Economic and Design Considerations for Membrane Filtration at a Lime Softening Plant

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BACKGROUND

The City of Murfreesboro Water and Sewer Department (MWSD) currently operates a 15.6 MGD Lime Softening/Mixed Media Filtration plant to provide drinking water to its approximately 25,000 customers. Although the plant has operated well over the last 40 years, increasing tight regulations coupled with concerns over aging filtration underdrains motivated City personnel to consider alternative filtration technologies to provide the best quality drinking water possible to its customers. The decision was made in 2004 to rehabilitate the existing treatment processes, and to include membrane filtration in the updated process scheme.

City personnel and engineering consultants wanted to determine which type of membrane filtration system best fit the City's needs, and the configuration in which the membranes should be placed. At issue was whether to use a vacuum driven, immersed membrane technology or a pressure driven, containerized design. Also at issue was whether the membranes should be installed before or after Granular Activated Carbon (GAC) filtration. In the end, the Murfreesboro Water and Sewer Department (MWSD) selected a pressurized, containerized membrane filtration system. In order to provide maximum flexibility for the renovated plant, a piping system was designed that would allow the membranes to operate either before or after GAC filtration. This should allow the treatment plant staff to determine the advantages and disadvantages of each operational mode on the full-scale plant, and make their own determination using real-world data.

This paper will discuss several of the factors considered during the evaluation of both membrane technologies. The results of four months of pilot testing on the selected system will also be discussed.

The Stones River Water Treatment Plant treats blended raw water from the East Fork Stones River and from the Percy Priest Reservoir. The composition of the raw water varies slightly depending upon the relative quantities of each of the sources utilized on any given day. General data on the blended raw water quality is provided in Table 1 below.

Table 1: Blended Raw Water Quality Data

PARAMETER	AVERAGE	MAXIMUM	MINIMUM
Temperature (deg. C)	18.3	29.0	4.2
Turbidity (NTU)	16.1	237.0	1.2
Alkalinity (mg/L as CaCO$_3$)	169.9	232.0	63.0
pH	7.9	8.5	7.5
Hardness (mg/L)	189.9	253.0	89
Iron (mg/L)	0.12	1.47	0.10
Manganese (mg/L)	0.09	0.87	0.10
TOC (mg/L)	2.51	5.84	1.12

The Stones River Water Treatment Plant is unique in that it is the only water plant in the State of Tennessee that utilizes lime softening as a treatment process. This practice began in the 1960's in order to provide softer water to the bakeries and industrial users within the City's water distribution system. Although the hardness of the raw water is considered moderate by most standards, the City offered the softened water in order to draw new business to Murfreesboro. A review of the plant's Monthly Operating Reports (MORs) indicates that the plant is not operated in a traditional excess lime softening mode. Instead, sufficient lime is added at the flash mix to bring the pH to approximately 9.5. This lime dosage averages approximately 80 mg/L. Ferric sulfate and polymer are also added to facilitate coagulation and sedimentation. The result is that the finished water is softened from approximately 190 mg/L to around 110 mg/L.

One initial concern with membrane filtration at Stones River was the possible requirement for recarbonation of the settled water. There are not a great number of membrane plants currently filtering lime softened settled water, however most of those in operation include recarbonation to adjust the pH prior to membrane filtration. The concern is that scaling of calcium carbonate on the membrane fiber could cause excessive fouling of the filtration surface which would lead to short run times and frequent chemical cleaning. Recarbonation could be effective at reducing this possibility, but it would require additional equipment and ongoing O&M costs to operate.

Both membrane manufacturers consulted on this issue felt certain that recarbonation would not be required as long as the feed water pH was maintained below a pH of 8.3. Since this was the case at the SRWTP, the decision was made to proceed as if recarbonation was not required, and to adjust if pilot testing indicated that its use was necessary.

MEMBRANE SELECTION AND ORIENTATION

The first consideration in the membrane selection process centered around which membrane filtration system best fit the long-term interests and needs of the MWSD. Both vacuum driven immersed, and pressure driven containerized membrane systems were considered. The Department decided early in the process to only consider those systems that had demonstrated a minimum 4.0 log reduction of Cryptosporidium through the Environmental Technology Verification (ETV) testing protocol. This program is a joint venture between the EPA and the NSF to verify the claims of manufacturers of new treatment technologies.

