Chapter 5

Standardized Data and Trending for RO Plant Operators

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Additional information is available at the end of the chapter

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1. Introduction: Necessary Practical Knowledge to Manage Membrane Systems

This paper is written to strengthen the management of membrane facilities. Day-to-day operation of most large systems is done in a systematic and effective manner. However, management of membrane system resources over the middle to long term has not been so well addressed. For example, we find that the on-site operators are quite capable in maintaining high pressure pumps, detecting sudden rises in salt passage, or rapid feed pressure up ramps, but are not often able to determine if the membrane elements are experiencing a slow loss of productivity, or why a drop in second stage differential pressure needs to be addressed.

This problem in dealing with medium to long term issues is due not to individual operator failings, but to a systematic lack of training and support. Operators are not given sufficient information about membrane technology to know what the system is telling them. But they are often 'on the spot' to make crucial decisions.

Fortunately for operators, there are tools available which can assist them in operating and managing membrane systems. Using these, operators can educate themselves on the job.

1.1. Managing versus operating membrane systems

The job of an operator in a membrane system facility can be quite difficult. Typically they are responsible for maintaining not only the membrane system, but also feed water sources such as wells, water transmission, and disposal of concentrate waste streams, the normal building maintenance, regulatory compliance record keeping, and the list goes on. It is thus understandable the operator's focus is on the here and now.

Yet many important tasks necessary for the proper operation of the facility require the collection, and interpretation of system data over months and years. Some of these tasks include system optimization, cleanings, and membrane replacement. Each of these tasks can be carried out in a straight forward fashion by operators, but only if they are given the requisite tools and the time to learn to use them.

1.2. Managing membrane system resources

The following list of tasks are needed to operate a membrane system over the medium and long term. They require the proper use of membrane system resources such as labor, system data, chemicals, and membranes. All or part of organizing these resources typically falls to system operators to accomplish.

Each of the listed tasks below can be planned and timed using information derived from the analysis of system data.

1.2.1. Optimizing day to day membrane system performance

Optimization of system performance involves adjusting and tweaking operating settings of existing membrane equipment to best achieve the facility management goals. These goals may be producing product water at the lowest cost per gallon, using membrane technology to produce a potable product water from a feed water containing a contaminate such as nitrate, operating the system to minimize waste water disposal, etc.

To carry out such optimizations requires understanding of how the system is currently running, and how it runs after making changes. Looking at system data using the right tools is the only way operators can carry out this task with a high degree of confidence.

1.2.2. Optimizing membrane cleanings

In the course of operating membrane systems some foulant will accumulate on the membrane surface reducing permeate flow. At some point the operators have to decide when to take the system off line and clean to restore productivity. If they clean too soon, the membranes are overexposed to cleaning chemicals. This can lead to shorter membrane lifetime. If they wait too long, the foulant may be very difficult to remove. Using the right tools allows operators to forecast from system data when to clean. In this fashion membrane cleanings are optimized such that the time between cleanings is maximized and the actual time to clean the system is minimized.

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1.2.3. Optimizing membrane change out

Membranes have a life time after which they have to be changed out and new membranes installed. They may fail due to degraded salt rejection, low productivity, or high differential pressure. They may no longer reject a particular contaminate and thus produce permeate water not meeting potable water standards.

As replacing a load of membranes is expensive and time consuming, it is almost mandatory that the event be forecast as far in the future as possible as can be done. Data analysis is required to make such forecasts.

1.2.4. Pilot Tests

Many facilities have small membrane pilot test system or frequently have such equipment bought in by vendors. The most common use of these pilot systems is to qualify new membranes made by different membrane manufacturers for use in the system. Other tests would include testing elements taken from the current load of elements to better qualify performance, or testing different operating conditions considered too risky to trial on the main system.

Proper analysis of the data from the pilot test as it is being run, and after the test is completed, is necessary for the test to have value.

1.2.5. Pathologies/Troubleshooting

As with all processes, there are occasional upsets, mistakes, or the unforeseen. The effects are usually obvious such as low productivity or low salt rejection. But the cause of the trouble cannot always be determined directly from reading the gauges or looking at the SCADA screen. Nor is it always obvious where to dig into the equipment to look for answers.

As we will discuss below, the answers for membrane system problems lie in analyzing how the system has operated over time.

