Sustaining the Productivity of Reverse Osmosis Plants

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INTRODUCTION

Across the spectrum of industrial and municipal water utilization and treatment plants, extensive desalination and purification of water relies on the use of reverse osmosis (RO) membranes. Sustaining the productivity of RO plants as continuous processes for water purification has been and still is a major technological challenge. This challenge is magnified by both the increasing shortage of water–thus driving down the quality of available raw water–and by the demand and high cost of lost production that can result from insufficient productivity of RO systems. Reduced productivity of RO plants exerts serious economic impact on the downstream production of steam, power, microelectronics, pharmaceuticals and beverages among other products. Loss of RO capacity to process waste-water can shut down production or operation of some industrial complexes.

The design and working of an RO system as a unit operation is quite simple[1] and as such is often grouped along with cooling systems and boilers for operation and maintenance (O&M). However, the tendency of RO membranes towards fouling has presented great challenges to O&M personne[1,2] When one realizes that RO is a process for water purification and is quite different from simply utilizing water as a medium for heat transfer, it stands to reason that it should be operated and maintained quite differently from cooling systems and boilers. Indeed, the chemistry for controlling fouling of RO is quite different from that of cooling systems and boilers. Insufficient attention to this results in our current industry practice of expecting just two to three years of membrane- service life, along with frequent stoppages for membrane cleaning and system maintenance. When optimally controlled, RO membranes have lasted more than 12 years. Systems exist that have operated continuously and have not needed to be cleaned for years.

In this article, we point to aspects of process chemistry peculiar to RO plants.[3-14] Based on attention to RO process chemistry and responsive servicing of RO plants, great value can be given to plant owners and to service companies as well.

Membrane Fouling Mechanisms

Feedwaters to RO systems typically are concentrated by a factor of two to 10 (50 to 90 percent recovery) during production of permeate water. For simplicity in classification, there are three classes of fouling:[10]

First, there is scaling. The solubility limits of various dissolved salts in the brine stream may be exceeded, leading to deposition and growth of crystals in the flow channels and membrane surface of the RO elements. This type of fouling is referred to as scaling. Most common examples of scales are calcium carbonate, sulfates of calcium, strontium and barium, calcium fluoride and calcium phosphate. In the examination of foulants by the naked eye or with a magnifying glass, crystals have well defined shapes. Inhibitors injected into feedwaters to suppress crystallization are called antiscalants.

Second, there is colloidal fouling. The foulants appear typically as colorless to yellow or brown jelly during autopsy. Particulate matter pre-existing in feedwater can aggregate and adhere to the membrane and brine-flow channels due to increased concentration, salinity, compaction, flocculation, surface interactions and other physical and chemical factors. The particles may be large enough to be removed with one- to five-micron RO pre-filters, such as silt, carbon fines, coagula and microbial clusters, or they may be colloidal particles that escape filtration even with the standard 0.45 micron filters used in Silt Density Index measurements. The colloids can be organic, inorganic or composites. Ferric, aluminum, calcium hydroxides and silicic acid grow to increasing particle sizes by polymerization. Cross-linking and complex of organic and inorganic polymers become gels as amorphous foulants commonly seen on membranes.[10] Biotic debris such as polysaccharides and dead cellular matter contribute largely to this type of foulants. Through solving numerous fouling problems in existing RO plants, it has become obvious that excessive and inappropriate application of pretreatment chemicals aggravate the tendency of natural colloids present in RO feedwaters to coagulate and become foulants. Recently developed anticoagulants and anti-deposition agents show promise in inhibiting this fouling process.

Third, biofouling is a prominent source of fouling. True of all water treatment or distribution systems is the growth and anchoring of microorganisms. Moderate temperatures and minimal nutrient levels in RO waters can support at times explosive growths of microorganisms. Bacteria capable of cell division every 20 minutes can grow from a normal count per unit volume of water to millions in an eight-hour shift. Due to the tendency of bacteria to secrete polymers that anchor themselves to surfaces to facilitate growth as the biofilm, this fouling mechanism is unique and poses a serious threat to the operation of RO systems. This threat is compounded by the great difficulty of treating and completely removing bio-film from the membrane surface.

