MEMBRANES

A METHOD TO AUTOMATE NORMALIZATION AND TRENDING FOR RO PLANT OPERATORS

Currently, reverse osmosis (RO) systems are incorporated into the overall treatment program for major municipal water utilities desalinating brackish, sea or wastewater. At the same time, many utility managers could describe their RO experience as crisis management. The relative fragility of RO membranes requires more skillful attention and understanding by the operators to protect the investment costs of the RO plant. Feedwater qualities often change over time, requiring operations and maintenance adjustments to obtain optimum performance.

While computer-controlled operating systems can handle expected variations in process parameters, trained operators must be available to handle the unexpected events, equipment failures, and decisions and performance of needed maintenance actions. Membranes are still a fragile component that can be ruined in less than an hour by incorrect operation. Ignoring gradual accumulation of foulants inside membrane elements, and incomplete recoveries of system performance after each cleaning can lead to membrane service lives of less than a year. Unscheduled and prolonged shutdowns of RO systems are to be avoided at all costs.

Since RO systems can be reliably operated over the long term when the proper equipment, staff, and technical resources are used, why do RO systems appear to be problematic in operation? Based on the authors' experiences, the answer to this question is the lack of appropriate RO data analysis resources. This deficiency results in operators and managers not being able to control their dynamic RO process. They often do not know the true current status of, and the future trend of, the RO systems performance for which they are responsible.

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System Data and Analysis

Consider the following case. A large municipal RO system produces approximately 2,100 gallons per minutes (gpm) of permeate. A graph of actual system data including productivity, feed pressure, and permeate conductivity is shown in Figure 1. The feed pressure can be seen to be increasing, the productivity remains approximately constant, and the permeate conductivity appears to be stable. A membrane cleaning was carried out sometime in November after which the feed pressure decreased, the productivity and differential pressure slightly increased, and the salt rejection dropped slightly.

Figure 1 documents the system's operation in a clear fashion. Yet to make management decisions as opposed to day-to-day maintenance, it is not clear how a RO system manager can get answers from this record of system data. For example, did the system need to be cleaned? Could the cleaning been delayed? Was the cleaning past due? Was the decision by the RO manager to clean a good use of the many thousands of dollars for cleaning chemicals and labor? Without the ability to analyze their data, managers cannot make important decisions on a factual basis. Instead they are forced to make decisions on operator hearsay, or by paying for consulting engineering support.

In contrast to the above case, consider the situation when the same system data shown in Figure 1 is used to calculate the values charted in Figure 2. In this case, the actual data is used to calculate 'normalized' permeate flow and salt rejection values. The mathematical procedure used to normalize data will be described in detail later in this article. However, in words, normalization takes current system data and calculates the productivity and salt rejection at a set of standard pressures, temperature, flows, and conductivities. The effect of this procedure is to eliminate changes in pressure, temperature, flow, and conductivity so that only changes in membrane performance are seen. Thus, the decline in productivity shown in Figure 2 is not because of a decline in pressure or temperature, but due to the membrane being less permeable, probably due to the deposition of a foulant

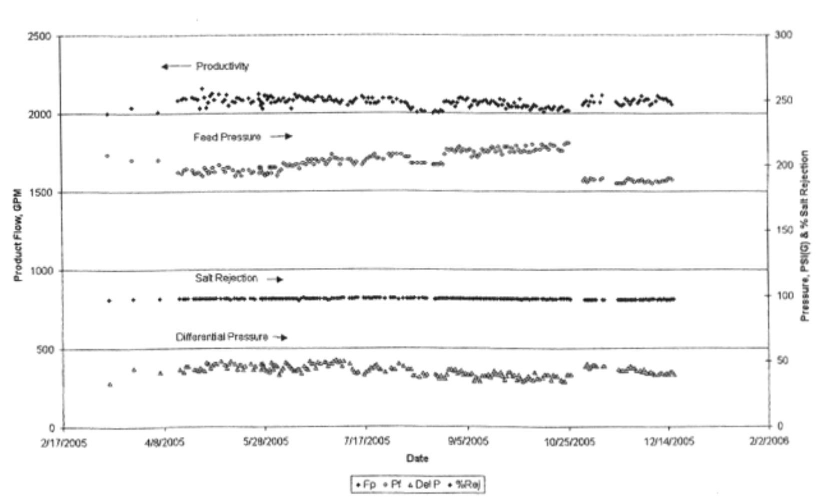

Figure 1. RO system raw data.

layer.

