum in the line which causes the suction liquid (biomass laden solids) to flow into the body of the eductor where liquid is entrained by the pressured liquid and circulated within the reactor vessel. Service water is used as the pressurized fluid. Each FBR is equipped with five (5) educators, specifically, four (4) eductors are located in the upper part of the fluidized bed at depths (from the top of the reactor) ranging between 9 and 15-feet, and the fifth is located deeper at a depth of approximately 25-feet from the top of the reactor. If biofilm development is advanced or if phosphate or micronutrients are under-dosed, the current educator system does not provide sufficient removal of biomass from the bed solids to prevent carry-over from FBR to carbon separator. The eductors are manually operated and used as needed to maintain the target bed expansion.

Three sub-options are identified as alternatives for reducing biomass on the 200W FBR bed solids. These alternatives include 1) use of a diaphragm pump(s) to recirculate the bed solids, 2) use of integral inlet eductors to process FBR bed-solids using inlet water as the motive fluid, and 3) sonic cleaning of bed-solids.

*Recirculation of Bed Solids using a Diaphragm Pump(s)*

The vendor of the FBR (Envirogen Technologies) has proposed diaphragm pumps as a mechanism to remove biomass from the bed solids. In this application, a recirculation loop is established using a pneumatic diaphragm pumps to recirculate a slurry of bed-solids. A diaphragm pump (also known as a membrane pump) is a positive displacement pump that uses a combination of the reciprocating action of a flexible diaphragm and suitable valves on either side of the diaphragm (check valve, butterfly valves, flap valves, or any other form of shut-off valves) to pump a fluid. Unlike rotary fan pumps that generally use electric motors to drive the pump, a diaphragm pump requires a pressurized fluid (typically compressed air) for operation. During pumping, excess biomass is separated from the solids by shear within the pump housing. Since diaphragm pumps are positive displacement pumps that use a flexible membrane to move fluids they can handle sludges and slurries with a relatively high amount of grit and solid content making their design appropriate for this application. In the simplest configuration, the pump discharge containing separated biomass and solids would be returned directly to the FBR. More sophisticated variations are possible where the fluid is further separated, and a bed-solid concentrate stream is returned to the FBR. Figure 4 provides a simplified conceptual diagram of a diaphragm pump to separate biomass from bed solids.

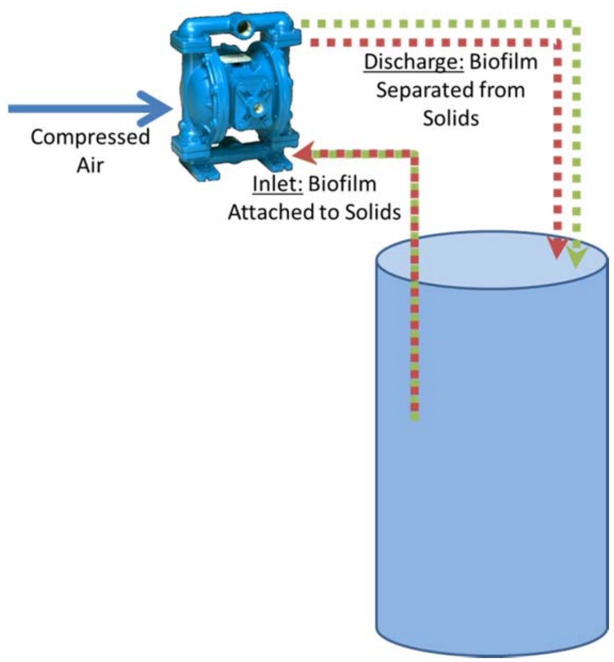



Figure 4. Illustration of the use of a diaphragm pump to separate biomass from bed solids. The positive displacement pumping action internal to the diaphragm pump provides hydraulic shear to separate biomass from bed solids.

Advantages:

- Modification has been implemented and operated for commercial biological-based FBR systems
- A simple recirculation system can be implemented using the existing 200W FBR access locations
- System could be operated continuously or semi-continuously without addition of process water.
- Reduces reliance on bed height monitoring since it operates continuously (cleaned particles returned to FBR will have greater settling velocity and move lower in the bed)

Disadvantages:

- Diaphragm pump(s) require compressed air for operation, current plant compressors are near capacity. Full implementation will require upgrade to plant air capacity

A diaphragm pump system for bed-solids cleaning is viable and recommended. A prudent first step toward consideration/implementation of the diaphragm pump option for bed-solid cleaning would be focused testing (e.g., a pilot test with the support from FBR vendor). Portable compressors can be used to support a pilot-test to determine effectiveness over the current educator system. Pilot-testing would also support determination of design parameters (air requirements) to support go/no-go decision for future implementation. If needed, the Hanford team could maintain some of the eductors along with the diaphragm pump option to provide complementary and supplementary bed-solids cleaning control.

*Processing of Bed Solids using Integral Inlet Eductor(s)*

We have developed an eductor based alternative concept for continuous or semi-continuous bed-solids processing/cleaning. We project that such a system would perform similarly to the recirculating diaphragm pump. For deployment, an eductor is placed just below the target FBR bed height. FBR inlet water (rather than finished process water) is used as the motive fluid. The eductor intake would draw in FBR fluids and remove biomass from the contained bed-solids as a result of internal turbulence. Figure 5 provides a simplified schematic of this concept. Using an industry standard booster pump, the motive fluid would be drawn from the FBR feed water (at a location where the fluids are clear and do not contain entrained solids). The outlet of the eductor would be released into the lower portion of the FBR where it would mix with the remaining fluidization flow. The booster pump would be packaged with standard components to maintain a desired outlet line pressure. This pressure could be adjusted (or the booster pump cycled) to vary the bed-solids cleaning intensity, thus supporting continuous or semi-continuous operation.

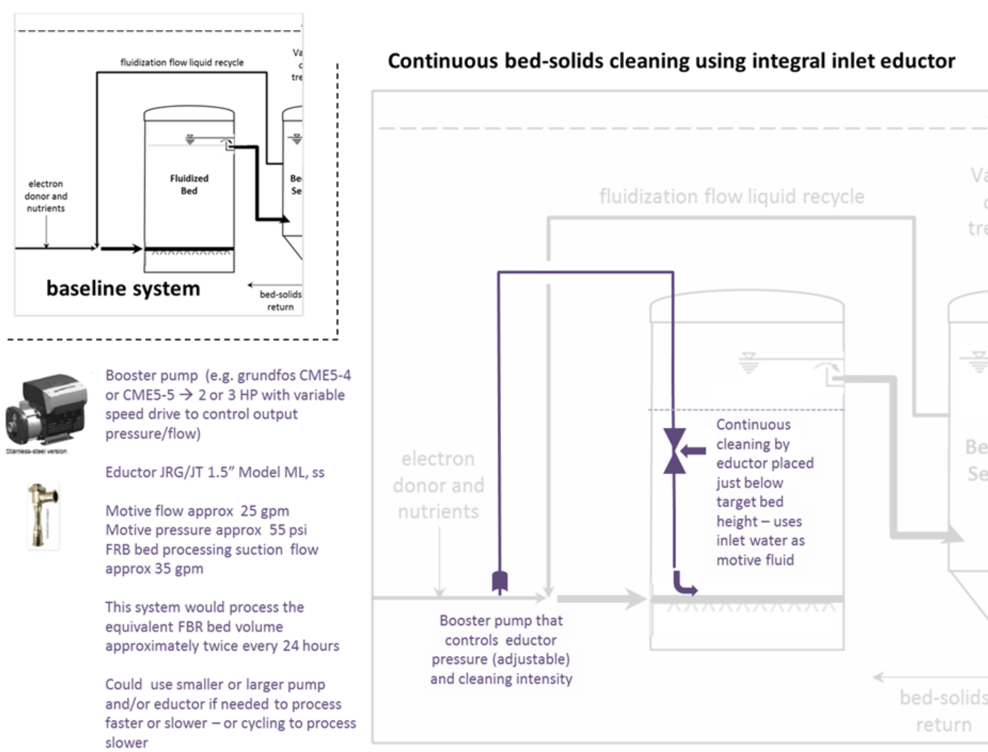



Figure 5. Simplified schematic of system for continuous bed-solids cleaning using integral inlet eductor

The advantages of the integral inlet eductor are similar to the diaphragm pump with the following additions – does not require plant air and system could use existing freeze protected lines that feed manual eductors. The primary disadvantage of this concept is that has not previously been used to support FBR bed-solids cleaning objectives in past/operating FBRs.

An integral inlet eductor system for bed-solids cleaning is viable and recommended. In fact, we recommend using FBR inlet water for all of the eductors throughout the FBR system (including those transferring solids back to the FBR) and believe this can be accomplished by properly sizing and deploying a packaged pressure controlled booster pump system (e.g. a Grundfos Multi-E with three CRE3 or CRE5 pumps) combined with simple piping modifications. A prudent first step toward implementation would be focused testing. If testing is positive, this would be a preferred alternative because it maximizes the use of existing infrastructure.

*In-Tank Sonication System*

Sonication provides an innovative alternative for maintaining optimal biomass on the FBR carbon (bed-solid) substrate. Sonication introduces high frequency sound energy into a target solution and is often used for parts/surface cleaning in a wide range of industrial, commercial, medical and research applications. Many industrial and commercial sonic cleaning applications are relatively small – for example jewelry cleaning and bench scale parts cleaning. However, the scale of commercial and industrial cleaning systems spans a wide range and includes systems where the cleaning is performed in large tanks and troughs. Most research applications of sonication are small benchtop operations. Note, however, that some of the research applications are directly relevant to the proposed FBR solid substrate cleaning concept; notably, the use of sonication to extract biomass from solids/sediments (such as the local Pacific Northwest National Laboratory (PNNL) study of 200W FBR solids by Lee et al. (2016)).

This option was envisioned as part of our technical assistance and systems engineering evaluation brainstorming process. At this juncture the potential for full scale application in the 200W is notional (approximate Technology Readiness Level, TRL, 3 to 5). The TRL scale ranges from 1 to 9, with {1} denoting basic research, {2 & 3} applied research and proof of concept, {4 5 & 6} technology development and demonstration, {7 8 & 9} system design and deployment (DOE, 2011). The availability of existing commercial sonication equipment used for industrial scale cleaning in tanks would support and expedite assessment of reasonableness. Mason and Tiehm (2001) describe a number of similar applications, outline the design of ultrasonic reactors for environmental remediation, and provide specific deployment examples of this type of technology, including for leaching solids and processing sludges/slurries.

A preferred design would use submersible components deployed down through tank top flanges to provide energy in the top several feet of the fluidized bed. Zenith Ultrasonics manufactures such components (constructed of stainless steel) for deployment in existing tanks (see, http://www.zenith-ultrasonics.com/sonics_existing_tanks.htm). These units can be designed to generate frequencies ranging from low (e.g., 25 kHz or below) to high (80 kHz or above) – or to provide combinations of selected frequencies. Low frequencies result in higher cleaning energy and less penetration distance into the surrounding liquid. Higher frequencies penetrate farther into the liquid and result in more "gentle" cleaning, typically supporting precision systems such as some medical applications. The performance characteristics of intermediate frequencies (e.g., 40 kHz or 55 kHz) would fall between those described above. An optimized sonication-based biofilm maintenance system for the 200W FBR could employ a combination of frequencies (a "multifrequency" option) with simultaneous application of two independently-controlled frequencies (e.g., 40 & 80 kHz or 25 & 40 kHz). Figure 6 shows a photographic example of commercially available submersible transducers ("a") and simplified sketches of hypothetical deployment scenario(s) ("b" and "c").

Figure 6a shows available commercial equipment with immersible ultrasonic units that are supported from the top of a tank. The immersible systems are supported by rigid stainless steel riser tubes that attach to a NEMA4X stainless steel support box. The wires from the transducers mounted inside and pass through the tube into the wire trough, and a single cable from the trough connects to the ultrasonic generator assembly. Although the immersibles in the photo all emit ultrasonic energy in the same direction, such a system could easily be created for multidirectional application.

For deployment at 200W, a support system would be inserted into the FBR tank and rigidly mounted to an upper tank flange; ultrasonic transducers would be mounted on a central riser (preferred for simplicity) and/or on deployable articulations. The transducers would provide ultrasonic energy in the upper zone of the fluidized bed. The transducers would be activated as needed to maintain the desired biomass film on the solid substrate. The key advantages of sonication are continuous-adjustable operation with no added process water. The key disadvantages include higher development and implementation costs and uncertainties related to O&M.

Implementation of a sonication based biofilm control technology is speculative but potentially viable for use in an FBR. A focused campaign of applied research would be required to provide more definitive information to support deployment decisions (e.g., required energy level, optimum frequency(ies), cost, reliability, O&M requirements, etc.). If viable, this technology might be a reasonable option for managing the biomass on the FBR solid substrate -- compared to the baseline multilevel eductors or to the proposed alternative diaphragm pumping strategies. As discussed in a later subsection, higher intensity sonic treatment of the fluids between the FBR and bed-solid ("carbon") separator is an independent option. In this latter case, the goal would be to "completely" remove biomass from the entrained solids feeding the bed-solids separator – increasing particle density and reducing particle stickiness to maximize the separation performance.

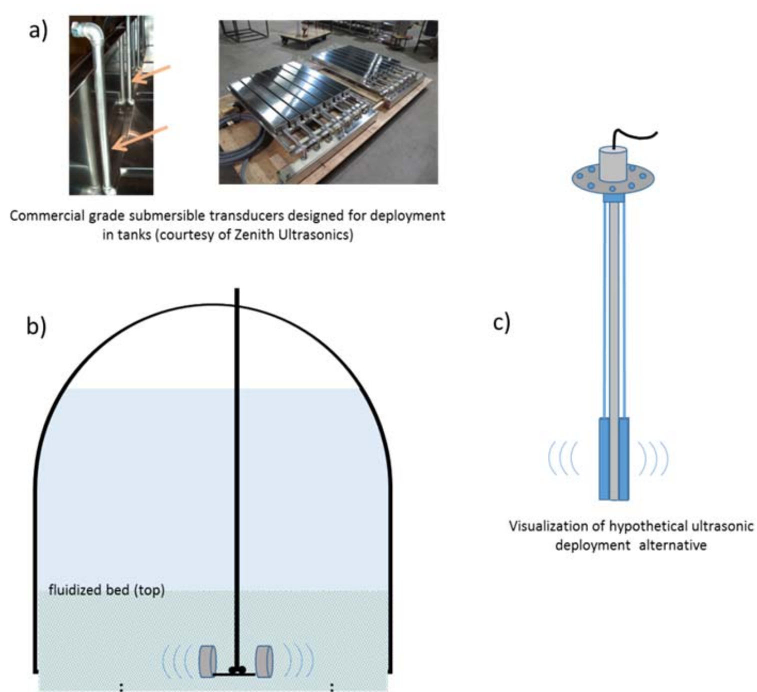



Figure 6. Illustration of potential sonic bed-solids cleaning equipment/concepts – a) example of commercially available transducers, b) recommended positioning of sonicators in the FBR and C) example deployment scenario

*Bed-Solids Cleaning Summary Assessment*
The baseline manual bed-solids cleaning approach using eductors has underperformed in maintaining target bed-solids biomass in the 200W FBR. The three bed-solids cleaning alternatives were all assessed to be technically viable. The alternatives based on an integral inlet eductor or a diaphragm pump, because of a higher maturity, were ranked as viable and recommended. The team suggests that pilot testing would be needed as a step in selecting and implementing. A third alternative, sonication, would require more up-front development and testing and was ranked as viable and conditionally recommended. Sonication would be a reasonable technology option to pursue if there are unresolvable challenges in implementing the the eductor or diaphragm pump strategies or if these underperform in pilot testing.

### *4.1.2 Bed-Solids ("Core") Substrate*

Key Points:

Altering the type of bed-solid core substrate used in 200W FBR may offer an opportunity for the Hanford team to modify the stratification profile within the fluidized bed to better control bed-solids and reduce carry-over of bed solids from the FBR

One of the most significant challenges of 200W FBR has been the operational management of bed solid substrate, the core material that serves as the medium for microbial growth. Materials such as sand, granulated activated carbon, coal, ion exchange resins, PVC, glass, garnet, sintered metal, and minerals such as vermiculite have been used for bed substrates. As fluid flows upward from the bed bottom stratification develops due to varying biomass production and particle bulk densities. Core substrates that are denser provide the potential for a different stratification profile compared to core substrates that are less dense (i.e., core materials with densities that are closer to biofilm density). Thus, the specific core material (and the resulting density profile) has the potential to provide a control knob to reduce the carry-over of bed-solids out of the bioreactor even in situations where biomass loadings are relatively high. Granular activated carbon (GAC) and sand core-substrates are often used in FBR systems. Note that there is a substantial difference in density and other properties (e.g., surface area) between these two materials. Alternative core substrates whose properties are intermediate between activated carbon and sand may provide improved control of bed-substrates while maintaining operations parameters and nitrate removal performance similar to the baseline GAC.

GAC based bed-solid substrates commonly used in FBR system are typically made from bituminous coal, coconut shell, and anthracite coal with a wide range of available particle sizes (See Figure 7).

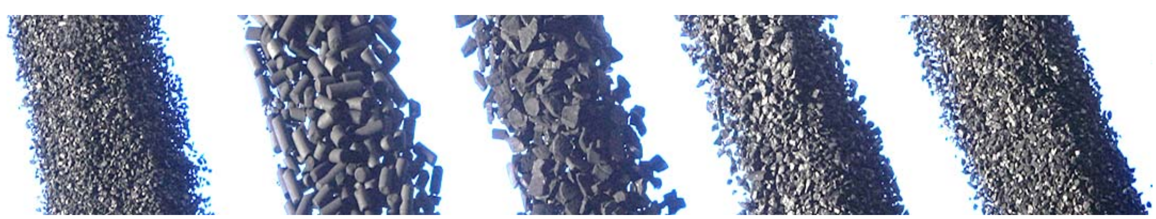


Figure 7. Different types of GAC (Courtesy of Evoqua water technologies)

While the GAC substrate satisfactorily meets the operational needs of the FBR system, the production of excessive biofilm growth and substrate washout support examination of alternative solid bed substrate materials with potentially improved performance. It should be noted that the expected benefits could be moderate to significant, and this strategy would likely need to be implemented in combinations with other technologies/strategies. A quick prescreening of alternative bed substrate for 200W FBR led the technical assistance team to suggest zeolite material. Note that other materials are also feasible, but zeolites are common, relatively low-cost materials that have appropriate characteristics. Zeolites are a prime example of a possible alternative – zeolites have a high surface area similar to the baseline activated carbon and a moderate density (intermediate between activated carbon and sand).

The use of zeolite (Figures 8 and 9) as bed substrate may provide a viable, cost-effective alternative to the baseline GAC substrate. The higher density core-material would help address operational challenges associated with excessive biomass production and bed-solid washout in the 200W FBR system. Zeolites are crystalline aluminosilicate minerals comprised of Si and Al oxygen-tetrahedral units that form a three-dimensional cage-like structure containing elaborate networks of channels, cages and pores. Zeolite framework structures are grouped into singly and doubly 4-membered, 6- membered, 8-membered, 10-membered and 12-membered rings based on how the Si (Al) tetrahedral units are connected with the oxygen atom bridges. Natural or synthetic zeolites (e.g. natrolite, chabazite, clinoptilolite, heulandite, erionite, mordenite, scolecite, Zeolite A, X, Y, ZSM-5 etc.) are characterized by molecular-size regular pore structures that find applications as catalysts, adsorbents, ion exchangers, and amendments. The Si/Al ratio and concentration of cations of microporous zeolite framework dictate the surface properties (e.g., hydrophobicity and acidity), adsorption, catalytic and ion-exchange properties of zeolites (Daramola et al., 2012).

Comparing the nominal bulk density of the current GAC substrate in the 200W FBR (400 – 500 kg/m$^3$) with those of zeolites (600 – 860 kg/m$^3$) and dry sand (1520 – 1920 kg/m$^3$), it is evident that the use of moderately dense zeolite substrate could afford a viable, low to moderate cost option for addressing bed-solids carryover into downstream system. For this option to be implementable a zeolite material would need to be selected and the various inter-related design parameters would need to be refined such as particle size and fluidization velocity within the FBR system. The result would be an optimized design that accounts for the moderate density core substrate and with a new stratification profile. Because there are few studies in literature that specifically study zeolite as a bed-solid substrate for FBR systems, additional testing may be needed to confirm the suitability of zeolite as a bed substrate for the 200W FBR.

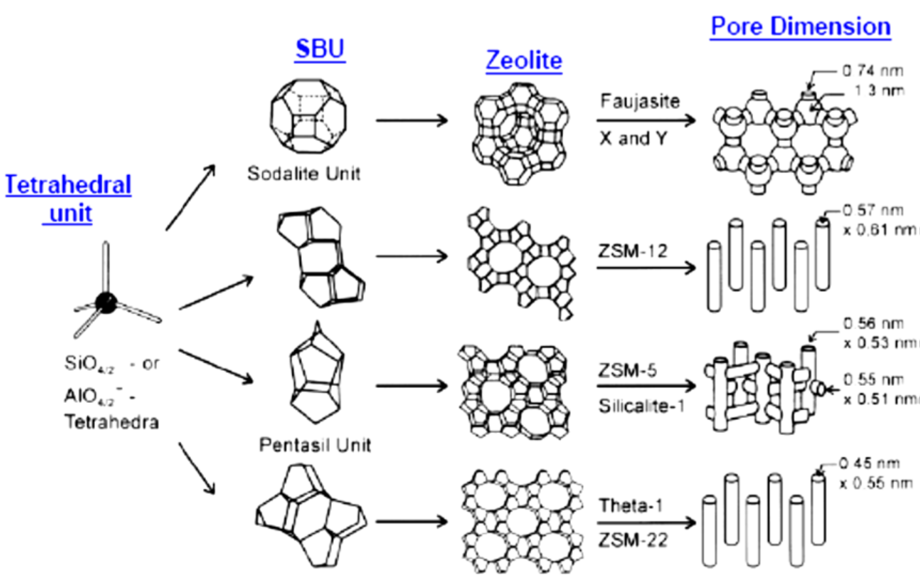



Figure 8. Zeolite framework structures (Weitkamp, 2000; Weitkamp and Puppe, 1999)

Figure 9. Examples of different particle sizes of natural zeolite, ranging from powder (left) to granules (3-5 mm, right) – (courtesy of D&W Corp Natural Zeolites)

Zeolites have a slightly lower nominal surface area (600 – 1000 $m^2/g$) compared to that of GAC (500 – >1500 $m^2/g$). Although internal porosity of bed substrate can provide additional sites for microbial attachments, biomass growths on zeolite substrate might be slightly lower in comparison to the GAC substrate. Zeolites granules are mined and ground (or are synthesized) in different particle sizes, ranging from few nanometer diameters to several mm and desired particle sizes can be specified or custom-made to meet specific FBR system requirements. Many zeolites would have somewhat better physical and chemical robustness compared to the characteristics of GAC. In addition to zeolites, many alternative core substrates are also possible, including: other minerals or ores, polymers and polymers containing modifiers such as iron or magnetite (see magnetic separation section), and others.

