One Water™ Solutions

Effluent Technical Review Services
Contract No. 60073

Prepared for

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Final Report

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Abbreviations

Abbreviation	Definition
CHPRC	CH2M Plateau Remediation Company

COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
DOE	Department of Energy
FBR	Fluidized Bed Reactor
GAC	Granular Activated Carbon
gpm	Gallons per Minute
MBR	Membrane Bioreactor
OWS	One Water Solutions
P&T	Pump & Treat
RDT	Rotary Drum Thickener
sCOD	Soluble (or Dissolved) COD

Executive Summary

Introduction and Purpose

One Water Solutions (OWS) was retained by CH2M Plateau Remediation Company (CHPRC) to provide an assessment of the 200 West Pump and Treat (P&T) treatment facility to assist with the evaluation and resolution of biological and chemical injection well fouling issues. The assessment focused on: (1) effluent chemical oxygen demand (COD), because the presence of biodegradable organic matter can lead to biological fouling, (2) effluent nitrate because of its association with biodegradable organic matter, and (3) manganese because of its association with chemical fouling. The assessment was based on a site visit by Glen T. Daigger, Ph.D., P.E., BCEE, NAE, President OWS, to 200 West P&T June 2 – 3, 2016, information provided by Mark A. Carlson, Ph.D., P.E., Process Engineer with CHPRC, written comments on a draft report prepared by OWS and dated June 23, 2016, and a telephone conference call with CHPRC staff on August 24, 2016.

Analysis of 200 West P&T Treatment Facility

Biodegradable carbon (MicroCg®), phosphoric acid, and a micronutrient solution are added proportionate to the nitrate concentration in the influent water to be treated and appear to be added in sufficient quantity. Analysis of the existing fluidized bed reactors (FBR's) indicates that, prior to April, 2016, their reliable removal nitrate removal capacity is limited to about 500 lb-N/day, which is reached at an influent loading of about 600 lb-N/day. Analysis of performance data for this period indicated that the treatment capacity of FBR A was significantly less than that of FBR B. FBR A was taken out of service in April, 2016 to repair a leak in the tank wall, and damage to the influent flow distribution system was detected. Poor influent flow distribution caused by damage to the influent flow distribution system was apparently adversely impacting FBR A performance. The tank, and the influent distribution system, were repaired, and FBR A was placed back in service in late June, 2016. Analysis of performance data following repair of FBR A indicates significantly improved treatment capacity for FBR A, with somewhat less mass removal by FBR B. This further suggests that FBR B should be removed from service, inspected, and any defects repaired. Further testing will be required to determine the capacity and performance capabilities of the repaired system.

Solids handling recycle streams (Rotary Drum thickener (RDT) filtrate, centrate) were directed to the MBR splitter box until August 31, 2015, and this appeared to adversely impact membrane bioreactor (MBR) performance as MBR performance improved when the solids handling recycles were re-directed to the FBR recycle tank after August 31, 2015. The MBR's demonstrated the capability to effectively remove soluble COD (sCOD) from the FBR effluent when solids handling recycle streams are directed to the FBR recycle tank.

Improvement Opportunities and Recommended Plan

Improvement Opportunities

Opportunities exist to improve the performance and capacity of the FBR's. Development of a leak in the FBR A tank revealed that the influent distribution system had been damaged, which likely created short-circuiting, dead zones, and non-uniform fluidization of the activated carbon media. FBR A treatment capacity increased significantly once it was repaired. More recent plant data indicate that FBR B is not performing as well as FBR A, suggesting that FBR B should also be removed from service and any deficiencies noted repaired.

Plant staff have identified FBR physical and operational modifications to improve performance and simplify operation, as summarized in Table ES-1. Carbon and nutrient dosing control could also be improved by providing on-line instrumentation to measure the nitrate concentration of the plant influent and use this to control carbon and nutrient dosing.

Table ES-1. Summary of Potential FBR Improvements Identified by Plant Staff.

Option	Description
Place eductors at varying distances from the floor to provide flexibility to clean the top of the fluidized bed for a range of fluidized bed levels.	Carbon bed level changes rapidly and fitters, insulators, electricians, and operators are required to perform LOTO and change the eductor level. This option makes it easier to respond to changing bed conditions.
Install a permanently mounted camera system that can be adjusted up and down.	Mount cameras with means to raise and lower them to track level of fluidized bed.
Keep carbon return system operating.	Periodically check that eductor system is operating correctly to assure carbon is returned to the FBR.
Get a full load of carbon in the FBRs.	Increasing the carbon load will increase the nitrate load the FBRs can accommodate. Do not exceed the design height of the fluidized bed.
Establish a program to maintain a full load of carbon (20 -ft. of fluidized bed).	It is necessary to add carbon periodically. Based on previous experience, about 35-cubic feet (1 supersack) per FBR will be needed every 4 months. Note that this is just an estimate and actual losses depend on how well the eductors and carbon return system operate.

The stock micronutrient solution used at 200 West P&T is knowingly added in excess. Laboratory studies described in the body of the report can identify which micronutrients are most limiting, necessary dosing levels, and can result in a dosing regimen which provides sufficient nutrients while avoiding over-dosing which could contribute to injection well fouling. These studies should be conducted, and adjustments to 200 West P&T micronutrient dosing made accordingly.

Two long-term improvement opportunities were identified should further performance and/or capacity improvements be needed: (1) add additional FBR unit(s) and (2) add a bioreactor prior to the submerged membrane units. Addition of a bioreactor prior to the submerged membrane units is the preferred option, should such additions prove to be needed. This option provides greater capability to adapt to varying plant influent nitrate loadings while achieving consistently lower MBR and plant effluent nitrate and COD concentrations, as compared to adding an additional FBR unit. It also provides more operational flexibility, and is likely to be less costly. FBR effluent and a portion of FBR influent (after MicroCg® and nutrient addition), along with solids recycled from the downstream submerged membrane units, would be diverted to the new bioreactor, and the bioreactor effluent would be directed to the submerged membrane splitter box. A design consultant would be retained to further develop this concept, size the bioreactor, and integrate the bioreactor into the plant. The potential for hydraulic expansion of the plant to 3,750 gpm should also be considered in the design.

Recommendations

1. Continue to direct the solids handling recycle streams (RDT filtrate and centrate) to the FBR recycle tank.
2. Remove FBR B from service, inspect it, and make any repairs indicated. Recent operating results suggests that it is not performing as well as the recently repaired FBR A.
3. Optimize the FBR's. Each of the measures listed in Table 1 are reasonable to consider and should be evaluated and implemented as possible. Optimization would also include adding on-

line instrumentation to measure the plant influent nitrate concentration and use it to automatically control carbon and nutrient dosing. The laboratory studies described above to determine the optimum nutrient mixture should also be conducted to avoid adding un-needed nutrients which are both costly and can contribute to injection well fouling. The goal should be to consistently achieve an FBR effluent COD concentration less than 10 mg/L and an FBR effluent nitrate concentration less than 5 mg-N/L, with a plant effluent COD concentration less than about 3 mg/L.

