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Impact of Increasing Membrane Bioreactor Solids on Removal of Chemical Oxygen Demand at 200 West Pump and Treat

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

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Contents

1 Purpose and Introduction **1**

2 Approach **1**

3 Results **3**

3.1 Results Using All Data in Data Set 4

3.2 Results from Data with Similar COD Loading 5

3.3 Results from Data with Similar COD Loading and Recycle 6

3.4 Summary of Results 7

3.5 Mean Cell Residence Time 8

4 Summary and Recommendations **9**

5 References **9**

Figure

Figure 1. Impact of MCRT on COD Removal at COD Loadings of 250 lb/d 9

Tables

Table 1. First Data Set Used to Evaluate Benefit of Increased Solids, "All Data" 1

Table 2. Second Data Set Used to Evaluate Benefit of Increased Solids, "Similar COD Load" 2

Table 3. Third Data Set Used to Evaluate Benefit of Increased Solids, "Recent Data" 3

Table 4. Impact of MBR Solids Content on COD Removal Using Data Set Named "All Data" 4

Table 5. Impact of MBR Solids Content on Reducing COD Flux to Injection Wells Using Data Set Named "All Data" 5

Table 6. Impact of MBR Solids Content on COD Removal Using Data Set Named "Similar COD Load" 5

Table 7. Impact of MBR Solids Content on Reducing COD Flux to Injection Wells Using Data Set Named "Similar COD Load" 6

Table 8. Impact of MBR Solids Content on COD Removal Using Data Set Named "Recent Data" 6

Table 9. Impact of MBR Solids Content on Reducing COD Flux to Injection Wells Using Data Set Named "Recent Data" 7

Table 10. Percent Removal of COD Based on Mass of COD Removed in Tables 5, 7, and 9 7

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Terms

AMT	aerated membrane tank
COD	chemical oxygen demand
EOSi	Environmental Operating Solutions, Inc.
FBR	fluidized bed reactor
MBR	membrane bioreactor
MCRT	mean cell residence time
P&T	pump and treat
TSS	total suspended solids

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1 Purpose and Introduction

The purpose of this document is to provide an analysis of whether an increase in the bacterial solids content in the membrane bioreactors (MBRs) at the 200 West Pump and Treat (200 West P&T) would reduce the amount of biodegradable material in the plant effluent. Biodegradable material, measured as chemical oxygen demand (COD), fuels biological growth. Biological solids have been observed in the injection well pipes and tanks at 200 West P&T and in the wells themselves.

The role of bacterial growth on injection well performance was first recognized in 2013 and documented in SGW-58170, *Finding the Balance Between Biological Groundwater Treatment and Treated Injection Water*. One area of focus is reducing the amount of COD that can fuel bacterial growth in the injection piping tanks and wells. This study evaluates whether increasing the bacteria inventory in the MBRs reduces the COD in the plant effluent.

The solids content of the MBRs is established by engineering based on standard ratios of food to micro-organisms for MBRs. A range of 0.1 to 0.2 kg COD per kilogram solids was targeted. This ratio was decreased to 0.05 to 0.1 kg COD/kg solids to provide a greater inventory of bacteria to remove COD. As a result, in May 2017 the solids target was increased from 2,000 mg/L to 4,000 mg/L. Measurements of the COD concentration in the MBR influent and effluent were recorded along with the flow rate. This information was used to calculate the mass flux of COD loaded to the MBRs as well as the mass flux removed by the MBRs. The COD load and COD removed were compared at conditions of low and of high solids content to determine whether increased solids removed more COD.

2 Approach

The concentration of COD in the MBR effluent and the COD removed by the MBR were used as measures of COD removal effectiveness. The concentration of COD as well as the mass flux of COD were considered. The mass flux, measured in pounds per day (lb/d), includes the contribution of both the concentration and the flow rate. The total suspended solids (TSS) concentration in the MBRs was used as a measure of bacterial inventory.