There are inherent advantages and disadvantages of both types of membrane filtration systems. In general, vacuum driven systems have lower electrical costs, however the cost of construction and installation is often higher than pressurized systems. Pressurized systems offer simpler installation and maintenance, however the user cannot visually inspect the fibers for fouling or damage. There are numerous other considerations that should be included in any evaluation of the two technologies. The factor that drove this particular evaluation was operating flux.

Membrane flux is a term analogous to the filter loading rate of a traditional granular media filter. It describes the quantity of water that can be filtered by a membrane per unit area of membrane surface. It is generally described in units of gallons per square foot per day or gfd. There is an apparent presupposition in the water and wastewater industry that operating membrane filtration systems at high fluxes can shorten the life of the membrane fibers. This sentiment is partially based upon the fact that as the loading rate on any membrane filtration system increases, so also does the rate at which that membrane will foul. The other consideration is that as the loading rate on any membrane filtration system increases, so also does the transmembrane pressure (TMP) across that membrane. This fact is directly tied to the permeability of the membrane structure. In general, microfiltration membranes have a permeability of approximately 7-9 gfd/psi at 20 degrees Celsius when they are completely clean. Therefore a membrane filtration system that is operating at 40 gfd and 20C will begin at between 4.4 and 5.7 psi. As the membrane surface fouls, the permeability will decrease, and the TMP will increase.

There is limited data available to substantiate whether operation at higher fluxes negatively affects membrane life. There are a number of plants in the United States currently operating at higher fluxes, and those plants have not documented any negative affects on permeability or membrane life. The speculation regarding this alleged detrimental affect appears to be more of a sales differentiator than a quantifiable phenomenon. This tactic is driven by the

fact that vacuum driven membrane systems cannot generally operate at as high of a flux rate as pressure driven systems. This is a limitation caused by the physics of atmospheric pressure that will not allow vacuum pressures to exceed -14.7 psi. For instance, while a pressurized system could theoretically operate in excess of 120 gfd, a vacuum system could not because the initial TMP required would be in the range of -13.3 to -17.1 psi. Generally, due to pumping and piping restrictions, manufacturers of vacuum driven systems prefer to operate in the range -3 to -10 psi. They also recommend at least 4 psi of operating range to allow for membrane fouling. This generally limits vacuum systems to fluxes of 20 to 50 gfd. This seems to place those manufacturers at a disadvantage when competing against pressurized systems that can operate at higher fluxes because as the flux increases, the number of membranes required for a given flow decreases. This decreases both the initial capital cost of the pressurized filtration system, and the subsequent cost of replacing the membranes when the fibers reach the end of their useful life.

The converse of this issue is that operation at higher fluxes requires additional energy. As stated earlier, as flux increases, so also does the pressure required to filter water. Pumping costs for pressurized systems can be as much as twice as high as those for vacuum systems. The significance of these costs can vary based upon the unit cost of energy in a given area. This point will be discussed later.

Another significant consideration in selecting membrane technologies is the construction cost associated with each type. Generally speaking, the construction cost of immersed systems is higher than that for pressurized systems. Immersed systems are usually contained in concrete basins. Those basins must be coated with a paint or other sealant that will protect the basin from the low and high pH levels required for chemical cleaning. The building design must include some provision for removing the membranes from the basin, which usually necessitates a traveling bridge crane. Additional air handling equipment is also generally advisable because of the potential for fuming of the cleaning solutions use. Conversely, containerized systems are generally skid mounted, and can be installed on a slab. Hoisting equipment is not generally required as the modules weigh less than 50 pounds.

At the SRWTP, another consideration was the excavation required for an immersed system. Because the membranes were to follow either sedimentation or GAC filtration, they had to either be located at a lower elevation than the existing basins, or the feed water would have to be pumped into the membrane basins. Both options were considered in the final analysis, however pumping into the basins, and then pumping through the membrane fibers proved to be economically unattractive. Also unattractive, however, was the prospect of excavating the membrane filtration basins. The logical physical location for the

membrane filtration system at the SRWTP was between the GAC filtration system and the clearwells. For the below grade immersed membrane option, this would have required excavation to elevations lower than the existing clearwell. Geotechnical information indicated that the site was underlain by a very hard limestone formation at approximately six feet below grade. This would necessitate blasting or other rock excavation within approximately 10 feet of the existing clearwell, to an elevation of 10 feet below the bottom of that structure. For obvious reasons, this was unattractive to the Department.