1.2.6. System equipment modifications/upgrades

For some unlucky operators, the membrane system itself is poorly designed, or has been retasked. Or the system has to be upgraded to meet new governmental or market demands. While in such circumstances facility managers call in engineering resources, the operators are also involved, especially if they have been collecting and analyzing the system data. In many cases it is the operators who may have initially identified the system deficiencies.

If operators have the proper tools and experience they can make significant contributions to retooling their systems.

2. Membrane System Variables and Interrelationships

To carry out the tasks listed above requires the operators to collect and analyze the operating data available on most membrane systems. Medium and larger membrane systems are organized into multiple stages, usually two stages. See Figure 1. Each stage has three process streams; feed, permeate and concentrate. Each stream is characterized by pressure, flow, temperature, and conductivity. So there are many variables available to record and analyze.

To further complicate data collection and analysis, the value of each of the variables is strongly dependent on the values of the other variables. For example as feed pressure increases, permeate and concentrate flows can increase and permeate conductivity decreases. As temperature increases, flow increases, permeate conductivity increases, feed pressure can decrease [1].

Without assistance, a system operator would be hard pressed to accomplish any task that required them to utilize the system data they have collected. Fortunately there are many easy to use computer tools available so that the operator need only collect the indicated data, enter it, and click a button on screen to get the required analysis.

All of these computer tools are based on a written procedure, #4516, distributed by the ASTM organization [2]. The ASTM procedure consists of a set of equations into which system data can be inserted and calculations performed. To avoid having to do the calculations by hand the equations have been put into Excel spreadsheets [3-5]. The added benefit of using the spreadsheet is the ease of creating graphs from the calculated values. These graphs are far easier to interpret than a table of numbers.

For this paper, we are going to use an automated spreadsheet program called System Wizard running under Microsoft Excel 2000 [6]. See references. Using System Wizard we will show how to carry out the tasks mentioned above.

3. System Wizard, an Overview

As discussed above the performance of membrane systems cannot be directly measured by following a single variable. Performance can only be seen after the system data has been analyzed. To carry out the analysis you need to be able to directly compare one day's data to another. But membrane system data can vary from day to day. Pressure can go up, and simultaneously temperatures go down. These changes affect the product flow and salt reject. The changes have to be sorted out. Thus it is necessary to create calculated values that allow for these interactions so that each days data can be standardized for direct comparison. Once we do that, we can graph the calculated values, look for system performance trends, and make well founded system performance evaluations.

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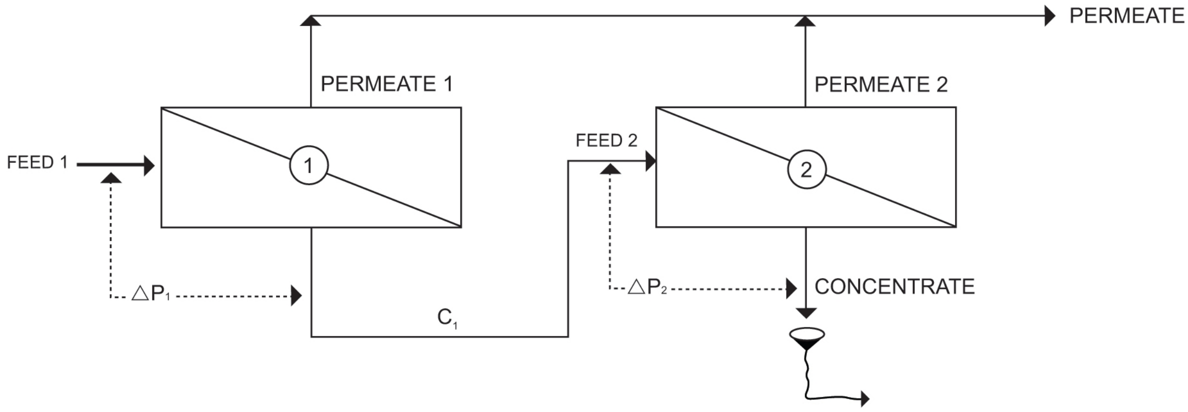

Figure 1. Medium and larger membrane systems are organized into multiple stages, usually two stages.