4. Determine the performance capabilities and capacity of the optimized system by gradually increasing the nitrate loading to one FBR and monitor its performance. As above, a treatment objective of 3 mg/L effluent COD and 5 mg-N/L effluent nitrate would appear to be appropriate. If sufficient plant capacity and performance is demonstrated, then no further action is required.
5. Should further improvements to plant performance and/or capacity be desired, adding a bioreactor to the MBR system would appear to be the best option, compared to adding more FBR's. Adding the bioreactor would provide the capability to remove an FBR from service for maintenance without decreasing plant capacity, and it is also likely to be less expensive than adding additional FBR capacity.

   A consultant would be retained to develop a preliminary design and cost estimate. Provisions to further expand the hydraulic and treatment capacity of the system by the addition of two more submerged membrane modules should be included in the design, along with the identification of other plant modifications that may be required (such as increasing the capacity of the air strippers). This latter information on plant expansion options could be useful to DOE as they consider increasing the plant throughput. Such expansion would not be necessary if the current plant hydraulic capacity (2,500 gpm) is maintained, although adding the bioreactor itself would provide more consistent removal of COD and nitrate, and allow the nitrate mass loading design capacity to be increased. The selected modifications would then be constructed and placed in service. Their performance would be assessed by the increased nitrate removal achieved and by lowered and less variable (mean and standard deviation) plant effluent COD concentrations. The capacity of the bioreactor and submerged membrane system would be tested by diverting flow around the FBR's to determine removal capacity.

Introduction and Purpose

The 200 West Pump and Treat (P&T), located on the U.S. Department of Energy's (DOE's) Hanford Site, is designed to capture and treat contaminated groundwater to reduce the mass of carbon tetrachloride, total chromium (trivalent and hexavalent), nitrate, trichloroethylene, iodine-129, and technetium-99 throughout the 200-ZP-1 Operable Unit. The facility is designed to treat up to 9,464 L/min (2,500 gallons per minute [gpm]) of extracted groundwater using two parallel treatment trains. The system is further designed to control the direction and rate of groundwater flow throughout the 200-ZP-1 Operable Unit using strategically-placed extraction and injection wells for flow-path control. Further details on the treatment plant are provided elsewhere (CH2M HILL, 2010a). The plant consists of ion exchange for uranium and technetium-99 removal from some waste streams, followed by fluidized bed denitrification reactors (FBR's) (2 units), followed by submerged membrane units, referred to as membrane bioreactors (MBR's) even though separate bioreactors are not provided (4 units), and air stripping. Off-gas from the liquid treatment train is collected and treated through gas-phase granular activated carbon (GAC). Supplemental carbon and nutrient addition are required for biological treatment, resulting in the production of a biological sludge which is processed through rotary drum thickeners (RDT's) (3 units), aerated storage, centrifuge dewatering (2 units), and lime stabilization prior to landfilling.

The 200 West P&T facility has consistently met effluent quality objectives since start-up, except for nitrate. Problems with nitrate removal performance were first observed beginning in the Spring of 2013 when elevated nitrate concentrations in the plant effluent occurred and the capacity of the injection wells declined, as quantified by Specific Injectivity (gpm/ft.). Biological and chemical fouling of the injection wells were subsequently identified as the cause for reduced Specific Injectivity. Elevated effluent nitrate concentrations were a result of an insufficient supply of micronutrients to the biological treatment systems, resulting further in elevated effluent chemical oxygen demand (COD) levels. Effluent nitrate and COD concentrations subsequently declined when micronutrient dosing was increased. Specific Injectivity has continued to decline, however, in spite of the fact that wells have been subject to several chemical cleaning events. The Specific Injectivity recovers after a well rehabilitation event, but not to previous levels, so a slow decline is observed. Further details are provided elsewhere (CH2M HILL Plateau Remediation Company, 2014).

The plant exhibited consistent performance when operated at less than design capacity, but nitrate removal deteriorated and effluent COD increased when influent flows and loadings subsequently approached design values, as discussed below. Operating difficulties with the FBR process have also been experienced which adversely impact their performance. One Water Solutions (OWS) was subsequently retained by CH2M Plateau Remediation Company (CHPRC) to assess the performance of the 200 West P&T treatment facility and suggest improvement opportunities. The evaluation focused on nitrate removal and effluent COD, as biological fouling is related to the presence of biodegradable organics contained in the effluent delivered to the injection wells, and biodegradable organics addition is required to provide nitrate removal. Chemical fouling is thought to be related to manganese oxidation and precipitation as manganese dioxide. Manganese is added in the micronutrient feed, and efforts are on-going to optimize manganese dosing to minimize the manganese concentration in 200 West P&T treatment facility effluent. A draft report on this investigation was submitted June 16, 2016, followed by this final report. The assessment of facility effluent COD and nitrate performance presented here is based on:

- A site visit by Glen T. Daigger, Ph.D., P.E., BCEE, NAE, President of OWS to 200 West P&T June 2 – 3, 2016

- A briefing and subsequent discussions provided by Mark Carlson, Ph.D., P.E., Process Engineer, CHPRC during the site visit described above and subsequent discussions (Carlson, 2016a)
- An EXCEL workbook presenting extensive 200 West P&T plant operating data (Carlson, 2016b)
- 200 West P&T design data.
- Comments received on the draft report and a telephone conference call with CHPRC staff on August 24, 2016.
- Receipt and subsequent analysis of a further updated version of the EXCEL workbook described above (Carlson, 2016c)

This report summarizes the results of the assessment conducted by OWS and recommends a path forward.

Analysis of 200 West P&T Treatment Facility

Historic Nitrate Removal and Effluent COD Performance

Figure 1 presents plant effluent nitrate and COD beginning after resolution of the micronutrient deficiency identified in the spring of 2013, through August, 2016. Stable performance, with occasional elevated effluent COD, was generally established for the period of March, 2014 through May, 2015, with plant effluent COD averaging 3 mg/L and plant effluent nitrate averaging 4.9 mg-N/L. Periods of moderately elevated effluent COD occurred beginning in June, 2015, followed by increased effluent nitrate in late October, 2015. The plant was operated at an influent nitrate concentration of about 23 mg-N/L for much of this period, increasing to 25 mg-N/L in February, 2015, compared to a design influent nitrate concentration of 40 mg-N/L. The influent nitrate concentration was increased further and became more variable beginning November, 2015, generally ranging from 28 to 34 mg-N/L. The influent flow was initially in the range of 1,000 to 1,500 gpm for much of this time, and then was gradually increased to roughly 2,000 gpm in the latter portion of this period, compared to the design value of 2,500 gpm. FBR A was subsequently taken out of service in mid-April, 2016 for repair, remained out of service during the site visit, and was returned to service following completion of repairs in late June, 2016. The plant influent flow was generally around 1,000 gpm while FBR A was out of service, but it was ramped up to around 2,000 gpm after FBR A was returned to service. Influent nitrate concentrations remained around 25 to 30 mg-N/L.