When evaluating alternative FBR core substrates, the Hanford team could also consider substrates that are less dense than GAC (such as an open cell polystyrene particles) and a reduced fluidization velocity. The use of a core substrate with a density closer to the biomass/biofilm would facilitate fluidization and promote more uniform fluidization (i.e., reduce the settled media zone thickness). This approach may be less sensitive to biomass overproduction and operate at a significantly lower recycle rate and lower total fluidization flow through the FBR and bed-solids separator -- thus reducing turbulence and maximizing separation process performance. The selection of core substrate is a multi-parameter optimization process that requires careful balancing of the various controlling factors. There are opportunities for improving overall system performance by adjusting this key FBR design feature.

It is likely that an alternative material such as zeolite, based on the net assessment of the characteristics described above, can be integrated into the existing FBR system with minimal modification. The use of an alternative bed substrate is relatively straightforward and would be implementable, viable and recommended. The anticipated costs would be low to moderate and the potential benefits moderate to significant. Natural or synthetic zeolites are recommended bed substrates for consideration that may be deployable using existing equipment.

*4.1.3 Electron Donor (Liquid Carbon Substrate)*

Heterotrophic bacteria utilize electron donors as an energy source to support metabolism as well as for synthesis of new cellular material (biomass). For denitrification, these bacteria generally require an external "supplemental" electron donor, typically a liquid carbon source. A wide range of carbon sources have been used to support denitrification, including methanol, ethanol, acetate, acetic acid, glycerol, carbohydrates (e.g., molasses, sugar, local waste products from food manufacturing, etc.), and proprietary mixtures. The choice of carbon source depends on attributes such as safety, cost and market stability, availability, product consistency, ease of use, as well as the technical/performance factors such as kinetics and yield. The dosage requirement is typically expressed in the amount of COD needed to remove each unit of nitrate (the COD:N ratio).

For the 200W treatment system, supplemental liquid carbon substrate is a key input and control parameter for the FBR. The performance of the liquid carbon substrate is a function of:

- Quantity - the amount of supplemental liquid carbon substrate added
- Operational Strategy - the process control parameters and algorithm for supplementation
- Type - the specific liquid carbon substrate used

For example, inadequate supplementation may result in underperformance (breakthrough of nitrate), an unstable microbial community, and the potential for episodic biomass wastage. Excess supplementation will result in excess biomass development and carryover of bed solids and COD into downstream processes. The Hanford team has demonstrated attention to the quantity of liquid carbon substrate and to the associated monitoring and process control. Monitoring data (flow rates, COD, FBR bed depth, nitrate concentration, pH, and other parameters) are collected throughout the system – for example from the "recycle tank" feeding the FBR, from the inlet to the FBR and from the outlet of the FBR system (after the bed-solids separator). These data are used with a control algorithm that is based on stoichiometry and observed system performance. A number of control charts are regularly prepared and monthly process engineering meetings provide a venue to refine the control algorithm to optimize performance. These are commendable "best practices". As a result we do not have any recommendations related to the quantity and operational strategy for the supplemental liquid carbon substrate.

The type of liquid carbon substrate, however, may represent and area of opportunity for the Hanford team. The current substrate is a proprietary carbohydrate-based liquid, MicroCg that was developed by Environmental Operating Solutions, Inc. (EOSi) for denitrification and anaerobic bioreactor applications (see http://www.microc.com). The materials to make the MicroCg are specified or provided by EOSi and are currently blended locally for delivery to the 200W system. EOSi has a range of products based on proprietary blends of carbohydrates, glycerin, alcohol, or custom formulations. While the MicroCg product is reasonably supporting operations of the FBR, there is potential for modest performance improvement using alternative liquid carbon substrates. Note, however, that the benefits would be expected to be incremental -- large or transformational benefits are not anticipated. A quick prescreening of 200-W FBR alternatives for type liquid carbon substrate is provided below (with +'s and -'s for each). This is based on our interactions with the Hanford team (PRC process engineers, Envirogen representative, and DOE), key references (e.g., EPA, 2013) as well as our technical experience.

- MicroCg – Baseline material – reasonable performance, safety availability and cost
- MicroC 2000 (glycerin based) – Compared to baseline – (+'s) potential for improved kinetics and lower cost – otherwise similar performance
- Acetic acid (38% solution) – Compared to baseline – (+'s) potential for improved kinetics and nonproprietary material (multiple sources), material of choice in some of the more recent Envirogen anaerobic FBRs for denitrification – similar cost – (-'s) may require new procedures, additional safety precautions, and a potential vinegar odor
- Sodium acetate (30% solution) or potassium acetate – Compared to baseline – (+'s) potential for improved kinetics at a similar cost – (-'s) higher viscosity that might require minor equipment modification
- Local waste carbon source (e.g., from agricultural or food processing, brewing, etc.) – Compared to baseline – (+'s) potentially low cost "green" concept -- (-'s) uncertain kinetics and supply reliability, inconsistent material that may be challenging to use in a large scale continuous process
- Alcohol – such as ethanol or methanol – (-'s) Not recommended because of flammability, safety and incompatibility with existing process equipment

The faster kinetics of some of the alternatives may reduce the carryover of COD into the membrane bioreactors and result in more robust performance by maintaining low nitrate concentrations under variable input conditions (i.e., during periods of higher nitrate concentration in the influent water). All of the listed electron donors would result in similar quantities of biomass.

Use of an alternative supplemental liquid carbon substrate is relatively straightforward and would be viable and implementable. The anticipated costs would be low and the potential benefits low (incremental). The recommended liquid carbon substrates for consideration include those with improved kinetics and that can be deployed using existing equipment (e.g., acetic acid or MicrCg2000, or sodium/potassium acetate). Implementation of this process change should be considered if there are compelling reasons to reduce the carryover of COD to the aerobic membrane bioreactors and to provide potential improvement in nitrate removal robustness.

#### *4.1.4 Microbial Nutrients and FBR Geochemistry*

Anaerobic FBRs that reduce concentration of nitrate, metals and volatile organic compounds rely on development of a specialized microbial population. The associated geochemical processes occurring in redox-sensitive environments, especially oxygen-limiting ones are susceptible to slight perturbations of system conditions, and, as such, system optimizations are often required. Imbalance in microbial nutrient demands may trigger an upset in the FBR system, leading to production of excessive microbial biomass (biofilms) and reduction in nitrate removal efficiency. This has been episodically observed in the 200W FBR treatment system.

Both macro- and micro-nutrients play critical roles in microbial health, and deficient nutrient levels generally promote rigorous growth of biofilms as a survival mechanism (Stanley and Lazazzera, 2004). The production of biofilm is regulated by availability of nutrients, and maximal biomass growths typically occur at suboptimal nutrient concentrations. At either nutrient-rich or nutrient-limiting conditions (both extremes); greater biomass is produced in the planktonic phase. Only if there is growth advantage will bacteria form biofilms, however under extreme conditions, there may be a need to exit the biofilm for the planktonic phase, where the bacterial cells can have access to a new, more favorable environment (Stanley and Lazazzera, 2004). In a broader sense biofilm comprises multicellular population of bacterial cells covered in a self-produced polymeric matrix (extracellular polymeric substance - EPS).

The 200W FBR has experienced operational challenges related to maintaining the low target treatment level for nitrate, bed-substrate (carbon) carryover and biofouling of the system. To address these challenges studies conducted to date provided evidence that micronutrient deficiency may be responsible for episodic excessive biofilm production and system upsets. Interestingly it was reported that aerobic heterotrophic bacteria dominated the FBR microbial population in a system where anaerobic denitrifying bacteria were expected to dominate the species population (Lee, et al., 2014). These aerobic bacteria have the potential to deplete micronutrients supplied to the system. Subsequent increases in micronutrient dosing (macro and micro nutrients increased approximately 10x while electron donor liquid carbon was decreased slightly) improved the FBR microbial balance by increasing the relative abundance of denitrifying bacteria (up to 50%). However, excessive biofilm production and well fouling continue to present operational challenges.

A survey of current (latest) dosing recipe (Table 1) used to augment micronutrients in the FBR showed that the range of concentrations generally meet recommended micronutrients requirements for standard FBR system (Schattauer, et al., 2011). As higher denitrification rates are attributed to iron and manganese, the concentrations of both metals warrant careful monitoring and optimization. For proper functioning of the FBR system the recommended concentration for dissolved iron (Fe), manganese (Mn) and selenium

(Se) varies from 200-700 µg/L, 10-250 µg/L and 5-75 µg/L, respectively (Schattauer, et al., 2011). Recent manganese data collected in the 200W FBR system suggest that dissolved Mn (approx. 40 µg/L) varies within sufficient range such that nutrient leaching from the FBR is not expected. It has been shown that Fe deficiency (i.e. dissolved Fe concentration <560 µg/L) promotes excessive biofilm production, leading to scavenging for Fe by bacterial siderophores, high-affinity Fe complexing agents that dissolve minerals (Hutchens, et al., 2003).

Adjusting the dose of micronutrients added to the FBR should be done with caution, as overly high concentrations could lead to system upsets and unintentional leaching of nutrients to downstream system. Because the nutrient requirement for each FBR system varies widely, micronutrient optimization for the 200W FBR system will likely involve an ongoing iterative fine-tuning process. It is recommended that the Hanford team continue their current "best-practice" process-engineering team approach: 1) monitoring micronutrient dosing/concentration and FBR performance metrics and 2) regularly modifying the control strategies and algorithms in response to observed changes in nutrient concentration, nitrate removal or biomass behavior. Additionally, we recommend consideration of micronutrient salts/compounds that contain a complexing agent such as the ethylenediaminetetraacetic acid (EDTA, preferably the micronutrient salt of EDTA) to introduce micronutrients to the FBR system. The advantage is that EDTA (an efficient metal chelator) significantly enhances the solubility of micronutrients in near neutral to neutral pH range (5.7 – 7.0), and it could also help alleviate odors associated with citric acid currently in use in the FBR system.

**Table 1: Current micronutrient supplements used in FBR system**

| Elements | Dissolved concentration (µg/L) | Recommended Concentration (µg/L) |
|---|---|---|
| Boron | 22 | 1 - 11000 |
| Iron | 1100 | 280 – 10000 |
| Manganese | 40 | 5 - 50000 |
| Molybdenum | 30 | 5 - 50 |
| Copper | 100 | 60 - 64000 |
| Zinc | 20 | 74 - 180 |
| Nickel | 8 | 5 - 5000 |
| Cobalt | 20 | 3 - 120 |
| Selenium | 0.1 | 8 - 350 |

In summary, we affirm the baseline approach being used to monitor and refine the dosing of macro- and micro- nutrients to the FBR. We recommend consideration of chelated micronutrients (rather than inorganic, e.g., sulfate, salts) if solubility issues for the nutrients are encountered. In a few cases, the Hanford team indicated that additional monitoring to assure flow of key nutrients (such as P) would potentially improve operations and help avoid process upsets. We support implementation of such standard process engineering modifications.

#### *4.1.5 Fluidized Bed Vessel Design and Hydraulics*

Three sub-options were evaluated related to Fluidized Bed Vessel Design and Hydraulics:

- Adjusting recycle flow in response to bed-solids density
- Replacing components to increase resilience
- Modifying FBR Vessel Geometry

<u>Adjusting recycle flow in response to bed-solids density</u>

Currently, the fluidization flow is maintained within a fairly narrow design-basis operating window. An alternative conceptualization, would view the fluidization flow as an adjustable parameter to include in the process operation algorithm. According to the modified paradigm, overall fluidization flow rate would be reduced as a function of increasing bed-solids biofilm. This would limit the discharge of the relatively less dense loaded particles and help maintain a target fixed expansion of the bed. In the case of the 200W FBR, fluidization flow is a blend of influent water and recycle from the bed-solid separator. Thus, reduction of recycle flow could be used to directly control overall fluidization flow. This strategy is consistent with anaerobic FBR literature (e.g., Diez Blanco, et al., 1995) in which the authors reduced the fluidization flow by approximately 20% in response to biomass development to maintain the FBR at a desired bed expansion. Implementation of this concept would require updated calculations, updated "modeling" of the FBR, care to assure no adverse collateral impacts (such as clogging of the inlet nozzles by biological growth), and modification to procedures to provide a responsive control algorithm. However, this concept would likely require minimal alteration to equipment and infrastructure (implementability is medium to high). It is unlikely that this strategy alone would result in stable and sustainable FBR operation. For example, fluidization flow would need to be maintained high enough to avoid an excessive depth of the settled media zone and to minimize the potential for an adverse feedback loop in which lower fluidization increases biomass which, in turn, signals lower fluidization rates. Nonetheless, explicitly including fluidization (and recycle) flow rate as an adjustable knob in the control algorithm would provide a potentially significant benefit that could work in combination with other technologies and strategies (i.e., improved bed-solids cleaning, pretreatment of bed-solids entering the separator, etc.). This strategy was determined to be viable and conditionally recommended.

<u>Replacing components to increase resilience</u>

A number of components have been impacted by erosion caused by entrained bed solids. These include the inlet nozzles at the base of the FBR (as well as pump parts, piping/fittings, etc.). The Hanford team has already instituted a process of replacing key components (e.g. nozzles and some piping) with stainless steel. This activity has been incorporated into the baseline. We affirm this as a prudent action that will generally improve system robustness and reliability, supporting near-term consistent operation and reducing O&M activities. However, that this class of action does not address the underlying critical need for improved bed-solids control and management. Thus, we recommend that these material replacement activities be done in combination with actions that will directly and beneficially impact the control and management of bed-solids.

<u>Modifying FBR Vessel Geometry</u>

A classical fluidized vessel design (Figure 10) often includes an enlarged upper section (e.g., Andrews, 1988). Because of the larger cross-sectional area, the upward fluid velocity decreases reducing the upward driving force in the treated water zone and improving the control of the upper surface of the fluidized bed. This geometric arrangement is required for FBR that contain uniform density particles. For FBRs that contain variable density composite particles (with a denser core material and varying amounts of surficial biofilm) the fluidized bed height can be maintained in a cylindrical vessels (such as 200W) by careful management of biofilm development and wastage – however, inclusion of an enlarged upper section (at/near the target bed height) would increase the robustness of fluidized bed control. The explicit hydraulic control would reduce the required precision on the biomass control and would reduce the potential for adverse impacts over a wider range of biomass.

Unfortunately, retrofitting the existing FBR vessels and changing vessel geometry is impractical and currently not recommended. However, if another treatment line is added in the future, we recommend that the Hanford team to consider a modified FBR vessel geometry to improve the robustness of operation.

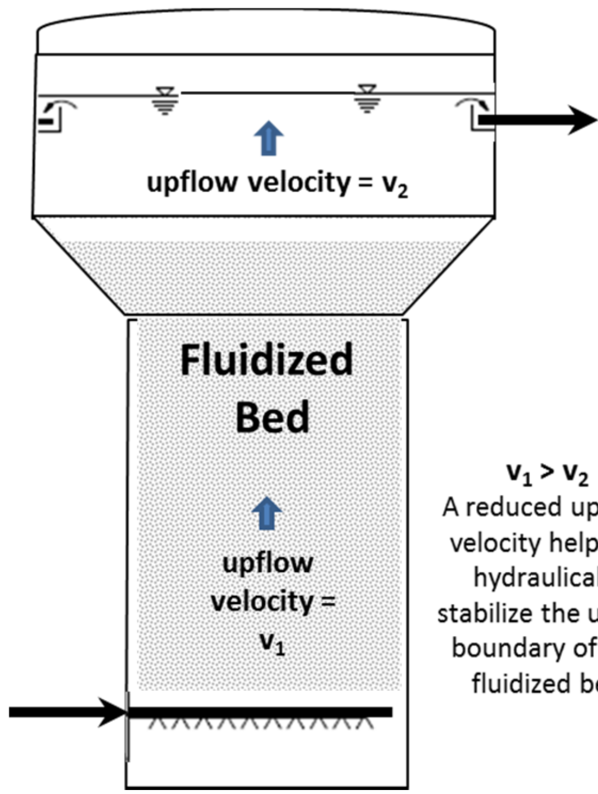



Figure 10. Classical fluidized bed vessel design with expanded upper section

*4.1.6 Monitoring in the FBR Vessel / System*

The Hanford Team currently collects: 1) continuous sensor data at key locations for master variables and some chemicals, 2) daily process control samples for key parameters, and 3) monthly samples for a more complete set of analytes. Appropriate quality controls and sample handling are in place. The data are organized (tabulated and graphed) and integrating control charts are prepared to support monthly meetings by the process control engineers. The engineers discuss the data and make adjustments to the operating algorithms to refine FBR operation. Our team affirms this monitoring baseline – in general, it is a best practice approach for this type of operating facility. Our team had no specific recommendations for additional or alternative sensors for continuous process monitoring. However, the approaches to monitoring the bed height and stratification within the FBR have underperformed and are not properly contributing to the maintenance and process control for the FBR.

The initial sonar-based sensors did not provide data of sufficient quality to support 200W process engineers. As a result the sonar sensors were removed and replaced with video monitoring (discussed below). We recommend that the Hanford team consider revisiting the sonar alternative – assessing other brands to see if an alternative has the potential for improved performance (see the Hawk sonar system as an example at www.hawkmeasure.com). One of the limitations of the commercial sonar systems is that they are generally designed to monitor clarifiers. Clarifiers are quiescent systems containing solids with bulk densities close to water – but without the particle motion and turbulence of an FBR. The conditions in the FBR are analogous to a clarifier but the differences will impact the performance of sonar monitoring systems. To meet the challenge of assessing the solids profile in clarifiers, each manufacturer employs their own proprietary sonar wavelengths and signal processing. It would be prudent to do a quick recheck of available equipment to determine if alternate hardware and signal processing would provide acceptable performance in the FBR. The resulting monitoring would be preferred over the manual use of the video monitoring strategy.

A video monitoring system is currently in use and is successfully providing some information of FBR bed height. This system, however, requires significant O&M (to keep the lens clean) and is a challenging hands-on operation. According to CHPRC staff:

> "*The primary video system involves 2 operators, 1 radiological technician, and one industrial health technician. Once a day, while staffed, they manually drop a camera (Sea Snake) into the FBR and find the top of bed and note the level of the fluidized bed. Then the camera is lowered in 1-foot increments with a 10-second pause at each step for the top 5 feet. The camera is then lowered to just 4-feet from the bottom of the bed. All this is recorded on a flash drive…. {CHPRC process engineers} review this video and direct which eductors to operate for what time period to maintain the bed. This approach works as long as we have timely information. It does break down if something goes wrong over the weekend or we fail to perform a "camera job" and we do not catch the problem early. For example, the orthophosphate pump has quit pumping over the weekend and we get EPS/biofilm encapsulating the media causing over-fluidization. Carbon media starts leaving the bed and the remaining media is so over-fluidized that the eductors are not particularly effective.*"

A secondary video system is deployed in the tank – in that system the camera must be within a few inches of the interface to provide a reliable visualization and the lens is subject to frequent fouling. The Hanford team has discussed developing a wiper system for the secondary camera video lens - such a system could be developed by a contractor, or a skilled machine shop (it is relatively straightforward and could work). This fix would likely help but would not eliminate the fundamental issue of ad hoc monitoring of the dynamic FBR bed height and bed structure – and the need for improved information availability to process engineers.

Note that the primary and secondary video monitoring systems are manually intensive and not available on weekends or when short staffed (e.g. sickness or training). As a result, the "feedback loop" for the process engineers with information on the FBR bed height is not robust. If a reliable sonar based technology cannot be implemented, modifications or upgrades to the video monitoring could be considered.

Other methods for continuously monitoring FBR bed depth might be worthy of study and review, including:

- pressure bubblers to sense density gradient – a standard methods of monitoring fluid levels that would be difficult to operate in the active FBR with high upflow velocities (limited potential for success)

- modified geophysical tools (measuring resistivity, self potential, magnetic susceptibility, density, or neutron capture). These methods might be particularly applicable if combined with changing of the core substrate (e.g., if the substrate has magnetic susceptibility) – moderate potential for success

These alternate methods would require a clear scientific basis for operation, careful development, and significant work to be viable.

## 4.2 Improving Bed Solids Separation and Control in the Bed-Solids Separator

### *4.2.1 Bed-Solids Separator Design*

Water and entrained particles leaving the FBR vessel enter a bed-solids separator (Figure 3, right). The entering fluids are introduced tangentially (along the wall) setting up a near field cyclonic separation process. Conceptually, the solids will settle and move downward along the wall and the clear-treated water will move upward. As with the FBR, the bed-solids separator is allowing a substantive quantity of solid granular carbon to exit at the top, impacting the recycle/downstream equipment and operations.

There are a number of design issues/factors that contribute to the underperformance of the Bed-Solids Separator. Importantly, the fluid is entering the vessel at a high flow rate resulting in localized turbulence in the nearfield cyclonic separation zone – some solids are entrained in fluids and swept into the upward flow zone. Quantitatively, the total flow entering the system is high (circa 2000 gpm) and the flow rate for withdrawal of the slurried solids at the bottom of the separator is relatively low (< circa 10 gpm). Thus, more than 99.5% of the overall fluid moves upward in the separator and less than 0.5% moves downward. Based on the driving forces, any underperformance in the cyclonic separation has a high potential to contribute to bed-solids reaching the recycle/effluent of the separator. The current design does not include an integral maintenance system to minimize clogging and sticking of bed solids in the lower portion of the separator vessel (currently, such maintenance is performed manually from the flange access points). A reliable and continuous/semi-continuous system for minimizing clogging would maximize the performance of the cyclonic separation action by keeping the bed-solids moving downward as rapidly as possible.

The overall vessel diameter is a significant weakness of the 200W separator design. As shown in Figure 3, the diameter of the separator is approximately 10 ft, while the diameter of the FBR vessel is approximately 14 feet. A more robust design would be to have a separator with a diameter that is the same as (or larger than) the associated FBR. In the 200W scenario, the overall fluid flow is the same in both vessels resulting in an upward empty vessel (Darcy) velocity that is significantly higher in the separator (3.5 ft/min) versus the FBR (1.8 ft/min). Conceptually, any particle that was entrained in the effluent from the FBR will have a density that, if not collected by cyclonic action, will be entrained and carried to the top of the separator. In general, the vertical upflow section for the bed-solids separator does not contribute to the separation process, rather it will effectively transfer any entrained solids to the funnel collectors used for recycle and effluent (each collecting about half of the total flow that originally entered the bed solid separator). Note that the effluent collection funnel is located one or two feet above the recycle collection funnel. This configuration would result in a short distance with a reduced upward Darcy velocity (about 1.7 ft/min – a velocity similar to the FBR). However, turbulence around the funnel style collectors would be expected to maintain the entrained particles in suspension, ultimately keeping the solids in both the recycle and effluent fluids.

The net impact of the weaknesses in the bed-solids separator design is poor performance and lack of robustness in continuous operation. The above framework suggests a wide range of bed-separator design sub-options for potentially improving separation performance, including the following five sub-options:

- Increasing the slurry flow rate (not viable)
- Redesigning the recycle and effluent collection funnels to minimize turbulence (not viable)
- Relocating the recycle collection location/configuration to provide more vertical distance with a lower upward Darcy velocity (not viable)
- Adding a continuous anti-clogging system for the cyclonic separation zone
- Increasing the bed-solids separator vessel diameter to reduce turbulence and reduce the upward driving force for entrainment of solids

These sub-options range in complexity, cost, and potential benefit.

