Direct Filtration Membrane Pilot Study

Summary Report

Ashland, Oregon
May 22, 2018

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A. Membrane Filtration Equipment Pilot Testing Protocol
B. AASI Pilot Testing Report
C. Inge Pilot Testing Report
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F. Bench Scale Ozone Test Report

Certification

City of Ashland, Oregon

Direct Filtration Membrane Pilot Study: Summary Report

This report for the membrane pilot testing effort conducted for the City of Ashland, OR has been prepared under the direction of the following Registered Professional Engineer in the State of Oregon:

Pierre K. Kwan
HDR Engineering, Inc.
(206) 826-4735

1 Introduction

The City of Ashland (City) is planning for a new water treatment plant (WTP) with a potential ultimate production capacity of 10 million gallons per day (MGD), which will replace the existing direct filtration WTP in supplying potable water to meet the City's future needs. As a part of this planning effort, the City's raw water supplies were characterized and summarized and treatment process recommendations were developed in 2017. The treatment process recommendations included direct filtration with low pressure membranes followed by granular active carbon (GAC) for the removal of taste and odor (T&O) compounds and potential algal toxins.

The City chose to pilot test several Membrane Filtration Equipment Manufacturers' (MFEMs) membrane systems in parallel to evaluate the effectiveness of direct filtration with low pressure membranes. Ultimately, the City piloted membrane systems from Aqua Aerobic Systems (AASI), Pall Corporation (Pall), and BASF/Inge (Inge). In addition, two bench-scale studies were performed on membrane filtrate using ozone and GAC for T&O removal. This report summarizes the methods and results of the pilot study and provides recommendations based on the results that can be used in the preliminary design effort.

This pilot testing effort is the contribution of multiple parties. The parties, and their roles, are:

- City of Ashland, Oregon – Owner and whose staff helped install and maintain the pilot units under direction of the MFEMs and Keller Associates.
- Keller Associates – Developed the pilot testing request of qualifications, developed the pilot testing protocol, and directed the pilot testing effort.
- MFEMs – Installed their respective equipment, provided guidance to City staff on how to maintain the system, provided remote and/or on-site assistance to troubleshoot issues, and prepared summary testing reports.
- HDR – Reviewed the acquired data upon completion of the pilot testing and coordinated with the MFEMs to compile this report.

2 Methodology

2.1 Pilot Objectives

Keller Associates developed the protocols for the pilot study in the Membrane Filtration Equipment Pilot Testing Protocol, provided as Appendix A. The objectives of the pilot study were to:

1. Provide operational staff experience with membrane processes
2. Evaluate compatibility of raw/pretreated water from Ashland Creek/Reeder Reservoir and Talent Irrigation District (TID) sources with membrane filtration process
3. Demonstrate flux through membrane system without excessive fouling

4. Demonstrate acceptable physical integrity test(s) and ability to meet warranties for fiber breakage for each piloted membrane system
5. Evaluate the causes of any excessive membrane fouling that may occur during pilot testing
6. Demonstrate the capability of membrane system to meet treated water quality requirements
7. Optimize and establish physical design parameters for the full-scale plant design that will allow determination of life-cycle costs, including:
    a. Flux (gallons per day per square foot of membrane material, gfd)
    b. Pre-treatment chemicals
    c. Backwash type, frequency, duration, and required flow rates for both air and water
    d. Water recovery rate (filtrate volume / feedwater volume)
    e. Cleaning chemicals and processes
8. Demonstrate membrane filter operating conditions established and recommended by the MFEM with minimum 28-day operation before chemical cleaning is required as determined through transmembrane pressure (TMP) measurements
9. Characterize the quantity and composition of treatment residuals including backwash water that contains solids that will require handling

2.2 MFEM Performance Criteria

In addition, performance criteria were established to determine the successful completion of each MFEM's pilot study, and allow subsequent bidding, if membrane processes are selected for the future WTP. These criteria were:

1. Reduction of turbidity to a membrane effluent turbidity of less than 0.05 NTU in 95 percent of measurements.
2. Reduction of color to less than 5 CU.
3. Operation at a recovery of 95 percent or greater.
4. Require clean-in-place (CIP) no more frequently than once every 28 days. This shall be demonstrated in a continuous design run with consistent operating parameters. The following Design Run termination criteria shall be used,
    a. Terminal TMP – the TMP immediately prior to a CIP.
    b. Successful operation for the 28 days at specified conditions.
    c. Exceeding maintenance clean time (60 minutes/day) or frequency. (Each vendor used a different term for a chemically-adjusted backwash. This report standardizes around the term of maintenance clean.)
    d. Exceeding acceptable downtime of 48 hours per run
    e. Exceeding membrane integrity criteria.

5. If more than one repair occurrence is required to maintain integrity of a membrane, the City reserves the right to exclude that supplier from bidding on the project.
6. Demonstrated ability of module to meet warranty provisions with respect to integrity and fiber breakage rates.
    a. Membrane integrity tests are to be run daily and reports submitted to the City.
7. Demonstrated membrane integrity testing procedure and fiber repair/plugging procedures during the pilot test consistent with requirements of the Long Term 2 Enhanced Surface Water Treatment Rule.

2.3 Pilot Configuration

Appendix A provides schematics of the pilot study developed by Keller. The MFEM pilot units were located to the west of the existing WTP near the powerhouse. Figure 1 shows the installed pilot testing equipment prior to the erection of the rain shelter. Raw waters were pumped through dedicated pipelines to a common 4-inch PVC pipeline to the pretreatment equipment (the white pipe in Figure 2). Membrane filtrate was discharged to Ashland Creek (the green pipe in Figure 2).

Figure 1: Photos of Pilot Testing Equipment

Figure 2: Raw Water Supply Pipe into Membranes (White Pipe) and Filtrate Pipe to Ashland Creek (Green Pipe)

The planned WTP will use two raw water sources: Ashland Creek flowing into and stored within Reeder Reservoir (Reeder) and the Talent Irrigation District canal (TID). Reeder, which is the primary source of the existing WTP, will also be the primary raw water source for the new plant. The report, Water Quality Summary and Review (HDR, 2017) indicated that the water quality is typical for a snowmelt-fed creek (i.e. lightly mineralized with low hardness and alkalinity) with low turbidity due to the settling time in Reeder Reservoir. Color is an important water quality parameter that needs to be adjusted.

TID will be an emergency source for the new WTP. The City currently buys TID water to supplement Reeder supply as a raw water feed to the existing WTP when needed. Historically, this has occurred in intermittent years and starting late summers when water levels in Reeder Reservoir are low. When utilized, TID water is pumped from the Ashland Canal via the Terrace Street Pump Station to the WTP, where it is mixed with Reeder Reservoir water prior to entering the WTP. In contrast to Reeder, TID has not been well characterized. The memorandum, TID Water Quality Summary (HDR, 2018) summarizes the data collected in a comprehensive sampling program in the summer and fall of 2017. The data found that the TID water was similar but likely more difficult to treat to Ashland Creek/Reeder Reservoir water due to the higher presence of pathogens and algae.

TID water was used for the raw water feed during Design Run #1 and Reeder water was used during Design Runs #2 and #3. Temporary submersible pumps were used to convey raw water from the respective sources to the pilot area:

- Reeder water - the Reeder Reservoir tailrace, and
- TID water - the Terrace Street Pump Station.