The FBR's represent the principal unit process at 200 West P&T responsible for nitrate removal. Biodegradable organic matter (MicroCg®) is added to the FBR process influent as a carbon source for heterotrophic denitrification, along with phosphoric acid and a micronutrient solution. The dosing procedures used appear to be sufficient to ensure that neither biodegradable organic carbon nor nutrients limit denitrification in the FBR's. Thus, the variation in overall plant process loading and resulting performance allows an assessment of FBR nitrate removal capacity to be conducted. A plot of the mass removal rate of a constituent (such as nitrate) as a function of the mass loading rate for that constituent will generally increase linearly until the limiting mass removal rate is reached. Comparison of the actual mass removal rate with the theoretical maximum, as represented by a line representing 100 percent removal, characterizes the removal efficiency over the loading rate range, resulting in the linear relationship between the constituent mass loading and mass removal rate.

Figure 2 presents such a plot for nitrate removal for the 200 West P&T FBR's for the initial period when both FBR's were in service (through mid-April, 2016). The nitrate removal rate increases as the nitrate mass loading increases, showing a consistently high removal efficiency, up to a mass loading rate of about 600 lb-N/day. Above this loading rate removal becomes less consistent. The results indicate that a mass removal rate of no more than 500 lb-N/day was reliably achieved during this period, even as the nitrate mass loading increased. A relatively high nitrate removal efficiency of approximately 80 to 90 percent is consistently achieved, with only minor excursions, for nitrate mass loadings less than 600 lb-N/day. Figure 3 extends the analysis for this operating period by considering each FBR separately and indicates superior performance for FBR B. A leak in the tank for FBR A developed mid-April, 2016, as described above, and damage to the influent flow distribution system was detected when the unit was subsequently taken out of service and emptied. Poor influent flow distribution caused by damage to the influent flow distribution system could provide an explanation for the poor performance for FBR A indicated by the data comparison presented in Figure 3.

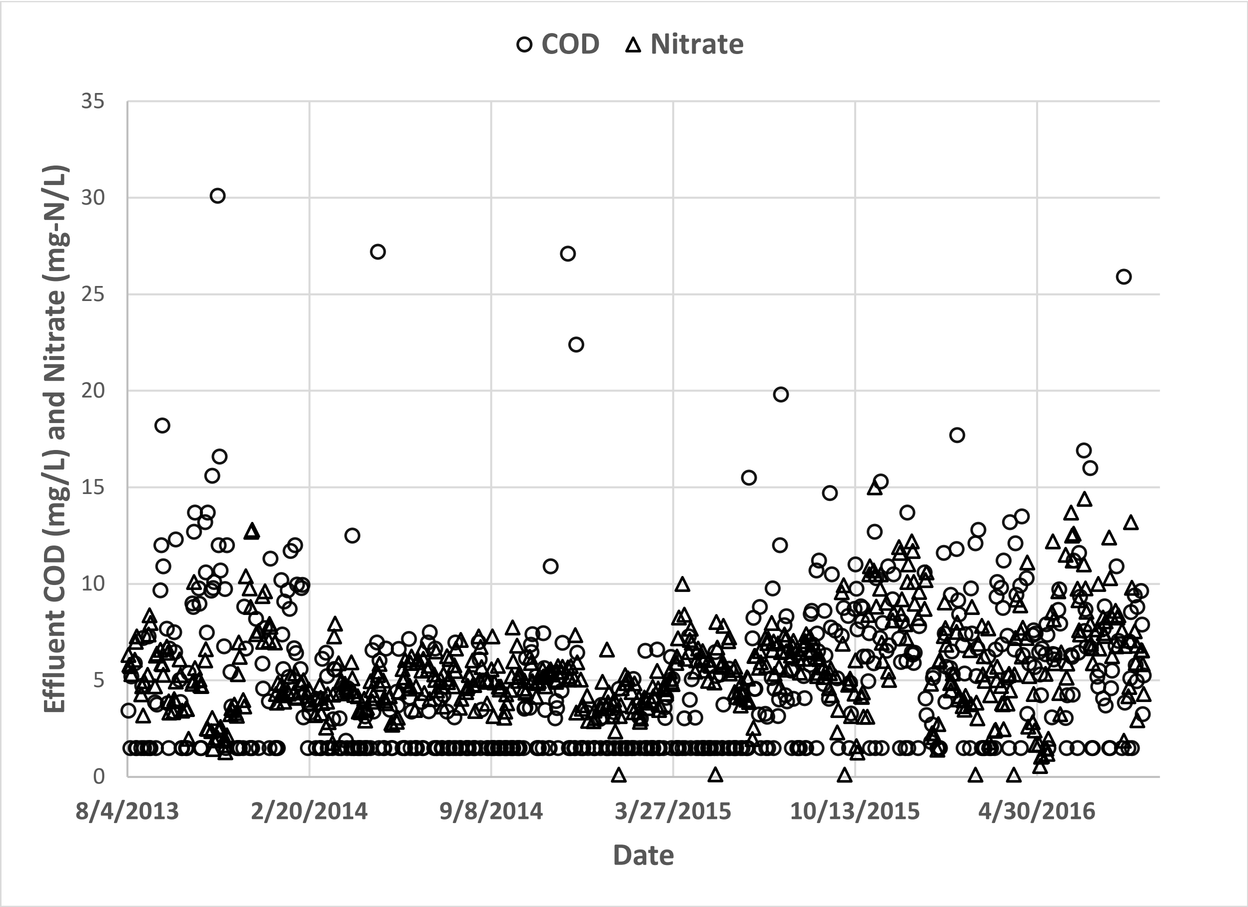

Figure 1. 200 West P&T Effluent Quality August, 2013 to August, 2016.

Figure 4 provides a similar analysis for the individual FBR's following repair of FBR A. These results demonstrate improved performance of FBR A, which consistently achieved 85 percent nitrate removal over the entire loading range, with somewhat less mass removal by FBR B. This analysis suggests that FBR B should be removed from service, inspected, and any defects, for example in the influent flow distribution system, repaired.