In the evaluation of systems for the Stones River Water Treatment Plant, all costs associated with initial construction, operation and maintenance of the filtration systems, and membrane replacement were considered in a 20 year Present Worth analysis. Both manufacturers requested that the actual data from that analysis not be published. However the final tabulation indicated the pressurized containerized system was the most cost-effective system for the Stones River Water Treatment Plant because of the low cost of electricity in Murfreesboro coupled with the high cost of excavation and construction. A procurement contract was negotiated with Pall Corporation, and design is underway on the plant expansion.

MEMBRANE PILOT TESTING

A requirement of the procurement contract with Pall Corporation was that they had to provide a pilot testing rig to demonstrate the ability of the system to operate at the elevated flux rate that they proposed. The testing protocol included two phases: A Verification Phase and a Challenge Phase.

Verification Phase

The Verification Phase was required to confirm that the Pall Microza system could operate at the proposed conditions without a chemical recovery clean for a duration of 30 days. The operating conditions for the testing are described in Table 2. The source water for the testing was settled water from one of the existing sedimentation basins at SRWTP. In order to simulate conditions at the design plant flow rate, that reactor clarifier and sedimentation basin were operated at their design flow rates. The other basins were operated as needed to provide for the rest of the plant demand.

Table 2: Membrane Pilot System Operating Parameters

Parameter	Value
Membrane Area (sf)	538
Filtrate Flow (gpm)	32.6
Flux (gpd/sf)	87.3
Simultaneous Air Scrub/Reverse Filtration (SASRF) Interval (min)	20.6
Air Scrub (AS) Duration (sec)	60.0
Reverse Filtration (RF) Duration (sec)	30.0
Enhanced Flux Maintenance (EFM) Interval (hr)	48.0
System Recovery (%)	97.2

The pilot test began on February 2, 2005 under these conditions. As illustrated in Figure 1, the system demonstrated stable operation from the onset. Unfortunately, it was discovered several weeks later that a leaking recirculation valve was allowing a crossflow across the membrane surface which was assisting with keeping the membrane surface clean. Upon review of the systems dataloggers, it was ascertained that this condition had occurred for approximately 14 days. This issue was corrected on March 3, and the pilot continued to operate at the design conditions for another 26 days. In all, the system operated for 55 days during the Verification Phase. Discounting the 14 days in which the valve malfunctioned, this still indicates that the system could operate for up to 40 days without a CIP recovery clean. The data suggests that while there was some scaling attributable to inorganics, there did not appear to be a need for recarbonation. The Verification Phase was considered successful.