Initially, all available data were screened for periods when the flow was greater than 2,000 gal/min. Using Microsoft® Excel® the data were then sorted by the TSS concentration in the MBRs, from low to high. The TSS concentration between the 30th percentile (3,000 mg/L) and 70th percentile (3,900 mg/L) were eliminated to provide two distinct data basis, one with high solids and the other with low solids as shown in Table 1.

Table 1. First Data Set Used to Evaluate Benefit of Increased Solids, "All Data"

Parameter	Low Solids Data	High Solids Data
Number of data points	90	89
Solids concentration (mg/L)	1,000 to 2,800 (average 2,400)	4,000 to 6,900 (average 4,900)
Total FBR flow rate (gal/min)	2001 to 2618 (average 2,161)	2008 to 2464 (average 2,264)
COD MBR inlet (mg/L)	1.5 to 30.4 (average 11.6)	1.5 to 74 (average 13.6)

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Table 1. First Data Set Used to Evaluate Benefit of Increased Solids, "All Data"

Parameter	Low Solids Data	High Solids Data
COD loading to MBR (lb/d)	36 to 819 (average 303)	36 to 2135 (average 368)

COD = chemical oxygen demand
FBR = fluidized bed reactor
MBR = membrane bioreactor

The desired outcome was two databases that were similar in every way except in solids concentration. Although these two data sets were similar, the average COD concentration in the MBR influent was 17% greater in the high solids data set than in the low solids data set. Likewise, the COD loading (pounds per day) was 21% greater in the high solids data set.

Having a greater COD in the influent has the potential to introduce bias in the outcome. The data set with more COD (high solids) has the potential to remove more COD simply because there is more COD to remove.

A second data set, termed "Similar COD Load," was created from the first by selecting COD loading between 100 and 1,000 lb/d. The resulting two data sets were more equal in COD loading as summarized in Table 2.

Table 2. Second Data Set Used to Evaluate Benefit of Increased Solids, "Similar COD Load"

Parameter	Low Solids Data	High Solids Data
Number of data points	82	57
Solids concentration (mg/L)	1,000 to 2,900	4,000 to 6,900
Total FBR flow rate (gal/min)	2001 to 2618 (average 2,153)	2008 to 2471 (average 2,258)
COD MBR inlet (mg/L)	4.2 to 30.4 (average 12.4)	7.12 to 38.5 (average 11.9)
COD loading to MBR (lb/d)	105 to 819 (average 324)	208 to 979 (average 323)

COD = chemical oxygen demand
FBR = fluidized bed reactor
MBR = membrane bioreactor

This second data set had the advantage of similar COD concentrations on the inlet (4% different) and similar COD loading in pounds per day (0.3% different). However, these data included two different operational practices that had the potential to cloud the impact of increased solids. During some days the recycle stream is sent to the splitter box, and other days the recycle stream was returned to the recycle tank upstream of the fluidized bed reactors (FBRs). The contribution of the recycle stream is not included in calculation of COD loading to the MBR because the COD of these streams is not monitored and the centrate flow is not recorded.

To avoid uncertainties associated with the recycle stream, a third data set was created. Termed "Recent Data," this third data set was created from the first data set by selecting a time period (October 2017 to February 1, 2018) when the recycle water was returned to the splitter box, not the recycle tank.

The third data set, termed the "Recent Data" data set, is summarized in Table 3.

Table 3. Third Data Set Used to Evaluate Benefit of Increased Solids, "Recent Data"

Parameter	Low Solids Data	High Solids Data
Number of data points	21	26
Solids concentration (mg/L)	2,000 to 3,900 (average 3,300)	4,300 to 6,900(average 5,000)
Total FBR flow rate (gal/min)	2,104 to 2,465 (average 2,352)	2,042 to 2,471 (average 2,406)
COD MBR inlet (mg/L)	2.6 to 16.6 (average 9.9)	1.5 to 12.5 (average 7.9)
COD loading to MBR (lb/d)	76 to 470 (average 278)	44 to 370 (average 228)

COD = chemical oxygen demand
FBR = fluidized bed reactor
MBR = membrane bioreactor

This third set of data was collected under similar operating conditions, but the COD concentration in the MBR inlet is 20% different (on average) and the COD loading is 18% different on average.