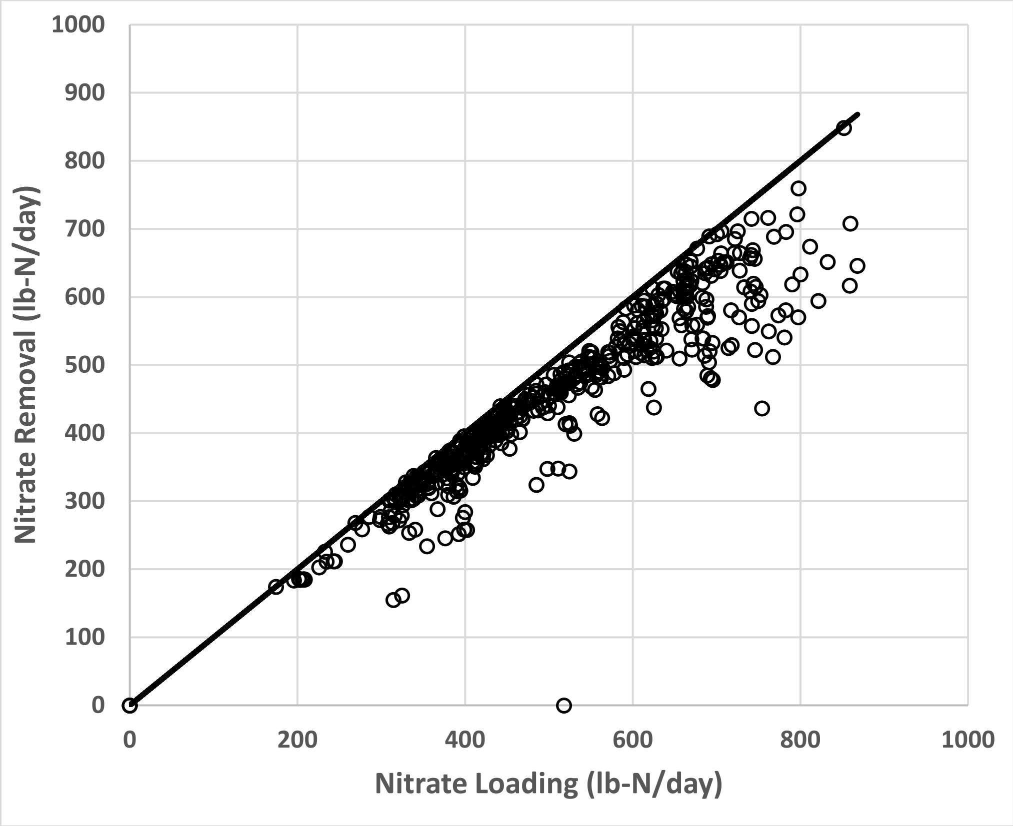

Figure 2. FBR Nitrate Mass Removal Rate as a Function of Nitrate Mass Loading for Two FBR's for Period of March, 2014 Through Mid-April, 2016.

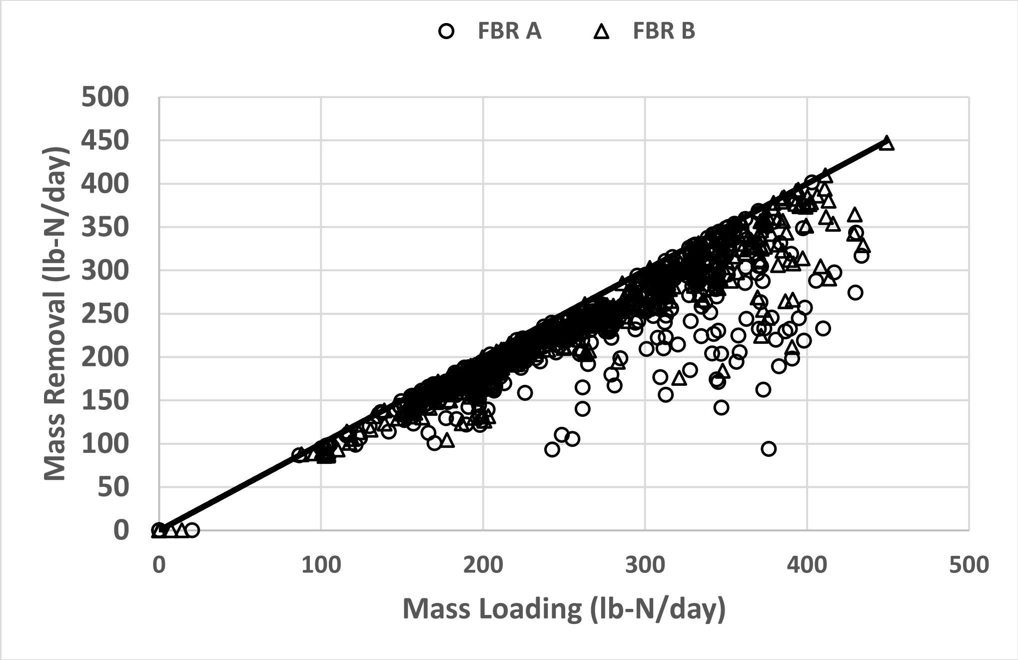

Figure 3. Nitrate Mass Removal Rate as a Function of Nitrate Mass Loading for Each FBR for the Period of March, 2014 Through May, 2016.

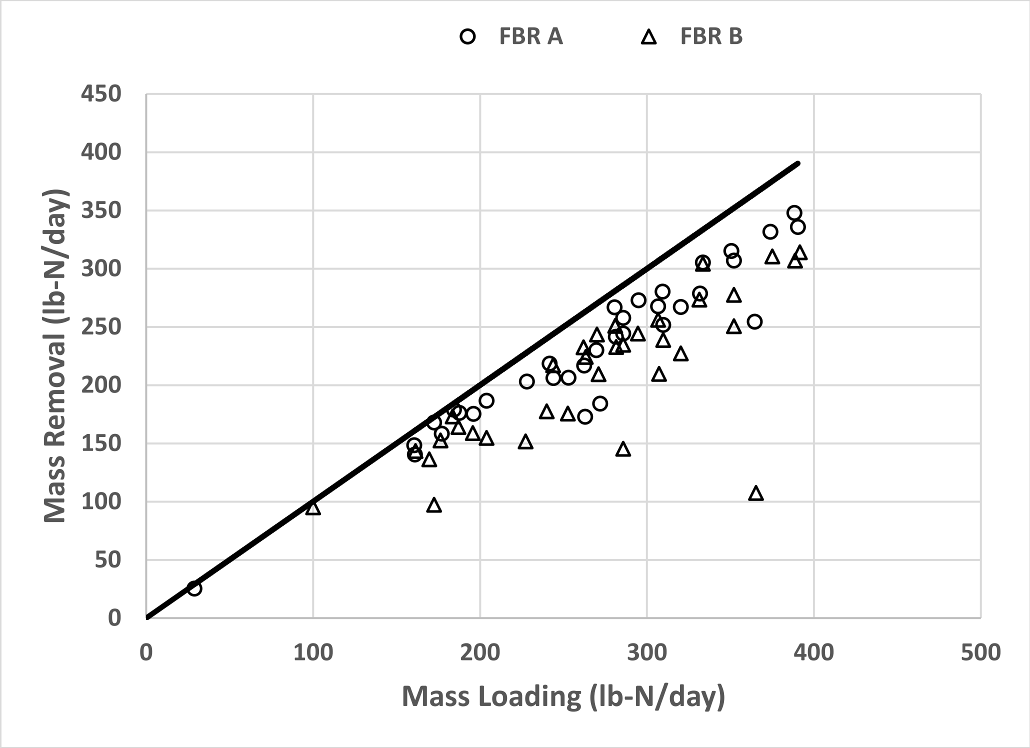

Figure 4. Nitrate Mass Removal Rate as a Function of Nitrate Mass Loading for Each FBR for the Period of Late June Through August, 2016 Following Repair of FBR A.