With normalization, the questions posed earlier in this section can be answered as follows:

- Did the system need to be cleaned? Using Figure 2, we can see that the permeate flow declined from 2,100 to 1,700 gpm. This is a drop of 19%. Generally, systems should be cleaned when the productivity decreases by 15%, or the differential pressure increases by 15%. Therefore, the system was slightly overdue for a cleaning.
- Was the cleaning successful? Yes, since the normalized flow after the cleaning was 2,100 gpm, the same flow as seen before the system was fouled.
- When will the system need to be cleaned again? From the chart it appears that the system lost 15% of the original 2,100 gpm in 130 days. Therefore, the next system cleaning would have occurred ideally around February 27, 2006.

Additional information can be extracted from Figure 2. However, the basic point has been made clear. Normalization permits managerial decisions to be made on the basis of the actual performance as shown by system data.

Basics of Normalization

The concepts of normalization are simple and can be used to calculate normalized productivity, salt rejection, and differential pressure. Starting with how to calculate normalized productivity, the mathematical procedure is based on three commonly known facts:

1. Permeate flow increases proportionally with increased net pressure.

2. Permeate flow increases with increased feed temperature.

3. At constant pressure and temperature, permeate flow decreases over time due to fouling, and increases over time because of membrane deterioration.

The first two of these observations can be reduced to the following statement: The ratio of permeate flow to net pressure, corrected for temperature, is a constant, depending on the characteristics of the membrane. This statement can be expressed mathematically as follows in Equation 1. *Editor's note: The article equations are placed together within the article in an Equations Table.*

As long as the membrane status does not change, we can accurately predict the permeate flow of an RO membrane, even if the pressure and temperature change significantly. On the other hand, if the membrane status does change, Equation 1 can be used to identify and quantify that change using RO data on the day of interest. We can interpret that quantitative change using our third observation, correlating permeate flow decline to probable causes of fouling, and permeate flow increase to membrane deterioration. Therefore it is possible for a system manager to spot changes in RO system productivity, quantify those changes, determine the most likely reason for those changes, and take action.

Just as K values for product water can

uses RO to produce 300 gpm of permeate for soft drink production. Using the automated spreadsheet, Northland Bottling saw a sudden decrease in normalize productivity starting Jan. 23, 2006, and e-mailed their data to the authors for review (Figure 5). It was discovered by an author that the product recovery had increased 3%. While this recovery increase was small, it was sufficient to increase the silica concentration past the edge of failure in the last stage and initiate scaling. It was determined by the Northland RO staff that the concentrate valve had been inadvertently closed too far after a cleaning. When this was corrected, and the system cleaned for silica, the productivity was restored.

Conclusion

The argument has been made that successful management of RO systems needs to be based on data analysis. We have described the type of data analysis appropriate for modern RO facilities. We have also demonstrated how operational personnel can carry out this analysis using an automated spreadsheet program.

In the future, we believe inclusion of data analysis as part of the specifications for the RO SCADA computer system will be the norm. Other possible developments could include instrumentation such that individual pressure vessel performance could be monitored and analyzed. As time goes on, and as municipal RO systems assume a larger and larger share of potable water production, water treatment professionals will embrace data analysis to optimize output and enhance reliability.■

References

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2. "FTNORM – Software to Normalize Operating Data", found at the following website: http://www.dow.com/liquidseps/design/ftnorm.htm, The Dow Chemical Co., Midland, Mich.
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Endnote

[a]The automated spreadsheet referred to in the text was developed by King Lee and is known as System Wizard™.

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TABLE A
Normalization Equations

Net Driving Pressure, P_{NET}

$$F_p^N = \frac{F_p P_{NETs} T_{cf}^S}{P_{NET} T_{cf}} \qquad \text{(T1-1)}$$

where $\Delta P = P_f - P_c$ (T1-2)

Temperature Correction Factor, *TCF*

$$TCF = 1.03^{(T-25)} \text{ or Vendor Equation} \qquad \text{(T1-3)}$$

Normalized Permeate Flow, F_p^N

$$F_p^N = \frac{F_p P_{NET}^s T_{cf}^S}{P_{NET} T_{cf}} \qquad \text{(T1-4)}$$

Normalized Salt Rejection, R^N

$$R^N = 1 - \left(\frac{F_p}{F_{ps}}\right)\left(\frac{T_{cf}}{T_{cf}^s}\right)\left(\frac{\langle C_{fb}^S \rangle}{\langle C_{fb} \rangle}\right)\left(\frac{C_f}{C_f^S}\right)\left(\frac{C_p}{C_f}\right) \qquad \text{(T1-5)}$$