**Figure 1: Verification Phase Results**
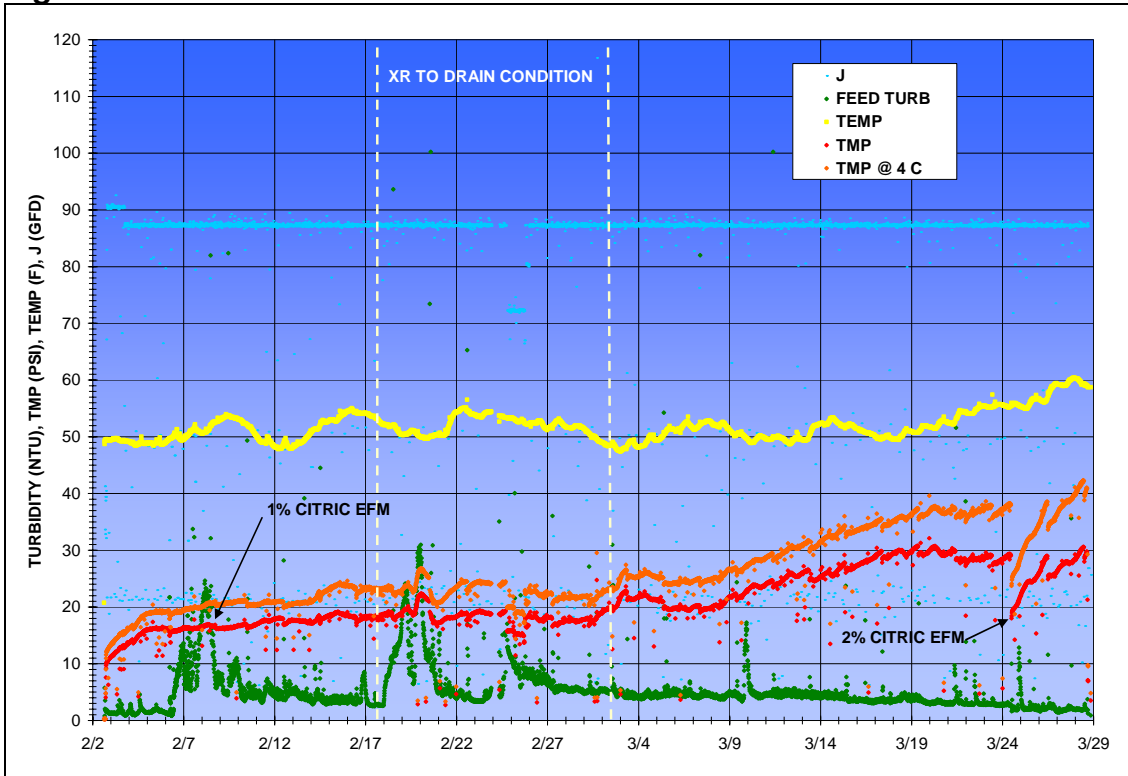
Challenge Testing

The Challenge Testing phase of the pilot test included several process modifications designed to test the operational limits of the membranes, as well as their response to lower feed water quality. Prior to the first modification, however, the SRWTP experienced a significant process upset that affected both the granular media filters, and the membrane filtration system. The plant's Streaming Current Monitor malfunctioned on April 3, causing both the ferric sulfate and polymer dosing pumps to overdose the reactor clarifiers and sedimentation basins. The effect of the overdose was immediately apparent on the membranes as evidenced by the TMP response seen in Figure 2. It is important to note that the foulants were cleaned from the membrane surface utilizing only two Enhanced Flux Maintenance (EFM) procedures. The EFM is a one hour maintenance clean typically utilized every other day on the Pall system. The membrane pilot continued to operate for ten more days after the process upset without a chemical recovery clean-in-place (CIP). The data from this portion of the test is illustrated in Figure 2.

The first modification to the pilot operation was disabling the EFM process. Pall has received scrutiny from competitors that claim that they place too much reliance on the EFM process. The EFM process was disabled on April 6. The

membrane filtration system continued to operate for eight days without an EFM or a CIP clean. In fact, the TMP level was actually decreasing at the end of this phase. This was likely a result of the water temperature increasing.