These three data sets were used to determine whether increasing solids loading helps remove COD. COD removal was evaluated by graphing COD removal as a function of COD loading. Regression lines through the resulting data were used to determine percent removal.

3 Results

The three data sets were evaluated separately in separate sections starting with data set 1, "All Data." The data sets become progressively select to screen out interference. It is of interest to identify whether this screening of the data results in additional insight.

The data were evaluated using four measures as follows:

- COD concentration in the plant effluent
- COD concentration decrease through the aerated membrane tank (AMT)
- Mass of COD released from the plant in pounds per day
- Mass of COD removed by the MBRs in pounds per day

Some of the difference between concentration and loading is that the amount of COD coming into the MBRs is variable depending on up-stream conditions such as FBR effectiveness and the presence of external sources of COD. The amount removed tends to correct for variations in COD influent.

The contrast between concentration and mass flux is that the mass flux includes the contribution of flow. For example, a low concentration of COD at a high flow rate may contribute a greater mass of COD than a high concentration at a low flow rate.

3.1 Results Using All Data in Data Set

The characteristics of this data set are summarized in Table 4 and include ranges to indicate the amount of scatter in the data.

Table 4. Impact of MBR Solids Content on COD Removal Using Data Set Named "All Data"

Parameter (mg/L)	Low Solids	High Solids
Solids concentration	1,000 to 2,900	4,000 to 6,900
COD concentration in FBR effluent*	1.5 to 30.4 (average 11.7)	1.5 to 74 (average 13.6)
COD in MBR effluent	1.5 to 15.5 (average 5.5)	1.5 to 10.7 (average 5.9)
COD removed by MBR	0 to 20.8 (average 6.2)	-3.2 to 72.5 (average 7.7)

*The FBR effluent is often the MBR influent. When centrate and filtrate are recycled to the splitter box, they carry additional COD that is not measured in the FBR effluent.

COD = chemical oxygen demand

FBR = fluidized bed reactor

MBR = membrane bioreactor

The results are mixed. The average COD in the plant effluent was lower in the low solids data (5.5 mg/L versus 5.9 mg/L). However, more COD was removed under the high solids condition (162 lb/d versus 13 lb/d). This is because the high solids data had a greater COD concentration coming from the FBRs.

The results are not clear and appear to be impacted by differing COD in the MBR influent.

The amount of COD removed by the MBRs with high solids ranged from -3.2 to 72.5 mg/L. The minimum is negative, indicating that the COD was greater in the MBR effluent than in the FBR effluent. It is theorized that during this time the water was being recycled to the splitter box just upstream of the MBRs, resulting in an increased concentration of COD going to the MBRs than indicated by the FBR effluent concentration.

The impact of solids on COD loading or flux is summarized in Table 5 and indicates a pattern similar to that provided by the concentration data. The high solids conditions were loaded with more COD and removed more COD. The low solids conditions resulted in lower flux of COD from the membranes.

The author believes that greater COD flux to the MBRs tends to result in a greater biological inventory, and a greater inventory would remove more COD. If that is true, then one would expect that high flux rates of COD to the MBR are associated with greater solids concentration and greater COD removal.

Table 5. Impact of MBR Solids Content on Reducing COD Flux to Injection Wells Using Data Set Named "All Data"

Parameter	Low Solids	High Solids
Solids concentration (mg/L)	1,000 to 2,900	4,000 to 6,900
COD loading from FBR* (lb/d)	36 to 819 (average 303)	36 to 2135 (average 368)
COD loading to injection wells (lb/d)	0 to 426 (average 142)	36 to 316 (average 161)
COD removed by MBR (lb/d)	0 to 541 (average 162)	0 to 2091 (average 213)

*The FBR effluent is often the MBR influent. When centrate and filtrate are recycled to the splitter box, they carry additional COD that is not measured in the FBR effluent.

COD = chemical oxygen demand

FBR = fluidized bed reactor

MBR = membrane bioreactor

3.2 Results from Data with Similar COD Loading

The second data set, called "Similar COD Load," was evaluated in a similar manner. Table 6 shows that when the influent COD is more similar, the lower solids conditions removed more COD and had lower COD concentrations in the plant effluent.