Normalized Differential Pressure, ΔPN

$$\Delta P^N = \Delta P \left(\frac{\langle F_B^S \rangle}{\langle F_B \rangle}\right)^{\zeta} \quad \text{(T1-6)} \qquad F_B = F_f\left(1 - \frac{r}{2}\right) \quad \text{(T1-7)}$$

Where Letters are defined as,
P = Pressure
F = Flow
C = Conductivity or Concentration
T = Temperature
Δ = *Differential*
r =recovery

Where Subscripts are defined as,
f = Feed
p=Permeate or Product
c=Concentrate
B=Bulk
osm=Osmotic
s=Standard Condition

Where Superscripts are defined as,
N=Normalized Value
ζ = *Empirical Value > 1*
and $\langle\ \rangle$ = *Average Value*

installed, the user can open either by clicking on the file icon on the Desktop window. Once opened, the Read Me file can be printed or read on the monitor. The automated spreadsheet Excel file when opened for the first time, requests the information listed in the Read Me file. Once this information has been entered in the set up forms, the file is ready for data entry. It is recommended that the file be closed at this point, and clicking "yes" when asked if the changes should be saved.

In operation, when the automated spreadsheet is opened to enter data, it automatically opens to the Entry Worksheet. The user enters the system data in the proper columns. When finished, the user clicks the "Data Entry Complete" button. The VBA program is then triggered. This program enters the data into the 'Data' worksheet, calculates the normalized values, and enters the new data into the charts, sets up the Entry worksheet to take additional data if required, and finishes by opening the chart showing the graphs of normalized productivity and salt rejection. A chart showing a graph of normalized differential pressure is also generated and available to the user.

In sum, the user has generated normalized data graphs by clicking an icon on the Desktop, entering the values on the Entry sheet just as is done with paper and pencil, and clicking a single command button. The automated Spreadsheet has reduced the training required by the user to a minimum. Figure 3 shows the Entry worksheet.

As discussed in the first section of this article, having graphs of normalized values allows users to spot trends in the performance of their RO systems. Based on these trends, managerial decisions can be made. Generally speaking, spotting trends in graphs of productivity, salt rejection, and differential pressure is not difficult. One can generally "eyeball" these graphs and see when to start thinking about cleaning, or replacing membranes. Thus, the automated Spreadsheet gives RO managers the means to make managerial decisions based on system performance using a very straightforward process. Figure 4 shows the data worksheet.

Case Study

The automated spreadsheet program has a command button to e-mail the tabulated data from RO sites to the authors. RO managers can use this option get a second opinion on their system performance. Consequently, the authors have reviewed many performance trends and assisted RO staff in diagnosing system problems. The following cases were picked to show 'real life' examples of data analysis.

Northland Bottling (a fictitious name) stacles to overcome when an RO manager wishes to adopt normalization.

There are five steps in carrying out the normalization and data analysis procedure:

1. Collect system data on a daily basis.

2. Calculate normalized values for flow, salt rejection, and differential pressure from system data.

3. Graph the normalized values versus date.

4. Analyze trends in the system data.

5. Make managerial decisions based on trend data analysis.

EQUATION TABLE

$$K = \frac{F_p}{P_{NET} T_{cf}} \quad \text{Eq. 1}$$

where:
K is a constant dependent only on the membrane/foulants,
F_p is the permeate flow,
P_{NET} is the pressure actually available to force water through the membrane,
T_{cf} is the temperature correction factor.

$$F_p^N = K P_{NET}^S T_{cf}^S \quad \text{Eq. 2}$$

where:
F_p^N is the normalized Product Flow,
K is the membrane constant,
P^S_{NET} is the standard net pressure,
T^S_{cf} is the temperature correction factor calculated at the standard temperature.

$$F_p^N = \frac{F_p P_{NETs} T_{cf}^S}{P_{NET} T_{cf}} \quad \text{Eq. 3}$$

where all the symbols are as defined in Equations 1 and 2.

At almost all plant sites, Step 1 is already part of normal procedure. RO data is collected and recorded in some fashion, generally in logbooks and in some cases electronically. However, Step 2 poses difficulties. At this time, there is a shortage of personnel having the necessary mathematical and technical skills to move from reading the literature to creating and setting up an on-site normalization procedure.