The MBR's are an aerobic biological treatment process and, while not capable of significant nitrate removal, they are intended to remove remaining biodegradable organic carbon from the FBR effluent prior to further treatment and injection. The FBR effluent and plant effluent are sampled and analyzed, rather than the MBR influent and effluent. Plant effluent should be reflective of MBR performance as little removal of soluble COD (sCOD) and nitrate is expected downstream of the MBR's. In contrast, recycle streams from the solids handling processes (filtrate from the RDT's and centrate from solids dewatering) were directed to the MBR splitter box for most of the 200 West P&T operating period. Figure 5 was produced following the June 2-3, 2016 visit and indicates that the MBR's consistently provide significant removal of soluble COD from the FBR effluent when FBR effluent COD concentrations are elevated, but consistently low effluent COD concentrations are not reliable achieved, even when FBR effluent concentrations are relatively low.

Potential reasons for the performance pattern observed in Figure 5 were discussed during the August 24, 2016 conference call, and it was mentioned that the location where solids handling recycle streams were directed to was changed at the end of August, 2015 from the MBR splitter box to the FBR recycle tank, so that biological treatment of these flows would be provided in the FBR's. During the August 24, 2016 conference call it was suggested that the sCOD contained in the solids handling recycle stream could represent a sCOD loading to the MBR's that was not represented for at least some of the data presented in Figure 5. This loading was not represented in the analysis presented in Figure 5 and, moreover, it could be adversely impacting MBR performance. To test this hypothesis, plant effluent sCOD was subsequently plotted for the preparation of this report as a function of FBR effluent COD for the period September, 2015 through August, 2016, as presented in Figure 6. These results more clearly reflect expectations, where the MBR's are now demonstrated to be generally able to consistently reduce FBR effluent sCOD concentrations. The average plant effluent COD concentration for the period of September, 2015 through August, 2016 (when solids handling recycles were returned to the FBR recycle tank) was 6.6 mg/L, and the effluent nitrate concentration was 6.4 mg-N/L. For the period of late June, 2016 through August, 2016 when the repaired FBR A was returned to service and solids handling recycle streams were directed to the FBR recycle tank, the plant effluent COD concentration averaged 6.0 mg/L and the plant effluent nitrate averaged 7.2 mg-N/L.

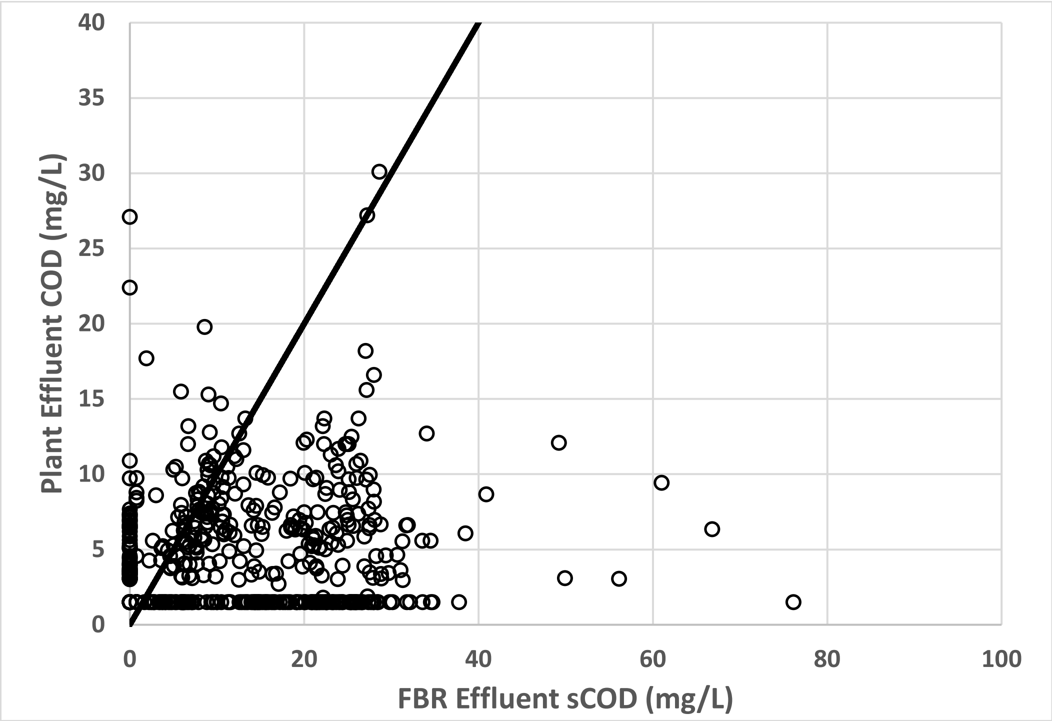

Figure 5. Relationship Between FBR Effluent sCOD and Plant Effluent COD Concentration for Period of March, 2014 Through Mid-April, 2016.

In summary, it can be concluded that, historically, plant nitrate removal was limited by the performance capability of the FBR's to about 500 lb-N/day, which was reached for plant nitrate loading rates of about 600 lb-N/day or more. Damage to the influent distribution system of FBR A, which was detected in April, 2016 and repaired in the early summer of 2016, was an important factor limiting plant treatment capacity, and repair of the FBR A influent distribution system has resulted in increased plant nitrate removal capacity. Plant data collected since FBR A was repaired and placed back in service indicates that the performance of FBR B does not match that of FBR A, suggesting that some factor is limiting the performance of FBR B.

It appears that directing solids handling recycle stream to the MBR splitter box adversely impacts the ability of the MBR's to produce a low COD effluent, and that performance was improved when this stream was redirected upstream to the FBR recycle tank. However, plant performance was not restored to the level achieved during March, 2014 through May, 2015, during which the plant effluent COD averaging 3 mg/L and plant effluent nitrate averaging 4.9 mg-N/L.