To use an analogy, if we wish to see how well our automobile is performing we may calculate the vehicle miles per gallon, mpg, after each fill up. To determine performance over the lifetime of the car, we can graph the mpg versus time to see how performance varies over time, season.

We can then use our mpg information to make decisions. For example if currently mpg is 27.3 and the new car mpg was 33.2 we can decide to get a tune up. After the tune up, we can see from the 'tuned up' mpg whether the work on the car was effective. We may look over previous mpg versus tune ups and see if it is time to start looking for a new car.

To use membrane system data to determine system performance we need to calculate values that cancel out variations in pressure, temperature, flow and conductivities. While there a great many ways of going about this [7], the ASTM organization has reviewed the membrane industry practice and published procedure #4516 that is now widely used.

The ASTM procedure calculates 'standardized' permeate flow and salt rejection values from daily system data. These calculated values are derived from equations that compare each of the system variables to a standard set of variables.

For example, suppose we use for standard values the values measured on the first day of operation of a new RO membrane system. Then we operate the system for a month. How as the system performance changed? Looking at Table 1, Day 30, Case 1 we see that the all the system values remained the same save permeate flow which has decreased from 1000 to 500 gpm.

How would we rate the system performance at 30 days? On the basis of permeate productivity we can easily see that the system is producing 50% less product even though the pressure, temperature, etc., are unchanged. So we see that the system performance has decreased by 50%.

In Case 1, it is easy to rate the productivity. Only the permeate flow has changed. However, if we look at Day 30, Case 2 we see that while the permeate flow and other values have not changed, the Feed and Concentrate Pressure has doubled. Has the permeate productivity performance changed?

System Variables	Day 1 Standard	Day 30 Case 1	Day 30 Case 2	Day 30 Case 3
Feed Pressure, psig	100	100	**200**	156
Permeate Pressure	0	0	0	2
Concentrate Pressure	90	90	**180**	146
Temperature, ºC	25	25	25	33
Permeate Flow, gpm	1000	**500**	1000	2000
Concentrate Flow	333	333	333	666
Feed Conductivity ,μS	500	500	500	689
Permeate Conductivity	5	5	5	5
Standardized Flow	**1000**	**492**	**479**	**998**
Flow Performance, %	**100**	**49.2**	**47.9**	**99.8**
Standardized Salt Rejection	**99.0**	**99.4**	**99.0**	**98.9**
Rejection Performance, %	**100**	**100.4**	**100**	**99.9**

Table 1. System Data and Standardized Data.

Yes, since it now takes twice the pressure to make the same amount of permeate. We see that again the system performance has decreased by 50%.

In Case 2, as in Case 1, the difference between the data of Day 1 and Day 30 was rather easy to see. The Feed and Concentrate pressure was doubled, but the permeate flow did not increase. In Day 30, Case 3, all the system values are different from Day 1. It is not possible to 'eyeball' this data set and say how the permeate productivity performance has changed. The pressures have gone up, the temperature has gone up, the flows have gone up, and the feed conductivity has gone up. This is where it is necessary to use the ASTM procedure to determine system performance.

Using System Wizard (that is based on the ASTM procedure) we can calculate the standardized values for each case. We enter the values of the variables listed in Table 1 and then click the on-screen button to calculate the standardized values. The results are shown in the last rows of Table 1. Here we have used the Day 1 data as the standard to compare against the three cases. As shown in Table 1 'Flow Performance%', we see that Case 1 and Case 2 permeate productivity is approximately 50% of the Day 1, while Case 3 productivity is virtually the same. We also calculated the standardized salt rejection for each case.

From these examples it is clear that standardized values are required if we are to be able to compare one days system performance to another days.

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4. Monitoring membrane system performance using System Wizard

Just as we may monitor our automobile and make decisions using mpg, we can use Standardized Flow and Salt Rejection to oversee membrane systems. Using System Wizard or similar programs we can evaluation system performance and best deploy facility resources including labor, chemicals and membranes.

4.1. Optimizing day-to-day membrane system performance

We have discussed calculating standardized values from system data. See Table 1. However, in practice we do not attempt to monitor system performance using a table of values. Instead we graph the standardized values versus time. The graphic format allows us to 'eyeball' a large number of data points so we can find trends in the data. Figure 2 shows a graph of the standardized values for a RO system. From the level trend of the data we can easily determine that this system's permeate productivity is quite constant. The salt rejection is also seen to be quite constant when we learn that the RO feed water alternates between two wells explaining the up and down grouping of the data points.