To overcome the lack of mathematical resources various products have been offered. Several organizations offer Microsoft Excel spreadsheets (2). These spreadsheets have pre-labeled columns into which the system data is entered and columns containing mathematic formulas that calculate normalized values using the values in the data cells. Charts for normalized flow and salt rejection are set up. To use these spreadsheets requires the following:

1. A computer running a reasonably current version of Microsoft Excel.

2. Some knowledge of how to download the spreadsheet from the Internet or from a CD.

3. Some knowledge of how to get to the Excel file containing the spreadsheet.

4. Some knowledge of how to use the Excel program, including entering data and how to update the charts as new data is entered.

Typically, these requirements are easily met if the user is technically trained, such as an engineer. However, when the RO manager and/or staff do not have such training, they are unable to use the spreadsheets. This lack of training is currently the norm in U.S. facilities. Thus, simple spreadsheets are not sufficient to encourage widespread adoption of data normalization and analysis.

The adoption of normalization would be promoted if the speed and convenience of using computer-based spreadsheets could be enjoyed without investing in training in the use of computer programs. This requires adapting the spreadsheets to the existing pool of users. Since calculating the normalized values from the system data, and then charting the resulting values, are repetitive tasks once the system data is entered, they can be automated. Thus, developing automated spreadsheets capable of calculating and graphing normalized values once system data has been entered appear to be an important step in promoting normalization and data analysis by water treatment agencies.

Because of the general availability of the Excel (3) program, and because this program includes a programming capability in the form of Visual Basic for Applications (VBA), an automated spreadsheet[a] was developed on this platform (4).

The requirements for running the automated spreadsheet are a personal computer running Microsoft Windows 97© or later version, Excel and Word 2000© or later, Outlook© or Outlook Express 2000© or later, a drive capable of reading a CD, and an internet connection. The automated spreadsheet program[a] is supplied on a CD containing an Excel file with the special spreadsheet. There is also a Word file containing Read Me information.

Very little computer knowledge is required to install or use the automated spreadsheet. The user can install it by copying the files to the hard disc of the computer. Typically, this step is handled by the operating system once the CD is inserted in the tray. Saving the files to the Desktop window is recommended. Once the files have been

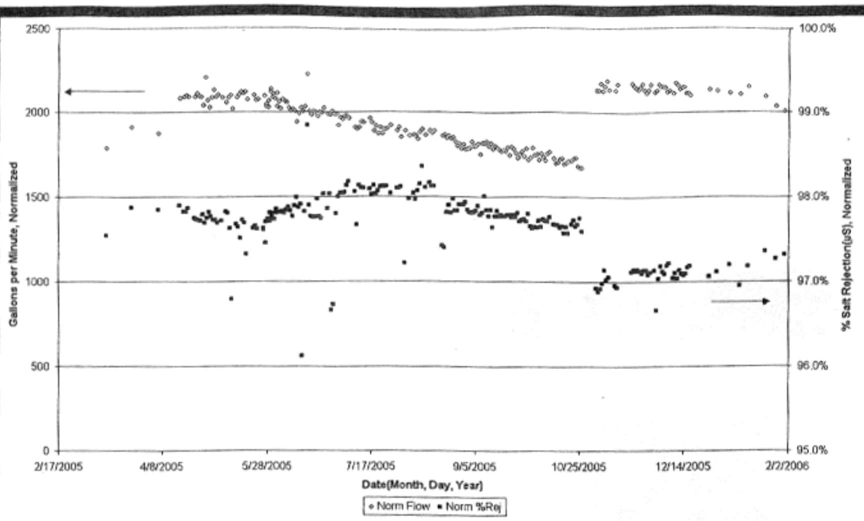

Figure 2. Normalized RO system data.

Click on this Button When Data Entry is Complete.>> [Data Entry Complete]

Data Entered Through >>>>>>>>>>>>>>>>>>>>>>> 03/29/06

	I	N	P	U	T	S				
Entry Data Page	Date	Feed Pressure	Permeate Pressure	Concentrate Pressure	Feedwater Temperature	Permeate Flow	Concentrate Flow	Feedwater Conductivity	Permeate Conductivity	Concentrate Conductivity (Optional)
	MMDDYY	PSIG	PSIG	PSIG	°F	GPM	GPM	µS	µS	µS
Enter Data Here>										

Figure 3. Entry worksheet.