Sub-Options that were assessed to be ineffective

As noted, a few of the sub-options were determined to be ineffective. These were rated as not viable and not recommended. These options are summarized below:

- Increasing the slurry flow rate would have limited effectiveness in altering the overall hydraulics and performance of the separator -- Since the slurry flow rate is currently < 0.5% of the overall flow, there is minimal potential for beneficially adjusting this parameter. Significantly increasing slurry flow (e.g., by 10x) would likely require equipment and control software modification. Even with such a substantial increase, the slurry flow would be < 5% of the overall flow and the change would not significantly contribute to reducing the primary upflow Darcy velocity in the bed-solids separator into a desired range (i.e., < 1.8 ft/min). This option was determined to be not viable due to its minimal impact.
- Redesigning the recycle and effluent line collection funnels to minimize turbulence -- The traditional design of a water treatment clarifier has standardized guidelines on the overflow weir length to minimize turbulence and reduce the entrainment and downstream carry-over of solids. Such standard design guidance (e.g., State of Washington Department of Ecology, 2015) suggest weir loadings of 15,000 gpd per linear foot – for the 200W system with a flow in each bed solid separator of about 2000 gpm (2,880,000 gpd) the associated outlet weir would need approximately 190 linear feet of collector length. Similarly, the traditional design guidance would require a surface area of 3600 sq ft (circa 68 ft diameter vessel). We recognize that the bed solids separator is different than a traditional clarifier and quite distinct. The distinction is primarily due to the fact that the bed-solids have a dense core and are not light sewage sludges – allowing some reliance on cyclonic separation action. Nonetheless, the principles of clarifier design suggest that the upflow velocities should be kept as low as possible and that the collector weirs should minimize local turbulence. Toward this end, a docking assembly could be fabricated and retrofit to the current collection funnel(s) to allow water to be drawn out with less turbulence. Based on the framework described above, we project that this would have minimal benefit (since entrained particles are being efficiently delivered to the top of the separator so that reducing local turbulence around the collector funnels would not be expected to substantially change the particles collected). This option was determined to be not viable due to its minimal impact.
- Relocating the recycle line location/configuration to provide more vertical distance with a lower upward Darcy velocity -- If some recycle was drawn out of the bed-solids separator feed line (and blended with the primary recycle line) or if the main recycle line collected fluids lower in the separator vessel then the length of the zone with reduced upward flow rate would be broadened and some of the turbulence in the separator could be reduced. Unfortunately, this approach would require significant engineering and equipment modification and would be unlikely to reduce upward flow sufficiently to have a significant beneficial impact. The approach has the

potential to for adverse impacts such as incrementally increasing the solids recycled back to for fluidization flow. This option was determined to be not viable due to its minimal benefit and potential adverse collateral impacts.

Adding a continuous anti-clogging system for the cyclonic separation zone

The bed-solids separator does not currently include an integral maintenance system to minimize clogging and sticking of bed solids in the lower portion of the separator vessel. If material builds up and clogs in the vessel, it must be removed manually from flange access point(s). We recommend consideration of a reliable and continuous/semi-continuous system for minimizing clogging. Such a system would maximize the performance of the cyclonic separation action by keeping the bed-solids moving downward as rapidly as possible – making way for additional solids to be collected. Rather than the mechanical scrapers and stirrers used in traditional clarifiers, we identified an alternative system originally developed to mitigate fouling on boat hulls or aid in industrial hopper feeding.

Figure 11 shows an exemplar of a commercial boat hull maintenance system (PYI Inc., see www.pyiinc.com) and a commercial vibrator system used to assist in hopper feeding (elecronic and pneumatic vibrators are available from many manufacturers, e.g., Martin Vibration System and Solutions, see http://www.shake-it.com). This type of system consists of transducers that can be mounted on target surfaces. The operation is “continuous” and automatic – for boat hulls, the ultrasonic vibrations keep undesired material (algae, moss, barnacles, etc.) from adhering/attaching. A reasonable configuration for the 200W application would be to mount transducers on the external surface of the bed-solids separator (analogous to use on boat hulls or industrial hoppers) in the lower angled cyclonic separation portion of the vessel. In the bed solid separator, the vibrations would maintain the downward flow of bed-solids after collection by cyclonic action and keep them from clumping and/or sticking to the walls of the separator vessel. The solids would continue to “walk down” the wall to maximize collection by the eductor for transfer back to the FBR. The illustrated boat hull maintenance system uses relatively low frequencies (e.g., 19.5 to 55 kHz) and has minimal control requirements or customization. Note that for boat hull maintenance the transducer spacing is relatively wide (10s of feet – a dual transducer system is designed to maintain “Yachts up to 56' in Length”). Prior to selection/implementation, an evaluation would be needed to assure that the vibrations would not cause long-term structural problems (e.g., fractures) in the fiberglass tank – note, however, that the boat system is specifically designed for fiberglass hulls and the manufacturer indicated that there have been no fiberglass structural impacts reported from the 10,000+ units deployed to date. This type of system would be implementable with minimal investment. Based on demonstrated performance for boats, each bed solid separator would require either one or two Sonihull duo systems (or an equivalent industrial system) with an associated total material cost of about $10000 to $20,000 for both bed-solids separators (plus any required engineering, planning and labor for installation and procedure development). While the proposed continuous anti-clogging concept is notional, it has a reasonably high probability of success with minimal cost. We rate the concept as viable and recommended.

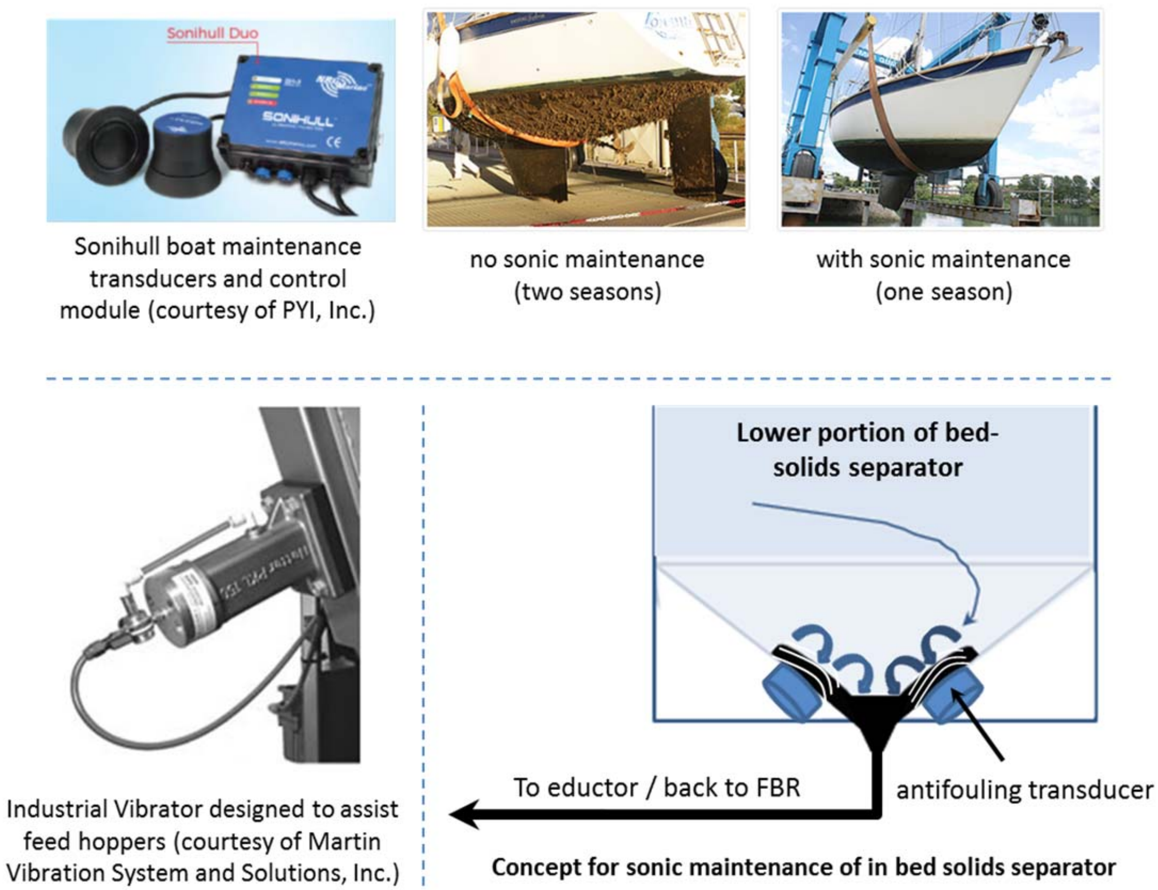



Figure 11. Illustration of commercial ultrasonic boat hull maintenance system, an industrial vibrator, and a conceptualized application for a continuous anti-clogging system for the 200W bed solids separator

<u>Increasing the bed-solids separator vessel diameter to reduce turbulence and reduce the upward driving force for entrainment of solids</u>

As noted above, a prudent sizing/design for the bed-solids separator would result an upward Darcy velocity that is less than the primary FBR vessel. This design concept would allow the separator to collect the bulk of any solids that are not removed by the primary cyclonic action, maximizing the overall performance. To meet this prudent design requirement, the separator would need to have a diameter that is larger than the FBR vessel (≥ 14 ft) – because of the dense core material of the bed solids, the separator would not need to be sized as a standard wastewater clarifier (≥ 68 ft diameter). The current 10 ft diameter 200W bed-solid separator design, and any design with a diameter less than 14 feet, will efficiently deliver solids that are not removed by the initial cyclonic action to the recycle and effluent lines (since the solids that enter the bed-solid separator would have already been entrained in the water exiting the FBR operating at a lower upward velocity).

One of the most effective modifications to help meet the DOE-RL objective of assuring “a stable and reliable operating system in the next two years” would be to add bed solid separator capacity (a major system modification). The most cost effective approach would be to use the existing bed-solids separators to service one of the FBRs and to add a new (larger) bed solids separator to service the other FBR (Figure 12). As depicted, the output from one of the FBRs would feed both current bed-solid separators. The lower feed flow to the separators would: 1) reduce turbulence – maximizing the performance of the cyclonic separation, and 2) reduce upward flow velocity and increase residence time in the separator – allowing additional settling of solids. The other FBR would be connected to a new separator unit.

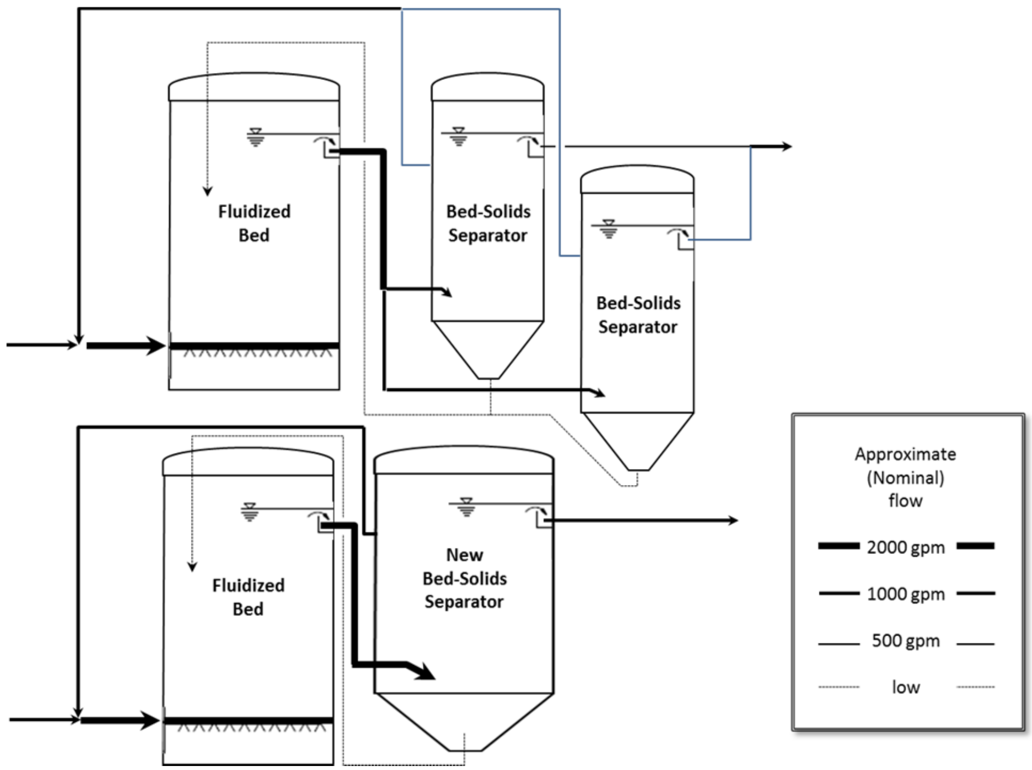



Figure 12. Modified system to add bed solid separator capacity

Additional bed-solids separator capacity would provide more robustness, reduce bed-solids carry-over and recycle, and improve 200W FBR performance. However, this is a major system modification with a high cost. Significant design changes would be required, a new bed solids separator would need to be acquired, process control systems and procedures would require modification, training would need to be updated, and installation would result in an extended system outage. It is likely that additional supplemental actions such as installing an anti-clogging system or bed-solids pretreatment might be required in conjunction with this change to provide maximum benefit.

Increasing the bed-solids separator capacity is viable and conditionally recommended. This major system modification should be considered if alternative actions, or combinations of actions, are not able to provide the desired robustness in long-term performance. This particular action represents one of the highest cost alternatives and should be one of the most impactful (beneficial) on long-term operations.

### *4.2.2 Bed-Solids Pretreatment*

In theory, the bed-solids with the lowest composite bulk density (i.e., those with high biomass loading) would comprise a substantial portion of the particles entrained in the fluids leaving the FBR. Thus, a technology to remove biomass and strip biofilms from the entrained particles would increase particle density and reduce particle stickiness, thereby improving the performance of the bed-solids separator. We assessed two approaches for such "pretreatment" for implementation between the FBR and the bed-solids separator: 1) use of an in-line static mixer and 2) use of inline high power sonication. Each of these would have advantages and disadvantages.

An inline static mixer provides high levels of turbulence by forcing the flowing liquid around mixing baffles ("elements"). Figure 13 shows some of the features of a typical in line mixer (see http://www.statiflo.com/). The turbulence in an inline static mixer would cause particle-particle contacts that would physically abrade/remove biomass. A significant advantage of an in-line mixer is that it represents a passive pretreatment that requires no active operation, minimal maintenance, and de minimis change in hydraulics and energy within the system. Typically, in line mixers are designed based on overall flow rate to: 1) maintain appropriate linear velocity (nominally in the range of 1 ft/sec), 2) provide a target degree of mixing (based on a standardized coefficient of variation (COV) in the exiting fluids nominally in the range of 0.05 to 0.1), and 3) operate with minimal/acceptable pressure loss. For the 200W pretreatment application a reasonable design basis would be based on a nominal 2000 gpm, linear velocity 1 ft/sec, COV of 0.1, and pressure drop of 0.2 ft or less. The resulting design calculation suggests that a standard stainless steel mixer (e.g., Statiflo R600) with a diameter of 2 ft, a length of 6 ft, and two mixing elements would provide the desired performance with a head loss of about 0.12 ft. In this application, the reagent injector ports would not be used and could be capped off or eliminated from the design. If mounted in the vertical section of line between the FBR and the bed-solids separator, there would be minimal potential for buildup of solids in the mixer assembly virtually eliminating maintenance. Compared to sonication, an inline static mixer would likely provide less energetic stripping of biomass from the entrained bed solids.

Pretreatment for the bed-solids separator using an inline static mixer is viable and conditionally recommended. This is a simple and low cost modification that has minimal collateral impacts. Selection of this technology should be considered if: 1) testing confirms the presence of high biomass on entrained bed-solids, and 2) testing confirms that the turbulence in a static inline mixer is sufficient to remove biomass to the extent required to support separation. If these conditions are met, then pretreatment with a static inline mixer is a preferred option.

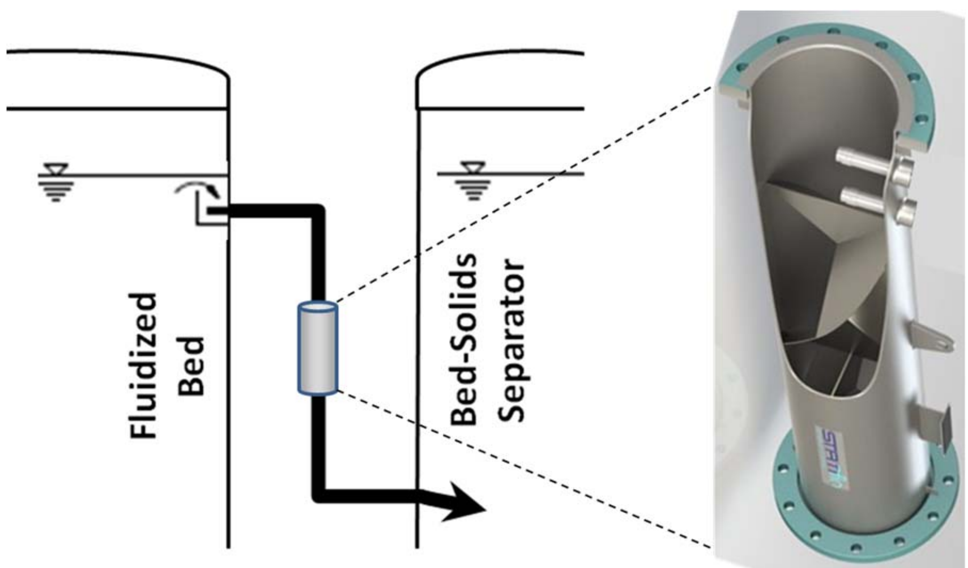



Figure 13. Concept for an inline static mixer pretreatment option for the 200W bed-solids separators and an example commercially available mixer unit (courtesy of Statiflo International. Ltd.)

Inline sonication is an alternative pretreatment technology to remove biomass from entrained bed solids (Figure 14). In this case, the fluid exiting the FBR would pass through a reactor equipped with high-energy ultrasonic transducers. These types of systems have been used for a number of environmental applications (see Mason and Tiehm, 2001) and are commercially available for full scale application (see: http://www.zenith-ultrasonics.com). In this concept, low (25 kHz or less) to moderate (40 kHz) ultrasonic frequencies would be employed at a high power level to strip biofilms and biomass from the entrained particles. Compared to the static inline mixer, the ultrasonic reactor would provide more aggressive biomass removal. However, implementation would require more intensive testing and development efforts. The ultrasonic option would: 1) be more costly, 2) require energy to operate, 3) require more O&M and procedure development, and 4) would add additional sound to the environment around the FBR and bed-solids separator.

Pretreatment of the fluids for the bed-solids separator using an inline sonicator is viable and conditionally recommended. Selection of this technology should be considered if: 1) testing confirms the presence of high biomass on entrained bed-solids, and 2) testing confirms that the turbulence in a static inline mixer is not sufficient to remove biomass to the extent required. If these conditions are met, then pretreatment with an inline sonicator is a reasonable alternative.

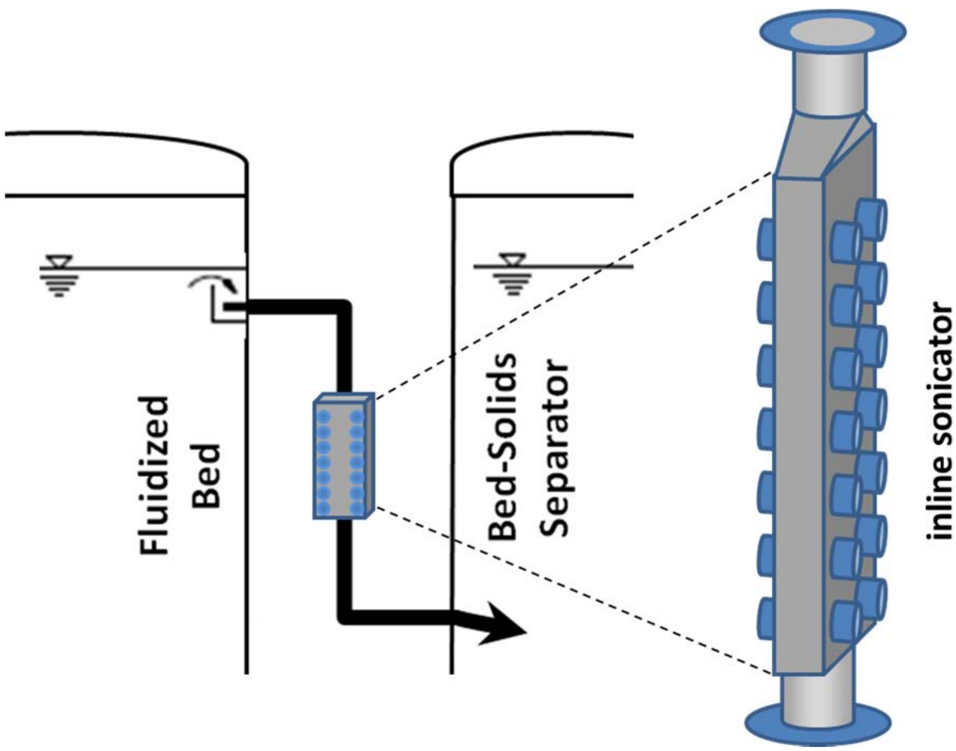



Figure 14. Concept for an inline sonicator pretreatment option for the 200W bed-solids separators

*4.2.3 Supplemental Magnetic Solids Collection*

Use of a magnetic “iron containing” core substrate in combination with a magnetic collection system could be used to improve solids collection in the existing bed-solids separators. This innovative idea is used in various laboratory-scale separations and is analogous to some of the processes that have been proposed over the past 20 years that use sorbents that contain magnetite (e.g., a magnetite core coated with ion exchange resin or reactive/porous mineral phases) – in general, these processes mix the sorbent with the water and then separate the sorbent using a magnet. Unfortunately, magnetite is unlikely to exhibit long-term geochemical stability in an active anaerobic bioreactor – the Fe(III) in the magnetite would be subject reduction (accepting an electron) and release as Fe(II) to the solution. This process has the potential to slowly erode core and alter the mineralogy of the particle (potentially reducing the magnetic susceptibility and ability to separate and collect).

We propose that sintered iron, as a core substrate, would be a potentially viable alternative to carbon as a FBR core substrate. This material would have a high magnetic susceptibility and collectability. In this case, the core substrate would contain elemental “zero valent” iron that would, in theory, be relatively stable in an anaerobic bioreactor. Sintered iron would have a relatively high surface area and may be able to be retrofitted into the FBR (by selecting an appropriate smaller particle size – the bulk density is similar to sand). A number of variants of sintered iron are commercially available including materials that incorporate ceramics. Sintered iron is used in large quantities in industry (e.g., for powder metallurgy) so the costs would be expected to be relatively low. Figure 15a shows two photographs of commercially available sintered iron. Some testing would be required to determine if this substrate a suitable surface for biofilm development and if a material is available that supports a reasonable fluidized bed design that is compatible with the existing FBR equipment and flow rates. Other core substrates such as polymer encapsulated magnetite or iron would also be compatible with this concept. For these polymeric alternatives, a fine-powder of magnetic material would be mixed into the polymer or a magnetic core particle would be coated with the protective polymer.