We can again see the stability of this RO system when we look at Figure 3. Here we graph the differential pressure of the system versus time. Again we see a level trend.

The system shown in Figure 2 and 3 operates on very good quality feed water. The trends are what all membrane systems would have ideally. However, it is more common that the feed water has significant fouling material. Where that is the case the productivity trends downward as shown in Figure 4. In this case, the effect of the foulant layer is to reduce the productivity by approximately 10% over the course of 17 months (from 6/21/11 to shortly before 01/07/12). For a large membrane system this decline is quite acceptable.

We see that trending standardized system data can tell us how well our membrane system is operating. We can take this procedure to a new level by making operation changes and following the effects.

4.1.1. Membrane Flux optimization

Membrane flux is the expressed as gallons of permeate per square foot of membrane per day. For the case where the feed flow is increased and the recovery is unchanged, the higher the flux is raised, the higher the total productivity of the system. However, as the flux goes up, the more likely that foulants will be drawn to the surface of the membrane which would reduce productivity.

By raising the flux in a step-wise fashion over a reasonable period of time and trending the productivity we can determine the point at which the productivity is maximized. What we would see when the data is graphed is the productivity trend would be relatively flat as seen in Figure 4 as the flux was increased. But then the productivity starts to slope down in a noticeable fashion as we pass the optimum flux and a faster rate of fouling is established. From these results we can determine the optiminum flux.

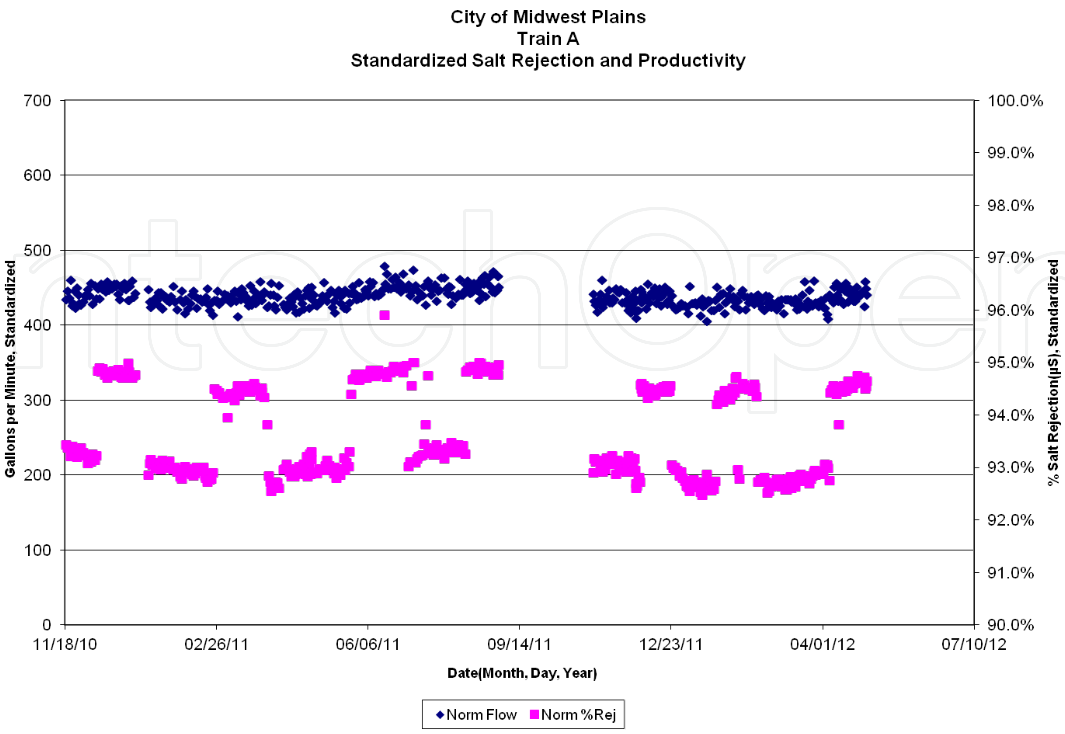

Figure 2. Standardized System Data: Permeate Productivity and Salt Rejection.