Table 6. Impact of MBR Solids Content on COD Removal Using Data Set Named "Similar COD Load"

Parameter (mg/L)	Low Solids	High Solids
Solids concentration	1,000 to 2,800	4,000 to 6,900
COD concentration in FBR effluent*	4.2 to 30.4 (average 12.4)	7.1 to 38.6 (average 12.0)
COD in MBR effluent	1.5 to 15.5 (average 5.9)	1.5 to 10.7 (average 6.5)
COD removed by MBR	0 to 20.8 (average 6.7)	-3.2 to 32.1 (average 5.4)

*The FBR effluent is often the MBR influent. When centrate and filtrate are recycled to the splitter box, they carry additional COD that is not measured in the FBR effluent.

COD = chemical oxygen demand

FBR = fluidized bed reactor

MBR = membrane bioreactor

The impact of solids on COD loading or flux was also evaluated. Table 7 summarizes the flux data and indicates a pattern similar to that provided by the concentration data. The low solids conditions had a lower load to the injection wells. The high solids conditions were loaded with more COD and removed more COD. The greater COD removal associated with high solids could be driven by higher COD loading.

Table 7. Impact of MBR Solids Content on Reducing COD Flux to Injection Wells Using Data Set Named "Similar COD Load"

Parameter	Low Solids	High Solids
Solids concentration (mg/L)	1,000 to 2,900	4,000 to 6,900
COD loading from FBR (lb/d)*	105 to 819 (average 324)	208 to 979 (average 323)
COD loading to injection wells (lb/d)	0 to 426 (average 153)	37 to 316 (average 176)
COD removed by MBR (lb/d)	-56.8 to 541 (average 172)	-93 to 816 (average 146)

*The FBR effluent is often the MBR influent. When centrate and filtrate are recycled to the splitter box, they carry additional COD that is not measured in the FBR effluent.

COD = chemical oxygen demand

FBR = fluidized bed reactor

MBR = membrane bioreactor

The amount of COD removed by the MBR is negative on some days. The negative values are believed to result from either normal analytical variations at low concentrations or from recycling the filtrate and centrate to the splitter box.

3.3 Results from Data with Similar COD Loading and Recycle

The third data set, called "Recent Data," includes data that have similar COD loading and collected while recycle was directed to the splitter box, not the recycle tank. Table 8 shows that lower solids conditions removed more COD but had higher COD concentrations in the plant effluent.

Table 8. Impact of MBR Solids Content on COD Removal Using Data Set Named "Recent Data"

Parameter (mg/L)	Low Solids	High Solids
Solids concentration	2,000 to 3,900	4,300 to 6,900
COD concentration in FBR effluent*	2.6 to 16.6 (average 9.9)	1.5 to 12.5 (average 7.9)
COD in MBR effluent	1.5 to 11.1 (average 6.7)	1.5 to 10.7 (average 6.1)
COD removed by MBR	-0.9 to 9.4 (average 3.3)	-3.2 to 10.7 (average 1.9)

*The FBR effluent is often the MBR influent. When centrate and filtrate are recycled to the splitter box, they carry additional COD that is not measured in the FBR effluent.

COD = chemical oxygen demand

FBR = fluidized bed reactor

MBR = membrane bioreactor

Table 9 shows the impact of solids content on COD loading. When the two solids conditions are compared, the low solids loading is associated with greater COD removal but a greater mass of COD released to the injection wells.

Table 9. Impact of MBR Solids Content on Reducing COD Flux to Injection Wells Using Data Set Named "Recent Data"

Parameter	Low Solids	High Solids
Solids concentration (mg/L)	2,000 to 3,900	4,300 to 6,900
COD loading from FBR (lb/d)*	75 to 470 (average 278)	44.5 to 370 (average 228)
COD loading to injection wells (lb/d)	42 to 315 (average 191)	44 to 316 (average 175)
COD removed by MBR (lb/d)	-26 to 265 (average 93)	-93 to 316 (average 56)

*The FBR effluent is often the MBR influent. When centrate and filtrate are recycled to the splitter box, they carry additional COD that is not measured in the FBR effluent.