Presuming that a suitable substrate for the FBR is identified, Figure 15b depicts a hypothetical deployment using the existing bed-solid separators. In this thought experiment, the system would operate in a batch mode. In the collection phase, the magnetic particles would be attracted to the energized electromagnet that is positioned in the upflow section of the separator (between the inlet and the recycle line). After an appropriate collection period, the magnet would be positioned below the inlet line and de-energized (dropping the particles into the slurry). These batch collections could be repeated as needed (perhaps daily or weekly). During the collection and release activities, water flow could continue upward to the recycle and effluent collection funnels.

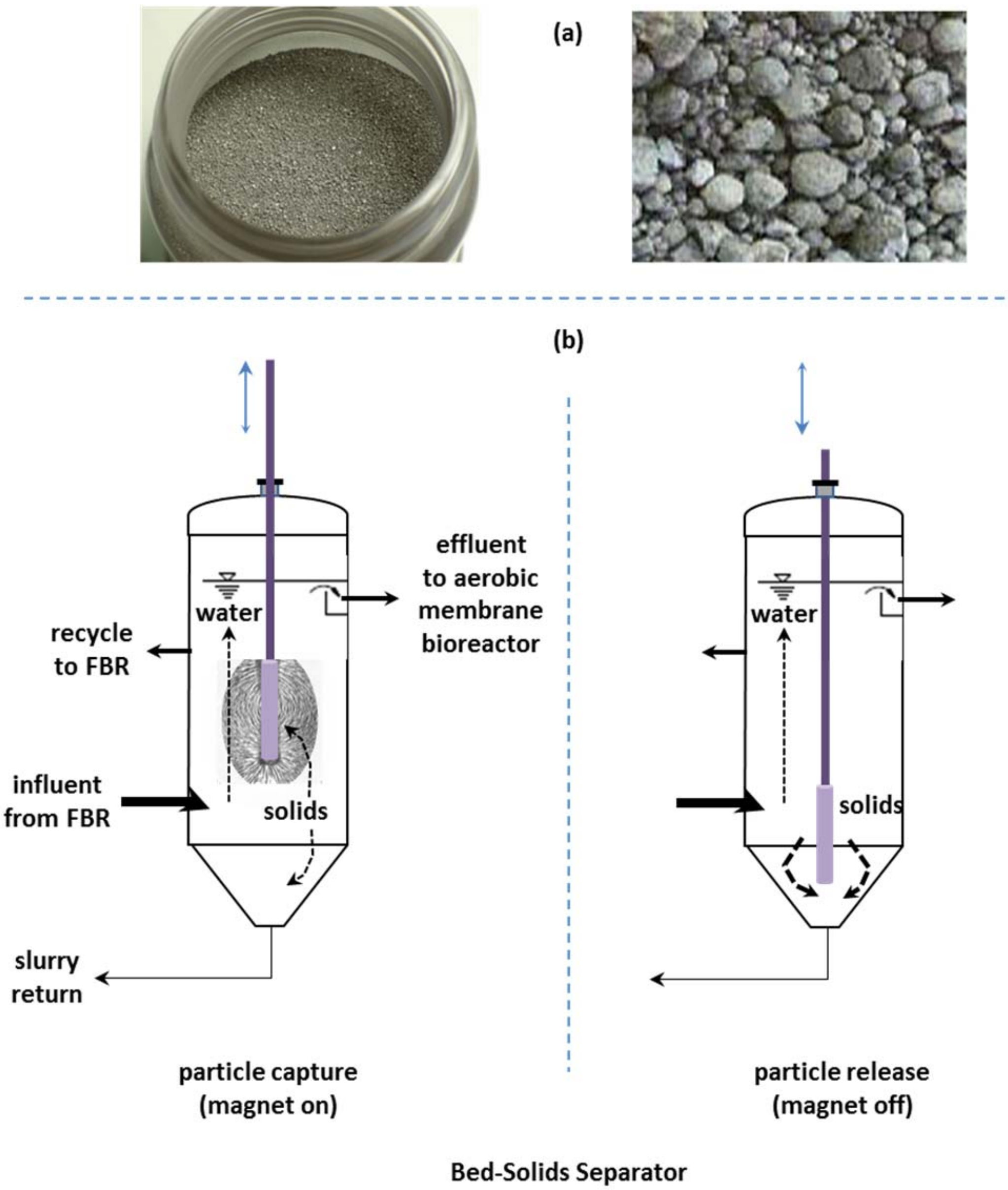



Figure 15. Simplified schematic for supplemental magnetic separation, showing: a) examples of commercially available sintered iron materials, and b) hypothetical deployment

This is a notional concept that has a relatively low TRL – it would require some development and testing. However, the required development is relatively straightforward and, if successful, this would provide significant improvement, effectively utilize the existing equipment, and eliminate the need to increase the bed-solids separator capacity.

Supplemental magnetic solids collection is technically viable and conditionally recommended. This is a major modification that would require some development and testing. Selection of this technology should be considered if some of the lower cost activities do not provide sufficient separation. This alternative might be attractive compared to adding additional bed-solids separator capacity.

## 4.3 Overall FBR Related Collateral Impacts to 200W Treatment System

FBR-related issues are causing adverse collateral impacts throughout the downstream 200W treatment process and contribute to issues that limit the treatment throughput of the overall facility. The carryover of bed-solids, electron donor and nutrients are all contributing to higher downstream maintenance (e.g., manual removal of solids from the aerobic membrane bioreactor feed splitter box) and to biofouling of the air stripper, distribution system and injection wells. For completeness a number of post-treatment options for mitigating the impacts of FBR underperformance were evaluated along with an overarching assessment of nitrate treatment goals and objectives.

### *4.3.1 Post-Treatment Options to Support Reinjection*

Following treatment by the FBR, aerobic membrane bioreactor and air stripping, liquid effluents are transferred to the effluent storage tank for distribution to the injection wells. Injection wells are installed both upgradient (to direct the contaminant flow toward the extraction wells) and downgradient (to slow contaminant flow toward the Columbia River). These wells are located at varied distances from the 200 West system and treated wastewater is delivered to the well heads using above-ground black high density polyethylene pipe.

Residual biological material and excess nutrients in this water are resulting in the fouling of effluent discharge lines and injection well screens of the 200 West system. This fouling reduces the volume of treated water that can be injected into the aquifer formation. Recent investigations (Carlson et al., 2015) indicate that biological fouling is a primary factor along with precipitated metal oxides (particularly manganese) contributing to the reduced performance of the injection well system. Of the two classes of fouling: 1) biofilm fouling is more severe though may be treatable with cleaning, and 2) manganese-based fouling that is more difficult to remove and may be irreversible.

As reported by Carlson (2015), the injection wells initially lost capacity as a result of fouling in early 2013. A potential source of the fouling was associated with earlier adjustments to the micronutrient feed to improve microorganism health in the FBR (Carlson, 2014), but the micronutrients were being overfed (particularly manganese) and this resulted in fouling of the injection wells. As a result, a rehabilitation campaign was initiated to restore specific injectivity by removing biological fouling and precipitated metal oxides. Intensive surging and development successfully removed clogging material from the injection wells. Repeated chemical treatments of sulfamic and citric acids were used to dissolve metal oxides and sodium hypochlorite was used to remove the biological growth. During this activity, large quantities of biological growth were found and removed from the screens of the injection wells. Carlson (2015) determined that too much micronutrient, especially manganese, fouls the wells decreasing performance and recommended that injection water contain less than 10 mg/L COD to limit biological growth (and the resulting biofilm in the wells) and less than 0.01 mg/L manganese to limit manganese-based corrosion of stainless steel well screens.

As shown in Figure 16 these efforts had limited effectiveness in removing metal oxides that had deposited in the screen zones. Carefully tracking and managing the FBRs and well performance monitoring are critical to balancing the needs of the treatment system while reducing fouling mechanisms in the injection wells.

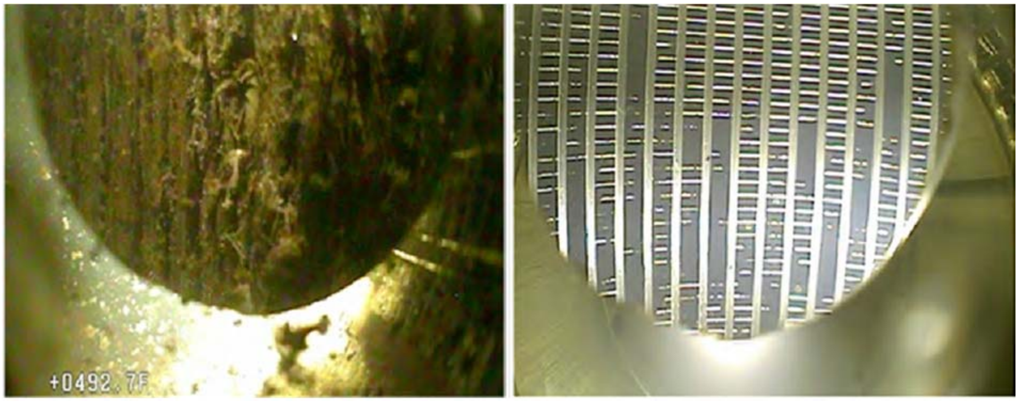



Figure 16. Injection well screen before (left) rehabilitation and after (right) rehabilitation. Cleaning efforts were effective in removing biological fouling but were incomplete in removing metal oxides (Source – Carlson et al., 2015).

Our team evaluated potential causes for poor injection well performance and identified the following factors that may be attributed to continued fouling and/or overall poor-performance of the injection wells:

- Biological fouling of well gravel pack and near well aquifer formation (outside of the well casing),
- During previous operations with high COD and manganese in the injected water, both biological and mineral fouling was observed inside the well casing. It is likely that during this period biological growth also occurred in both the filter pack and near well aquifer zone. Forgoing other contributing factors, once this fouling is removed, established operational controls should limit the future occurrence of this fouling.
- Regrowth of biofilms associated with residual COD in the injected water.
- A viable consideration for continued diminished performance of the injection wells is regrowth of biofilms in both the transfer lines to the wellhead and in the injection well. Control charts for the 1Q-2017 indicate that the effluent of the MBR contains COD varying between 1.5 mg/L to 10 mg/L. As a unit operation the air stripper has minimal impact on COD. This residual COD could serve as a potential source for biological fouling in the reinjection system.

In the upstream FBR, phosphorus is an essential macronutrient for biological conversions and is dosed as a ratio of the amount of COD fed to the system. Values less than 0.2 mg/L indicate that phosphorus may be limiting for growth and cause the formation of extraneous biomass in the form of extracellular polymeric substance (EPS). Historically total phosphorus in the effluent of the FBR is on the order of 0.2 mg/L. Phosphate removal is a combination of biological uptake and sorption to ferric-hydroxide solids and biomass – the formal removal path would be in the aerobic sludge-solids from the MBR.

A potential catalyst for biological growth could be associated with the addition of phosphorus, an essential nutrient for biological growth, in the form of anti-scalant. While other elements may also control biomass growth, e.g. nitrogen, phosphorus is often the limiting nutrient in biological systems (e.g., Griffiths et al., 2012). The 200W anti-scalant product is predominantly sodium phosphate that prevents formation of minerals by providing ligand (phosphate) that act as binding or sequestering agent. In this role, phosphates form water soluble, stable metal complexes and suppress precipitation. Phosphate is an effective anti-scalant for iron, manganese, calcium and magnesium. Additionally, the phosphate will contribute to biological metabolism (reacting with residual carbon and nitrate) as water is stored and flows through the air stripper, downstream tanks, distribution piping and injection wells. Based on process chemistry data and limited data from the injection wells, it appears that the anti-scalant is contributing of phosphorus to the treated water – levels that may be sufficient to stimulate biomass growth and biofouling. For example, measured concentrations in treated process water are typically in the range of 0.2 to 1 mg/L as P and concentrations at injection well 299-W6-13 in the summer of 2016 was reported at 2.1 and 3.7 mg/L as P.

Our team has identified specific in-plant technologies and wellhead options to address the factors that have been identified as contributing to the fouling of the injection wells. These options include:

- In Plant Technologies
  - Alternate Anti-Scalant for Air Stripper
  - Chlorination and Disinfection
  - Removal of Residual COD using supplemental bioreactions
  - Removal of Residual COD using an Advanced Oxidation Process
- Wellhead Technologies
  - Alternate Well Cleaning Technologies
  - Reinjection Well System – Screen Design
  - Vadose Zone Injection

Alternate Anti-scalant (In Plant Technology) –
The current system effluent has residual COD on the order of 5 to 10 mg/L and residual nitrate on the order of 2 to 10 mg/L. To minimize scale formation and clogging in the air stripper, an anti-scalant chemical is added to the water. The current anti-scalant/corrosion inhibitor, Nalco CL-50, is phosphorus-based and is added to the influent to the air stripper. This scalant or equivalent was identified in the remedial design report (DOE, 2010). In a phosphorus-limited system, the specified anti-scalant could provide phosphorus, a key macronutrient that in combination with the residual COD and nitrate would foster microbial growth. One technical sub-option to consider is the replacement of Nalco CL-50 with a low or non-phosphorus anti-scalant.

Anti-scalants are surface active materials that interfere with precipitation reactions of dissolved species, primarily metals. The mechanisms of inhibiting precipitation vary depending upon the specific formulation (usually proprietary). Potential mechanisms that anti-scalants use include: maintaining supersaturated solutions of sparingly soluble salts, distortion of crystal shapes as initial precipitation occurs that results in soft non adherent particles, and through dispersancy. Dispersancy is the ability of some anti-scalants to adsorb on crystals or colloidal particles and impart a high anionic charge, which tends to keep the crystals separated.

In recent years numerous low-phosphorus or non-phosphorus based anti-scalants have been developed (Shaikh et.al, 2015; Popov et. al, 2016; Pervov and Andrianov, 2017) – many of these were initially developed to support reverse osmosis and membrane-based treatment systems by minimizing the formation of biofilms on the membranes. The anti-scale agents have also been used in boilers and other extreme environments. The non-phosphorus anti-scalants are typically based on organic polymers including sodium salts and copolymers of polyacrylic acid, polymaleic acid, and polyepoxysuccinic acid. Several manufacturers have commercial "green" non-phosphorus anti-scalants. While not comprehensive, the following are potential non-phosphorus anti-scalants:

- Avista Technologies (http://www.avistatech.com/anti-scalants):
  - Vitec® 1000 and Vitec® 8200 Green are free of phosphate and phosphonate. These all-polymer blends are NSF-certified for use in systems producing drinking water.
- PWT Chemicals (https://www.pwtchemicals.com/):
  - SpectraGuard™ 100 and SpectraGuard™ 111 are phosphate-free formulations and are classified for use in systems producing drinking water (ANSI/NSF Standard 60)

Other “green” anti-scalants are identified in the cited publications of Shaikh (2015), Popov (2016), and Pervov (2017). In addition, the local Hanford chemical supplier for the facility may have access to low/non-phosphorus based anti-scalants (or blendable commodity chemicals such as the sodium salt of polyacrylic acid). For implementation, required system modifications should be minimal as low/non phosphorus anti-scalants are available and used in water treatment systems and similar dosing levels. Implementation will require the introduction of new chemical to system. Overall the team supports further evaluation of the potential use of a low/non phosphorus based anti-scalants , as well as encouraging assessment by the Hanford team related to the potential for eliminating anti-scalant (is it actually needed to protect the air stripper?).

Use of an alternative anti-scalant (or no anti-scalant) is relatively straightforward and would be viable and recommended. The anticipated costs would be low. If fouling of the distribution lines and injection wells is related to phosphorus as a limiting nutrient, the potential benefits could be significant. Some testing to confirm the role of phosphorus in downstream biofouling would be prudent. If confirmed, the alternative anti-scalants should be considered by the Hanford team.

Chlorination and Disinfection (In Plant Technology)

The effluent of the treatment system has residual COD. Upon leaving the treatment plant, the treated water goes through a distribution system similar in size to the drinking water system of a small metropolitan area. In these systems, chlorination is used to control microbial growth. Typically, high enough doses of chlorine arrest biological growth or kill certain bacteria and other microbes and leave some residual disinfection capacity in the water. The residual disinfection is typically measured in units of residual free chlorine (with target values in the range of about 0.5 mg/L) or as oxidation reduction potential (with target values in the range of +500 mV). At these doses, the resulting water is suitable for a public-potable water supply. For post-treatment application in the 200W system, chlorination could be performed to inhibit biological growth in the distribution system and associated injected wells. Numerous packaged systems exist for chlorination in water supply systems; and key chemicals that could be dosed into the water for this application are already in use in the 200W facility (e.g., sodium hypochlorite solution). Figure 17 is a simplified schematic of a typical disinfection system. Note that the sketch indicates that the dosing can be done after the air stripper or before the air stripper. Dosing before the air stripper has the potential to mitigate biofouling in the air stripper tower if biomass growth is adversely impacting air stripper O&M. Most packaged disinfection systems operate using ORP control (to maintain a target oxidation potential). This generally simplifies and automates operations but results in added operator tasks for sensor maintenance and documentation.

Disinfection is technically viable and conditionally recommended. Overall the addition of a disinfectant such as hypochlorite would inhibit the growth of biological material in the distribution system and wells (and potentially in the air stripper). Similar to a potable water system, the treated water from the 200W process could be discharged to the reinjection distribution system with a free chlorine level in the range of 0.5 mg/L. Sodium hypochlorite is currently used within the process so no new chemicals are introduced. Implementation could be done with simple dosing equipment and does require an additional major unit operation. Additional testing would be needed to determine if the residual disinfection capabilities are maintained into the reinjection wells; further loss of disinfection potential as the liquids enter the formation would still allow biomass to form in the subsurface. Thus, this option should be considered in combination with other actions (such as reducing phosphorus levels) that could work in partnership to mitigate biofouling potential. Implementation would require review of permitted injection water characteristics, and if required, modification of permits prior to implementation.

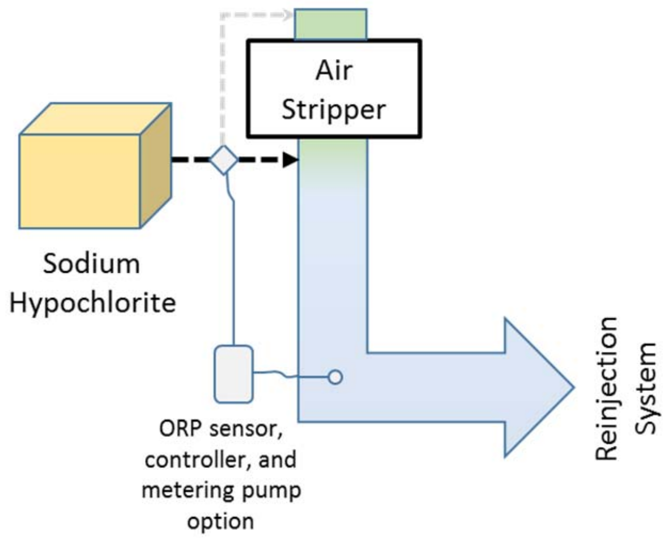



Figure 17. Simplified schematic of a typical packaged disinfection system

Removal of Residual COD using Supplemental Bioreactions (In-Plant Technology) –
The aerobic membrane bioreactors are the principal unit operation for removing COD and residual macronutrients from the treated water following the FBR. This suboption focuses on improving the performance of the aerobic membrane bioreactors so to improve the performance toward those objectives. In general, this suboption would add an aerobic pretreatment and preconditioning reactor in front of the aerobic membrane bioreactors. This would allow time to: 1) develop a more robust aerobic microbial community, 2) initiate the removal processes for COD and macronutrients, and 3) provide water into the membrane bioreactors that is geochemically and biologically ready for maximum treatment rates. Positioning supplemental biological treatment in front of the aerobic membranes would allow these units to perform at maximum effectiveness and provide for the clear-filtered water to the air stripper and reinjection system.

The high target flow rate of the 200W system limits the hydraulic residence time in the membrane bioreactors. Conceptually, the input of anoxic water to the membrane bioreactor, with an anaerobic microbial assemblage and a limited residence time may not allow for sufficient conversion of COD and uptake of macronutrients. One approach to supplementing the bioreactors would be to add a preconditioning vessel, basin or trench in which the water is aerated and time for the initial growth phases for the required aerobic microbial assemblage is provided. A simplified sketch for the concept is provided in Figure 18.

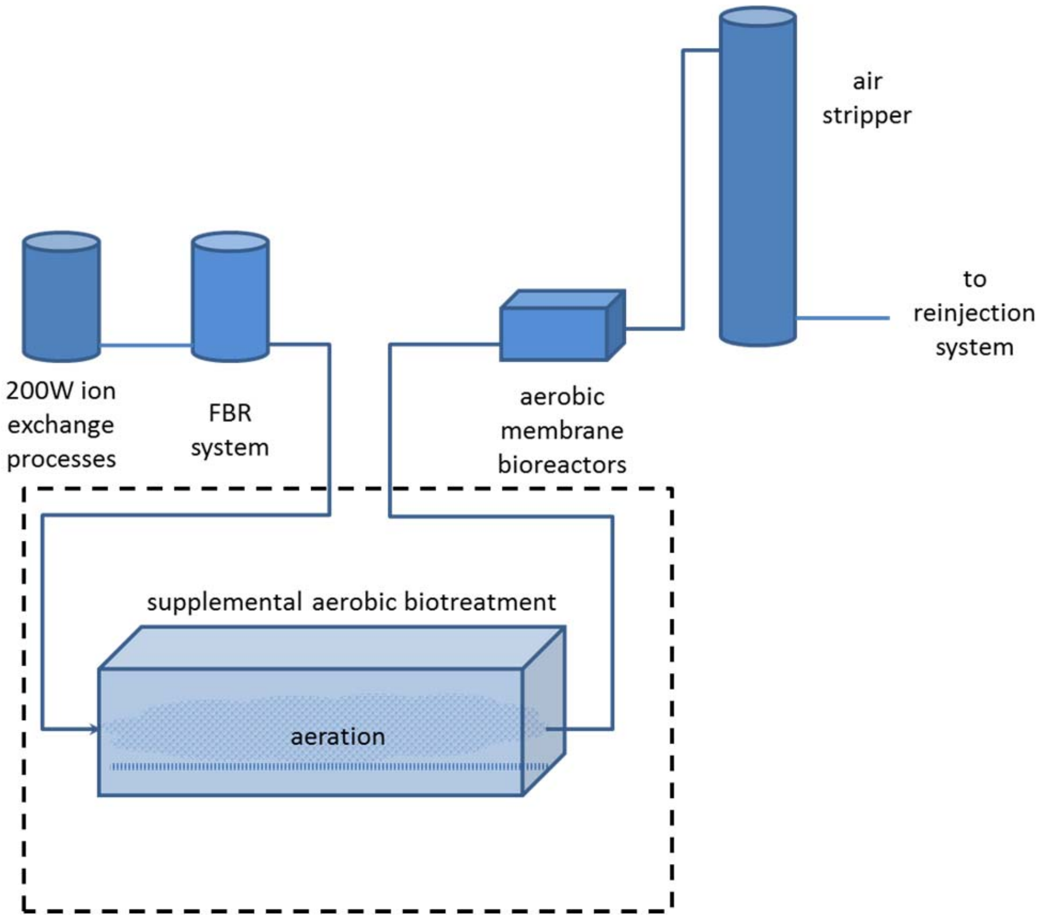



Figure 18. Simplified schematic of supplemental aerobic biotreatment concept for pretreating water before the aerobic membrane bioreactor

The general idea is relatively simple – the water would be provided some time and oxygen. As a scoping exercise, a hydraulic residence time of 2 to 4 hours would be a reasonable starting point. Using industry standard aeration requirements (1000 to 2000 standard cu ft per lb of BOD), a BOD/COD of 5 mg/L and nominal flow rates of 2000 to 2500 gpm, a preconditioner might require a total volume in the range of 300,000 to 500,000 gallons and an air flow rate of 100 to 200 scfm.  The system could be seeded with a standard aerobic wastewater treatment microbial consortium. Other standard aerobic wastewater biotreatment designs could also be utilized.