Figure 2: Process Upset and Recovery Data
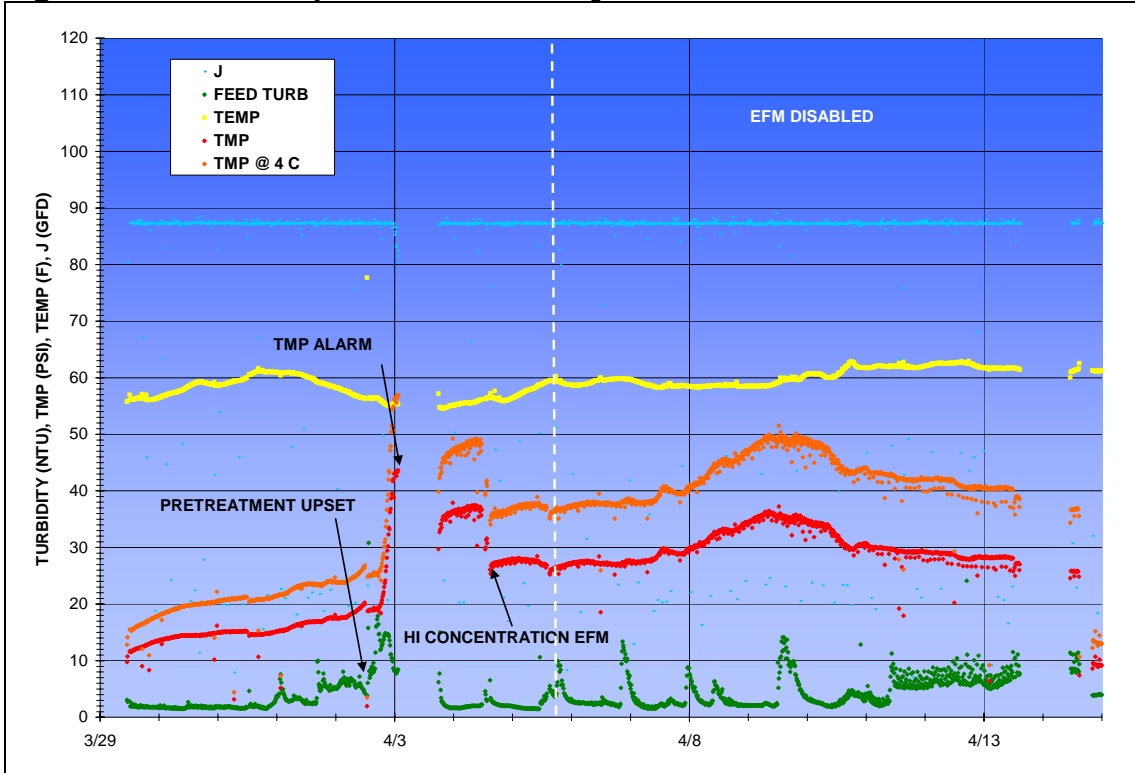
The second portion of the challenge testing involved increasing the membrane flux. As stated previously, Pall is commonly criticized for operating their membrane system too close to its operating limits. However, the pilot flux rate was systematically increased to 120 gfd between April 20 and April 27. While the TMP and the apparent rate of fouling increased significantly at these flux levels, the system recovered quickly when the flux was decreased. Two citric EFM's utilized after the flux reduction indicated that a significant portion of the fouling that occurred was from inorganic contamination, likely the result of calcium carbonate scaling. The citric EFM's, followed by a full CIP on May 6 also confirm that the foulants were easily removed from the membrane surface despite the high flux operation. This data is illustrated in Figure 3.

The third phase of the challenge testing involved moving the point of withdrawal for the feed water supply from the sedimentation basin effluent trough to upstream of the baffle wall at the head of the sedimentation basin. This testing was to simulate bypassing the sedimentation basins entirely, and treating water

directly from the reactor clarifiers. As indicated in Figure 4 below, this modification had very little impact on the fouling rate of the membranes.