Pre-treatment consisted of in-line coagulant injection and mixing. This was a common feed to all MFEM systems and resulted in all units receiving the same coagulated water to the membranes. Aluminum chlorohydrate (ACH) was used as a coagulant upstream of the membrane pilot systems without clarification (direct filtration mode). Note that the existing WTP uses aluminum sulfate; the reason for using a different coagulant for testing is uncertain.

ACH dose was targeted at 4 mg/L (8 mg/L of a 50 percent solution) throughout all three design runs. However, on October 12, 2017 it was discovered that no ACH had been dosed throughout all of Design Run #1 and from October 3 to October 12 during Design Run #2. After the ACH feed was restored it was dosed at 4 mg/L throughout the remainder of Design Run #2. During Design Run #3, ACH was again dosed at 4 mg/L, with the exception of November 22 to November 27, when ACH feed was temporarily stopped. According to the report supplied by Inge, when the ACH feed was restored on November 27 the pump was placed in a manual operating mode and was delivering an ACH dose of 24 mg/L or more for 2 – 3 days. AASI and Pall do not mention this overdosing in their reports, and there are no other records.

The MFEM systems were oriented in parallel with the individual filtrate lines joining to a common pipe prior to being returned to WTP raw water basin.

2.4 Pilot Test Runs

The study was conducted during the period of August 2017 to December 2017. Equipment installation and initial optimization to the TID water source was from August 7 to 29, 2017. This was followed by three discrete design runs: Design Runs #1, #2, and #3. These design runs were planned to be a minimum of 28 days in duration and are described in Table 2-1.

Table 2-1. Pilot Study Design Runs

Parameter	Design Run #1	Design Run #2	Design Run #3
Period	8/30/17 to 9/27/17	10/3/17 to 11/31/17	11/14/17 to 12/12/17
Duration (days)	28	28	28
Feed Water Source	TID	Ashland Creek/Reeder Reservoir	Ashland Creek/Reeder Reservoir

2.5 MFEM Systems

Potential MFEMs were screened through a Request for Qualifications (RFQ) process in May 2017. As a result of this process, three MFEMs were selected to participate in pilot testing:

- Aqua-Aerobic Systems (AASI) with the Aqua MultiBore C-3, ceramic microfiltration membrane.
- Pall Corporation using the Asahi UNA-620A, polymeric microfiltration membrane.
- Inge GmbH with multibore XL 0.9 MB 70 WT, polymeric ultrafiltration membrane.

Table 2-2 provides a summary for the specifications for each module.

Table 2-2. Comparison of Membranes

Parameter	Units	Value		
		AASI Aqua MultiBore C-3	Pall UNA-620A	Inge GmbH (BASF) Multibore 0.9
Size of Module	mm	180 x 1500	152.4 x 2000	250 x 1720
Configuration	(none)	Cast monolithic module	Multiple single-bore fibers in plastic housing	Multiple multi-bore fibers in plastic housing
Inside Diameter of Channels	mm	2.5	0.7	0.9
Active Membrane Area per Module	SF	269	538	753
Flow Direction	(none)	Inside out	Outside in	Inside out
Number of Channels per Module	Number	2,000	6,400	2,210
Available Operating Modes	(none)	Dead end	Dead end	Dead end
Membrane Material	(none)	Modified alumina	PVDF	PES modified
Nominal Membrane Pore Size	micron	0.1	0.1	0.02
Acceptable Range of Operating pH	SU	1 - 12	1 - 10	1 - 13

2.5.1 Membrane Operating Conditions

The MFEMs were instructed to target moderate fluxes in Design Runs #1 and #2 and aggressive flux rates in Design Run #3. Table 2-3 provides a summary of operating conditions that the MFEM reported.

Table 2-3. MFEM Pilot Systems Operating Conditions

Parameter	Units	AASI Pilot	Pall Pilot	Inge Pilot
Design Run #1 – September 1, 2017 to October 5, 2017				
Flux	gfd	50	55	(Pilot functionally inoperable)
Flow Rate	gpm	9.3	20.5	(Pilot functionally inoperable)
Terminal TMP	psi	15	43.5	(Pilot functionally inoperable)
Filtration/Backwash Cycle	minutes filtrate minutes backwash	45 1 - 3	19.5 1	(Pilot functionally inoperable)
Design Run #2 – October 3, 2017 to November 4, 2017				
Flux	gfd	50	70	55
Flow Rate	gpm	9.3	26.2	28.8
Terminal TMP	Psi	15	43.5	20
Filtration/Backwash Cycle	minutes filtrate minutes backwash	60 for first 2/3 of run; 720 for last 1/3 of run 1 - 3	15.3 1	40 0.7
Design Run #3 – November 14, 2017 to December 12, 2017				
Flux	gfd	150	85	75
Flow Rate	gpm	28	32	39.3
Terminal TMP	Psi	15	43.5	20
Filtration/Backwash Cycle	minutes filtrate minutes backwash	90 1 - 3	12.6 1	35 0.7

2.6 Water Quality and Pilot Operations Monitoring

Table 2-4, below, provides a summary of the frequency and locations of the water quality grab samples collected by the City during the pilot testing period.

Table 2-4. Grab Sample Water Quality Monitoring by City Staff

Parameter	Feed Water	MFEM Pilot Filtrate	MFEM Pilot Backwash	Existing WTP Filtered Water (Reeder Raw Source only)
pHH	Daily	Daily	Weekly	Daily
Total organic carbon (TOC)	Weekly	Weekly		Weekly
Dissolved organic carbon (DOC)	Weekly	--	-	-
UV light at 254 nm	Weekly	Weekly	-	Weekly
Color	Weekly	Weekly	-	Weekly
Manganese	Weekly	Weekly	Weekly	Weekly
Iron	Weekly	Weekly	Weekly	Weekly
Aluminum	-	Weekly	Weekly	-
Total suspended solids (TSS)	Weekly	-	Weekly	-
Alkalinity	Weekly	Weekly	-	Weekly
Hardness	Monthly	-	-	-
Algae Counts	Weekly	Weekly	-	Weekly
Trihalomethane formation potential (THMFP)	Monthly	Monthly	-	Monthly
Haloacetic acid formation potential (HAAFP)	Monthly	Monthly	-	Monthly
Geosmin	Monthly	Monthly	-	Monthly

To monitor the pilot operations, the following parameters were also manually analyzed and logged once per day by City staff:

- Raw water flow rate to pilot units
- Coagulant feed flow rate
- Coagulant feed calibration check

Additionally, each MFEM pilot units recorded the following parameters at a 15-minute maximum logging interval:

- Feed water (entering the membrane unit) – temperature, pressure, flow rate, turbidity
- Filtrate – pressure, flow rate, flux, turbidity

- Backwash – flow rate, frequency and duration.
- Maintenance clean – frequency and duration.
- Clean in place (CIP) – frequency and duration.
- Transmembrane pressure.

2.7 Disinfection By-Product Formation Potential Tests

Disinfection by-product (DBP) formation potentials were assessed for raw water and filtrate four times during the pilot study: once for Design Runs #1, twice for Design Run #2, and once for the final Design Run #3. Trihalomethane formation potentials (THMFP) and haloacetic acids formation potential (HAAFP) was identified using the protocol outlined in the pilot testing plan, which called for membrane filtered water samples to be chlorinated with 2.0 mg/L as free chlorine and held in the dark at constant temperature for 96 hours prior to analysis. The samples were sent to Eurofins Eaton Analytical (EEA) for the DBP measurements.