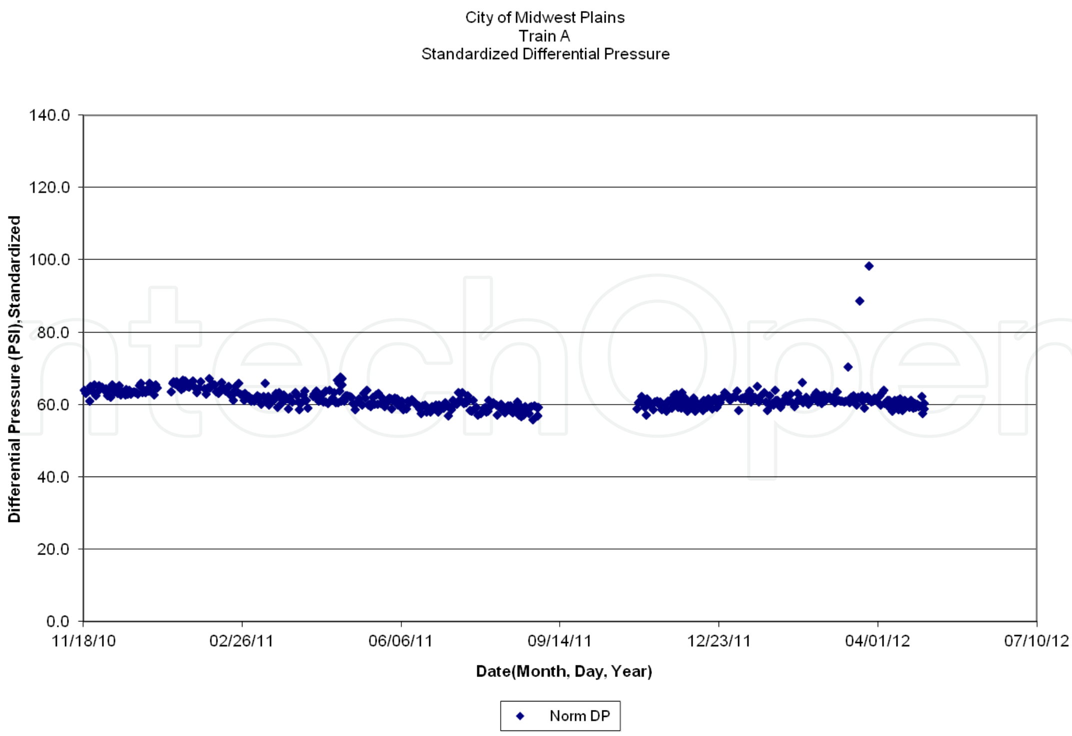

Figure 3. Standardized System Data; Differential Pressure.

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4.1.2. Recovery optimization

Recovery is the percentage of permeate water produced from feed water. Recovery can range from 30% to 90% depending on quality and cost of the feed water and cost of concentrate disposal. For the case where the feed flow is kept constant but the permeate flow increases and the concentrate flow deceases, the recovery of the system increases resulting in higher productivity. Under these conditions the bulk flow (average flow of water through the system from feed inlet to concentrate outlet) decreases since more water is flowing through the membrane. The slower the bulk flow does not sweep the surface of the membrane as well as the original higher bulk flow and can result in a higher fouling rate.

Additionally, the flux also has also increased which can lead to faster fouling. When the standardized productivity is graphed versus time we would see initially a relatively flat trend. As we step up the recovery over a few weeks or months there would come a point where the recovery is high enough that the fouling rate affects the productivity and it starts to trend downward a rapid rate. From these results we can determine the optimum recovery.

4.1.3. Other Optimizations

As discussed above, the effect of any membrane system change can be evaluated by examining the resulting productivity, salt rejection and differential pressure trends. For example, besides changes in membrane flux, and recovery, operators can determine the effect applying permeate back pressure to balance flows from individual stages of multi-stage systems.Another use of this procedure is the very common situation in which the feed water is affected by introducing a new source such a newly dug well. By trending the standardize system values it is possible to see the effects the changed feed water and see if the current blend of source waters needs to be adjusted. It is also possible to determine if additional pretreatment is needed.