Antifoulant Chemical Design and Application

The term antifoulant is used here in its broadest meaning covering scaling, particulate fouling and microbial fouling. Strategies aimed at controlling each type of fouling are:

- For scale control, the development and application of antiscalants is well known and reviewed in the field of boiler water and cooling water chemistry and applied to boilers, evaporators, cooling towers and cooling systems. Anionic polymers, polyphosphates and organophosphorous compounds, sometimes referred to as threshold inhibitors and dispersants, are used in substoichiometric amounts, usually in the range of 1-5 mg/L concentrations in RO systems. By binding to surfaces of growing crystal nuclei, the rates of crystallization from supersaturated solutions are retarded and crystal-packing orders are modified. By this mechanism, crystallization rates are so retarded that although supersaturation of solutes in the water will eventually equilibrate through crystallization, within the residence time of the water in the system, there is little or no scale formation. The uniqueness of RO among water conditioning systems is that the residence time is very short (a few seconds), concentration of seed crystals is low and temperature is constant. For this reason, higher levels of supersaturation without crystallization are possible. On the other hand, the limits of saturation and rates of scaling are hard to model, measure and predict. Interference comes from other solutes in the water, organic or inorganic. Assumptions of RO fouling limits vary considerably among practitioners.

- For controlling fouling by preexisting particulate matter, the task is much more challenging due to the variety of types of potential foulants and the complexity of their interactions with each other in the same water and with the membrane.[3,4,8-11,13,14] Stability and agglomeration of colloidal particles is a subject of major importance in natural waters as well as in the treatment of process waters.[14] Drawing on the basic science of colloids and testing of model foulants suggested by RO foulant analysis data, progress is made steadily with the development of antifoulants.[10-14]

- Concerning prevention and management of biofouling in water treatment systems, the literature is extensive. Much of the art and science that is found useful is applicable to RO systems as well. Several factors peculiar to the RO system can be mentioned. Chemicals used to sanitize and clean the system have to be compatible with the thin, salt-rejecting, polyamide or cellulose acetate barrier membrane. Of prime concern is that accumulation and exponential growth of the microorganisms should not be allowed to occur within the system. Pretreatment of feedwater; adequate maintenance of upstream unit operations; continuous flow of water through the RO unit; good

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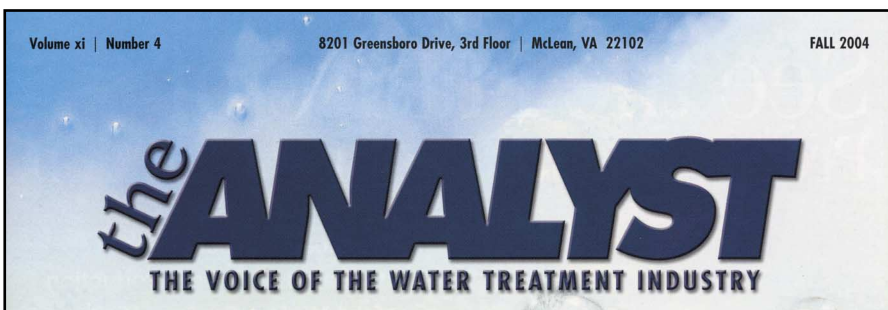

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monitoring and sanitization program; and used of preservatives during downtime[15] are important to this end.

Normalized permeate flow and differential pressure in the system are sensitive indicators of biofouling.

Membrane Cleaning

Practical procedure for maintenance cleaning is limited to the recirculation of cleaning solutions through the membrane elements. By a patented method[16] of membrane reconditioning, spiral wound elements with the hard casing removed are routinely used in selecting effective cleaners for cleaning by recirculation. This allows for visual inspection of the membrane surface after each cleaning test. It is apparent that except for easily soluble foulants such as calcium carbonate or ferric and aluminum hydroxide, nearly all RO foulants are only slightly dissolved in even the best matched cleaning solutions with extensive soaking. Removal requires high tangential flow velocities and is usually partially effective especially where flow channels are clogged and large patches within the elements are inaccessible to the recirculating solution. For this reason, the need for cleaning should be minimized or completely eliminated by the new antiscalants and antifoulants now available, and adequate pretreatment and pilot testing of process designed. When cleaning is necessary, it should be performed at the earliest stages of fouling.

It is generally agreed among membrane manufacturers and practitioners that RO systems should be cleaned before the following performance changes are reached:

1. Loss of 10 to 15 percent in normalized permeate flow-rate.
2. Increase of 10 to 15 percent in differential pressure.
3. Decrease of 1 to 2 percent in salt rejection.

If a cleaning procedure fails to fully restore the system performance to reference RO system startup values, it is certain that continued use of the same cleaning procedure will lead to accelerating decline in system performance and increasing cleaning frequency. For this reason, it is important to address two issues at this point: 1) find an improved cleaning procedure, 2) investigate possible improvement of pretreatment to avoid membrane fouling. Continue cleaning and process improvement efforts until stability of the RO performance is attained.