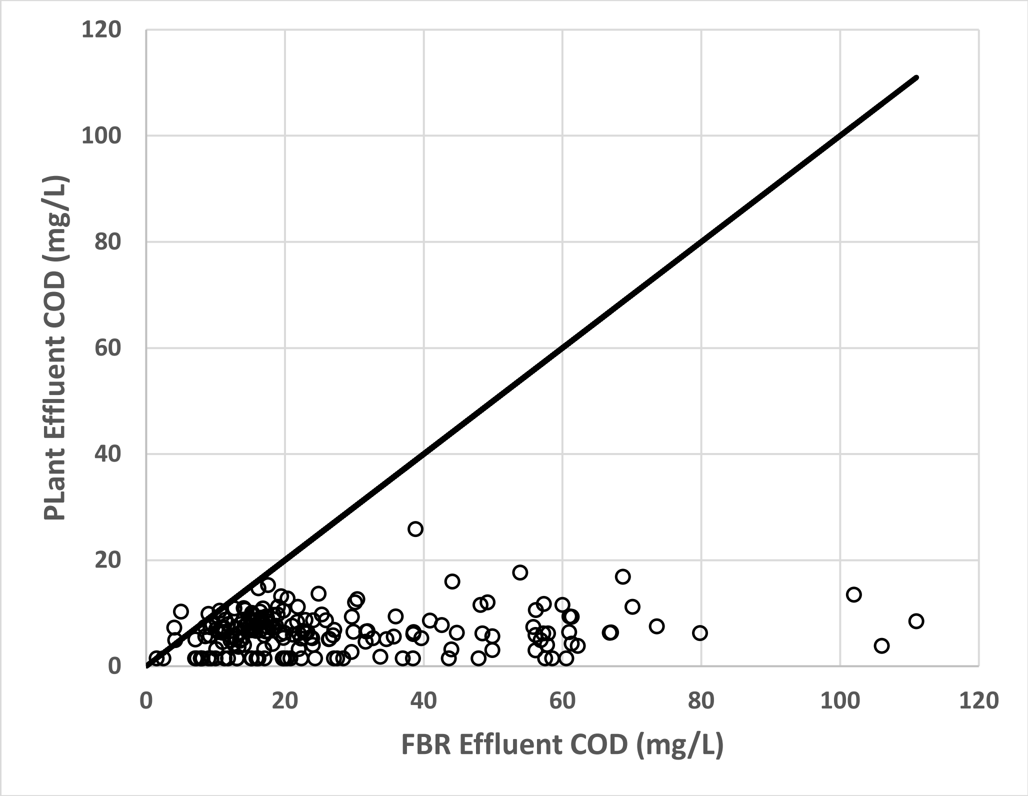

Figure 6. Relationship Between FBR Effluent sCOD and Plant Effluent COD Concentration for Period of August, 2015 Through August, 2016.

Improvement Opportunities

Several opportunities exist to improve the treatment performance and capacity of the 200 West P&T treatment facility. They are addressed one at a time in this section.

Optimize FBR's

Several observations suggest factors which limit the performance of the FBR's and which could be corrected to increase treatment capacity. The leak in the tank for FBR A detected in April, 2016 revealed that the distribution system had been damaged. This created elevated discharges from portions of it, which resulted in jets which abraded the tank wall lead to the leak which was repaired. Damage to the distribution system also resulted in uneven distribution of flow into the unit, leading to short-circuiting and dead zones and inefficient use of the bioreactor capacity present. Analysis of plant operating data demonstrated that the capacity of FBR A was significantly less than FBR B prior to repair of this damage, but became somewhat greater than FBR B following completion of the repairs. More recent plant operating data, presented in Figure 4, suggests that some factors might be adversely impacting the capacity and performance of FBR B, further suggesting that it should be removed from service, inspected, and any deficiencies repaired.

Plant operating staff have also closely observed the operation of the 200 West P&T FBR's and have assembled a list of potential FBR improvements. The list, as provided by plant staff, is presented in Table 1. The FBR's are currently operating, for a variety of reasons, with less than the full charge of media (activated carbon). Operating experience has indicated that the existing biomass control system does not provide sufficiently precise control of carbon bed height, leading to variable nitrate removal performance and also to excessive carbon loss. The efficacy of the potential modifications listed in

Table 1 can only be assessed by implementing them on one FBR. Potential benefits of the proposed modifications include increased nitrate removal capacity; reduced effluent nitrate and COD variations, leading to more consistent performance (and reduced plant effluent COD); less operational time required for FBR operation; and reduced carbon loss. FBR nitrate and COD removal capacity would be increased in direct proportion to the increased carbon inventory maintained in the system.

Table 1. Summary of Potential FBR Improvements Identified by Plant Staff.

Option	Description
Place eductors at varying distances from the floor to provide flexibility to clean the top of the fluidized bed for a range of fluidized bed levels.	Carbon bed level changes rapidly and fitters, insulators, electricians, and operators are required to perform LOTO and change the eductor level. This option makes it easier to respond to changing bed conditions.
Install a permanently mounted camera system that can be adjusted up and down.	Mount cameras with means to raise and lower them to track level of fluidized bed.
Keep carbon return system operating.	Periodically check that eductor system is operating correctly to assure carbon is returned to the FBR.
Get a full load of carbon in the FBRs.	Increasing the carbon load will increase the nitrate load the FBRs can accommodate. Do not exceed the design height of the fluidized bed.
Establish a program to maintain a full load of carbon (20 -ft. of fluidized bed).	It is necessary to add carbon periodically. Based on previous experience, about 35-cubic feet (1 supersack) per FBR will be needed every 4 months. Note that this is just an estimate and actual losses depend on how well the eductors and carbon return system operate.

Plant performance for the period of March, 2014 through May, 2015, which was identified previously as a period of good plant performance, can be used to establish benchmarks to be achieved through optimization. The plant nitrate loading during this period averaged 468 lb-N/day (standard deviation 105 lb-N/day) and resulted in an FBR effluent COD concentration of 9.3 mg/L (standard deviation 5.6 mg/L) and FBR effluent nitrate concentration of 3.7 mg-N/L (standard deviation 4.0 mg-N/L). As noted, the plant effluent COD concentration was typically around 3 mg-N/L. Note that these levels of treatment were not achieved following return of FBR A to service following its repair in late June, 2016, even though plant nitrate loadings were only modestly higher at 539 lb-N/day (standard deviation 152 lb-N/day).