This technology is viable and conditionally recommended. The anticipated costs would be moderate to high; construction and up-front costs would be somewhat controlled by the simplicity of the proposed system. This concept would maximize the use/value of the existing installed aerobic membrane bioreactor system. Some additional air capacity would be needed. Some testing and development would be needed to confirm the conceptual basis and support the design. The potential/anticipated benefits in terms of maintaining injection capacity are potentially significant.  Overall this is recommended as a contingency - as implementation requires the addition of a new unit operation to the existing treatment train – with associated procedures, training, safety evaluations, and O&M. If testing indicates that this is viable to remove COD and macronutrients, this concept would be preferred versus the Advanced Oxidation Process.

Removal of Residual COD using an Advance Oxidation Process (In-Plant Technology) –
This option would insert a major new unit operation – an Advanced Oxidation Process (AOP) – prior to reinjection. An AOP unit operation could be installed to remove COD. This system would mineralize COD, disinfect the water and oxidize some dissolved minerals.

The basis for this sub-option is the conceptual framework that undesirable biofouling in the reinjection piping and injection wells is due, in part, to carry over of dissolved carbon compounds ("COD") and nutrients in the treated water following the upstream 200W treatment train (ion exchange, FBR, aerobic membrane bioreactor, and air stripping). Deployment of an advanced oxidation process (AOP) following the air stripper has the potential to oxidize the bulk of the residual COD and disinfect the water thus eliminating the transference of carry over microbes to the reinjection system. While a number of AOP configurations are feasible, a typical scenario would use an oxidant reagent in combination with ultraviolet (UV) disinfection and be deployed as a homogeneous process (i.e., only in the liquid-aqueous phase with no solids added). Properly designed, this type of AOP would generate free radicals that are capable of destroying most forms of COD. In practice, this type of system is now deployed at many sites and would have a relatively high TRL (approximately 6 to 8) Deployment would require some follow-up study, calculation and design, but development of new science and technology would not be required. Existing systems are used to treat water generated by fracking. Such systems have been documented to destroy oils, benzene, benzene and related compounds (BTEX), and polycyclic aromatic hydrocarbons. There are also a number of studies and implementations of AOP to treat carbon tetrachloride and other chlorinated solvents. A stretch implementation concept would replace the air strippers with AOP to perform all of the liquid treatment required after the membrane bioreactors.

For 200W, the most desirable configuration would use chemicals that are already in place with existing safety and handling procedures and operation experience. Consistent with the above discussion, a conceptual AOP for post treatment of 200W would use sodium hypochlorite (from stored totes or generated onsite) combined with commercial high flow rate UV disinfection units (Figure 19a). There are many manufacturers of high quality industrial scale UV disinfection systems that are built using stainless steel to appropriate codes and standards. Figure 19b illustrates one such UV system from Atlantic Ultraviolet (https://ultraviolet.com/megatron-ultraviolet-water-disinfection/) – each pictured unit is capable of treating 450 to 560 gpm (in clear water) so that six standard units would treat >2500 gpm. These units have automated wipers to maintain the clarity of the quartz tubes surrounding the UV lamps. Many other configurations are possible. There are a number of cautions related to AOP and UV systems. Importantly all cost effective UV systems currently use lamps that contain mercury (emerging UV diodes for disinfection are much too expensive for large scale application) so that waste generation resulting from lamp replacement and maintenance and procedures to address containment from breakage would be needed.

A secondary benefit of AOP deployment would be the option to control the system based on the redox potential (e.g., using controllers and probes set ORP to 500 mv or higher for a residual free chlorine to 0.5 mg/L) in the treated water, further limiting the potential for biofouling in the reinjection pipe network or the injection wells.

This technology is technically viable and conditionally recommended. The anticipated costs would be moderate to high; construction and up-front costs would be somewhat controlled by the availability of commercial equipment but anticipated O&M costs would be high. Some testing and development would be needed to support design. The potential/anticipated benefits in terms of maintaining injection capacity are potentially significant. Overall this is recommended only as a last resort as implementation requires the addition of a new unit operation to the existing treatment train – with associated procedures, training, safety evaluations, O&M, and a small amount of additional solid waste.

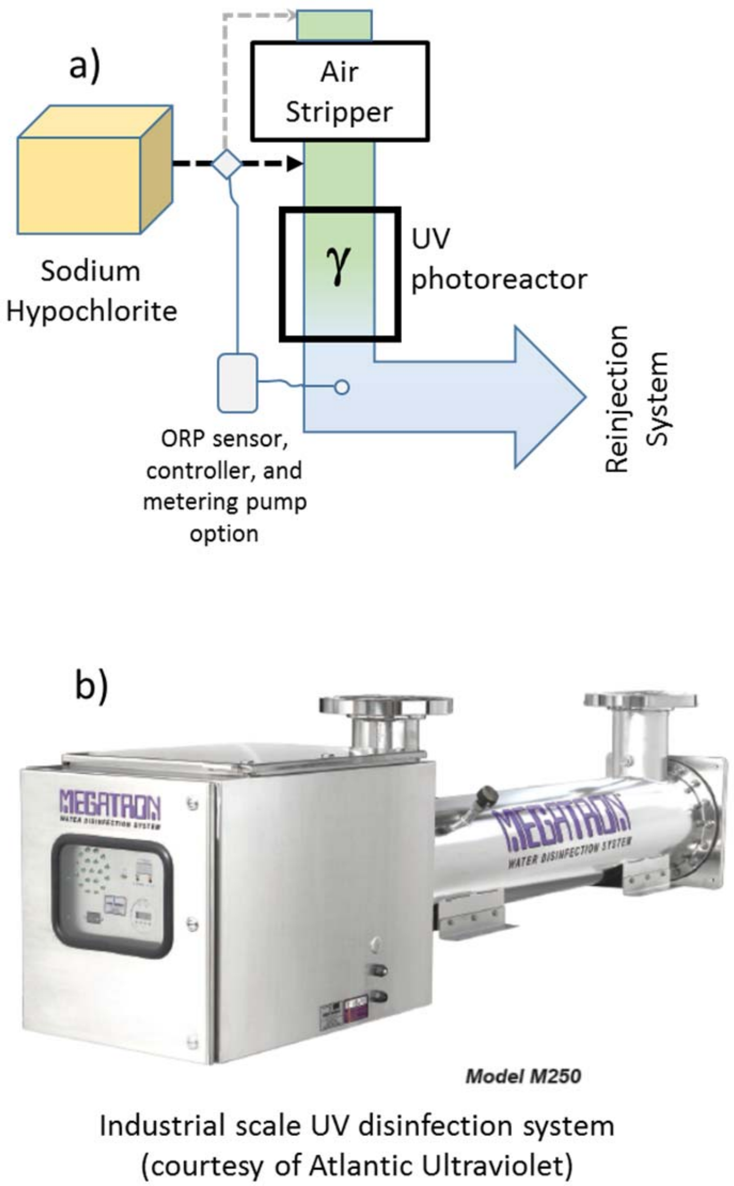



Figure 19. Illustration of potential AOP concepts/equipment– a) example system based on hypochlorite and UV oxidation and b) typical industrial scale unit.

Alternate Well Cleaning Methods (Wellhead Technology) –
Previous well cleaning efforts targeted fouling that was identified inside the well casing of the injection wells. As discussed, Carlson (2015) determined that a combination of sulfamic and citric acids worked well to dissolve metal oxides and sodium hypochlorite effectively removed the biological growth. These methods were coupled with intensive surging and development techniques to remove clogging material from the injection wells. While these techniques were effective in cleaning the interior of the well, fouling likely exists in both the gravel pack and the near well aquifer formation. This concept is illustrated if Figure 20 where biomass has blocked screen openings and penetrated filter pack and possibly the aquifer formation reducing the available flow area. The challenge is to identify well rehabilitation techniques and methods that will target fouling beyond the inner casing and into the gravel pack and near well formation.

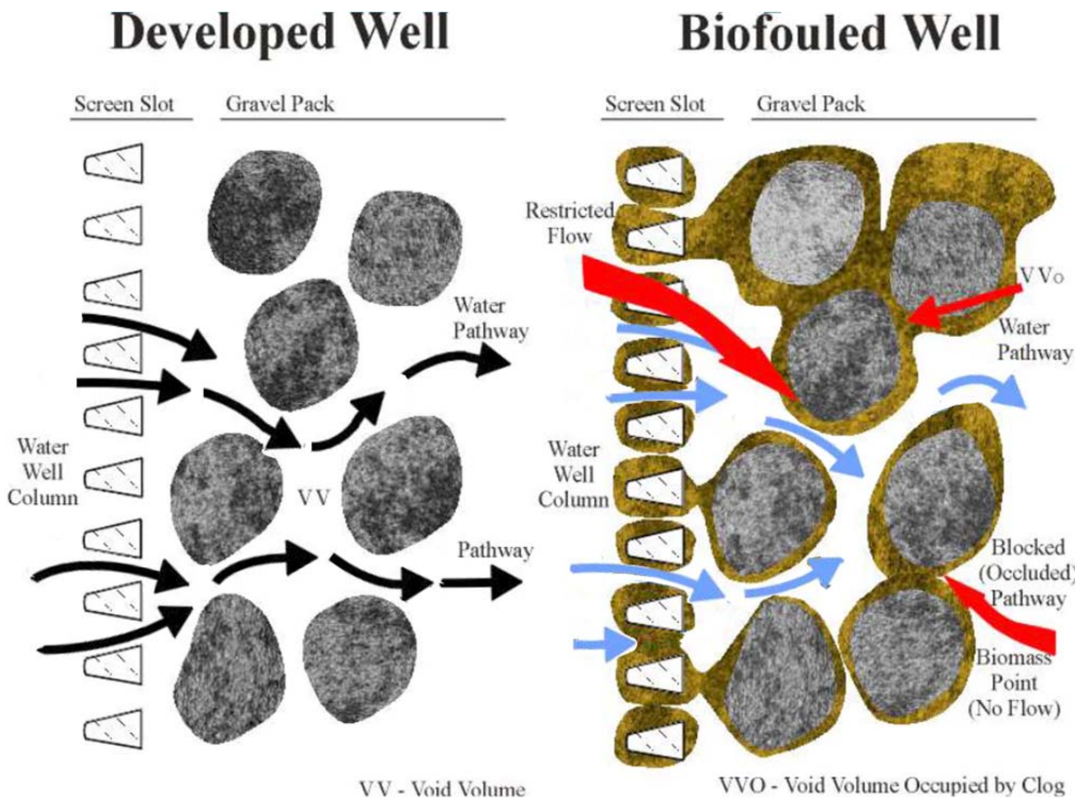



Figure 20 Developed well (left) with clean screen openings and voids in filter pack and formation open. Fouled well (right) where biomass has blocked screen openings and penetrated filter pack and formations reducing available flow area.

Well rehabilitation is defined as restoring a well to its most efficient condition by various treatments or reconstruction methods. Well rehabilitation is usually done when a well has deteriorated beyond the point when maintenance programs cannot resolve the decrease in yield. Rehabilitation of wells to restore or improve production requirements requires an evaluation of the probable causes of clogging. For the 200 West injection wells, video surveys determined that biological fouling was the dominant source of reduced well capacity with some mineral precipitation occurring. As identified by Carlson (2015), carefully tracking and managing of the FBRs and well performance monitoring are critical to balancing the needs of the treatment system while reducing fouling mechanisms in the injection wells. These activities coupled with removal and/or control of COD in the effluent, and future fouling issues should be minimized or eliminated.

One contributing factor to past biofouling may have been the use of phosphorous-based acids. While effective these acids have limited advantages over others except for sulfate salt removal. When used, phosphorus is left behind on minerals or residual Fe or Mn hydroxides and can serve as a nutrient for regrowth of bacteria.

Should additional rehabilitation of the injection wells be needed, application should be tailored for the specific well problem. Assuming future COD effluent and growth is controlled in the distribution lines of the 200W system, most of the residual fouling should be exterior of well casing. Generally this type of fouling requires "blended" or combined approaches. Most well service providers utilize surging and jetting approaches.

Surging with over-pumping is a common well rehabilitation procedure. Surging can be performed by using surge blocks or by injecting air in the casing above the well screen. It is labor-intensive, and often requires specialized equipment (e.g., service rigs). Manual brushing also is effective in dislodging material from the well screen and casing. Over-pumping involves removing water from the well, either by bailing or pumping, and allows water from the aquifer to flow into the well, removing any fines or biofilm fragments that were dislodged through surging or brushing. Jetting approaches also may be used to dislodge fines and biofilms from well screens. Jetting is carried out using a perforated jetting tool and a high-pressure water source. Because jetting has the potential to pack debris against the borehole wall, it is coupled with an airlift pump to promptly remove the debris.

More advanced (often trademarked or patented) technologies induce energy into the filter and gravel pack to dislodge materials. These include:

- Boreblast™ is a rehabilitation tool which can deliver up to 3500 psi of energy which provides percussive movement needed to break up deposits. Utilizing this technology has proven successful on its own but with the addition of chemicals this tool will deliver these chemicals deep into the formation and assist in dispersing mineral deposits with the powerful agitation employed with its use.
- Sonar Jet is a custom fabricated detonating cord that produces a harmonic frequency of shock waves to assist in mineral deposit removal.
- Aqua Freed is the controlled injection of liquid ($CO_2$). Liquid $CO_2$ expands 540 times from a liquid phase to the gaseous phase. It is this expansion which produces a great amount of energy to dislodge materials from the well screen, gravel pack and formation. This expansion also allows for greater penetration into the surrounding formations more than any other method of rehabilitation.

All of the listed services are available through Layne Christensen Company.

Percussive methods use downhole tools that generate rapid and high-energy pulses using high pressure air or other gas. Two methods that are available in North America are the Airburst Method, pulse generated by a Bolt Technologies gas gun, and the Airshock Method developed by Flow Industries, using a series of gas impulse guns of their own design. SRS evaluated an earlier variant of these technologies for effectiveness in both groundwater and vapor extraction wells (Burdick, 2000). The PulseWave technology utilizes the release of high pressure nitrogen in the screen zone to create "pressure bursts" which micro-fracture the formation, removing obstructions to flow. It is easily implemented and produces less investigation derived waste than conventional methods. However, the effectiveness of this technology was limited and the results did not indicate a reliable ability to increase well performance, in fact, reductions in performance were observed in some wells and improvements in performance were temporary in some of the other wells. Selection of this technology class (or any of the other technologies for improving well performance) should be based on documentation, and the likelihood that the selected method will address the specific challenges of the target wells.

Chemical well rehabilitation involves tailored strategies, based upon the cause of the problem, well construction details, and type of formation. The solutions must achieve effective removal of the fouling material, with good agitation and penetration into the surrounding formation. Our team understands that both phosphoric and sulfamic acid have been used in past applications at the 200 West injection wells. An alternative acid to consider is hydroxyacetic acid (glycolic acid).

Hydroxyacetic acid is less known and less used in well rehabilitation than hydrochloric acid (the most popular) or sulfamic acid. Hydroxyacetic acid has the benefit of being a bactericide that directly inhibits numerous bacteria, including “iron bacteria”, a common bacteria associated with biological fouling of wells. Glycolic acid has antibacterial and metal chelating properties, and is particularly suited to attacking iron bacteria biofilms. Being weaker than sulfamic acid, longer contact times are required.

Exploring alternate cleaning technologies that couple using targeted chemical agents with sonication/surging technologies that penetrate beyond the well screen are viable if fouling of wells continues to be an issue. Fortunately most states provide wide latitude on well rehabilitation methods.

Reinjection Well System – Screen Design (Wellhead Technology) –
The following section discusses alternative well screen materials for consideration by the Hanford team when installing future injection wells.

The 200W Pump and Treat system includes twenty-one (21) groundwater injection wells. These wells are 8 inches in diameter and are installed upgradient of the groundwater plumes to recharge the aquifer and downgradient for flow-path control. Section 2.2.3.4 of the remedial design report (DOE, 2010) indicates that the injection wells will generally be installed at a depth of approximately 82.3 m (270 ft) and have a screen length of approximately 45.7 m (150 ft). Further narrative in the injection well section stipulates that sieve analyses will be used to size the filter pack and well screen slot size as described for the extraction wells. The extraction wells (Section 2.2.3.3) are constructed of Schedule 10, Type 304 or Type 316, stainless-steel, V-slot, continuous wire-wrap screen equipped with an approximate 1.5 m (5-ft)-long, stainless-steel bottom sump and end cap.

Our discussions with engineers and technical staff indicate that the injection wells are constructed as described in the remedial design report with V-slot screens. This is supported by images presented in Figure 16 that depict injection well screen before rehabilitation and after rehabilitation. The image after rehabilitation appears to be an interior view of standard, V-slot, continuous wire-wrap well screen.

The use of continuous wire-wrap V-slot screen is standard for groundwater extraction wells. The well screen is fabricated using a continuous V-shaped wire that is wound around supports and welded to create a rigid well screen assembly. These are commercially available from numerous vendors. When a trapezoidal or triangular shaped cross-sectional wire is used to form the screen surface, V-shaped openings are created. These V-shaped openings are designed to be non-clogging with the narrowest opening at the outer face of the screen and widen inwardly. In groundwater extraction applications, this geometry ensures that oversized particles are retained outside the screen and not close off the openings Figure 21. A sand grain that will pass through the narrow outer part of the V-shaped opening enters the screen without wedging in the slot (Driscoll, 1986).

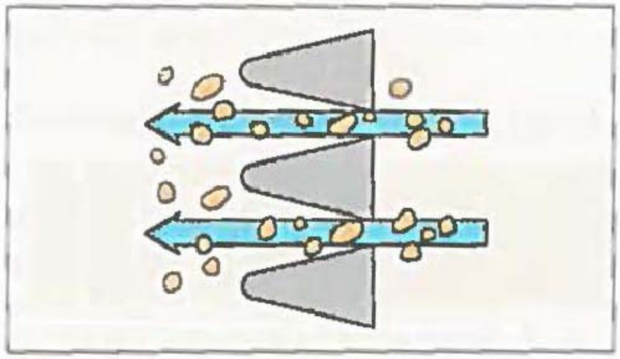
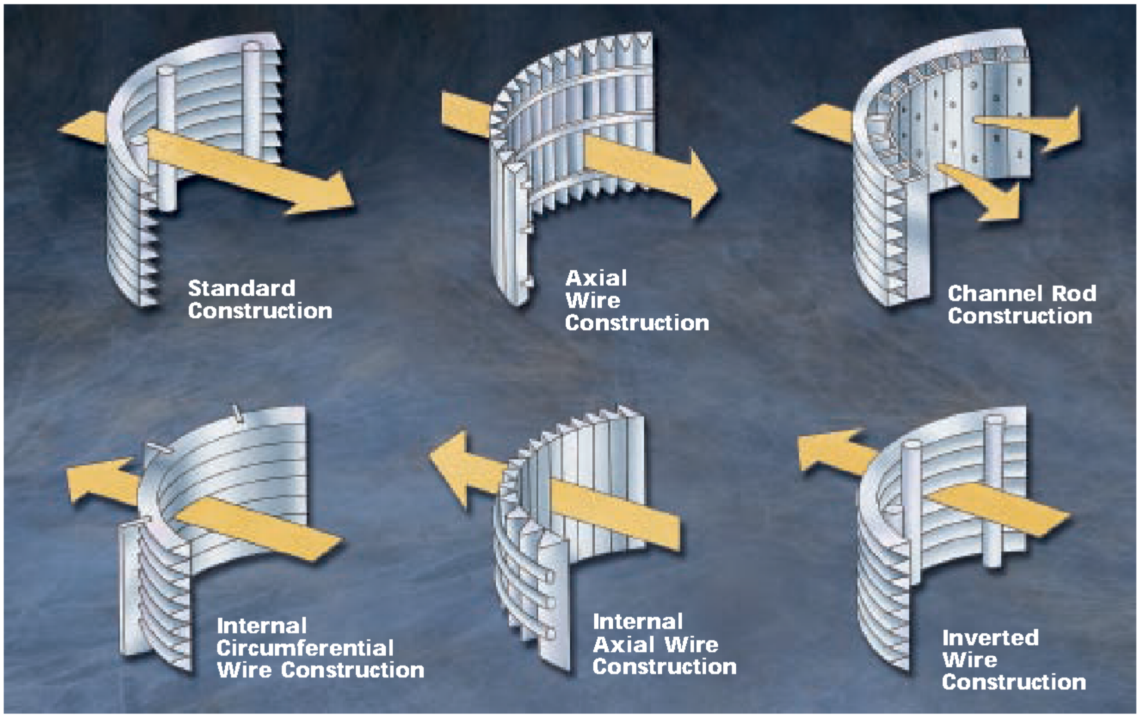


Figure 21. Slot openings are V-shaped in continuous-slot screen designs. The slots widen inwardly. Particles passing through the narrow outside opening can enter the well without clogging (Adopted from Driscoll, 1986).

Johnson Screen, Inc. (a subsidiary of Aqseptence Group, Inc.) is a recognized leader in Vee-wire™ screens for multiple industrial applications, including groundwater. Johnson screens provide welded cylindrical screens that are designed and categorized based upon the direction of fluid flow relative to the screen - either from the outside (extraction) or from the inside (injection) of the screen. Figure 22 provides a summary of screen configurations available based upon these flow directions (Johnson Screens, Inc., 2006).

When screens of the standard configuration are used for injection applications, any material entrained in the flow that is larger than the outside slot will be trapped and accumulate within the V-slot. This accumulation will likely be harder to remove due to the thickness off the wire and the penetration depth (thickness) of the accumulated material in the wedge shaped funnel. Screens manufactured using either the internal or inverted wire construction reduce the accumulation of material and help keep it on the interior surface of the well – simplifying cleaning. Of the three configurations (bottom row of Figure 22), either of the internal wire construction configurations are preferred as they both provide a smooth interior surface. Ideally any entrained material in the flow that does not pass through the screens would settle into the sump of the injection well where it could be periodically removed using air-lift pumping during scheduled maintenance periods. Due to the smooth surface of these designs the interior surfaces could be cleaned using wipers or brushes compared to the interior surfaces of the standard construction. While an improvement on the standard construction, the inverted wire construction does have the support wires internal to the screen which would hinder cleaning with wiper assemblies or brushes. The various screen designs used for injection are not as widely used and would likely be a special order (increasing cost and lead time). Since material costs are only a small part of the well installation costs, however, the increased screen cost should not substantially the overall cost of the well. The benefit of using these screens would be expected to be modest (incremental) – but using the correctly oriented screen is a recommended practice.

Use of alternative well screen materials for new injection wells is viable and recommended. Fitting injection wells with internal or inverted wire construction screen is feasible, and should be considered versus standard V-slot screens. Our team recommends the preferential use of internal circumferential or axial screen construction or alternative us of inverted wire construction screens for any wells that may need to be replaced.




**MULTIPLE CONSTRUCTION OPTIONS ARE AVAILABLE**

Our welded cylindrical screens can be categorized as designed with the media retention surface either on the outside or the inside of the screen.