2.8 Bench-Scale Taste and Odor Tests

In order to evaluate GAC adsorption for the removal of the T&O compound Geosmin, the City sent effluent samples from the membrane pilot study to an outside lab for testing. Rapid small-scaled column tests (RSSCTs) were performed by Engineering Performance Solutions, LLC (EPS) on a sample taken from the effluent of the pilot and spiked with an average of 70.4 ng/L Geosmin. The RSSCTs used the reagglomerated bituminous carbon Filtasorb 300 from Calgon Carbon and simulated a 1 MGD flow at an empty bed contact time of 7 minutes. Breakthrough curves were established for TOC and Geosmin.

Additionally, ozone demand and decay tests were performed be EEA on samples taken from the effluent of the Pall pilot during Design Runs #1 (TID feed) and #3 (Reeder Feed). Samples spiked with Geosmin were tested for removal to the odor threshold concentration OTC. Tests were run at 3 and 21 degrees Celsius with ozone doses ranging from 1 to 3 mg/L.

3 Results

The following section summarizes the operations and performance of the pilot units. Appendices B through D are the reports submitted by each MFEMs used for this summary. For clarity, the term “feed water” refers to the water entering the membranes.

3.1 Design Run #1

TID water was the feed water source for Design Run #1; this water is considered to be a potentially more challenging water to treat than Reeder Reservoir water. Water quality monitoring conducted 2017 characterized the TID water and found it to exhibit higher turbidity, iron, manganese, and algae than the historical surface water entering the WTP; additionally, HDR concluded that the daily variability of water quality would pose operational challenges in treatment (HDR, 2018).

Table 3-1 provides a comparison of TID water quality observed during the 2017 monitoring to the feed water quality observed during Design Run #1. Some water quality parameters in the TID water supplied to the pilot equipment during Design Run #1 were near or within the range of values observed during the 2017 monitoring; however the following parameters were found to be lower than the 2017 data range:

- Hardness (based on only one sample),
- Color, and
- Algae.

Table 3-1. Design Run #1 Raw Water Quality

Parameter	Units	Feed Water Quality During Design Run #1 AVG (MIN – MAX)	TID Water Quality 2017 Monitoring[1] AVG (MIN – MAX)
pH	SU	Not measured	7.79 (7.31 – 8.55)
Turbidity	NTU	Not measured	8.20 (0 – 209)
ORP	mV	Not measured	246.5 (31.9 – 338.7)
Dissolved Oxygen	mg/L	Not measured	9.3 (4.7 – 13.4)
Specific Conductivity	mS/cm	Not measured	0.08 (0 – 0.28)
Temperature	°C	Not measured	17.4 (8.1 – 24.9)
Alkalinity	mg/L as $CaCO_3$	37.5 (35.0 – 42.5)	35 (27 – 44)
Hardness	mg/L as $CaCO_3$	22.5 (one sample)	34.4 (30.3 – 43.6)
Total Organic Carbon (TOC)	mg/L	2.6 (2.4 – 2.9)	3.00 (2.48 – 3.39)
Iron	mg/L	0.332 (0.180 - 0.450)	0.474 (0.392 – 0.514)
Manganese	mg/L	0.016 (<0.010 – 0.030)	0.0386 (ND - 0.0488)
Color	CU	12 (9 – 15)	22 (20 – 25)
Pathogens	-	Not measured	Zero for *Cryptosporidium* Two positive for *Giardia*
Toxigenic Cyanobacteria	Cells/mL	Not measured	152 (0 – 351)
Algae	Cells/mL	144 (54 – 230)	1032 (930– 1178)

Notes:

1. Data from 2017 Water Quality Data Summary (HDR 2018)

3.2 Design Runs #2 and #3

Reeder Reservoir water was supplied during Design Runs #2 and #3. Table 3-2 lists the observed pilot raw water quality during these periods. The observed data is representative of the typical Reeder Reservoir water that the existing WTP has experienced.

Table 3-2. Design Runs #2 and #3 Raw Water Quality

Parameter	Units	Feed Water Quality – Average (Min – Max)	
		Design Run #2 Feed Water Quality	Design Run #3 Feed Water Quality
pH	SU	-	-
Turbidity	NTU	-	-
Temperature	°C	-	-
Alkalinity	mg/L as $CaCO_3$	40.0 (37.5 – 42.5)	40 (40 – 40)
Hardness	mg/L as $CaCO_3$	25.0 (25.0 – 25.0)	28.8 (27.5 – 30.0)
Total Organic Carbon (TOC)	mg/L	1.6 (1.4 – 1.9)	2.7 (2.2 – 2.9)
Iron	mg/L	0.018 (0.010 – 0.020)	0.060 (0.030 – 0.100)
Manganese	mg/L	0.004 (<0.010 – 0.012)	0.009 (<0.010 – 0.025)
Color	CU	12 (10 – 13)	21 (14 – 28)
Algae	#cells/mL	117 (16 – 220)	202 (48 – 370)

3.3 Filtrate Water Quality

Filtrate water quality was monitored by the City and the MFEMs (see Section 2.6). The pilot study's stated water quality evaluation criteria focused on turbidity and color. Note that the Inge pilot did not report operations or water quality data for Design Run #1 due to mechanical issues with their backwash system.

3.3.1 Turbidity

Filtrate turbidity data trends are provided in Figure 3. Turbidity in each MFEM's filtrate was consistently below 0.05 NTU with the following exceptions:

- Turbidity data reported by AASI during Design Run #1; these data were marked with a note about meter malfunction, as indicated on Figure 3.
- From November 23 to 25, when ACH feed stopped temporarily, the AASI pilot reported turbidity up to 0.07 NTU. While this is above the prescribed pilot performance criteria of 0.05 NTU, it is well within full-scale design criteria of 0.1 NTU. It must be noted that the other two MFEMs did not show any detriment.