Optimize Nutrient Dosing

The procedures currently used to control nutrient dosing appear to be reasonable, but can be improved. The stability of the nitrate and dissolved oxygen (DO) concentrations in the extraction wells feeding 200 West P&T allow a simple flow balance to be used to estimate plant influent DO and nitrate concentrations, confirmed by daily grab sampling and off-line analysis of the plant influent. Carbon and nutrient dosing is then set based on the calculated influent concentrations, while the resulting FBR effluent nitrate concentration is monitored through on-line instrumentation. Phosphoric acid is fed separately from micronutrients and is also measured in daily FBR effluent grab samples, along with nitrate and soluble COD. The micronutrient solution fed is that identified and found to be effective in response to the spring, 2013 incident describe above. It was necessary at that time to resolve the micronutrient deficiency quickly, and a stock micronutrient solution was used and the dose was selected to provide an excess of all micronutrients. Thus, it is unknown whether all micronutrients that the stock solution contains are actually needed, and whether dosing of the remaining micronutrients can be reduced. While this is simply an economic issue for most micronutrients, injection well fouling is an issue concerning manganese as it is thought to be one factor leading to injection well chemical fouling. Thus, providing sufficient manganese to not limit biological treatment, while avoiding excess addition resulting in elevated injection water concentrations, is of importance.

Control of carbon and nutrient dosing can be further improved by installing on-line instrumentation to measure the plant influent nitrate and DO concentrations and use these data, along with the plant influent flow, to compute the plant nitrate mass loading. This signal would then be used to control carbon and nutrient dosing. The current procedure using periodic measurement of the nitrate concentration in extraction wells has worked satisfactorily, but improved control, and hence even better matching of carbon and nutrient dosing with the actual nitrate mass loading, could improve process performance and reduce potential bleed-through of carbon and nutrients into the effluent and, subsequently, into the injection wells. On-line instrumentation is currently used and functions properly to monitor the nitrate concentration in the FBR effluent. Instrumentation was originally provided to measure the FBR influent nitrate concentration, but it was located downstream of carbon addition, resulting in rapid fouling. Instrumentation could be placed up-stream of carbon addition, however, with the expectation that fouling would be significantly reduced.

Micronutrient dosing can be further optimized by determining which nutrients needed to be added, and in what proportions to COD loading. One approach to doing this is to simply reduce micronutrient dosing to the 200 West P&T systems and monitor response. There are important limitations to this approach, however, including the potential to disrupt plant operation and performance, and the general inability to determine which micronutrients are more limiting and to adjust the micronutrient solutions "recipe" accordingly. The alternate approach is to conduct laboratory-scale studies where more control is possible and plant performance is not affected.

Laboratory studies would use 200 West P&T feed water with excess biodegradable carbon and phosphoric acid added but no micronutrient solution. Biomass grown without micronutrient supplementation would then be analyzed to determine its macronutrient (nitrogen and phosphorus) and micronutrient content. Comparing the relative concentrations of micronutrients to macronutrients in the biomass grown to that expected for typical biomass allows determination of the micronutrients present in the most limiting proportions. Biomass is then subsequently grown with the most limiting micronutrients added, and the procedure is repeated until the essential micronutrients to avoid growth limitations are identified. A modified micronutrient feed solution, based on these results, would then be applied to the full-scale plant. The benefits could include cost savings but also the potential for reduced fouling of the injection wells.

Additional FBR's

Additional FBR units could be added, should the measures described above prove insufficient to provide the nitrate and COD removal capacity and performance desired to reduce injection well fouling. The unit(s) would incorporate lessons learned at 200 West P&T and could be used to demonstrate features that could subsequently be retrofitted to the existing units. It is understood that DOE is interested in increasing the facility's throughput, and the capacity of additional FBR's could be selected to provide the additional capacity desired.

Add Bioreactor to MBR

the addition of a bioreactor to the existing MBR system is another option to provide additional nitrate and COD removal capacity, should it prove to be needed. The existing MBRs simply use the volume inherent in the submerged membrane system to maintain an aerated suspended biomass. The results presented in Figure 6 indicate that the MBRs are capable of achieving significant COD removal. Nitrate removal is limited, however, due to the highly aerated environment inherent in the membrane basins. Another inherent feature of use of the volume inherent in the submerged membrane system as the bioreactor is that biological treatment and effluent removal through the submerged membranes occurs simultaneously. Thus, effluent removed at the inlet portion of the submerged membrane module would have received less biological treatment than effluent removed by the more downstream submerged membranes.

Additional biological treatment would be provided if a separate suspended growth bioreactor was added prior to the submerged membrane modules. The separate bioreactor would receive FBR effluent, influent flow which is diverted around the FBR's, and recycled solids from the downstream submerged membrane units. The bioreactor contents would be mixed to suspended biomass but not aerated so that denitrification would occur, although some aeration could be provided at the effluent end of the bioreactor to further remove any remaining biodegradable COD. Nitrate, biodegradable organic matter, and nutrients would be present, either those remaining in the FBR effluent or those in the flow diverted around the FBR, and denitrifying organisms would be present because they would be introduced in the FBR effluent and through the recycle of accumulated solids from the downstream submerged membrane units. Space is available to construct the reactor(s) adjacent to the existing submerged membrane units, with FBR effluent and influent diverted to it, along with the pumped recycle flow from the submerged membrane units. Bioreactor effluent would be returned to the existing submerged membrane splitter structure to deliver flow to the existing submerged membrane units. The bioreactor would be sized to provide the additional nitrate and COD removal desired and would provide reliable and consistent removal of both nitrate and biodegradable COD. In contrast to the FBR's where the maximum nitrate removal capacity is determined by the amount of media in them, nitrate removal in the bioreactor would increase in proportion to the plant nitrate loading as the suspended biomass concentration would simply increase or decrease as needed. Biological treatment would be complete prior to flow entering the submerged membrane units, resulting in improved effluent quality.

The ability to divert influent after supplemental carbon and nutrient dosing around the FBR's would be provided so as to allow the FBR's to be loaded at a rate where stable performance is achieved, thereby simplifying their operation, and to ensure a relatively consistent nitrate and biodegradable COD loading on the expanded MBR process to optimize its performance. A bioreactor volume of approximately 250,000 to 300,000 gallons is indicative of what is likely to be necessary to provide an additional 500 lb-N/day of nitrate removal capacity. In fact, the capacity of the 200 West P&T biological treatment system could be increased 50 percent (to 3,750 gpm) by adding further bioreactor volume and two more submerged membrane units (space for them is allowed in the existing plant design).

The volume listed above is simply indicative, and a complete process and facility design would be required if this option is pursued further. As a component of an enlarged and modified biological treatment process, a proper process and facility design considering not only the size but also the configuration of the bioreactor, mixing and aeration, the need to cover it and connect it to the existing gas phase GAC system, tank drainage, and other considerations would need to be completed. Addition of a separate bioreactor would increase the nitrate removal capacity of the plant but would not increase and would likely reduced slightly solids production per unit of nitrate removed. The solids produced would be of similar characteristics to those currently produced, and their nature should not affect operation or performance of the existing RDT's or downstream centrifuges. More reliable and robust treatment would be achieved because the biomass concentration in the modified MBR system would automatically respond to the plant nitrate loading, resulting in more consistent nitrate removal than is currently experienced, and consistently lower effluent COD values. The biomass could be maintained in the system during relatively short (a few days) shut-downs, but they would need to be removed and processed through the existing solids treatment system for more extended shut-downs. Start-up would be quick, however, due to the seeding of biomass from the up-stream FBR's. The addition of a separate bioreactor would also allow one of the two existing FBR's to be removed from service for maintenance without reducing plant through-put. The option of adding a separate bioreactor is likely to be less expensive than adding an additional FBR.