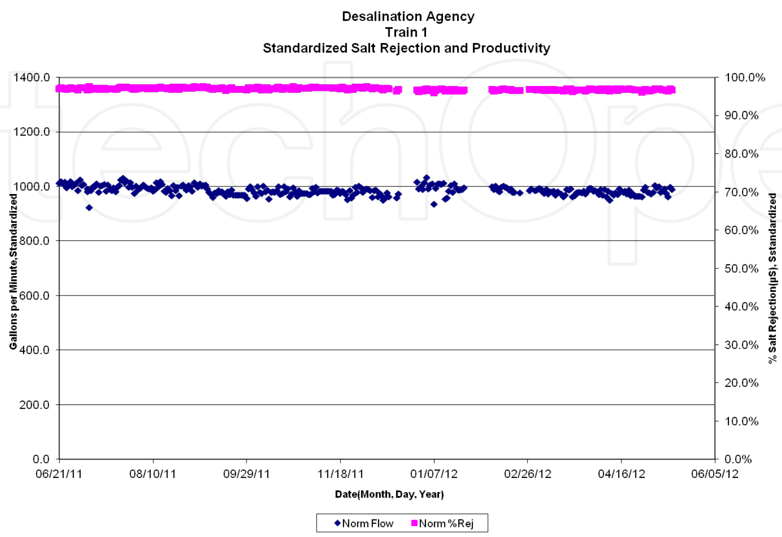

Figure 4. Normal Fouling and Salt Rejection.

4.2. Membrane Cleanings

All membrane systems eventually need to be cleaned. Knowing when to clean, and deciding if the cleaning was successful, are key decisions operators must make. Waiting too long to clean can result in having so much foulant on the membrane that it is very difficult to remove. Cleaning too soon exposes the membrane to harsh chemicals too frequently which can lead to chemical aging of the membrane. A good rule of thumb is to clean membrane systems when the productivity has decreased by 15% since the last successful cleaning. This rule can be modified based on the experience of the operators.

An instance of membrane cleaning is shown in Figure 5. The system was put on line May 29th, 2011. The initial standardized productivity on that date was 1206 gpm. On October 21st, after 292 days in service, the operators took the system off line to be cleaned. On that date the standardized productivity was 1073 gpm, a decline of 11% as compared to May 29th. After cleaning the system was put back on line November 1st. The standardized productivity for that date was 1197 gpm. Since this productivity is 99.3% of that of May 29th, we conclude that the cleaning was successful as it restored the productivity to the same level seen on May 29th.

Taking our procedure to the next level we can use the time between cleanings as another measure of system performance. Since we are determining when to clean based on the data we can assume that 'cleaning period', the time between cleanings, should be constant. If we change the operation of the system in some fashion we can evaluate the change on how the cleaning period is affected.

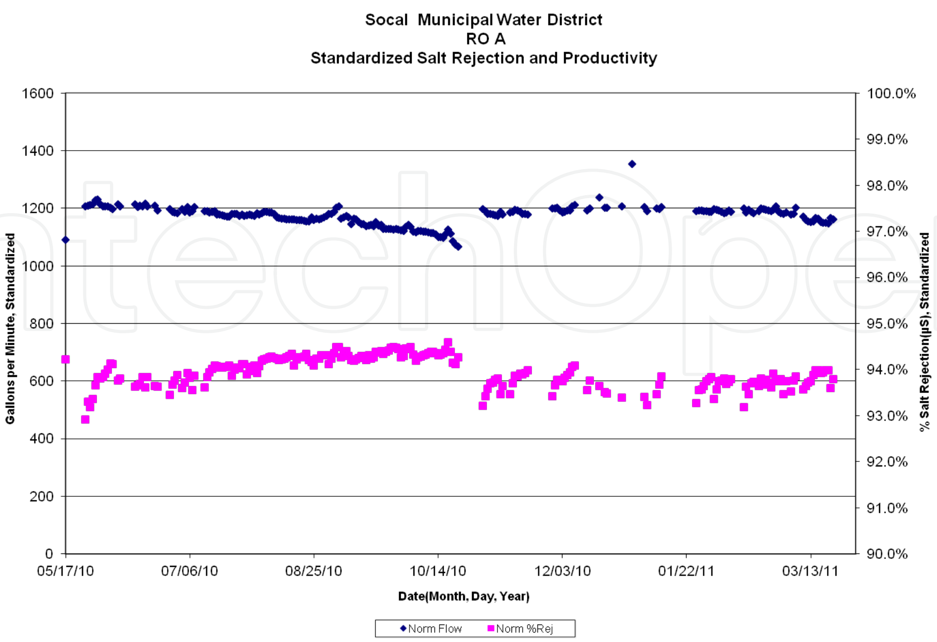

Figure 5. Trending Membrane Cleaning.