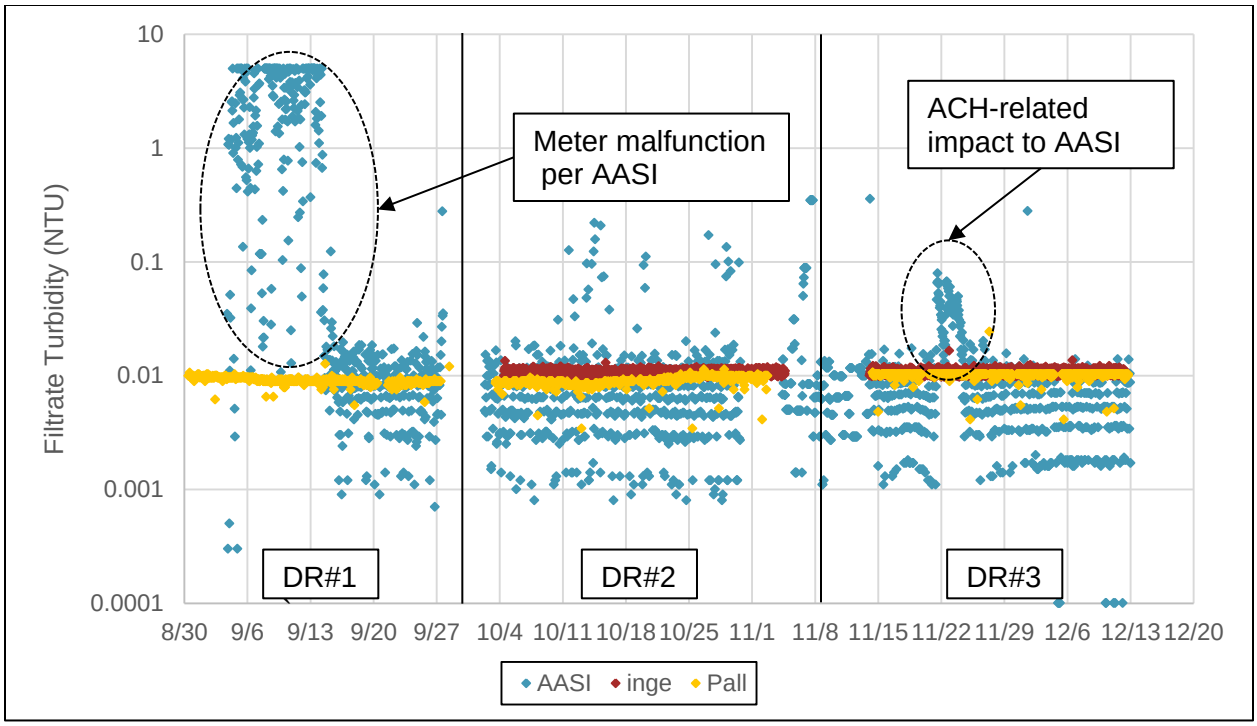

Figure 3: Filtrate Turbidity as Reported by MFEMs

The variability of the AASI pilot testing data is a combination of how the MFEM control panel recorded as well some process instability. The data is due to the pilot testing itself and not likely representative for a full-scale AASI membrane system.

3.3.2 Color

Figure 4 provides the color measurements from the feed water (prior to coagulation) entering the pilot units and the filtrate from the three pilot units. For Design Run #1 (TID water with no coagulant), the Inge and Pall membranes showed essentially no color removal while AASI a reduction from 12 CU to 8 CU. This reduction could either error from analysis with just one grab sample or that the molecules causing the color are actually adsorbing onto the ceramic membrane.

Color reduction when coagulant feed occurred in Design Runs #2 and #3 had the filtered water color between 5 to 7 CU for all membranes. The color reduction is not due to the membranes but from coprecipitation of the color-inducing molecules onto the coagulant flocs, followed by floc removal by the membranes. Since the majority of color contributors in surface waters are contributed by organics, coagulation is required to remove color through membrane filtration. The data for Design Run #1 demonstrate that the lack of proper coagulation resulted in little to no reduction in color through the membranes.

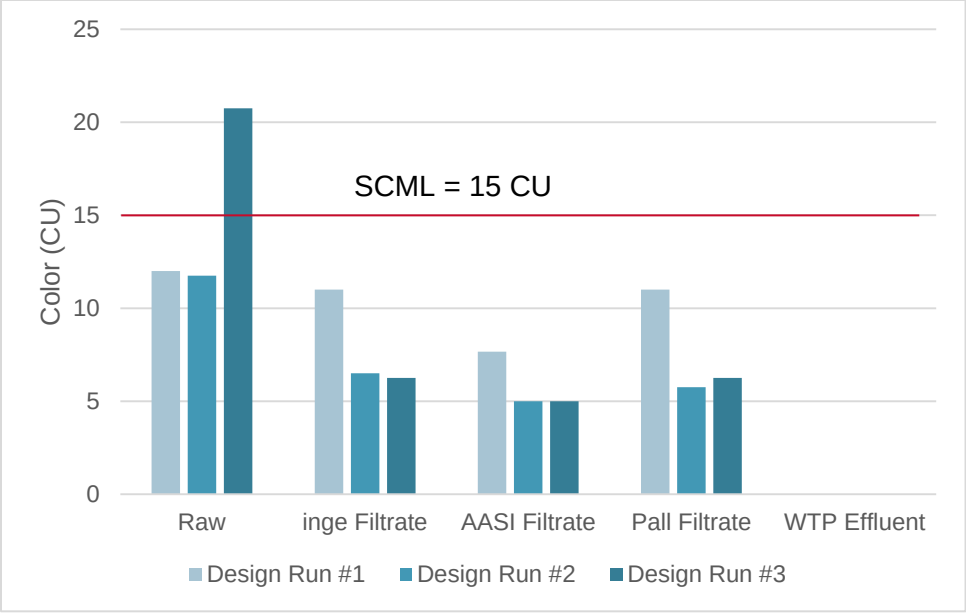

Figure 4: Raw Water and Filtrate Color

3.4 Flux, Transmembrane Pressure, and Specific Flux

3.4.1 Flux

The flux is the amount of water that can pass through a set area of membrane and has units of gallons per day per square foot (gfd). A higher flux means greater filtration for a given membrane area. The MFEM reported fluxes are provided in Figure 5. Flux (J) is given by Equation 1, below. The data shows that the flux setpoints (Table 2-3) were maintained throughout the design run periods.