EXTERNAL RETENTION SURFACE
(Outside-in flow)

**Standard Construction** features external circumferential wire and internal support rods.

**Axial Wire Construction** produces vertical slots which allow beds of media to move up and down without abrading the individual grains.

**Channel Rod Construction** uses perforated channels as the internal support elements and flow control surface. When used as a collector, flow is outside in; as a distributor, flow is inside out.

INTERNAL RETENTION SURFACE
(Inside-out flow)

**Internal Circumferential Wire Construction** uses external support rods to create an unobstructed internal screen face.

**Internal Axial Wire Construction** creates long, parallel slots. In vertical applications, media can move up and down with abrading. In horizontal rotating applications, flow moves across the wire edges for efficient dewatering.

**Inverted Wire Construction** presents the wire face to the cylinder interior and uses internal support rods.

Figure 22. Construction options available from Johnson Screens using Vee-wire™ geometry. Existing injection wells have standard construction screens with flow reversed. Internal or Inverted wire construction could reduce clogging (Johnson Screens, Inc., 2006).

Vadose Zone Infiltration (classified as Wellhead Technology) –
An alternative to injection wells would use near surface vadose infiltration (trenches or horizontal wells). This is described below and revisited in the subsequent nitrate objective section.

The capacity of injection wells to deliver water into the subsurface, and the fouling or clogging of these injection wells, is currently one of the significant issues impacting the throughput of the 200W system. Maintenance of the wells is labor intensive and drilling new wells to increase capacity is expensive. The Hanford team is exploring the alternative of near surface infiltration using trenches or horizontal wells (Figure 23). Infiltration has a number of potential advantages and disadvantages. Figure 23 highlights some of the key features of the infiltration concept currently being considered, notably: 1) the infiltration needs to be done in a relatively clean area where the percolating water will not mobilize past contamination, 2) the infiltrated liquids need to meet the 200 cleanup levels, and 3) the liquids need to effectively migrate downward (several hundred feet) to the water table to maintain water levels and to assist in hydraulic control of the groundwater plume. Currently, the site is working to identify areas that meet all of these criteria. An infiltration trench would provide the relatively robust ability to infiltrate large volumes of water into the subsurface; however the sustainability of the infiltration is not assured if the characteristics of the treated water are unchanged from past performance, specifically, treated 200W water resulted in high levels of biomass and biofouling in the injection wells and would likely result in similar fouling of an infiltration trench or horizontal well, though the performance reduction would likely occur over a longer timeframe. Thus, a fourth criterion should be added to those listed above: 4) designed to operate sustainably, maintaining capacity, minimizing fouling and minimizing O&M. The use of shallow infiltration does not eliminate the need to address the fundamental causes of biofouling.

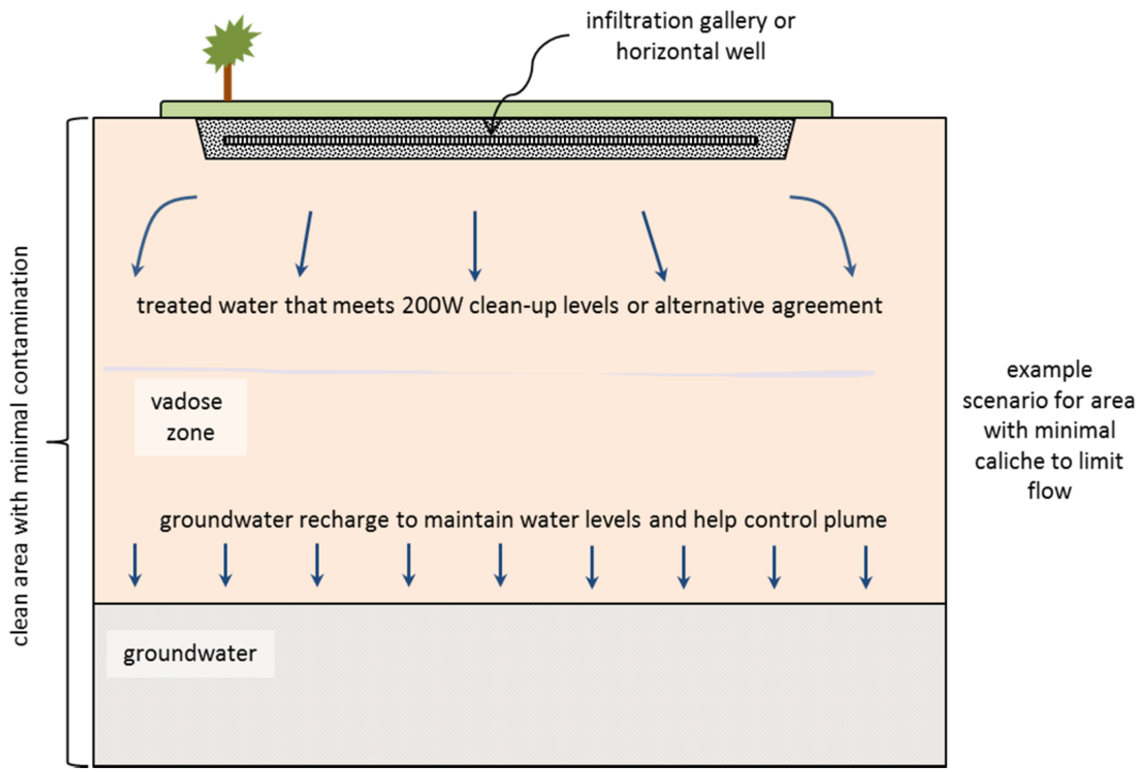



Figure 23. Schematic of shallow vadose infiltration highlighting key requirements that were emphasized by the Hanford team – this scenario is in an area with minimal caliche

To identify locations for possible shallow vadose infiltration, the Hanford team is currently focused on the challenge of assuring effective downward migration – since there is a low permeability caliche interval that occurs in the "mid-vadose" zone over much of the Central Plateau. Ideally, a location with little or no caliche could be identified. In Figure 23 this ideal scenario, minimal caliche, is depicted.

A potentially useful alternative is sketched in Figure 24. In this diagram, there is a significant caliche zone – water will tend to accumulate above this layer as perched water. The perched water will collect in low areas of the caliche and will migrate through areas where the caliche is thin or discontinuous (Figure 24 middle). This figure also depicts caliche bypass drains which can be installed to better control and distribute the downward movement of water. These would ideally be located in low areas (based on geophysical surveys) and would shunt water from above the caliche to the lower vadose zone to allow continued movement of water toward the water table (Figure 24 left and right). A caliche bypass drain is a simple system installed with standard drilling equipment. A borehole is drilled through the caliche and completed using a well screen and gravel pack; the riser pipe can sealed below grade or can be brought to the surface for monitoring purposes and/or for eventual abandonment. The cost for installing a caliche bypass drain should be less than an injection well and this technology would broaden the potential candidate areas for shallow vadose infiltration.

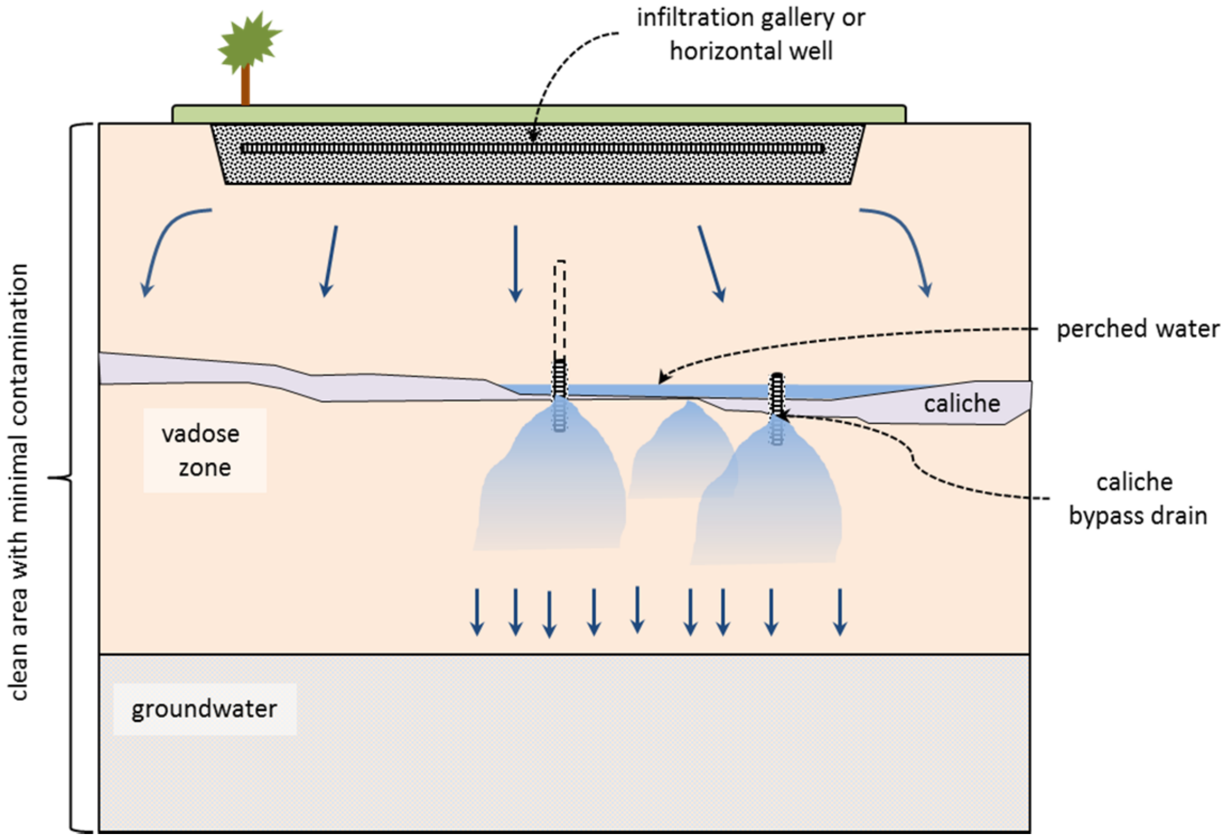



Figure 24. Schematic of shallow vadose infiltration highlighting the presence of perched water and potential use of caliche bypass drains

A large and continuous flow volume into the subsurface of will ultimately recharge the aquifer – in all cases either for shallow infiltration or deep injection. The selection of areas with minimal caliche and/or use of caliche bypass drains provides added assurance that the water that is infiltrated in the vadose zone will move as desired to meet the plume migration control objectives. As shown in Figures 23 and 24, water that is infiltrated will move downward due to gravity and laterally due to capillarity. Documentation of the performance of recharge could be monitored periodically using geophysics and by monitoring water levels in the underlying aquifer.

The large and continuous flow of water also relates to the potential for developing technically defensible alternative concentration limits and cleanup levels, because the water is released in a different subsurface location and percolates through several hundred feet of vadose zone. Unfortunately, nitrate is relatively mobile and is not subject to significant breakdown under the aerobic conditions typical in the Hanford subsurface. It would be difficult to set up a sustainable in-situ treatment zone (or permeable reactive barrier) because of the need to operate at high flowrate-continuously for decades. Based on these factors, it is likely that the cleanup levels for nitrate leaving the 200W treatment facility would need to remain at 10 mg/L to maintain the agreed level of protection – even with the expanded flow distances.

Near surface vadose infiltration is viable and conditionally recommended. For new capacity, this approach would likely cost less than using injection wells (i.e., more injection capacity per $). If the presence of caliche and perched water are problematic, then caliche bypass drains can be installed to shunt water to the lower vadose zone. Infiltration trenches are subject to the same biofouling as injection wells. Upstream modifications will be needed to remove nutrients and electron donors in order to sustainably use either infiltration or injection. The current 200W cleanup levels would likely need to be maintained for shallow infiltration due to the mobility and stability of nitrate.

#### *4.3.2 Nitrate Treatment Goals and Alternatives*

Nitrate is a contaminant that is common and well-understood in the State of Washington and in the western US. Because of this, the Hanford team may have opportunities to work with regulators and stakeholders to develop alternative nitrate treatment goals and/or strategies that are both protective of the environment and that simplify or reduce FBR operational challenges. The associated framework:

- Nitrate is one of the most common groundwater contaminants in the state of Washington (WA) (Morgan, 2016). As a result, WA state regulators and stakeholders have a deep and nuanced understanding of this contaminant
- Blended water in the 200W treatment system is about 30 to 50 mg/L – approximately 3 to 5x the allowable concentration in groundwater (i.e., the current 200W cleanup level of 10 mg/L) – note that future nitrate levels will vary and will be episodically higher depending on the areas being pumped
- Nitrate treatment operations and collateral impacts to the 200W treatment and reinjection systems are limiting the throughput of water and the associated ("important") treatment rate of radionuclides
- Nitrate pollution from agriculture, industry and urban runoff is common in the western US and has been widely studied – leading to a range of documented and successful innovative control strategies (e.g., Baker 1998).

Based on this framework, we evaluated three potential sub-options that represent alternatives to the baseline 200W system:

1) Develop Alternate Concentration Limits – Work with regulators and stakeholders to develop an alternative point of compliance and/or alternative concentration limit for injection (not recommended)
2) Vadose Infiltration – discussed above – using near surface trenches or horizontal wells rather than reinjection wells – include caliche bypass drains as needed (conditionally recommended)
3) Wetland treatment systems (eliminate FBR system entirely) – include caliche bypass drains as needed (not recommended)

<u>Develop Alternate Concentration Limits</u>

In this alternative, the Hanford team, in collaboration with regulators and stakeholders would work through the regulatory guidelines and the sequential steps to determine if an alternative concentration limit could be developed that would limit or mitigate risk and be protective of the environment. Typically the evaluation accounts for exposure scenarios(s), and estimated risk. Factors such the nature and strength of the contaminant source, as well as receptor location(s), institutional controls, hydrologic driving forces and site biogeochemistry will be important. At Hanford, negotiated long term planning documents, agreed end states, and umbrella documents/commitments on how limits will be set (e.g., the Tri-Party Agreement) would also control this sub-option. Based on our review, all of the above ideas were discussed and all of the governing documents and mechanisms were in place when the initial 200W cleanup levels were negotiated/set. Thus, while there may be a technical basis for setting somewhat higher limits by performing additional study (open regulatory and stakeholder discussions should continue), the potential for near-term success of this sub-option is low.

Developing and implementing Alternative Concentration Limits is technically viable and is conditionally recommended. We urge the Hanford team to continue active and vibrant technical dialog with regulators; however, the likelihood of expeditiously implementing alternate concentration limits is low unless regulators and stakeholders alter perspectives and risk weighting (e.g., considering the relative risks of technetium versus nitrate for example). Importantly, if injection/recharge infrastructure is modified (e.g., moving from injection wells to shallow vadose infiltration or engineered wetlands), the probability for developing a defensible and protective alternate concentration limit may be altered – serving as a basis for re-engaging regulators and stakeholders.

<u>Near surface vadose infiltration (trenches or horizontal wells) rather than reinjection wells</u>

This option was described above.

<u>Wetland treatment systems (eliminate FBR system entirely)</u>

Construction of an engineered wetland to treat nitrate is an extreme option to mitigate the issues associated with the FBR – such a system could eliminate the FBR and the aerobic membrane bioreactors. Nitrate pollution from agriculture, industry and urban runoff is common in the western US and has been widely studied – leading to a range of documented and successful innovative control strategies. While this technology class initially appears to be a poor match for the central plateau (arid high-desert grassland ecosystem), several of engineered wetlands for treatment of nitrate have been constructed in the western U.S. in similar settings (see Baker, 1998 and Gelt 1997).

A simplified schematic of an engineered wetland treatment system is shown in Figure 25. The major advantage of this system would be bypassing the existing FBR and associated processes. Electron donor and nutrients would be dosed into the water after the air stripper – immediately before release into the wetland. Typically, these constructed wetlands are designed based on a target ratio of carbon (electron donor) to nitrate – similar to the FBR and using similar ratios (Baker, 1998; Lu et al., 2009). The required size and approximate performance can be estimated based on the technical literature: a) for 200W the required area of constructed wetland would be about 150,000 square m assuming a hydraulic load of 0.1 m/day, with b) a nominal nitrate removal in the range or 70 to 80%. The wetland treatment cells and the infiltration ponds/galleries would need to be located in the areas where re-infiltration is desired. The same overarching criteria as near surface vadose infiltration would need to be followed along with the potential need for caliche bypass drains. Constructed wetlands, in the right settings and implementations, are often considered a "green" treatment that would generate a area with interesting diversity and ecology.

Unfortunately, this concept has many disadvantages and major risks. In the central plateau, this system would result in a major ecosystem perturbation – requiring planting of non-native species and allowing growth of and drawing in non-native flora and fauna. The geochemistry and buildup of carbon in the wetland have the potential for concentrating trace contaminants (constituents that are initially present well below standards) potentially generating waste. After operations cease, the wetland system would be unsustainable, potentially requiring costly restoration activities. Based on the literature (e.g., Chang et al., 2013), denitrification rates in winter would be significantly lower than the nominal values. The system would not return all of the pumped water to the subsurface due to evapotranspiration – however the amount of water lost would be relatively small (<3% of the total flow based on the area listed above assuming a reasonable potential evapotranspiration rate in the 200W area of 1 m/yr (Farnsworth et al., 1982)). Clogging of the anaerobic sediments would reduce infiltration over time and separate area for infiltration might be required. Elimination of the FBR and aerobic membrane bioreactor is both an advantage (reducing costs to offset resources needed for wetland construction and monitoring) and a disadvantage (system does not beneficially use existing infrastructure for nitrate removal). Finally, the open constructed wetland system would provide limited process control options for adjustment if nitrate removal is insufficient.

We assessed this option to be viable but not recommended. While the idea has a technical basis for consideration, the disadvantages are numerous and overwhelming.

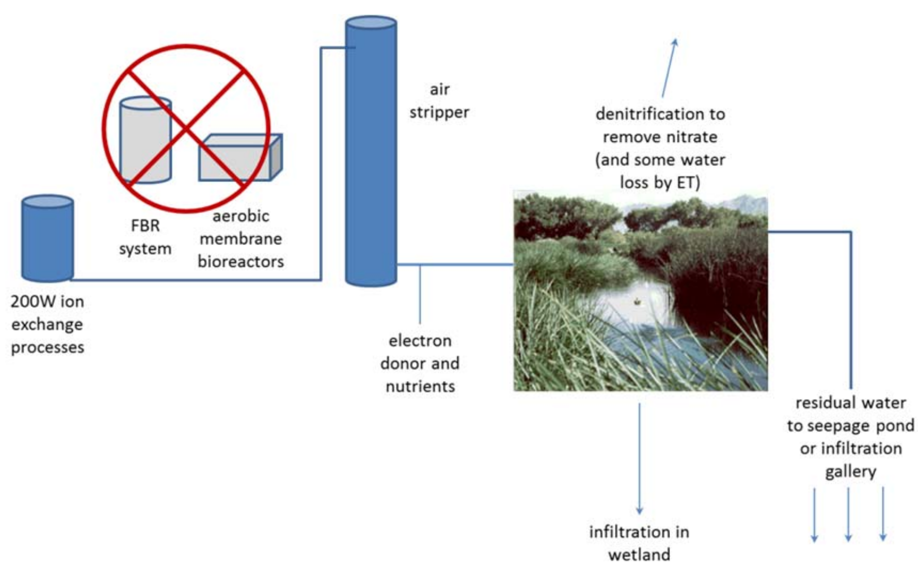



Figure 25. Simplified schematic of a constructed wetland system to perform denitrification and reinfiltrate water to the subsurface

## 5.0 Conclusions

The centerpiece of the evaluation and conclusions is a table that provides a matrix summary of the above discussion (Table 2). This table is organized by rows that represent each of the topics and sub-topics that we evaluated. Figure 26 is a snapshot and roadmap for these topics and sub-topics. The table's columns include: (1-2) name and description, (3-6) the various evaluation categories (potential benefits, implementability/cost, advantages and disadvantages), and (7) a summary assessment. Each cell within the table represents a synopsis of our team's consensus evaluation. The summary assessments were binned as follows: viable and recommended, viable and conditionally recommended, viable but not recommended, and not viable. If a technology was designated as viable and conditionally recommended, then the summary also includes a description of the associated conditions. A condition might indicate technologies that need to be done in combination to be fully effective. Alternatively, in the case of two technologies that target the same issue, the condition might indicate order of preference and the distinguishing selection criteria. Specific examples are provided in the Recommendations section below. In several cases, we included the baseline technology/approach in the table and affirmed and/or annotated recommended adjustments to the baseline.

The alternative strategies and technologies were binned as follows:

<u>Viable and Recommended:</u>
(Cleaning of Bed Solids) - Processing of Bed Solids using Integral Inlet Eductor(s)
(Cleaning of Bed Solids) - Recirculation of Bed-Solids using diaphragm pump
(Bed-Solids "Core" Substrate) - Consider Change-out of bed-solids substrate to a new material
(Bed-Solids Separator Design) - Adding a continuous anti-clogging system
(Post-Treatment Options to Support Reinjection) – Consider Alternative Anti-Scalant
(Post-Treatment Options to Support Reinjection) - Reinjection Well Screen Design

<u>Viable and Conditionally Recommended</u>
(Cleaning of Bed Solids) - In-Tank Sonic Cleaning
(Electron Donor) - Type of Liquid Carbon Substrate
(Microbial Nutrients and FBR Geochemistry) - Use of chelating agent salts for some trace nutrients
(Fluidized Bed Vessel Design and Hydraulics) - Adjusting recycle flow in response to bed-solids density
(Fluidized Bed Vessel Design and Hydraulics) - Replacing components to increase resilience
(Bed-Solids Separator Design) - Increasing the bed-solids separator capacity
(Bed-Solids Separator Pretreatment) - In-line static mixer
(Bed-Solids Separator Pretreatment) - In-line sonicator
(Bed-Solids Separator Supplementation) - Magnetic Solids Collection
(Post-Treatment Options to Support Reinjection) – Disinfection
(Post-Treatment Options to Support Reinjection) - Removal of COD using supplemental biotreatment
(Post-Treatment Options to Support Reinjection) - Removal of Residual COD using AOP
(Post-Treatment Options to Support Reinjection) - Vadose Zone Infiltration
(Nitrate Treatment Goals and Alternatives) - Develop Alternate Concentration Limits

<u>Viable but Not Recommended</u>
(Nitrate Treatment Goals and Alternatives) - Wetland Treatment System

<u>Not Viable</u>
(Fluidized Bed Vessel Design and Hydraulics) Modifying FBR Vessel Geometry
(Bed-Solids Separator Design) Increasing the slurry flow rate
(Bed-Solids Separator Design) Redesigning the recycle / effluent line collection funnels
(Bed-Solids Separator Design) Relocating the recycle line location/configuration

Affirmed Baseline
(Electron Donor) - Quantity of Liquid Carbon Substrate
(Electron Donor) - Control Strategy
(Microbial Nutrients and FBR Geochemistry) – Control Strategy
(Monitoring) - Chemical Parameters and Hydraulics – Baseline

Extend Baseline or Continue Baseline until Alternative is in Place
(Cleaning of Bed Solids) Multilevel Eductor (Manual Operation) – Baseline
(Monitoring) - FBR bed height
(Post-Treatment Options to Support Reinjection) - Alternative Well Cleaning

## 6.0 Recommendations, Path Forward or Future Work

The technical assistance process is structured to triage technologies and strategies that address the issues and objectives provided to the team. The process encourages brainstorming, dialog and allows rapid identification and prioritization of possible options. The result is a simplified systems engineering analysis, it is not a detailed design or formal engineering calculation. This is a key reason that the output is partitioned into broad bins. This allows the site engineers, managers and other experts to further vet the options, and to develop a plan that is most consistent with local conditions. As technologies are more formally selected for implementation, additional engineering evaluations will need to be performed and formal designs developed. On any of the technology/strategy topics, particularly for cases where an innovative concept was initially envisioned and proposed by the technical assistance team, we can provide additional evaluation and more detailed support as a part of future work.