Comparison of Alternatives

Table 1 compares the four upgrade options identified above. Optimizing the existing FBR's and nutrient dosing both offer several advantages and no apparent disadvantages. It is possible that the distribution system in FBR B is somewhat damaged or could become so with continued operation. Thus, repairing it could both improve performance and extend the life of the unit. Modifying the biomass control system to increase its sensitivity will potentially simplify operation and could reduce carbon loss. Adding the ability to measure the plant nitrate mass loading automatically would further improve process control and would build on experience with the existing instrument used to measure the FBR effluent nitrate concentration. While a modest investment in laboratory work would be needed to optimize nutrient dosing, this investment is likely to pay back over time and will reduce injection well fouling potential.

Table 2. Comparison of Upgrade Options.

Option	Advantages	Disadvantages
Optimize FBR's	• Maximizes Use of Existing Infrastructure. • Extends Life of Existing Infrastructure. • Potentially Simplifies Operation. • Potentially Reduces Carbon Loss.	• None Apparent.
Optimize Nutrient Dosing	• Reduces Injection Well Fouling Potential. • Potential Long-Term Cost Savings.	• Modest investment in Laboratory Work Required.
Additional FBR's	• Site-Specific Experience on Which to Base Design. • Potential for Increased Capacity Based on Site-Specific Lessons Learned.	• Actual Performance of Existing Units Does Not Appear to Meet Original Design Expectations. • Existing Operating Sensitivities Retained. • Likely to be Most Costly Option.
Add Bioreactor to MBR	• Relatively Simple Operation. • Potentially More Stable Performance. • Easy Retrofit. • Likely Less Costly Than Additional FBR's. • Can be Coupled with Additional Submerged Membrane Units to Increase Hydraulic and Treatment Capacity.	• New Technology at 200 West P&T .

The first step is to optimize the FBR's, with the objective of ensuring that both FBR's are in proper operating condition and a full charge of media is reliably and consistently maintained. FBR B would be removed from service, the carbon it contains removed and stored, the structure and influent flow distribution inspected to ensure that it is in proper physical condition, and any necessary repairs made. This might be the proper time to modify the educator system and add the permanent camera, as described in Table 1, if these modifications are judged to assist with maintenance of a full bed of media. Return this unit to service, with a full load of carbon, and gradually increase the nitrate mass loading until the design nitrate mass loading of 600 lb-N/day [based on 1,250 gpm (half of the design flow) at 40 mg-N/L nitrate] is achieved and assess performance. The design criteria for the FBR's indicate that they are 14-foot-diameter units with a maximum tank height of 20 feet (CH2M HILL, 2010b). The minimum media volume is specified to be 1,850 ft^3, which would correspond to a consolidated (not expanded) bed height of 12 feet. The nitrate mass loading at the design nitrate mass loading, based on this consolidated (not expanded) bed volume, is 325 lb-N/1,000 ft^3-day, compared to an industry standard bench-mark of 400 lb-N/1,000 ft^3-day (Grady, *et al.*, 2011). At this loading a nitrate removal efficiency of 80 to 90 percent would be expected.

Nutrient addition optimization can be pursued as time is available. Time will be required to conduct the laboratory studies described, and there is no reason to wait to initiate them as they will not interfere with plant operations or require a significant time investment from plant personnel. Procuring and installing a nitrate analyzer similar or identical to the existing one should also be relatively straightforward and can proceed as plant staff are able but with a lower priority than optimizing the FBR's, as described above.

The other two options, additional FBR and the addition of a bioreactor to the MBR's, are alternatives to each other and would be implemented only if insufficient capacity can be obtained from the existing FBR's or an increase in plant capacity is desired. Consequently, only one of the two would be chosen, if needed. Both can be sized to provide the total nitrate removal capacity desired. Addition of a bioreactor to the MBR's is likely to be the simplest to operate, to provide more stable performance and higher quality effluent, and is likely to be less expensive to implement. In contrast, plant staff are already familiar with FBR's. Plant hydraulic capacity, along with nitrate removal capacity. can be increased most readily through the addition of a bioreactor to the MBR's, along with the addition of the two additional submerged membrane units that were provided for in the original plant design.

Recommended Plan

1. Continue to direct the solids handling recycle streams (RDT filtrate and centrate) to the FBR recycle tank.
2. Remove FBR B from service, inspect it, and make any repairs indicated. Recent operating results (Figure 4) suggests that it is not performing as well as the recently repaired FBR A.
3. Optimize the FBR's. Each of the measures listed in Table 1 are reasonable to consider and should be evaluated and implemented as possible. Optimization would also include adding on-line instrumentation to measure the plant influent nitrate concentration and use it to automatically control carbon and nutrient dosing. The laboratory studies described above to determine the optimum nutrient mixture should also be conducted to avoid adding un-needed nutrients which are both costly and can contribute to injection well fouling. The goal should be to consistently achieve an FBR effluent COD concentration less than 10 mg/L and an FBR effluent nitrate concentration less than 5 mg-N/L, with a plant effluent COD concentration less than about 3 mg/L.

4. Determine the performance capabilities and capacity of the optimized system by gradually increasing the nitrate loading to one FBR and monitor its performance. As above, a treatment objective of 3 mg/L effluent COD and 5 mg-N/L effluent nitrate would appear to be appropriate. If sufficient plant capacity and performance is demonstrated, then no further action is required.
5. Should further improvements to plant performance and/or capacity be desired, adding a bioreactor to the MBR system would appear to be the best option, compared to adding more FBR's. Adding the bioreactor would provide the capability to remove an FBR from service for maintenance without decreasing plant capacity, and it is also likely to be less expensive than adding additional FBR capacity.

   A consultant would be retained to develop a preliminary design and cost estimate. Provisions to further expand the hydraulic and treatment capacity of the system by the addition of two more submerged membrane modules should be included in the design, along with the identification of other plant modifications that may be required (such as increasing the capacity of the air strippers). This latter information on plant expansion options could be useful to DOE as they consider increasing the plant throughput. Such expansion would not be necessary if the current plant hydraulic capacity (2,500 gpm) is maintained, although adding the bioreactor itself would provide more consistent removal of COD and nitrate, and allow the nitrate mass loading design capacity to be increased. The selected modifications would then be constructed and placed in service. Their performance would be assessed by the increased nitrate removal achieved and by lowered and less variable (mean and standard deviation) plant effluent COD concentrations. The capacity of the bioreactor and submerged membrane system would be tested by diverting flow around the FBR's to determine removal capacity.

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