$$J = \frac{Q}{A_m} \qquad \text{Equation 1}$$

Where,
Q = flow rate, gallons per day
A_m = membrane area, square feet

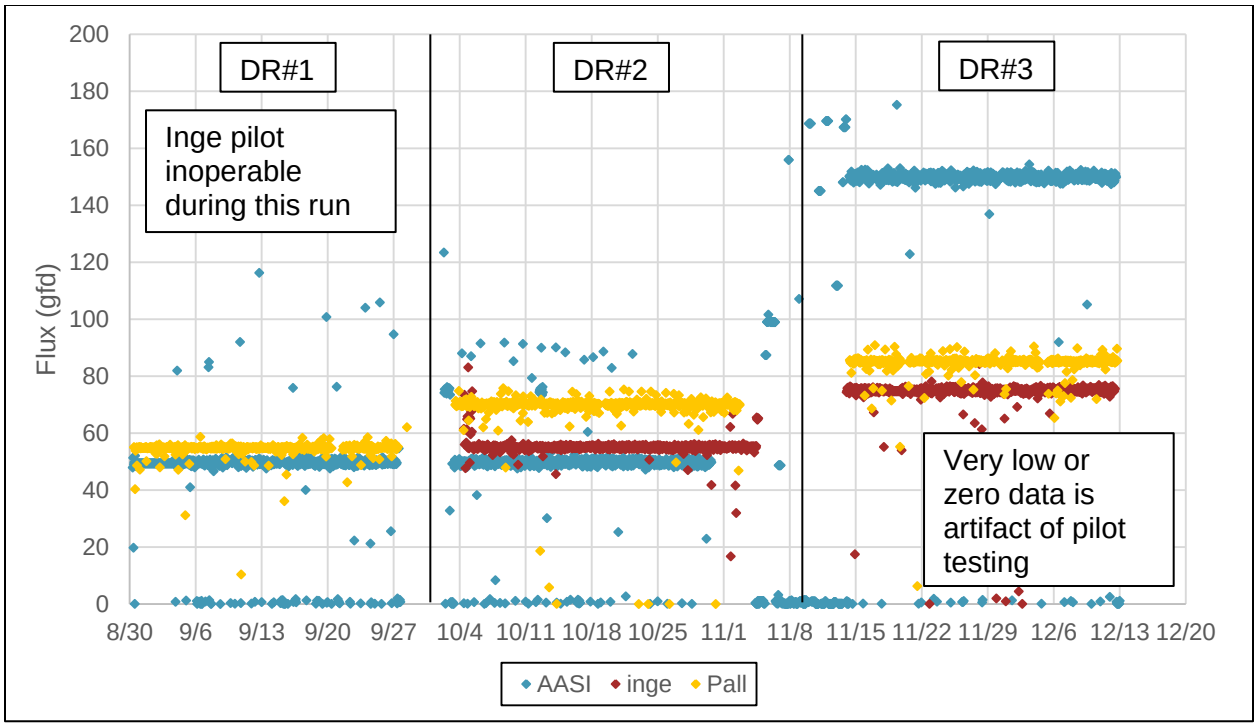

Figure 5: Membrane Flux

3.4.2 Transmembrane Pressure

Transmembrane pressure (TMP) trends are shown in Figure 6. These data trends show the how transmembrane pressure increases between maintenance cleans/chemically enhanced backwashes. Throughout Design Run #1 and for the first half of Design Run #2, TMP increases rapidly between cleanings for the AASI and Pall membranes, likely due to the lack of ACH feed. However, Pall was able to stabilize operations compared to AASI even with a lack of coagulant. As noted earlier, the lack of coagulant feed was one of the reasons the Inge membrane was functionally inoperable.

The latter half of Design Run #2 shows the most stable TMP trends in the study for Pall and Inge. AASI had consistently low and stable TMP for two weeks in October before the MFEM made another switch in operations that caused TMP to become more variable, but on a regular basis.

In Design Run #3, the combination of higher flux and a disruption in ACH feed results in TMP instability for all three units. The Pall unit especially, reached the terminal TMP of 35 psi prior to the 28-day CIP. Upon review, the data from all three MFEMs indicate that while the systems could operate with the higher fluxes, operations were by no means stable or likely sustainable for the long-term.

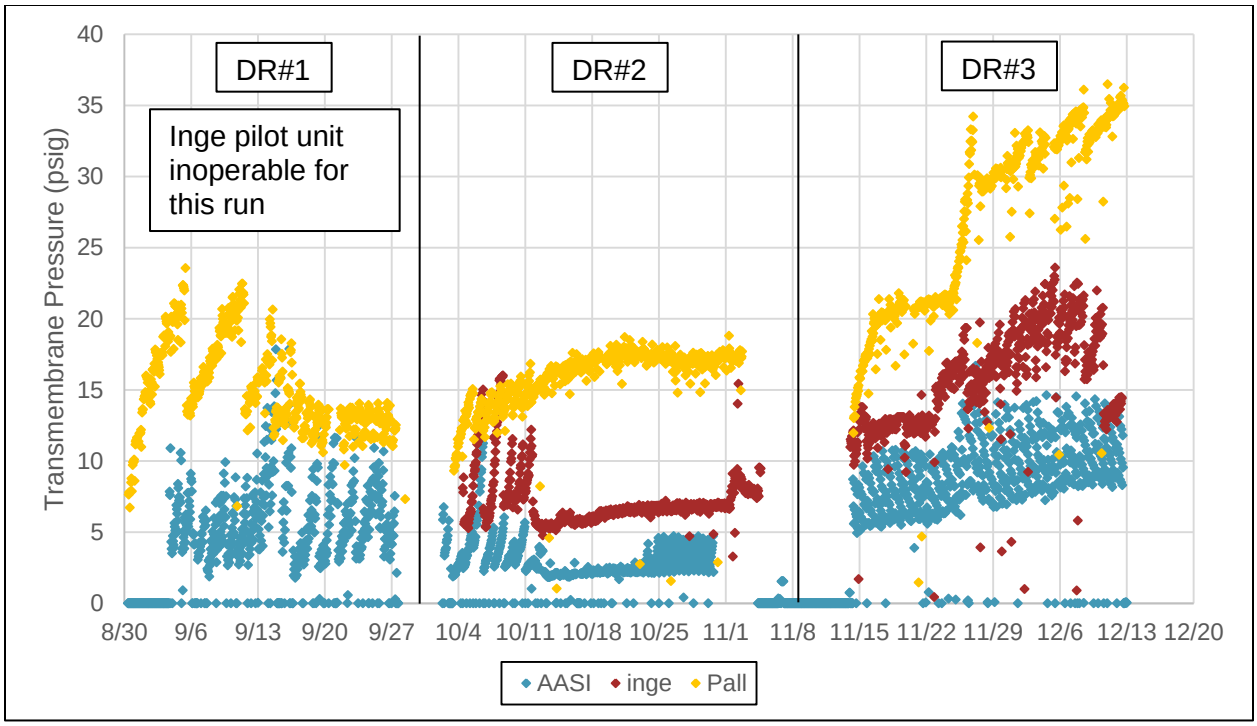

Figure 6: Transmembrane Pressure

3.4.3 Specific Flux

Specific flux, M, is a measure of the flux per unit of transmembrane pressure TMP. The specific flux is calculated with Equation 2, giving units of gfd/psi. Specific flux can be corrected for the effect of higher water viscosity as temperature decreases, as given in Equations 3 and 4, resulting in a temperature corrected value reflecting the specific flux at 20 degrees Celsius (M_{20}). (A temperature of 20 degrees is a standard value used by the water industry for analyzing membranes). It is important to note that this is not operational data, it is a parameter used to compare membrane performance across tests without the variability associated with water viscosity.

$$M = \frac{J}{TMP} \qquad \text{Equation 2}$$

Where,
TMP = transmembrane pressure, psi

$$M_{20} = M * TCF \qquad \text{Equation 3}$$

Where,
TCF = temperature correction factor based on viscosity of water, as given in Equation 4

$$TCF = \frac{1.784 - 0.0575T + 0.0011T^2 - 10^{-5}T^3}{1.002} \qquad \text{Equation 4}$$

Where,
T = water temperature in degrees Celsius

Figure 7 provides temperature corrected specific flux calculated from MFEM reported data throughout the three design runs of the pilot period. As with the prior data, results

that are less variability (greater stability) and higher are preferable to more variable (unstable) and lower values. In this context, AASI consistently high values but the very high variability would mean constantly changing filtration rates and greater operator attention, whereas Pall had lower values, meaning more membranes, but a very stable operations for robust, less operator-dependent monitoring and control.