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4.3. Membrane change out

Membranes are changed out due to poor rejection, poor productivity or high differential pressure. In some cases, the change out is due to a sudden event such as an accidental exposure of the membrane to an oxidant. But in the remaining instances a membrane change out is due to normal wear and tear over time. In these cases it is possible to forecast when a change out will occur using trends from standardized system data.

An example of such a forecast would be trending declining salt rejection. After a set of elements has been cleaned a number of times over the years, the salt rejection can start to deteriorate due to chemical aging and irreversible fouling. By comparing the salt rejection after the last cleaning to the previous cleanings, or graphing such values over time, salt rejection decline can be trended. Operators can predict when the membranes will need to be changed out by extrapolating the trend into the future to the point at which the salt rejection falls below the systems product water specification.

4.4. Pilot tests

Some membrane facilities have pilot test equipment in which individual membrane elements can be tested. Pilot test equipment can be used to answer simple questions such as does a particular element have low productivity. However, when the questions are more complex, the data generated from the test must be properly analyzed.

Operators can use the standardized data approach in pilot tests by first running the test element under a set of baseline conditions for reasonable period of time to establish a trend. Then the element can be run under the test conditions and that data trended. The baseline and test trends can then be compared and evaluated.

Another use of pilot test equipment is to qualify new types of membranes. Using standardized data allows direct and unambiguous comparison.

4.5. Pathologies

Membrane systems without problems have straight level trend lines similar to Figure 2 and 3. Any deviations are due to the usual operating problems such as scaling. For example we can see in Figure 5 the effect of fouling on the productivity trend line. However, when unusual situations arise, they can also have a particular effect on trend lines.

4.5.1. Low Bulk Flow

Bulk flow is the average flow through a stage of a membrane system. For example, a second stage containing 10 pressure vessels may receive 400 gpm and recover 200 gallons as permeate, thus 200 gpm of concentrate exits the stage. The bulk flow is the average of 400 gallons in and 200 gallons out, and would be equal to 300 gpm.

Maintaining sufficient bulk flow is important. Bulk flow sweeps the surface of the membrane keeping foulants in suspension and pushing them out of the stage. If the bulk flow drops too low, foulants can accumulate on the membrane surface and rapidly reduce permeate flow.

Bulk flow can be reduced for example if the stage recovery is too high, or the stage receives too little feed water from the upstream membrane stages. However, knowing when bulk flow is problematic can be difficult to determine before the system has actually started. Site specific factors may lead to operating conditions the system designers did not anticipate.

Trending the differential pressure (dp) of each of the systems stages can be used to diagnose bulk flow problems. Figure 6 is a graph of the first and second stage differential pressures versus time. Approximately July 2006 the system was cleaned. Both the stage dps immediately start trending down. That indicates that the bulk flow in each stage is decreasing since differential pressure, inlet pressure minus outlet pressure, is directly proportional to bulk flow. As bulk flow goes down, differential pressure goes down.

The reason that the first stage dp is going down is that the second stage is being rapidly fouled and losing productivity. To make up this loss in productivity the first stage must make more permeate which lowers the amount of water exiting the first stage and going to the second stage. Remember that bulk flow is the average of the inlet and outlet flow, thus both stage dps must go down.

An example is shown in Table 2 below. You can see that the inlet to the first stage and outlet from the second stage are constant, meaning the recovery is constant. Initially, the first stage makes 200 units of permeate and the second stage makes 100 units.