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DoubleClick this button to Email File to King Lee Technologies for Analysis

DoubleClick to Recalculate

DoubleClick to Re-array Data

Daily RO Operating Data | **Calculated Values** | **Charted Values**

Date	Pf	Pp	Pc	Temp	Fp	Fc	Cf	Cp	Ce	Ff	rec	Del P	Posm	Pnet	Norm Flow	Norm %Rej	Norm DP
3/12/2006	208	13	174	70	2000	325	1529	39	9400	2325.00	86.0%	34.00	29.09	148.91	1791	97.5%	36.02102
3/24/2006	204	11.5	159	70	2037	362	1515	32	7900	2399.00	84.9%	45.00	29.11	141.89	1914	97.9%	44.82898
4/6/2006	204	11.8	162	70	2010	368	1540	33	8040	2378.00	84.5%	42.00	29.32	142.88	1876	97.9%	42.18367
4/16/2005	195	11.41	151	70	2084	335	1477	31		2419.00	86.2%	44.00	28.25	133.34	2084	97.9%	44
4/18/2005	194	11.5	152	70	2089	339	1480	32		2428.00	86.0%	42.00	28.22	133.28	2090	97.8%	41.70436
04/13/05	196	11.4	150	70	2097.0	326	1465	32.0		2423.00	86.5%	46.00	28.29	133.31	2088	97.8%	46.12556

Figure 4. Data worksheet.

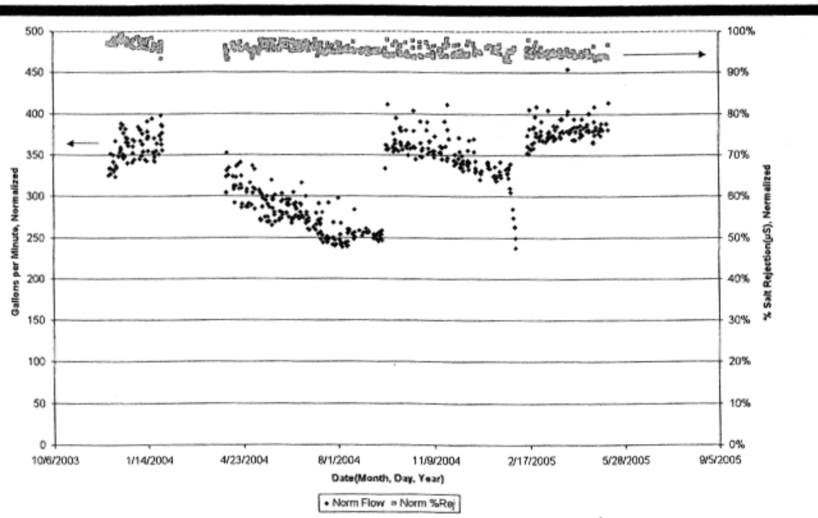

Figure 5. Example of performance data generated using the automated spreadsheet program.

be calculated from system data, the same approach can be taken to calculate K's for salt rejection and differential pressure. Thus, system managers can, in principle, determine how all systems performance measures change with time using nothing more than the above discussed procedure (i.e., they can calculate and compare K values to quantify how their system is changing over time). However, in practice it is more advantageous to carry out such calculations using a calculation approach known as "normalization and trending".

Data is reduced to a standard when it is normalized. For RO data, normalization is carried out at standard pressure, temperature, and flow. To normalize RO product water flow, Equation 1 is rearranged and reinterpreted as follows in Equation 2.

The normalized product flow is a calculated value, while the standard net pressure and temperature correction factors are fixed values. The value of K is calculated from current system data using Equation 1. As the value of K changes due to changes in membrane condition, the normalized product flow changes.

It should be noted that the K membrane constant does not appear in the literature. To ease computation, Equation 1 is used to eliminate K from Equation 2. The result is Equation 3, and is the equation found in the ASTM Procedure D 4516-00, Standard Practice for Standardizing Reverse Osmosis Performance Data (1). All the symbols are as defined in Equations 1 and 2. The equations for normalized salt rejection, and differential pressure are shown in Table A.

Once the calculations have been performed, the normalized data is graphed so that trends in the data are more easily found. An example of such a graph is shown in Figure 2. In this graph, both normalized product flow and salt rejection are shown. Since all the data points are normalized to the same standard pressure and temperature, any trends in the data are due to changes in membrane performance.

Normalization and Automation

Normalization of RO data has not been widely adopted by the water treatment community. This is in spite of the above-stated benefits of this approach and the availability of many normalization products in the market, most of which are free. However, there are practical ob-