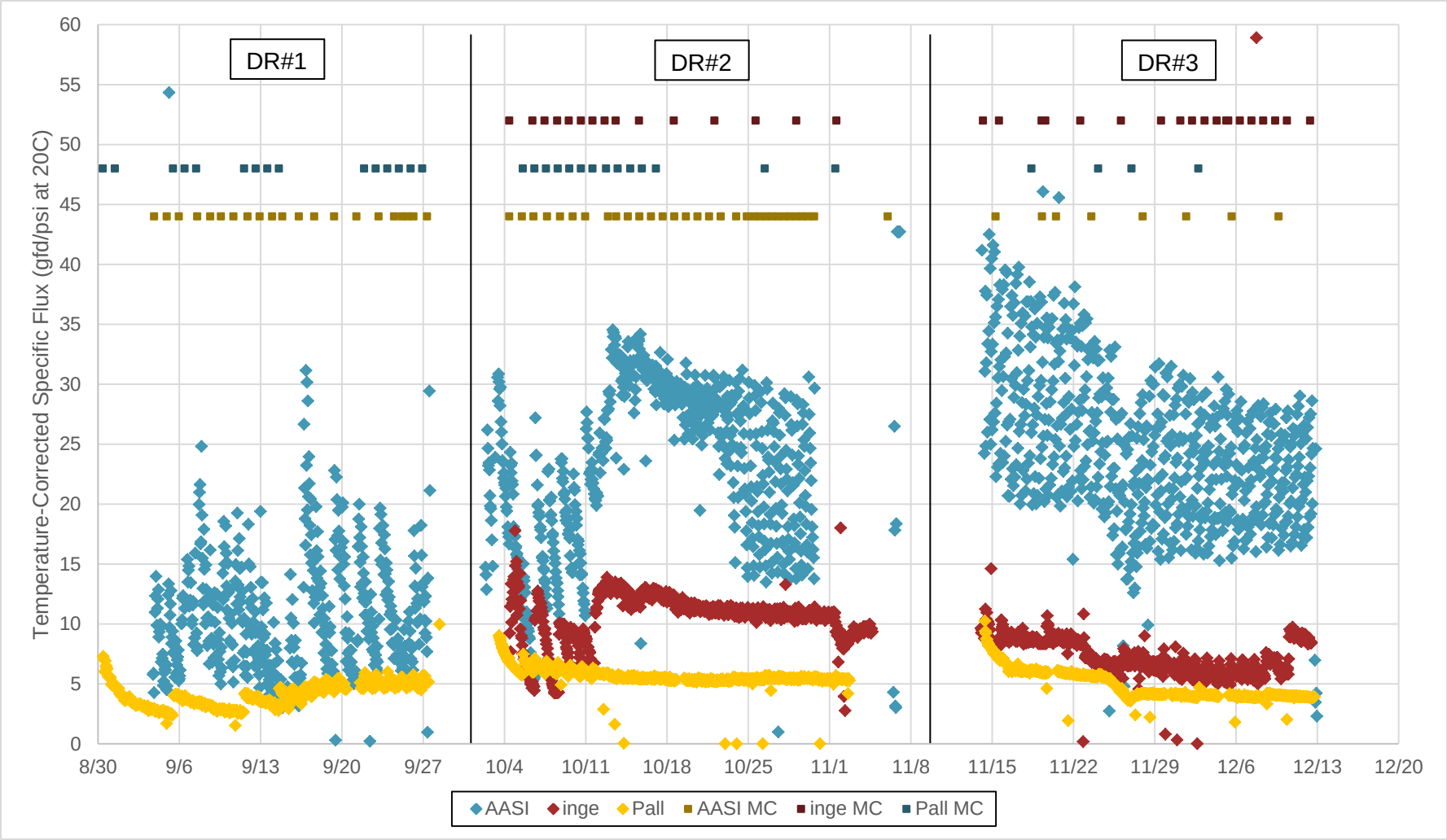

Figure 7: Temperature Corrected Specific Flux

3.5 Cleaning Assessment

Table 3-3 provides a comparison of maintenance cleans and CIPs conducted during the design runs and chemicals used. AASI had the highest specific flux but required twice as much cleanings and chemical usage compared to Pall, which had the lowest specific flux but considerably less chemical usage.

Table 3-3. Maintenance Cleans and CIP Data

Parameter	AASI Pilot	Pall Pilot	Inge Pilot
Design Run #1 Maintenance Cleans	21	15	Pilot unit functionally inoperable
Design Run #2 Maintenance Cleans	31	14	15
Design Run #3 Maintenance Cleans	9	5	19
Maintenance Clean Solutions	pH 1-2 HCl solution 100-300 mg/L NaOCl	500 mg/L NaOCl	pH 12.2 NaOH solution pH 2.4 H_2SO_4 solution
Maintenance Clean Recirculation/Soak Time	20 minutes HCl 40 – 60 minutes NaOCl	30 minutes	15 minutes recirculation and 15 minutes soak per solution
CIP Solutions	1% citric acid 300 mg/L NaOCl	0.2% mg/L NaOCl with 1% NaOH 2% citric acid	Defined as “high pH solution and low pH solution”. Likely same as maintenance clean solution.
CIP Recirculation/Soak Time	2 hours recirculation and 2 hours soak per solution	2 hours recirculation for base solution followed by 1 hours recirculation acid solution	Values not indicated

3.6 MFEM Performance Criteria Evaluation

Each MFEM was evaluated versus the Performance Criteria established in the Pilot Protocol, provided in Section 3.2 above. These criteria are reorganized and grouped for ease of comparison in this report.

3.6.1 Filtrate Water Quality

<u>Filtrate Water Quality Performance Criteria:</u>

- Reduction of turbidity to a membrane effluent turbidity of less than 0.05 NTU in 95 percent of measurements.
- Reduction of color to less than 5 CU.

Table 3-4 summarizes the percentage of turbidity readings that were less than 0.05 NTU. Overall, the MFEM pilot units were able to maintain turbidity in the filtrate below 0.05 NTU.

Table 3-4. MFEM Turbidity Measurements vs. Performance Criteria

	Design Run #1	Design Run #2	Design Run #3
AASI	<0.05 NTU in 99% of readings after 9/15 when turbidity instrument mounting issue was fixed.	< 0.05 NTU in 97% of readings.	< 0.05 NTU in 97% of readings.
Inge	Pilot unit functionally inoperable	< 0.05 NTU in >99% of readings.	< 0.05 NTU in >99% of readings.
Pall	< 0.05 NTU in >99% of readings.	< 0.05 NTU in >99% of readings.	< 0.05 NTU in >99% of readings.

As noted earlier, since coagulation is the primary mechanism of obtaining color removal through direct filtration, the evaluation of the MFEM units in this regard should take into account for the lack of ACH feed at times in the study. In addition, as with the existing WTP, color removal can be optimized by adjustments to coagulant dosage whereas the dosage for the pilot testing was fixed for comparative purposes. The end result is that all three MFEMs could meet the color requirements.

3.6.2 Recovery

Recovery Performance Criteria:

- Operation at a recovery of 95 percent or greater.

Recoveries reported by MFEMs are summarized as follows:

- AASI reported overall system recoveries (defined as 100 percent minus the reject flow rate, which is the sum of backwash and chemically enhanced backwash flows) of 97%, 98.3%, and 99.5% during Design Runs #1, #2, and #3, respectively.
- Inge reported overall system recoveries (defined as the ratio of net filtrate to net feed) of 95.6% and 96.4% during Design Runs #1 and #2, respectively.
- Pall reported overall system recovery (defined as the ratio of net filtrate to net feed) of 96.4% during all design runs.

All three MFEM units showed recovery greater than 95 percent. Caution should be taken in comparing exact values due to small differences in the way each MFEM calculated the value. Pall did not include maintenance cleans in their accounting of net feed, and it is not apparent that any MFEM included CIP wastes in the calculation. Accounting for these omissions would change the exact value by an insignificant amount and does not change the fact that each membrane was capable of providing a water-efficient filtration process.