Choosing Cleaners

Major membrane manufacturers generally define five types of foulants for which various generic chemicals are recommended for blending at the site where cleaning solutions are prepared:

1. Acid-soluble Foulants
2. Biofilm/Bacterial Slime/Biological Matter
3. Carbon-containing Oils/Organic Matter
4. Dual Organic and Inorganic Coagulated Colloids
5. Silica and Silicates

Proprietary booster cleaners formulated on site are commercially available to fortify the effectiveness of generic cleaners. For convenience and technical support, a large variety of proprietary RO membrane cleaners are available from chemical suppliers that specialize in RO operations.

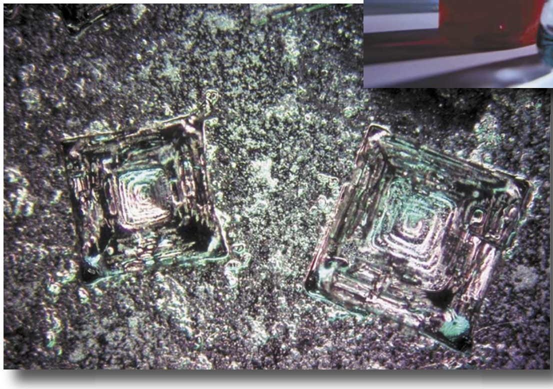
Cleaning Strategies

Experience has shown that within the same class of foulants, responses to the same cleaning solution can vary considerably. Elemental analyses of foulants and cleaning studies have shown that more than one type of foulant can be present on the membrane at the same time, requiring sequential cleaning with different cleaners. Sometimes even the order of cleaners used makes a significant difference. Thus, the choice of cleaners and the cleaning procedure to be used is an empirical exercise. For a given set of conditions in a plant, cleaning efficiencies are improved by trial over time. The progress of improvement can be greatly accelerated by conducting off-line cleaning studies on single fouled elements taken from the plant.

When a better cleaning method is needed in the plant, one of the following strategies can be used:

Strategy 1: If the plant has a history of using generic cleaning chemicals and modest improvement in effectiveness is needed, consider purchase of proprietary booster cleaners.

Strategy 2: If a significant cleaning improvement is needed, look for proprietary cleaner supplier with associated cleaning expertise.



Option 1: With prior knowledge of the characteristics of the foulant on hand, with consultation with the supplier, select a combination of cleaners for trial in the plant.
Option 2: Send one to three fouled elements to a specialist for cleaning study, foulant analysis and review of plant performance history and pretreatment process. Document the findings along with pilot cleaning results using a recommended improved cleaning procedure. Simultaneously, address recovery of the plant and avoidance of repeated fouling.
Option 3: Send all fouled elements for off-site cleaning by specialist.

Strategy 3: If all cleaning efforts by re-circulation of cleaning solutions have failed, consider non-routine methods like using proprietary membrane conditioning liquids or a patented membrane reconstruction process by which the membrane bundle is unrolled, cleaned leaf by leaf, then restored with a new hard-casing.

In-Place Cleaning Procedure

There are six steps in the cleaning of membrane elements in place in RO systems:

1. Mix Cleaning Solution.
2. Low Flow Pumping. Pump preheated cleaning solution to the vessels at conditions of low flow rate (about half of that shown in Table 1) and low pressure to displace the process water. With the RO concentrate throttling valve completely open to minimize pressure during cleaning, use only enough pressure to compensate for the pressure drop from feed to concentrate. The pressure should be low enough that essentially no permeate is produced. A low pressure minimizes redeposition of dirt on the membrane. Dump the concentrate, as necessary, to prevent the dilution of the cleaning solution.
3. Recirculate. After the process water is displaced, cleaning solution will be present in the concentrate stream. Recirculate the concentrate to the cleaning solution tank and allow the temperature to stabilize.
4. Soak. Turn the pump off and allow the elements to soak. Sometimes a soaking period of about one hour is sufficient. For difficult-to-clean foulants, an extended overnight soaking period of 10 to 15 hours is beneficial. To maintain a high temperature during an extended soaking period, use a slow re-circulation rate (about 10 percent of that shown in Table 1).
5. High Flow Pumping. Feed the cleaning solution at the rates shown in Table 1 for 30 to 60 minutes. The high cross-flow rate flushes out the foulants removed from the membrane surface by the cleaning, with minimal or no permeation through the membrane to avoid compacting the foulant. If the elements are heavily fouled (which should not be a normal occurrence) a flow rate 50 percent higher than shown in Table 1 may aid cleaning. At higher flow rates excessive pressure drop may be a problem. The maximum recommended pressure drop is 20 psi per element or 60 psi per multi-element vessel, whichever value is more limiting.