The final phase of the testing involved systematically increasing the recovery rate of the system. The recovery rate indicates how much water is wasted through activities like reverse filtration (backwashing) of the membranes and EFM versus the treated water throughput of the system. In this testing, the recovery rate was increased from the design value of 97.2 to 99.5% by increasing the Simultaneous Air Scrub/Reverse Filtration (SASRF) frequency from once every 20.6 minutes to once every 107.4 minutes. As indicated in Figure 4, the system demonstrated stable operation for 15 days despite these rigorous conditions.
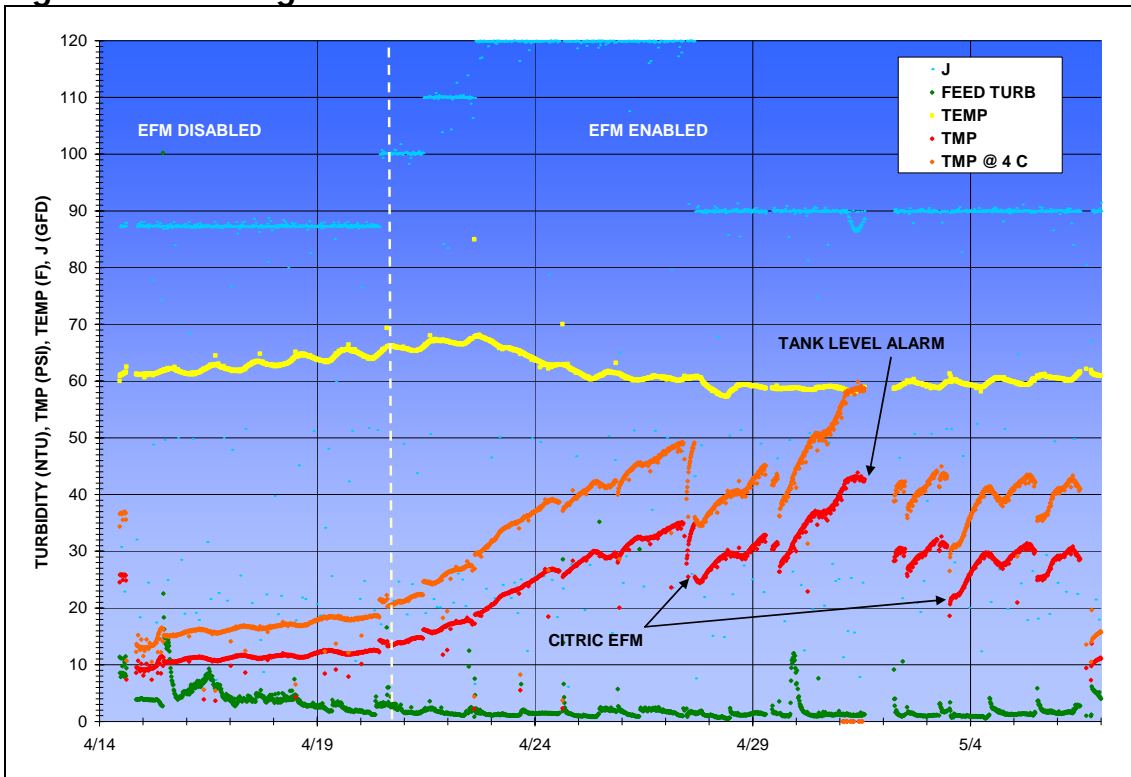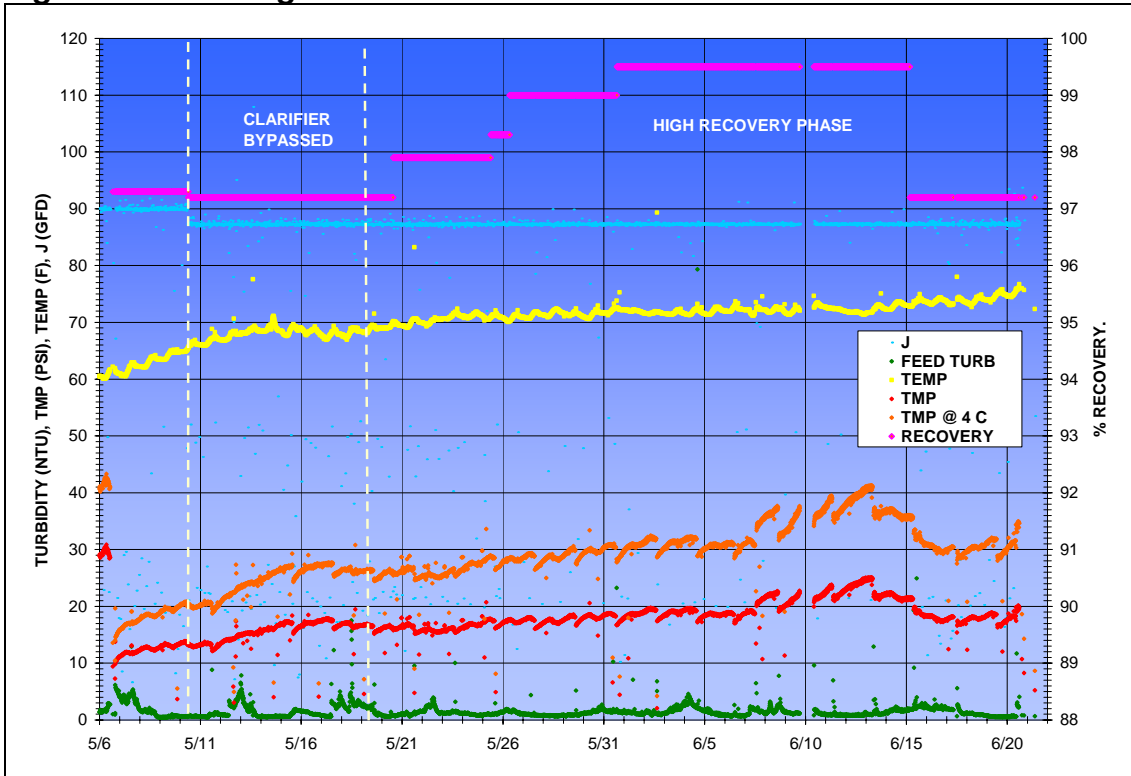
Figure 3: Challenge Phase Results