3.6.3 CIP Interval Demonstration

CIP Interval Demonstration:

- Require clean-in-place (CIP) no more frequently than once every 28 days. This shall be demonstrated in a continuous design run with consistent operating parameters. The following design run termination criteria shall be used,
    - Terminal transmembrane pressure
    - Successful operation for the 28 days at specified conditions
    - Exceeding maintenance clean (chemical enhanced backwash) time (60 minutes/day) or frequency
    - Exceeding acceptable downtime of 48 hours per run
    - Exceeding membrane integrity criteria.

The criteria from the Keller Pilot Protocol dictated a CIP no more frequently than once every 28 days. Pall and AASI show continued operation without a CIP for the required 28 days in all three design runs, where as Inge met the requirement for Design Runs #2 and #3 (the system was functionally inoperable for Design Run #1).

The criteria also stipulated consistency in operating parameters, which is assessed with regard to TMP (Figure 6) and temperature-corrected specific flux (Figure 7):

- Only the Pall unit ran consistently in Design Run #1 despite not having the required ACH coagulant feed.
- All three MFEM units ran consistently in Design Run #2 after ACH feed was restored. All three units operated below the recommended terminal TMP points (Table 2-3).
- All three MFEM units experienced inconsistent operation at the higher flux rates prescribed in Design Run #3. Particularly, all three exhibited climbing TMP that could not be restored with maintenance cleans. The result was that all three vendors could operate at the much higher fluxes but system operations was unstable and likely unsustainable for longer periods with Ashland Creek/Reeder Reservoir water or for any period with TID water.
- As a result, the performance of Design Run #2 is a better indicator for long-term sustained operations...

3.6.4 Membrane Integrity

Membrane Integrity Performance Criteria:

- If more than one repair occurrence is required to maintain integrity of a membrane, the City reserves the right to exclude that supplier from bidding on the project.
- Demonstrated ability of module to meet warranty provisions with respect to integrity and fiber breakage rates.
    - Membrane integrity tests are to be run daily and reports submitted to the City.

- Demonstrated membrane integrity testing and fiber/module repair procedures during the pilot test consistent with requirements of the Long Term 2 Enhanced Surface Water Treatment Rule.

The pilot testing only partially accomplished this performance criterion. None of the MFEM had any membrane fiber or ceramic module breaks during the pilot study. However, the requirement to run daily integrity testing was only completed by Pall. The other MFEMs conducted such testing on an intermittent basis.

Finally, there was no demonstration of the fiber/module repair procedures by any MFEM. Since none of the pilot units reported a breakage, this demonstration would have required deliberate breaking of a fiber or module, followed by a repair. This activity was not conducted by any MFEM.

3.7 Disinfection By-Product Formation Potential

Table 3-5 provides a summary of TOC and DBP results in during the pilot study using the protocol established in the pilot testing plan.

Table 3-5. DBP Formation Potential

Parameter	Units	Design Run #1 Samples Collected 9/6, 9/12, 9/19 No Coagulation	Design Run #2 Samples Collected 10/3 No Coagulation	Design Run #2 Samples Collected 10/31 Coagulation at 4 mg/L ACH	Design Run #3 Samples Collected 12/5 Coagulation at 4 mg/L ACH
TOC - Raw Water	mg/L	2.4 - 2.9	1.9	1.5	2.8
TOC - Filtrate	mg/L	2.2 - 2.5	1.7 - 3.1	0.72 - 0.82	1.4 - 1.4
Total Potential THMs - Filtrate	µg/L	48.4 - 103	71.8 – 101	17.0 - 18.1	33.3 - 33.4
Total Potential HAA5 - Filtrate	µg/L	49.0 - 119	121 – 152	18.3 - 21.4	38.0 - 39.0

The following observations are made:

- The protocol did not include measuring residual chlorine after the 96-hour hold time so there is no data available to know if chlorine stability was equal to or better than the current filtered water. One potential flaw, though unlikely, was that all the chlorine had been consumed and DBP concentrations could have been higher than analyzed.
- During Design Run #1 and #2 when ACH was not fed, TOC was not significantly removed through filtration. This led to THMFPs and HAAFPs present in the filtrate above the EPA DPB thresholds of 80 µg/L for THMs and 60 µg/L for HAAs.
- For samples collected on October 31 (end of Design Run #2) and December 5 (near the end of Design Run #3), coagulant feed was active at 4 mg/L ACH and the effect is seen in the reduction of TOC and the presence of less total potential THMs and HAA5.

- In general, despite a very high chlorine dose, DBPs in the membrane filtrate are comparable or slightly lower than the DBPs found in the current distribution system. The better results are likely to the greater removal of organics by the tighter membranes.

3.8 Bench-Scale Taste and Odor Tests

3.8.1 GAC RSSCT

The following results were obtained from the RSSCTs on filtrate samples:

- The water sample initially had a TOC concentration of 1.25 mg/L and UV-254 absorbance of 0.011 cm^{-1}.
- Breakthrough of UV-254 absorbance closely followed TOC breakthrough, indicating that UV-254 could be used as a surrogate for TOC in GAC column effluent. TOC breakthrough reached 1 mg/L between 65,600 and 68,600 bed volumes.
- In the spiked sample, Geosmin (initially 70.4 ng/L) reached the lower and upper OTCs (5 and 10 ng/L, respectively) between at interpolated bed volumes of 9,134 and 16,570, respectively.
- The competition of TOC for the GAC adsorption sites led to Geosmin breakthrough after a relatively small number of bed volumes.

The implication is that full-scale GAC contactors provides two distinct sets of water treatment benefits with correspondingly two different costs. The GAC contactors could be used continuously to remove TOC from a considerable amount of water before media changeout. Per published literature, but not directly demonstrated in this pilot testing, lower TOC water is associated with lower initial chlorine demands, more stable chlorine residuals in the distribution system, and lower DBP formation.

However, the same GAC contactors used for Geosmin removal and T&O control would be effective for only small volumes when newly installed (one-sixth of that for TOC removal), and only partially effective even TOC removal is still high. As a result, if T&O control is with GAC contactors, these contactors would need to be used only when T&O issues arise and shut-off at all other times. Even then, Geosmin breakthrough could still occur within a single season.

3.8.2 Ozone Test

The following results were obtained from the ozone demand/decay tests on filtrate samples:

- Design Run #1 (TID) Sample
  - TOC concentration = 2.54 mg/L
  - Initial ozone demand ranged from 0.51 to 1.04 mg/L
  - A dose of 2 mg/L was required to remove spiked Geosmin from 65 ng/L to 6.4 ng/L (removal of 29.3 ng Geosmin/mg ozone), below the upper OTC.

- Design Run #3 (Reeder) Sample
  - TOC concentration = 0.78 mg/L
  - Initial ozone demand ranged from 0.20 to 0.70 mg/L
  - A dose of 1 mg/L removed spiked Geosmin from 85 ng/L to 30 ng/L (removal of 55 ng/mg); no data was reported for Geosmin concentration in sample with a higher dose of ozone applied.

Due to the lack of ACH addition during Design Run #1, the concentration and characteristic of the TOC in the sample is representative a difficult full-scale operation. The sample during Design Run #3 was more characteristic of TOC in the existing WTP filtered water and the results indicate that a dose of more than 1mg/L is likely needed to remove Geosmin below the OTC; however, the spiked value of Geosmin (85 ng/L) is 20 percent higher than the highest observed concentration of Geosmin in Reeder Reservoir, and approximately three-fold higher than has been measured at the WTP tailrace..