In a few cases, there are multiple technologies that are viable and recommended, or conditionally recommended, to address the same issue – for example the three alternatives for bed-solids cleaning. In this specific example, we recommended primary consideration of an integral inlet eductor or diaphragm pump recirculation and performance of a pilot test. We indicate that in-tank sonication is a viable backup that could be used if problems or issues with the primary options are identified. A similar scenario is in play for two options for pretreatment of bed-solids prior to the bed-solids separator (inline static mixer versus in-line sonicator). It is interesting that three innovative sonication based technologies were ultimately evaluated for potential application to the 200W FBR. Two were for bed solids cleaning, and one for anticlogging. The potential applicability of this class of technology throughout the 200W system is related to the nature of the solids in the FBR and the types of handling and manipulations required. After the evaluation, only the anticlogging system was ranked as viable and recommended – the other two sonication technologies are backup technologies to more mature and/or lower cost methods. The unexpected potential for broad applicability of sonication is notable, however and might inform future responses to technology needs in the 200W system.

The challenges of the 200W FBR system are complex and inter-related. Therefore, a combination of actions will be needed to move toward more stable and robust operations. We recommend assembling a portfolio of compatible technologies from the viable and baseline bins above. Alternative portfolios will have different levels of cost and risk. Many portfolios are possible that range from relatively low cost (likely to improve performance but with a lower level of confidence) to very high cost options that would substantially improve performance with a high level of confidence. A few of these are listed below:

**Low cost portfolio (improved bed solids control and reinjection capability):**

- Cleaning of Bed Solids – Processing using Integral Inlet Eductor or Recirculation of Bed-Solids using diaphragm pump
- Bed-Solids "Core" Substrate - Consider Change-out of bed-solids substrate to a new material
- Bed-Solids Separator Design - Adding a continuous anti-clogging system
- Electron Donor - Type of Liquid Carbon Substrate
- Microbial Nutrients and FBR Geochemistry - Use of chelating agent salts for some trace nutrients
- Fluidized Bed Vessel Design and Hydraulics - Adjusting recycle flow in response to bed-solids density
- Fluidized Bed Vessel Design and Hydraulics - Replacing components to increase resilience
- Bed-Solids Separator Pretreatment - In-line static mixer
- Post-Treatment Options to Support Reinjection - Alternative Anti-Scalant
- Post-Treatment Options to Support Reinjection – Disinfection
- Post-Treatment Options to Support Reinjection - Reinjection Well Screen Design
- Monitoring - FBR bed height
- Post-Treatment Options to Support Reinjection - Consider Vadose Zone Infiltration

**Medium cost portfolio option 1 (further improves reinjection capability over low cost portfolio):**

- All items in low cost option
- Post-Treatment Options to Support Reinjection - Removal of COD using supplemental biotreatment or AOP

**Medium cost portfolio option 2 (further improves bed solids control over low cost portfolio):**

- All items in low cost option
- Supplemental Magnic Solids Collection - Increasing the bed-solids separator effectiveness

**Medium-High cost option 1 (further improves bed solids control over low cost portfolio):**

- All items in low cost option
- Bed-Solids Separator Design - Increasing the bed-solids separator capacity

**Medium-High cost option 2 (further improves all capabilities over low cost portfolio):**

- All items in low cost option plus
- Supplemental Magnic Solids Collection - Increasing the bed-solids separator effectiveness
- Post-Treatment Options to Support Reinjection - Removal of COD using supplemental biotreatment or AOP

**High cost portfolio (further improve all capabilities over low cost option):**

- All items in low cost option plus
- Bed-Solids Separator Design - Increasing the bed-solids separator capacity
- Post-Treatment Options to Support Reinjection - Removal of COD using supplemental biotreatment or AOP

A reasonable path forward would be to phase key activities in the in the low cost portfolio and determine performance and effectiveness.

**Improving Bed Solids Separation and Control in the Fluidized Bed Reactor Vessel:**

- **Bed-Solids Cleaning**
  - Manual Eductors (Baseline)
  - Processing Bed-Solids using Integral Inlet Eductor
  - Recirculation of Bed Solids using a Diaphragm Pump(s)
  - In-Tank Sonication System
- **Bed-Solids ("Core") Substrate**
  - Change-out bed-solids substrate to a new material
- **Electron Donor (Liquid Carbon Substrate)**
  - Quantity of Liquid Carbon Substrate
  - Control Strategy
  - Type of Liquid Carbon Substrate
- **Microbial Nutrients and FBR Geochemistry**
  - Microbial Nutrients and FBR Geochemistry
  - Use of chelating agent for some of the trace nutrients
- **Fluidized Bed Vessel Design and Hydraulics**
  - Adjusting recycle flow in response to bed-solids density
  - Replacing components to increase resilience
  - Modifying FBR Vessel Geometry
- **Monitoring**
  - Monitoring chemical parameters and hydraulics
  - Monitoring FBR bed height

**Improving Bed-Solids Separation and Control in the Bed-Solids Separator:**

- **Bed-Solids Separator Design**
  - Increasing the slurry flow rate
  - Redesigning the recycle / effluent line collection funnels
  - Relocating the recycle line location/configuration
  - Adding a continuous anti-clogging system
  - Increasing the bed-solids separator capacity
- **Bed-Solids Separator Pretreatment**
  - In-line static mixer
  - In-line sonicator
- **Bed-Solids Separator Supplementation**
  - Magnetic Solids Separation

**Overall FBR Related Collateral Impacts to 200W Treatment System**

- **Post-Treatment Options to Support Reinjection**
  - Alternative Anti-Scalant (In Plant Technology)
  - Disinfection (In Plant Technology)
  - Removal of Residual COD using supplemental biotreatment (In Plant Technology)
  - Removal of Residual COD using AOP (In Plant Technology)
  - Alternative Well Cleaning (Wellhead Technology) - Baseline
  - Reinjection Well Screen Design (Wellhead Technology)
  - Vadose Zone Infiltration (classified as Wellhead Technology)
- **Nitrate Treatment Goals and Alternatives**
  - Develop Alternate Concentration Limits - Baseline
  - Vadose Zone Infiltration (see above)
  - Wetland Treatment System

Figure 26. Roadmap for the topics and sub-topics (rows) in Table 2

| Technology/ Strategy | Description | Potential Benefit (- 0 +) | Implementability (- 0 +) / Cost (high medium low $) | Advantages | Disadvantages | Overall |
|---|---|---|---|---|---|---|
| **Improving Bed Solids Separation and Control in the Fluidized Bed Reactor Vessel** | | | | | | |
| **Cleaning of Bed Solids** | | | | | | |
| Multilevel Eductor (Manual Operation) - Baseline | Operate eductors positioned at different depths in the FBR (as needed) to mechanically agitate and clean biomass off of particles | - to 0<br>Baseline -- no added benefit -- equipment in place and currently operating with existing procedures | + / low $ | Currently operating and providing some control on biomass | Requires monitoring and response via manual operation; does not provide continuous steady state biomass control for stable operation | Continue as baseline if one of the alternatives is not selected |
| Recirculation of Bed-Solids using diaphragm pump | A pneumatic diaphragm pump is used to recirculate a slurry of bed-solids. Excess bacteria are separated from the solids by hydraulic shear. In the simplest embodiment the solution of separated biomass and solids is returned to the FBR. | 0 to +<br>System would simplify operation and allow continuous bed cleaning | 0 to + / low to medium $<br>pilot testing would be prudent | Modification currently used in similar commercial FBRs; a simple recirculation system can be implemented using the existing FBR access points. | Diaphragm pump uses compressed air, current plant compressors are near capacity. Full implementation may require upgrade to plant air capacity. | Viable and recommended -- this is a good option for cleaning of bed solids. This modification is being implemented commercially in similar biological based FBR systems. A simple recirculation system can be implemented using the existing FBR access locations. |
| Processing of Bed-Solids using integral inlet eductor | A an eductor based alternative concept for continuous or semi-continuous bed-solids processing/cleaning. For deployment, an eductor is placed just below the target FBR bed height. FBR inlet water (rather than finished process water) is used as the motive fluid. The eductor would pump FBR fluids and remove biomass from the contained bed-solids as a result of internal turbulence. | 0 to +<br>System would simplify operation and allow continuous bed cleaning | + / low to medium $<br>pilot testing would be prudent | We project that such a system would perform similarly to the recirculating diaphragm pump -- can be implemented using the existing FBR access points and existing freeze protected lines. | Would require some testing and procurement of booster pump and in-line eductor. | Viable and recommended -- this is a preferred option for cleaning of bed solids. |
| In-Tank Sonic Cleaning | Sonication introduces high frequency sound energy into a solution to clean parts or components. Operate sonic transducers in the upper portion of the FBR to strip biomass. Adjust frequency and energy to achieve steady continuous operation | 0 to +<br>System would simplify operation and allow continuous bed cleaning | 0 to + / low to medium $<br>Innovative technology idea - some development and testing would be needed | Potential for simple and compact installation and continuous operation | Innovative technology (development needed); potential for added sound in the area of the FBR | Viable and conditionally recommended -- consider this technology if the diaphragm pumping option is not implemented or have the desired effectiveness |
| **Bed-Solids ("Core") Substrate** | | | | | | |
| Change-out bed-solids substrate to a new material | Replace GAC with another material such as zeolite with a higher density and the potential for more effective separation | 0 to +<br>promising concept to improve performance | 0 to + / low to medium $<br>swap out - alternative bed solid substrates would have similar or lower costs | Straightforward to implement with a relatively high TRL; likely could be implemented with existing equipment. | Requires technical evaluation and quantification of benefits and risks; requires process engineering and documentation; need to make sure that any material selected will not worsen downstream impacts (e.g., abrasion of pumps); need to make sure that a new bed profile and attached biofilms will adequately remove nitrate. | Viable and recommended. Study and consideration of this option would support potential changes and improved bed-solids performance |
| **Electron Donor (Liquid Carbon Substrate)** | | | | | | |
| Quantity of Liquid Carbon Substrate | Baseline - Deficient or excessive electron donor can lead to an unstable biological community in the FBR or to underperformance of denitrification; Current carbon addition protocols are reasonable and performing well; each FBR system requires fine-tuning based on monitoring data and process engineering decision meetings. | ------------------- | ------------------- | ------------------- | ------------------- | Affirm Baseline |
| Control Strategy | Baseline - ibid. | ------------------- | ------------------- | ------------------- | ------------------- | Affirm Baseline |
| Type of Liquid Carbon Substrate | Alternative liquid carbon substrate to increase kinetic rates while maintaining safety, cost and operability. The recommended liquid carbon substrates for consideration focus on those with improved kinetics and that can be deployed using existing equipment (e.g., acetic acid or MicrCg2000 (glycerin based), or sodium acetate) | 0<br>Expect modest (incremental) benefit | + / low $<br>simple swap out - alternative liquid carbon substrates would have similar or lower costs | Faster and/or more complete reactions would reduce COD carry over from FBR and improve nitrate removal effectiveness | Requires technical evaluation and quantification of benefits and risks; requires process engineering and documentation | Viable and conditionally recommended. Implementation should be considered if the Hanford team has compelling reasons to reduce the carry over of COD to the aerobic membrane bioreactors or modestly improve nitrate control. |

| Technology/ Strategy | Description | Potential Benefit (- 0 +) | Implementability (- 0 +) / Cost (high medium low $) | Advantages | Disadvantages | Overall |
|---|---|---|---|---|---|---|
| **Microbial Nutrients and FBR Geochemistry** | | | | | | |
| Microbial Nutrients and FBR Geochemistry | Baseline - Deficient or excessive nutrient levels can lead to overproduction of biofilm or underperformance of denitrification; Current micronutrient dosing rates suggest sufficient nutrient availability for microbial growth; each FBR system requires fine-tuning based on monitoring data and process engineering goals. | ------------------- | ------------------- | ------------------- | ------------------- | Affirm Baseline |
| Use of chelating agent for some of the trace nutrients | Consider EDTA (chelate) salts of key nutrients (e.g., iron) to improve solubility and stability of dosing solution and make these ions readily available in solution to the FBR microbial community. | 0 to +<br>may improve robustness of nutrient addition | + / low $<br>simple swap out - alternative nutrient mix would be modestly more expensive | Straightforward change and potential for improved micronutrient solution stability and increased metal solubility. EDTA is a better chelator than current additives. EDTA should biodegrade in FBR and/or MBR. | Would require new chemical formulation and associated planning and procedure changes. Would require a period of close monitoring to adjust and optimize new mix. | Viable and conditionally recommended. Consider use of EDTA salts if micronutrient mix, stability and solubility are sources of problems. |
| **Fluidized Bed Vessel Design and Hydraulics** | | | | | | |
| Adjusting recycle flow in response to bed-solids density | Refine flowrates to reduce carry over. | - to 0<br>Expect limited benefit beyond the optimization that has occurred to date | + / low $<br>ongoing | If bed-solids control could be achieved using simple flow adjustment, it would provide the lowest cost option | This type of refinement has been ongoing with limited success to date - would not add any robustness to the bed-solids control | Viable and conditionally recommended. This needs to continue and be combined with other options to increase robustness of control and operation |
| Replacing components to increase resilience | Replace nozzles in the base of the FBR, pump components and selected piping to improve resistance to abrasion and damage from entrained solids. Use resilient material such as stainless steel. | 0 to +<br>improve short term operations by reducing O&M | 0 to + / low to medium $<br>components are more costly but offset by reduced O&M moving forward | Would provide short term benefit of reduced O&M | Does not address underlying issue of poor bed-solids control. Other actions to reduce bed-solids carryover and recycle would need to be done also. | Viable and conditionally recommended. Does not address fundamental issue and represents a temporary (short term) benefit -- not the stable sustainable operation requested by DOE. This is a prudent action but need to be combined with other actions. |
| Modifying FBR Vessel Geometry | Expand the upper region of the FBR vessels to reduce upflow velocities in that zone and better pin down the bed level and limit particle movement. | 0 to +<br>Promising concept to improve performance | + / high $<br>major project | Would add significant robustness to the bed-solids control. | Major engineering and retrofit would result in extended downtime. Likely to be infeasible for existing FBR vessels. | Not Viable for existing FBR vessels. Consider this option for a new treatment train if added in the future. |
| **Monitoring** | | | | | | |
| Monitoring chemical parameters and hydraulics | Baseline - Daily process monitoring of key parameters along with and more complete weekly or monthly monitoring are performed. The data are tabulated and control charts are generated and used to inform process engineer meetings that generate refined algorithms for the operators. In general, this is a best practice. | ------------------- | ------------------- | ------------------- | ------------------- | Affirm Baseline |
| Monitoring FBR bed height | Baseline -To date, systems for monitoring bed height in the FBR have underperformed. The initial sonar based sensors did not provide data of sufficient quality to support the process engineers. We recommend that the Hanford team consider revisiting other brands of sonar to see if an alternative has the potential for improved performance. A video monitoring system is currently in use but requires significant O&M (to keep the lens clean) and is a challenging hands-on operation (camera must be within a few inches of the interface to provide a reliable visualization). The Hanford team has discussed developing a wiper system for the video lens - such a system is relatively straightforward and could work. | ------------------- | ------------------- | ------------------- | ------------------- | Affirm Baseline with the added recommendation to revisit alternative vendors for sonar to determine if different signal processing might provide more reliable data. Note that sonar may perform better if using a denser bed-solids core substrate (see related recommendations). While a wiper has been proposed for the optical system, an optical based technology is not considered the right solution for the problem. |

| Technology/ Strategy | Description | Potential Benefit (- 0 +) | Implementability (- 0 +) / Cost (high medium low $) | Advantages | Disadvantages | Overall |
|---|---|---|---|---|---|---|
| **Improving Bed Solids Separation and Control in the Bed-Solids Separator** | | | | | | |
| **Bed-Solids Separator Design** | | | | | | |
| Increasing the slurry flow rate | Increase the pumping of slurry from the bottom of the bed-solids separator back to the FBR | - Minimal projected benefit | 0 to + / low $ | Straightforward action | The slurry flow rate is only about 0.5% of the total in the system -- changes in this rate (even large factors such as 5x) would be projected to have minimal impact on overall bed solids performance. | Not viable. Expected benefit would be minimal. |
| Redesigning the recycle / effluent line collection funnels | Fabricate docking assemblies to redesign collection funnels to increase the active length and decrease turbulence | - Insufficient space available and minimal projected benefit | 0 / low to medium $ requires rework and re-piping | Potential to collect water with less local velocity and turbulence. | Unlikely to provide much improvement in performance; minimal impact because solids are being efficiently delivered to the top of the bed-solids separator and will be collected by any geometry of collection system; would require moderate design effort and likely require some testing to assure no adverse collateral impacts. | Not viable. Expected benefit would be minimal. |
| Relocating the recycle line location/configuration | Draw a portion of recycle out of the bed-solids separator feed line (and blend with the primary recycle line) or relocate the main recycle line to collect fluids lower in the separator vessel. This will reduce turbulence in the bed-solids separator and provide more vertical distance with a lower upward Darcy velocity | - Minimal projected benefit | 0 / low to medium $ requires rework and re-piping | The length of The zone with reduced upward flow rate would be broadened; some of The turbulence in the bed-solids separator could be reduced. | This approach would require significant engineering and equipment modification and would be unlikely to reduce upward flow sufficiently to have a significant beneficial impact; the approach has the potential to for adverse impacts such as incrementally increasing the solids recycled back to for fluidization flow. | Not viable. Expected benefit would be minimal. |
| Adding a continuous anti-clogging system | Mount ultrasonic transducers on the external surface of the bed-solids separator (analogous to use for antifouling on boat hulls) in the lower angled cyclonic separation portion of the vessel. These would operate continuously or semi-continuously to help maintain bed-solids control. | 0 to + Promising concept to improve performance | 0 to + / low $ straightforward concept using available commercial equipment | In the bed solid separator, the vibrations would maintain the downward flow of bed-solids after collection by cyclonic action and keep them from clumping and/or sticking to the walls of the separator vessel. The solids would continue to “walk down” the wall to maximize collection by the eductor for transfer back to the FBR. | New application -- some testing would be prudent. Need to confirm that vibrations will not cause long term damage to fiberglass tank. | Viable and recommended |
| Increasing the bed-solids separator capacity | Adding bed solid separator capacity is a major system modification. The most cost effective approach would be to use the existing bed-solids separators to service one of the FBRs and to add a new (larger diameter) bed solids separator to service the other FBR; the output from one of the FBRs would feed both current bed-solid separators; the other FBR would be connected to the new separator unit. | + Promising concept to improve performance | - to 0 / high $ A major system modification with a high cost. | The lower feed flow to the separators would: 1) reduce turbulence – maximizing the performance of the cyclonic separation, and 2) reduce upward flow velocity and increase residence time in the separator – allowing additional settling of solids; Additional bed-solids separator capacity would provide more robustness, reduce bed-solids carry-over and recycle, and improve 200W FBR performance. | Significant design changes would be required, a new bed solids separator would need to be acquired, process control systems and procedures would require modification, training would need to be updated, and installation would result in an extended system outage. It is likely that additional supplemental actions such as installing an anti-clogging system or bed-solids pretreatment might be required in conjunction with this change to provide maximum benefit. | Viable and conditionally recommended. This system upgrade should be considered if alternative actions, or combinations of actions, are not able to provide the desired robustness in long-term performance. This particular action represents one of the highest cost alternatives and should be one of the most impactful on operations. |
| **Bed-Solids Separator Pretreatment** | | | | | | |
| In-line static mixer | Install an in-line static mixer to remove biomass and strip biofilms from the entrained particles to increase particle density and reduce particle stickiness, thereby improving the performance of the bed-solids separator. The mixer provides high levels of turbulence by forcing the flowing liquid around mixing baffles causing particle-particle contacts that would physically abrade/remove biomass. | + Promising concept to improve performance | 0 to + / low to medium $ straightforward concept using available commercial equipment | A passive pretreatment that requires no active operation, minimal maintenance, and *de minimis* change in hydraulics and energy within the system. A standard stainless steel mixer would provide a base design performance with a head loss of about 0.12 ft. If mounted in the vertical section of line between the FBR and the bed-solids separator, there would be minimal potential for buildup of solids in the mixer assembly virtually eliminating maintenance. | Compared to sonication, an inline static mixer would likely provide less energetic stripping of biomass from the entrained bed solids | Viable and conditionally recommended. Selection of this technology should be considered if: 1) testing confirms the presence of high biomass on entrained bed-solids, and 2) testing confirms that the turbulence in a static inline mixer is sufficient to remove biomass to the extent required. If these conditions are met, then pretreatment with a static inline mixer is a preferred option. |