COD = chemical oxygen demand

FBR = fluidized bed reactor

MBR = membrane bioreactor

3.4 Summary of Results

Table 10 summarizes the results in terms of percent removal based on loading rates. The low solids conditions appear to remove more COD than high solids after correcting for similar COD loading and recycle stream.

Table 10. Percent Removal of COD Based on Mass of COD Removed in Tables 5, 7, and 9

Data Set	Low Solids (%)	High Solids (%)
All data	53	58
Similar COD load	53	45
Recent data	33	25

COD = chemical oxygen demand

It is striking that the more recent data show much lower removal by the MBRs. During this period the FBRs have released a lower mass, on average, of COD, so there is less for the MBRs to remove. The lower mass of COD from the FBRs is likely a function of the recycle stream going to the splitter box rather than the recycle tank and generally good operation of the FBRs.

In summary, the amount of solids did not appear to benefit COD removal. This may appear to be counterintuitive if one assumes that more solids represent more bacteria, and more bacteria will consume more COD. However, in an effort to reduce the COD in the treated effluent the MBRs are operated in an environment of nutrient and energy limitation. For comparison, most MBRs have a load of 5,000 rather than 300 lb/d COD. Given the low COD load, it is not surprising that the MBRs do not need a high solids content.

Under the low COD conditions bacteria slow their metabolism and enter into a resting state, from which they can be awoken when nutrients become available again. The MBR bacteria probably spend part of

their existence in growth arrest. At some point increasing the solids concentration simply results in a greater portion of bacteria in growth arrest and at risk of dying off. The best strategy is to maintain enough bacteria that can quickly respond to increase in COD loading but not enough to result in death and cell lysis.

Environmental Operating Solutions, Inc. (EOSi), the supplier of the carbon substrate, performed an evaluation and found that the COD in the treated effluent contained no carbon substrate. The effluent COD was composed of the following two items: (1) residual polymer from the recycle of filtrate and centrate, and (2) biological byproducts from cell lysis.

EOSi was not able to quantify the relative contributions of cell lysis or polymer. EOSi believed that these materials were difficult to biodegrade; in the time available in the MBR, the lowest COD achievable was 6 to 7 mg/L. Additional solids would not make an appreciable impact on this value.

3.5 Mean Cell Residence Time

During the course of this investigation, another parameter, the mean cell residence time (MCRT), was evaluated. MCRT is defined as an expression of the average time (days) that a microorganism will spend in the membrane bioreactor. This can be a useful parameter for operating a biological plant. It is derived from the mass of biota in the bioreactor and the waste rate (Equation 1):

$$MCRT = \frac{VX}{QX} = \frac{V}{Q} \tag{1}$$

where:

MCRT	=	mean cell resident time (d)
V	=	volume of bioreactors = 4 reactors x 1,9018 gal/reactor = 76,072 gal
X	=	biological solids concentration
Q	=	solids waste rate (gal/d)

For example, given a sludge waste rate of 55 gal/min, the MCRT would be as shown in Equation 2:

$$\text{MCRT} = \frac{76{,}072\ gal}{55\ gallons\ per\ minute} \div 1440\ \frac{minutes}{day} = 0.96\ days \tag{2}$$

When the impact of MCRT on COD is evaluated the resulting relationship (Figure 1) shows maximum COD removal at 0.95 days. When compared to other operations, 1 day is a little short, which is a reflection of the relatively low COD load. An MCRT of 0.95 days is typically associated with a bacterial population that is in a growth phase.

Equation 1 can be rearranged to solve for Q, the rate of solids waste to determine the optimum solids waste rate. When four AMTs are on line the optimum waste rate is 55 gal/min. With three AMTs on line for more than 2 days, such as during membrane replacement, the optimum decreases to 40 gal/min. The optimum waste rate is likely dependent on the COD load to the MBRs. The values presented are for illustrative purposes only and should not be considered as optimum for all conditions.