4 Discussion

4.1 Compliance with Evaluation Criteria

MFEM performance is evaluated in Section 3.6. The overall compliance to the performance criteria is summarized as follows in Table 4-1.

Table 4-1. Compliance with Evaluation Criteria

Item	AASI Pilot	Pall Pilot	Inge Pilot
Filtrate Water Quality	Yes	Yes	Yes
Recovery	Yes	Yes	Yes
Consistently in Operation	Showed inability to operate consistently without coagulant feed.	Generally consistent, but could not operate at high flux in Design Run #3 without coagulant feed.	Did not report data due to mechanical issues in Design Run #1. Could not maintain TMP under its terminal value in Design Run #3.
Integrity Tests	Yes	Yes	Yes

4.2 Compliance with Pilot Testing Objectives

Table 4-2 describes the results of the study with regard to the objectives set out in the Pilot Protocol.

Table 4-2. Review of Study Objectives

Objective	Was Objective Completed?
1. Provide operational staff experience with membrane microfiltration process	Incomplete. Discussions with WTP staff indicted that their effort during the testing effort was limited to only information collection. As a result, the staff did not learn about system optimization, normal maintenance, troubleshooting, or repairs.
2. Evaluate compatibility of raw/pretreated water from Reeder Reservoir and Talent Irrigation District (TID) sources with membrane filtration process a. Summer (high temperature / high algae concentrations)	Despite the difficulty without ACH feed, the Pall membrane showed that it could successfully treat the TID water while the AASI membrane showed treatment but with unstable operations. ACH feed would have improved operations to both membranes though likely greater benefit to AASI as the Pall membrane was already successfully treating the water. There can be no conclusion made for the Inge membrane as it was inoperable during this period.
3. Demonstrate flux through membrane system without excessive fouling:	The operations of Design Run #2 demonstrated that each of membrane systems could operate for long durations without excessive fouling whereas Design Run #3 clearly demonstrated that each system was pushed past the point of sustainable operations.
4. Demonstrate acceptable physical integrity test(s) and ability to meet warranties for fiber breakage for each piloted membrane system:	Partially completed. No fiber or module breakages were reported and integrity tests providing passing results. However, only Pall completed integrity testing on a daily basis as required by the protocol.
5. Evaluate the causes of any excessive membrane fouling that may occur during pilot testing:	There were two causes that were identified: lack of coagulant feed (Design Run #1) and excessive flux (Design Run #3).
6. Demonstrate the capability of membrane system to meet treated water quality requirements:	Completed. The turbidity water quality goal was met by all MFEM systems. The color goal was not met consistently due to the lack of coagulation of dissolved color contributors prior to filtration.
7. Optimize and establish physical design parameters for the full-scale plant design that will allow determination of life-cycle costs, including: A. Flux (gallons per day per square foot of membrane material, gfd): B. Pre-treatment chemicals: C. Backwash type, frequency, duration, and required flow rates for both air and water: D. Water recovery rate (filtrate volume / feedwater volume) E. Cleaning chemicals and processes	A. The flux rates in Design Run #2 (50 to 70 gfd) may be reasonable design criteria for full scale with a raw water feed primarily composed of Reeder water. B. Pre-treatment was coagulation with 4 m/L ACH was found to be adequate for the testing conducted. However, other chemicals should be considered to determine if the dose or chemical ideal, recognizing that dosage will need to change to accommodate changes in water quality. C. Completed. See Table 2-3. D. All vendors demonstrated >95 percent recovery. E. Completed. Chemical use varied by MFEM. The pilot study has identified which chemicals may be necessary at full scale.

Table 4-2. Review of Study Objectives

Objective	Was Objective Completed?
8. Demonstrate membrane filter operating conditions established and recommended by the MFEM with minimum 28-day operation before chemical cleaning is required as determined through transmembrane pressure measurements:	Completed. The terminal TMPs for AASI, Pall and, Inge were not exceeded during Design Run #2, but were either exceeded or nearly exceeded in Design Run #3. For this reason, the flux set points in Design Run #2 are the more reasonable design values.
9. Characterize the quantity and composition of treatment residuals including backwash water that contains solids that will require handling:	Not completed. Data on residuals quality is limited. Quantity (as a function of recovery) was calculated.

4.3 Pilot Test Gaps and Limitations

The following gaps and or limitations were identified with the Pilot Study as part of HDR's evaluation of the testing and preparation of this report.

- The setup of the pretreatment did not allow for changes in coagulant or coagulant dose for each specific membrane. Further optimization is warranted if membranes are selected for the future full-scale facility.
- Allowing MFEMs to set their own flux point without regard to terminal TMP creates difficulties in comparing their results. As a result, the data shows that fluxes were Design Run #2 were clearly sustainable whereas the fluxes in Design Run #3 were clearly the opposite. A possibility exists that fluxes in-between these two runs are sustainable, allowing for smaller and less costly membrane systems.
- Inge did not report data for Design Run #1. Mechanical issues caused their backwash not to function properly
- The testing protocol was established assuming direct membrane filtration. Inclusion of a sedimentation process prior to the membranes would allow for higher coagulant dosages and removal of the formed solids prior to filtration. The end result would be that membrane performance in terms of flux, TMP, and cleaning frequencies would all improve and that the finished water quality could have been better.

4.4 Recommendations

Strict adherence to the pilot study performance criteria described in pilot protocol would mean that only Pall would be eligible to bid for successive phases should this project proceed with membrane filtration. However, given the issues encountered with the operation, it is HDR's opinion that all of the membranes could have met the conditions of the pilot and treat this water had the coagulant feed been optimized and delivered without interruption.

Coagulant feed is required for the AASI membrane and was shown to provide performance improvements to the Pall membrane (no such comparison can be made for Inge due to lack of data from Design Run #1).

Design Run #1 provided information that direct membrane filtration is appropriate for the TID water source and Design Runs #2 and #3 showed that it is appropriate for Reeder as well. While Design Run #1 did not operate as intended, the results still provided data that Pall was able to operate with this source, while we hypothesize that AASI and Inge could have too. Overall, direct membrane filtration is viable technology for the new WTP. With optimized pre-treatment and sufficient post treatment to meet T&O concerns.

4.5 Preliminary Membrane Design Criteria

Table 4-3 provides preliminary design criteria if the City wishes to use membranes as the filtration process for the new WTP.

Table 4-3. Preliminary Design Considerations

Design Criteria	Value
Recommended design flux for sustainable operations	50 – 60 gfd
CIP interval	30 days
Maintenance clean frequency under design flux for sustainable operations	1-2 per week.
Pre-treatment	Coagulant feed is needed. ACH at 4 mg/L is shown to work but other coagulants and dosages may be more advantageous for water quality performance and/or cost.

5 References

Keller Associates, 2017. City of Ashland Water Treatment Plant and Reservoir Project – Membrane Filtration Equipment: Pilot Testing Protocol.

HDR. 2017, City of Ashland Water Treatment Plant and Reservoir Project – Water Quality Summary and Review

HDR. 2018, TID Water Quality Summary

Appendix A. Membrane Filtration Equipment Pilot Testing Protocol

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Appendix B. AASI Pilot Testing Report

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Appendix C. Inge Pilot Testing Report

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Appendix D. Pall Pilot Testing Report

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Appendix E. RSSCT Report

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Appendix F. Bench Scale Ozone Test Report

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