| Technology/ Strategy | Description | Potential Benefit (- 0 +) | Implementability (- 0 +) / Cost (high medium low $) | Advantages | Disadvantages | Overall |
|---|---|---|---|---|---|---|
| In-line sonicator | Inline sonication is an alternative pretreatment technology to remove biomass from entrained bed solids . The fluid exiting the FBR would pass through a reactor equipped with high-energy ultrasonic transducers. Low (25 kHz or less) to moderate (40 kHz) ultrasonic frequencies would be employed at a high power level to strip biofilms and biomass from the entrained particles. | + Promising concept to improve performance | 0 to + / low to medium $ straightforward concept using available commercial equipment; would require more development than static mixer | Compared to the static inline mixer, the ultrasonic reactor would provide more aggressive biomass removal. | Implementation would require more intensive testing and development efforts. The ultrasonic option would: 1) be more costly, 2) require energy to operate, 3) require more O&M and procedure development, and 4) would add additional sound to the environment around the FBR and bed-solids separator. | Viable and conditionally recommended -- Selection of this technology should be considered if: 1) testing confirms the presence of high biomass on entrained bed-solids, and 2) testing confirms that the turbulence in a static inline mixer is not sufficient to remove biomass to the extent required. |
| **Bed-Solids Separator Supplementation** | | | | | | |
| Magnetic Solids Separation | This requires two major changes: 1) replacing carbon as a core substrate in the FBR with a material that has a high magnetic susceptibility, and 2) adding a magnetic collection system in the bed-solids separator. A possible substrate would be sintered iron. The collection could be done in a batch mode. | + Promising concept to improve performance | - to 0 / medium to high $ innovative concept that would require significant development and testing | Relatively straightforward concept that would improve solids collection and management while using existing infrastructure. | Low TRL. Need to make sure that proposed substrate is stable and compatible with denitrification biomass support needs. If sintered iron is not suitable for a biomass substrate, would need to develop magnetic polymer or similar core material for use. Need to develop practical and robust system for magnetic collection. | Viable and conditionally recommended -- A new-innovative concept -- significant development would be needed. Selection of this technology should be considered if the Hanford team determines that the development effort and risks are justified (e.g., versus adding bed-solids separator capacity) |
| **Overall FBR Related Collateral Impacts to 200W Treatment System** | | | | | | |
| **Post-Treatment Options to Support Reinjection** | | | | | | |
| Alternative Anti-Scalant (In Plant Technology) | The current anti-scalant added at the air stripper is phosphorus based. In a phosphorus limited system the anti-scalant could provide key nutrients to foster microbial growth in the presence of COD. Consider replacement of Nalco non-phosphorus antiscalant. | + If testing indicates that phosphorus is contributing to biofouling then this is a promising concept to improve performance | + / low $ | Straightforward change out of anti-scalant using commercial non phosphorus material. Some testing is recommended to assure adequate performance. | Would introduce a new chemical into process. | Viable and recommended. If fouling of the distribution lines and injection wells is related to phosphorus as a limiting nutrient, the potential benefits could be significant. Some testing to confirm the role of phosphorus in downstream biofouling would be prudent. |
| Disinfection (In Plant Technology) | Current system effluent has residual COD, the addition of a biological disinfectant would inhibit downstream growth of biological materials in the distribution system and injection wells. Standard packaged dosing system could be used to treat the effluent tank or distribution line. Alternatively the dosing could be done before the air stripper to mitigate the potential for biofouling in the stripper. | 0 to + If testing indicates that disinfection and maintaining a residual free chlorine (similar to drinking water) then this is a promising concept to improve performance | 0 to + / low to medium $ | Addition of a disinfectant such as hypochlorite would inhibit growth of biological material. Potable water systems generally maintain a free chlorine level of 0.5 mg/L. Sodium hypochlorite is currently used within the process so no new chemicals are introduced. | Additional testing would be needed to determine if the residual disinfection capabilities are maintained into the reinjection wells; this option should be considered in combination with other actions (such as reducing phosphorus levels) that could work in partnership to mitigate biofouling potential; implementation would require review to assure compliance with injection permits. | Viable and conditionally recommended. Consider in combination with other actions (such as reducing phosphorus levels) to mitigate biofouling potential. |
| Removal of Residual COD using Supplemental Biotreatment (In Plant Technology) | Add supplemental aerobic treatment contact time before the aerobic membrane bioreactor to enhance the performance of the COD and macronutrient removal before the water is sent to the downstream air stripper and distribution system for reinjection. | 0 to + Promising concept to improve performance | 0 to + / medium to high $ simple to implement using commercial equipment | If testing indicates that this would enhance COD removal in the aerobic membrane bioreactor, the would be a "most reliable strategy" to assure that there is no downstream biofouling. | Addition of a major modification to a unit operation in the existing treatment train. New equipment would need to be acquired. New procedures, control system mods, and O&M would be needed. | Viable and conditionally recommended. Overall this is recommended if testing confirms viability and if less costly options do not adequately address FBR related reinjection issues. This option is preferred versus AOP for improved COD removal. |
| Removal of Residual COD using AOP (In Plant Technology) | Add a new unit operation -- advanced oxidation processes (AOP) -- to mineralize and remove COD and sterilize water before it is released to the distribution system for reinjection. | + Promising concept to improve performance | - to 0 / high $ uses available commercial equipment but would require significant investment | This polishing step would be the most reliable strategy to assure that there is no downstream biofouling. | Addition of a major unit operation to the existing treatment train. New equipment would need to be acquired. UV systems use lamps that contain mercury so that waste generation would result from lamp replacement and maintenance and procedures would be needed to address O&M. | Viable and conditionally recommended. Overall this is recommended only as a last resort since implementation requires the addition of a new unit operation to the existing treatment train. Combinations of the other recommendations should be considered first. |

| Technology/ Strategy | Description | Potential Benefit (- 0 +) | Implementability (- 0 +) / Cost (high medium low $) | Advantages | Disadvantages | Overall |
|---|---|---|---|---|---|---|
| Alternative Well Cleaning (Wellhead Technology) - Extended Baseline | Previous well cleaning efforts targeted fouling inside well casing. Fouling likely exists in both the gravel pack and the near well aquifer formation. Challenge is to target beyond the inner casing and into the gravel pack and near well formation. We recommend continuing and extending the baseline to incorporate a range of well rehabilitation techniques. | ------------------- | ------------------- | Explore alternate cleaning technologies using stronger chemical agents or sonication/surging technologies. | Use of strong chemical agents may require regulatory approval. | Affirm and extend baseline -- Under current configuration more effective cleaning techniques are needed to maintain injection well design flowrates. |
| Reinjection Well Screen Design (Wellhead Technology) | Wire wrap screens are available (designed and categorized) based upon the direction of fluid flow relative to the screen - either from the outside (extraction) or from the inside (injection). When screens of the standard configuration are used for injection applications, they are subject to clogging. The alternative screen design is recommended for future injection well installations. | 0 to +<br>Promising concept to improve performance | + / low $<br>cost and lead time would be higher (likely special order) but roughly comparable to standard screens | Screens designed for injection are less subject to clogging (because the v slots widen toward the outside of the well. Also, the smooth surface of these designs is easier to clean. | None - not feasible for existing wells | Viable and recommended -- Alternative screens would be a better choice for use in future injection wells. |
| Vadose Zone Infiltration (classified as Wellhead Technology) | Use near surface vadose infiltration (trenches or horizontal wells) instead of injection wells to distribute the treated water into the subsurface. Key features of the infiltration concept include: 1) the infiltration needs to be done in an relatively clean area where the percolating water will not mobilize past contamination, 2) the infiltrated liquids need to meet the 200 cleanup levels, 3) the liquids need to effectively migrate downward (several hundred feet) to the water table to maintain water levels and to assist in hydraulic control of the groundwater plume, and 4) designed to operate with maintain capacity and minimize fouling and require minimal O&M. | 0 to +<br>Promising concept to improve performance | - to 0 / medium $<br>cost could be lower than injection wells but difficult to find location that meets all of the requirements | For new capacity, this approach would likely cost less than using injection wells (i.e., more injection capacity per $). If the presence of caliche and perched water are problematic, then caliche bypass drains can be installed to shunt water to the lower vadose zone. | Infiltration trenches are subject to the same biofouling as injection wells. Upstream modifications will be needed to remove nutrients and electron donors in order to sustainably use either infiltration or injection. The current 200W cleanup levels would likely need to be maintained for shallow infiltration due to the mobility and stability of nitrate. | Viable and conditionally recommended. Depends on identifying location that meets all of the criteria and developing consensus with regulators and stakeholders. |
| **<u>Nitrate Treatment Goals and Alternatives</u>** | | | | | | |
| Develop Alternate Concentration Limits - Baseline | Collaborate with regulators and stakeholders -- work through the regulatory guidelines and the sequential steps to determine if an alternative concentration limit could be developed that would limit or mitigate risk and be protective of the environment. | 0 to +<br>If agreement is reached, , this could be a significant action | - to + / low $<br>implementability uncertain | Typically the evaluation accounts for exposure scenarios(s), and estimated risk. Factors such the nature and strength of the contaminant source, as well as receptor location(s), institutional controls, hydrologic driving forces and site biogeochemistry. At Hanford, negotiated long term planning documents, agreed end states, and umbrella documents/commitments on how limits will be set (e.g., the Tri-Party Agreement) would also control this sub-option. | Based on our review, all of the above ideas were discussed and all of the governing documents and mechanisms were in place when the initial 200W cleanup levels were negotiated/set. Thus, while there may be a technical basis for setting somewhat higher limits by performing additional study (open regulatory and stakeholder discussions should continue), the potential for near-term success of this sub-option is low. | Viable and conditionally recommended. We urge the Hanford team to continue active and vibrant technical dialog with regulators; however, the likelihood of expeditiously implementing alternate concentration limits is low unless new considerations or risk weights are developed. |
| Vadose Zone Infiltration (see above) | ------------------- | ------------------- | ------------------- | ------------------- | ------------------- | The new configuration (flow through a few hundred feet of vadose zone) does not provide compelling basis for an Alternate Concentration Limit. |

| **Technology/ Strategy** | **Description** | **Potential Benefit** (- 0 +) | **Implementability** (- 0 +) **/ Cost** (high medium low $) | **Advantages** | **Disadvantages** | **Overall** |
|---|---|---|---|---|---|---|
| Wetland Treatment System | Design and build wetland treatment cells in the areas where re-infiltration is desired. The same overarching criteria as near surface vadose infiltration would need to be followed. In this case the FBR would be eliminated (water would go from the recycle tank straight to the air stripper with pH adjustment as needed). Electron donor (liquid carbon substrate) and nutrients would be added just before the wetland and denitrification would occur in the wetland setting. infiltration would occur in the wetland and downstream infiltration pond or gallery. | - to +<br>If agreement is reached, , this could be a significant action | - / high $<br>high risk concept with a high cost -- elimination of FBR would provide some offset | This has been studied and documented in the literature for application in similar western US locations - thus a design basis envelope is available for scoping. Reasonable performance in urban, industrial and agricultural applications. A "green" treatment that would generate a wetland with interesting diversity. | Many disadvantages, including a large area ecosystem perturbation, potential for concentrating trace contaminants and generating waste, drawing wildlife to an area and setting up an un-natural and unsustainable environment (when turned off). Limited options for control if nitrate removal is insufficient. | Viable but not recommended. While the idea has a technical basis for consideration, the disadvantages are numerous and the technology is poorly matched to the local 200W ecosystem. |

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# Appendix A.

**Scope Statement: Technical Evaluation of the Hanford 200 West Water Treatment System**

The Hanford Site is extracting groundwater in the 200 West Area and treating it to remove target organic, inorganic, radionuclide, and metal contaminants. A key step in the process is the fluidized-bed bioreactor (FBR) designed to remove nitrate, as well as hexavalent chromium and carbon tetrachloride. The FBR contains granular activated carbon and an active microbial community. Key inputs to the FBR are contaminated groundwater, a supplemental carbon substrate and macro-nutrients. Outputs from the FBR system include treated water, offgas, and waste sludge/solids. Initial operational data indicated that the FBR is generally effective in reducing target contaminants to required cleanup levels. However, operational experience with FBR also identified challenges including: carbon carry-over in the treated effluent, over production of microbial extracellular polymeric substances (biofilms), and over production of hydrogen sulfide. Continuous operation of a large-scale FBR is complex, requiring careful attention to system monitoring data and changing conditions (e.g., flow rates or feed streams) and developing a set of associated technically-based operational paradigms. Key to successful and stable operation is the explicit identification of the available control parameters, how these parameters interact and impact the FBR system, and how these can be adjusted under different scenarios to achieve operational goals.

In response to the operational challenges, Hanford commissioned a number of studies/evaluations. Notably, Lee et al. (2014)[1] investigated the functional diversity and activity of the microbial community in the FBR at different times. Findings from these analyses indicated: 1) after a period of operation, the microbial community within the bed was different than inoculation and was likely influenced by the groundwater; 2) as time progressed, the microbial community in the FBR bed became more diverse; and 3) qPCR analyses indicated that bacteria involved in nitrogen cycling, including denitrifiers and anaerobic ammonia oxidizing bacteria, were dominant in the bed.

These studies suggest that a review of the overall design of the bioreactor is appropriate. The review will focus on improving the operational paradigm based on an integrated strategy that considers carbon and macronutrient balances, micronutrients, and microbiology. Such a paradigm could have a number of control parameters including influent and effluent chemistry, amendment selection/addition, FBR internal flow/recycle, sludge removal/handling, and others. A gap in the evaluations to date is explicit linkage of the monitoring information (e.g., microbial community structure) to the operational upsets – specifically, what changes in the microbial community would result in carbon carry-over, in excessive biofilm development, in the production of hydrogen sulfide? Also, what changes in control parameters would beneficially impact the microbial community structure?

[1]Lee MH, SD Saurey, BD Lee, KE Parker, EER Eisenhauer, EA Cordova, and EC Golovich. 2014. Characterization of Biofilm in 200W Fluidized Bed Reactors. PNNL-23679, Pacific Northwest National Laboratory, Richland, WA.

**Work Plan**

SRNL will provide a team to perform a facilitated systems engineering evaluation of the 200 West Groundwater Treatment fluidized-bed bioreactor (FBR); specifically, the design review will focus on identification of key control parameters which might be modified to improve operational efficiency as described above. Initially, SRNL will review key documents prior to visiting the site. The team will visit the Hanford site and perform a walk down of the facility and meet with key technical personnel. The team will provide a close-out briefing to Hanford personnel at the end of the site visit. The draft report will be completed within 2 weeks after the site visit, and the final report will be completed 2 weeks after comments on the draft report have been received.

**Review Team**

Dr. Brian Looney (technical lead), Dennis Jackson P.E., Dr. John Dickson, and Carol Eddy-Dilek (team lead)

**Period of Performance/Deliverables**
Relevant documents will be reviewed prior to team visit.

Team meeting at RL to include team tour of the facility and discussions with key personnel. A close-out presentation at conclusion of the team meeting documenting main team recommendations

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|---|---|
| Draft Team Report | 2 weeks after team site visit |
| Response to Comments | 2 weeks after comments received from DOE |
| Final Team Report | 3 weeks after comments received from DOE |

**Appendix B: Team Biographies**

**John Dickson**
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Dr. John Dickson is a Principal Scientist with the Savannah River National Laboratory and an adjunct professor in the Biology Department at University of South Carolina, Aiken. He earned a B.S., M.S. and Ph.D. in Environmental Soil Science/Agricultural Chemistry from Moscow State, University, Russia and a Ph.D. in Environmental Soil Chemistry from the Washington State University, Pullman. His research interests are directed at understanding the role of advanced porous materials in controlling the fate and transport of contaminants in the environment using analytical, microscopy and spectroscopy tools. His previous experience includes consulting work as a soil scientist for a number of design/environmental firms to address migration of contaminants in water resources (wastewater, storm water run-off, wetlands mitigation, and ecosystem health). Currently Dr. Dickson works in the interface of contaminant immobilization, reactive transport modeling in the subsurface and the coupling of characterization and remedial technologies to meet site specific cleanup goals. He received leadership and organizational awards from the Bullitt Foundation and WSU President's LEAD and has authored and reviewed many publications.

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Carol Eddy-Dilek is a Senior Technical Advisor at the Department of Energy Savannah River National Laboratory and adjunct instructor at Miami University in Oxford, Ohio. For the past 25 years, she worked on a variety of programs focused on development and deployment of innovative approaches and tools for environmental characterization and remediation, specifically, the design and optimization of phased characterization strategies that can be applied to complex and challenging environments. Her efforts resulted in the successful development or deployment of over twenty innovative methods for subsurface access and characterization that have been successfully applied within the DOE complex.

Since 2002, she has been the technical lead for the Department of Energy's Technical Assistance program at the Savannah River National Laboratory that provides technical support to the DOE complex. Since 2006, she has organized more than 25 teams that have visited eleven DOE sites and made recommendations yielding an estimated cost savings of $100M.

**Dennis G. Jackson**
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Dennis Jackson is a Fellow Engineer at the Department of Energy's Savannah River National Laboratory. Mr. Jackson holds Bachelors and Masters Degrees in Mechanical Engineering from the University of Alabama at Birmingham. He began his career at the Savannah River Site in 1990, and is involved with research and development in support of the DOE's Environmental Management Program. During his career at SRNL Mr. Jackson has evaluated and developed techniques to improve monitoring, characterization, and remediation of organic compounds, heavy metals, and radionuclides in various environmental compartments at several DOE and DoD facilities. Mr. Jackson is a Registered Professional Engineer in the State of South Carolina and currently holds seven patents in the field of environmental characterization, monitoring, and remediation.

Engineer in the State of South Carolina and currently holds seven patents in the field of environmental characterization, monitoring, and remediation.

**Brian B. Looney**
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Dr. Brian Looney is a Senior Advisory Scientist with the Savannah River National Laboratory and an adjunct professor in the Earth and Environmental Science Department at Clemson University. Brian earned a B.S. in Environmental Science from Texas Christian University and a Ph.D. in Environmental Engineering from the University of Minnesota. For the past 33 years, he has developed environmental characterization and remediation technologies for metals, radionuclides and organics. His work focuses on matching characterization and cleanup technologies to the specific conditions and needs at each site and developing technical approaches for that matching process. Dr. Looney coordinates development and deployment of innovative environmental characterization and clean-up methods at the Savannah River Site, and serves as a technical advisor supporting the DOE Environmental Management Program. He has received numerous awards and has authored and edited many publications including the book *Vadose Zone Science and Technology Solutions*. Dr. Looney has ten patents for innovations in environmental technology.

## Appendix C: Table of Patents

| Patent | Date | Assignee | Title | Synopsis |
|---|---|---|---|---|
| US #6,706,521 | 3/16/2004 | Envirogen, Inc. | Bed cleaning system for fluidized-bed bioreactors | A reaction chamber to contain a fluidized bed having a slurry of liquid, media and biomass. A lift and motive fluid are provided to urge slurry from the reaction chamber through a passage from a slurry inlet to a slurry discharge. The height of the slurry inlet is adjustable with respect to the bottom of the reaction chamber to help control the fluidized bed. |
| US #5,861,303 | 1/19/1999 | Envirogen, Inc. | Biofiltration apparatus and method with chemical pre-treatment of contaminated air | An apparatus and method for removing contaminants from a gas, wherein the gas flows through a gas treatment chamber having a biological treatment zone and a chemical treatment zone. The amount of a chemical treatment agent that is introduced into the chemical treatment zone is adjusted in response to a sensed condition or conditions |
| US #5,788,842 | 8/4/1998 | Envirogen, Inc. | Biomass separation apparatus and method | A separator for use with a fluidized-bed bioreactor. A lift draws a slurry of liquid, media and biomass from the fluidized bed. A biomass discharge is connected to the lift and located above the height of the fluidized bed for discharging excess biomass. A media discharge, also connected to the lift, discharges media from the slurry and returns the media to the fluidized bed. |
| US #5,750,028 | 5/12/1998 | Envirogen, Inc. | Biomass separation apparatus and method with media return | A separator is provided for use with a fluidized-bed bioreactor. A lift draws a slurry of liquid, media and biomass from the fluidized bed. A biomass discharge is connected to the lift for discharging excess biomass. A media discharge, also connected to the lift, discharges media from the slurry and returns the media to the fluidized bed by means of a media return assembly. |
| US #5,487,829 | 1/30/1996 | US EPA | Internal media cleaning device for aerobic fluidized bed reactors | An improved reactor for treatment of wastewater having an influent line for wastewater, and effluent line for treated wastewater, and an aerobic bed fluidized by wastewater from the influent line. The improved reactor consists of an internal particulate media cleaning means located between the bed and an outlet to the effluent line for creating turbulence which shears excess biomass from the particulate media within the cleaning means and permits controlled exit of the excess biomass from the cleaning means and the reactor while maintaining cleaned media within the reactor. |

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| US #4,681,685 | 7/21/1987 | Dorr-Oliver Inc. | Method and apparatus for concentrating bioparticles | A method and apparatus for controlling biomass growth in a fluidized bed reactor during anaerobic or aerobic treating of a waste feed. In particular, means is provided for concentrating a portion of bioparticles, the bioparticles being media with biomass adhered thereto and the concentrating means being integral to the fluid bed reactor, so that bioparticles delivered to a separator means for separating the biomass from the media are of high concentration requiring little downstream processing of the biomass separated thereby. |
| US #4,681,685 | 7/21/1987 | Dorr-Oliver Inc. | Method and apparatus for concentrating bioparticles | A method and apparatus for controlling biomass growth in a fluidized bed reactor during anaerobic or aerobic treating of a waste feed. In particular, means is provided for concentrating a portion of bioparticles, the bioparticles being media with biomass adhered thereto and the concentrating means being integral to the fluid bed reactor, so that bioparticles delivered to a separator means for separating the biomass from the media are of high concentration requiring little downstream processing of the biomass separated thereby. |
| US #4,612,115 | 9/16/1986 | Enso-Gutzeit Oy | Floating bed reactor | A floating bed reactor which is used for biological purification of fiber-containing liquid suspensions and for simultaneous clarification. What is essential in the invention is that the removal of fiber agglomerate from the reactor has been arranged with the aid of an open-top collecting vessel placed in the reactor and disposed to collect fiber agglomerate in itself. |
| US #4,534,864 | 8/13/1985 | L'air Liquide, Societe Anonyme Pour L'etude Et L'exploitation Des Procedes Georges Claude | Process and device for the regeneration of a group of solid particles having a coating of a biological material | Solid particles coated with a biological material are developed at the upper end of a bed which is fluidized by a supply of water. The particles are removed and decanted and then introduced through a pipe of an auxiliary anaerobic fermentation column which converts the biological coating into a gaseous mixture which escapes. The regenerated particles are withdrawn and conveyed to the purifying bed. Application in the biological purification of waste waters. |
| US #4,534,864 | 8/13/1985 | L'air Liquide, Societe Anonyme Pour L'etude Et L'exploitation Des Procedes Georges Claude | Process and device for the regeneration of a group of solid particles having a coating of a biological material | Solid particles coated with a biological material are developed at the upper end of a bed which is fluidized by a supply of water. The particles are removed and decanted and then introduced through a pipe at the upper end of an auxiliary anaerobic fermentation column which converts the biological coating into a gaseous mixture which escapes. The regenerated particles are withdrawn and conveyed to the purifying bed. |

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| US #4,322,296 | 3/30/1982 | Kansas State Univ. Research Foundation | Method for wastewater treatment in fluidized bed biological reactors | Wastewater is subjected to biological reaction in a bed containing the biological reaction bacteria on a particulate carrier wherein the lower portion of the bed is fluidized while the upper portion is maintained as a fixed bed. When the fixed bed portion becomes clogged with cellular material, the entire bed is fluidized and wash water is passed through the bed to remove excess cellular material. |
| US #4,322,296 | 3/30/1982 | Kansas State Univ. Research Foundation | Method for wastewater treatment in fluidized bed biological reactors | Wastewater is subjected to biological reaction in a bed containing the biological reaction bacteria on a particulate carrier wherein the lower portion of the bed is fluidized while the upper portion is maintained as a fixed bed. When the fixed bed portion becomes clogged with cellular material, the entire bed is fluidized and wash water is passed through the bed to remove excess cellular material. |
| US #4,250,033 | 2/10/1981 | Ecolotrol, Inc. | Excess-growth control system for fluidized-bed reactor | A control system to prevent the accumulation of excessive cellular material in a fluidized-bed reactor wherein waste water or other liquid to be processed is conducted upwardly at a velocity conducive to fluidization through a bed of particles which function as a carrier for the growth of the material. |
| US #4,250,033 | 2/10/1981 | Ecolotrol, Inc. | Excess-growth control system for fluidized-bed reactor | A control system to prevent the accumulation of excessive cellular material in a fluidized-bed reactor wherein a waste liquid to be processed is conducted upwardly at a velocity conducive to fluidization through a bed of particles which function as a carrier for the growth of the material. As a consequence, the sheared material is washed away through the draw-off port, whereas the partially stripped carrier particles fall back into the fluidized bed. |
| US #4,177,144 | 12/4/1979 | Ecolotrol, Inc. | Excess-growth control system for fluidized-bed reactor | A control system to prevent the accumulation of excessive cellular material in a fluidized-bed reactor wherein waste water or other liquid to be processed is conducted upwardly at a velocity conducive to fluidization through a bed of particles which function as a carrier for the growth of the material. |