Figure 4: Challenge Phase Results

After the Challenge Phase was completed, the membranes received a final CIP cleaning. As Figure 5 below indicates, these cleanings all indicated that greater than 99% of the initial permeability had been restored. While a four month pilot test certainly cannot be extrapolated to predict membrane life, it does not appear that operation at high system fluxes, contamination by high levels of ferric sulfate and polymer, operation at high recoveries, or operation on lower source water quality adversely affected the permeability of the membrane filtration system. The pilot testing was completed on June 20 and is considered a complete success.

Figure 5: Recovery Clean Results
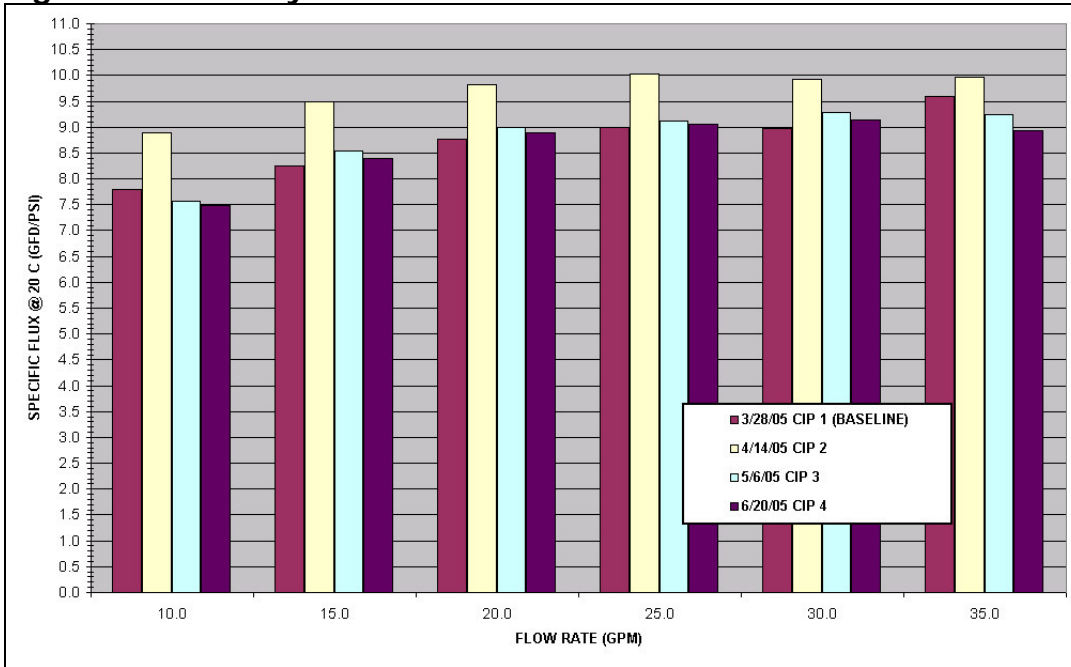
CONCLUSIONS

There has been a great deal of conjecture in the municipal drinking water market about the operation of membrane filtration systems at high fluxes. Those who generally oppose operating at high fluxes cite the possibility of irreversible fouling as the justification for those claims. There has been very little analytical data to substantiate these claims. The anecdotal data generated from full scale plants across the country and the results of this pilot testing indicate that short duration operation at high fluxes and high recoveries can be sustained without any measurable loss of membrane permeability. While further testing is certainly warranted on this matter, municipal personnel should make informed decisions on membrane selection based upon available information and a Present Worth Analysis of all costs and considerations associated with membrane system installation and operation.