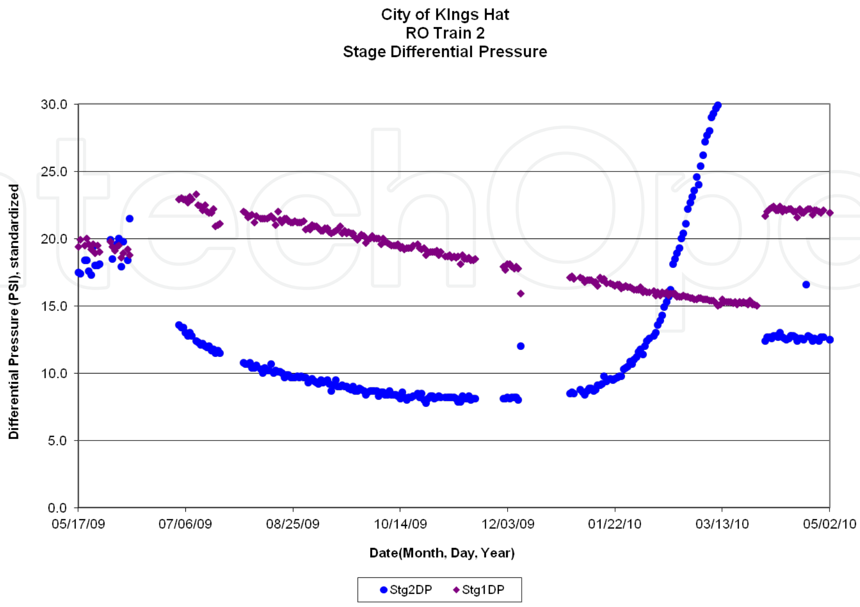

Figure 6. Low Bulk Flow.

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Later, the second stage is only making 50 units. This forces the first stage to increase permeate flow to 250 units. Consequently, the bulk flows for both stages goes down and so do the respective stage dps.

Stages		**First Stage**				**Second Stage**		
Flows	Inlet	Outlet	**Permeate**	**Bulk Flow**	Inlet	Outlet	**Permeate**	**Bulk Flow**
Initial	400	200	**200**	**300**	200	100	**100**	**150**
Later	400	150	**250**	**175**	150	100	**50**	**125**

Table 2. Example of Data for Initial and Later Bulk Flows.

Going back to Figure 6, we can see after December 2009, the second stage dp starts to rise and continue to rise dramatically going from 10 to 60 psi. This occurs as the second stage fouling starts to fill in the feed spacer and restricts flow. The effect is the same as putting a thumb over the end of a garden hose. This is a very serious condition and requires immediate attention.

4.5.2. Particle Fouling

Particle fouling occurs when solid debris passes through the systems macroscopic pretreatment filtration, enters the membrane system and starts to fill the membrane element feed spacer. The first stage of the system of the system is affected and the first stage differential pressure begins to rise. Graphically the first stage dp is trending up while the second stage dp remains unchanged.

As an example of a sudden increase in first stage dp there might be a well casing failure. This eventual will be spotted from normal gauge readings. However, if the stage dp data are collected and trended it is often possible see the increase very early on and potentially to step in and correct whatever malfunction is the cause.

4.6. System Equipment Modification

For some unlucky operators, the membrane system itself is poorly designed, or has been retasked. Poor or inadequate design is more common for smaller membrane systems but larger systems also can have issues. Using standardized data to trend system performance allows operators to see that the problems they have to deal with are not some new factor that developed over time, but began at systems initial startup. For example, if the system was designed for an optimistically high permeate flux, the fouling rate of the system may be too high. In this case the operators may be faced with very frequent membrane cleanings. Another example would be poorer than expected feed water quality. This again may lead to very frequent cleanings. Yet another case would be an imbalance between the system high pressure pumps and the membranes loaded in the system. This has been seen where the pumps cannot supply sufficient flow to the second or third stages of a membrane train. There are many ways that a new system or a newly re-tasked system can run into difficulties. Trending standardized data from initial start up not only identifies but also documents design problems which can be important when dealing with contractual performance guaranties and warranties.

5. Summary and Conclusion

Standardizing and trending data using available computer tools enables operators to carry out tasks such as system optimization, membrane cleaning, membrane replacement, etc., as part of their daily routine in an effective and efficient manner.

Currently, most operators are not using these tools to assist them to manage their membrane systems. Consequently membrane systems are not managed as efficiently as they could be.

Using available tools to standardize and trend system data would educate operators on the job on how membrane systems actual work, what to look for, and how to make good decisions.

Supervisors and managers of membrane systems who want to optimize overall operation of their facilities can move forward by encouraging the adoption of standardization and trending by operators.

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