It is advisable to consider the MCRT in the operation of the MBRs and develop guidelines for varying COD loads. Such an endeavor may take time to develop, but once complete would provide useful guidance for maintaining low COD in the plant effluent.

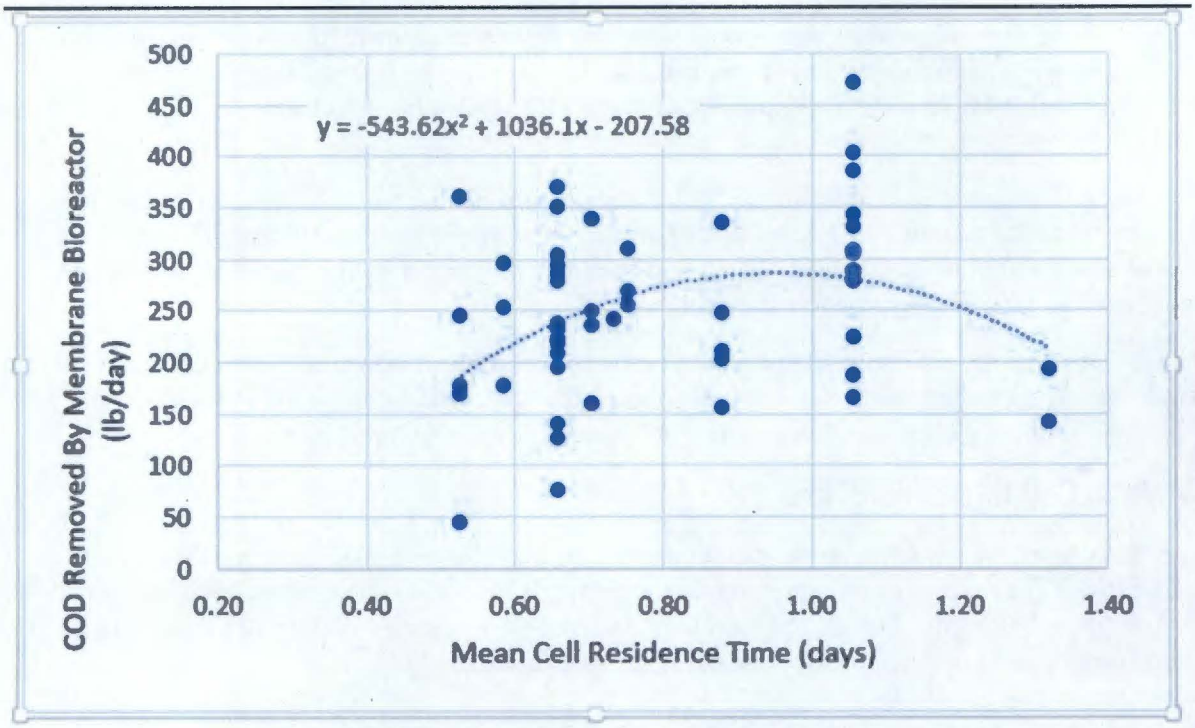

Figure 1. Impact of MCRT on COD Removal at COD Loadings of 250 lb/d

4 Summary and Recommendations

In summary, increasing solids above approximately 3,000 mg/L has minimal impact. The best strategy is to provide enough biological inventory to respond to sudden increases in COD load. It appears that in most cases a solids concentration of 3,000 mg/L is sufficient.

Further evaluations of MCRT, especially under different loading conditions, may be helpful, particularly during excursion events such as when glycerin is flushed from new membranes. During the last such event, the COD in the plant effluent often exceeded 10 mg/L. If an MCRT target was previously established, additional COD may have been removed during the glycerin flush event.

However, the effort will have fairly small improvement under normal conditions. It has been estimated by EOSi that it will be difficult or impossible to decrease the COD below 6.5 mg/L in the plant. In March 2018 COD in the plant effluent has averaged 6.5 mg/L.

5 References

SGW-58170, 2018, *Finding the Balance Between Biological Groundwater Treatment and Treated Injection Water*, pending, CH2M HILL Plateau Remediation Company, Richland, Washington.

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