(Note: In this cleaning mode, foulants are generally partially dissolved in the cleaner and partially dislodged physically from the membrane and flow channels without dissolving. An in-line filter removes the recirculated particles and should be monitored for cartridge replacement.)

6. Flush Out. Pre-filtered raw water can be used for flushing out the cleaning solution, unless there are corrosion problems such as with seawater corroding stainless steel piping. To prevent precipitation, the minimum flush temperature is 20 °C.

(Additional Notes: The pH should be monitored during acid cleaning. The acid is consumed when it dissolves alkaline scales. If the pH increases more than 0.5 pH units, add more acid.)

Multi Stage Systems

For tapered multi-staged systems the flushing and soaking steps can be performed simultaneously in the entire array. However, the high flow-rate recirculation step should be carried out separately for each stage, so the flow rate is not too low in the first stage and too high in the last. This can be accomplished either by using one cleaning pump and operating one stage at a time, or using a separate cleaning pump for each stage.

Control and Improvement of Cleaning Process

To assure complete recovery of membrane performance by cleaning, the system performance should be adequately controlled by trending of normalized flux, differential pressure and salt rejection to:

1. Trigger a cleaning when any monitored parameters change from normal baseline by 10 to 15 percent.
2. Record the trended parameters before and after each cleaning.
3. Initiate improvement actions for better cleaning if membrane performance does not fully recover.

TABLE 1: Recommended High Re-circulation Flow Rates During Cleaning

Feed Pressure* (psig)	Element Diameter (inches)	Feed Flow Rate Per Vessel (gpm)
20 - 60	2.5	3 - 5
20 - 60	4	8 - 10
20 - 60	6	10 - 20
20 - 60	8	30 - 40

**Dependent on the number of elements in the presure vessel.*

A change in responsiveness to a previously effective cleaning process signals a change in fouling pattern that requires immediate attention. If partial cleanings are allowed to continue, the system performance will decline at increasing rate and will become increasingly difficult to recover.

In-place cleaning processes are improved primarily by the choice of cleaning chemicals and the order of the application sequence. Depending on the composition of the complex foulants, when two or more cleaners are found necessary, often the order in which they are used is important. Also critical, but to a lesser extent, are the variables of time, temperature and cross-flow rate.

Through thorough review of the water and pretreatment chemistry; analyses of the foulant composition and source; and customized selection of antiscalants, dispersants and high performance cleaners, both fouling voidance and reliable plant performance can be attained.

Business Overview

A severe and increasing gap in the demands on the O&M of ever-increasing number of RO systems and available O&M manpower and expertise offers excellent opportunities to O&M service companies. The economic value to the owners of RO systems is proportional to the gap between supply and demand of O&M capability.

On the demand side, continuous, reliable and cost-effective operation of RO systems are obvious where pure water production is critical to the production of power, steam, drinking water, microelectronics, beverages, pharmaceuticals and other end products. The reclamation of water from municipal and industrial wastewaters adds a special demand on the capability and efficiency of the O&M services due to the poor qualities of the feedwaters and the low prices of the product water.

On the supply side of qualified O&M services to RO systems, it is well known that many systems large and small are designed and installed with no provisions made for trained and dedicated monitoring and service personnel. The problem is compounded by the fact that each RO system is a unique process for the purification of large volumes of low-quality water. If the process is not adequately designed, tested, optimized, monitored and maintained, fouling of the membranes will be severe, resulting in frequent and extended downtime for cleaning, maintenance of pretreatment equipment and premature replacement of membranes and parts.

Being a supplier of core RO technology, our collaborators can benefit in the following ways:

1. Rapid adoption of technical competence with RO systems through hands-on work with our guidance.
2. Add value to existing and prospective customers.
3. Competitive in landing utility O&M contracts.
4. Solve RO problems to maintain existing O&M contracts.
5. Increase chemical sales.
6. Maximize value to customers and sales margins.
7. Adoption of unique chemistry now increasingly specified by design engineers and system manufacturers, facilitating the supply of chemical and services following qualification of new installations.

Conclusion

Sustaining the productivity of reverse osmosis plants is a business model that is much needed, is profitable and is easily practiced through collaboration, including workshops, information exchange forums and through technical associations.

References

1. Z. Amjad, J. Zibrida and R.W. Zuhl, "Reverse Osmosis Technology: Fundamentals and Water Applications", Analyst, Fall (1999).
2. D.H. Paul, "The Four Most Common Problems in Membrane Water Treatment Today", Analyst, Winter (2003).
3. R.Y. Ning, "Discussion of Silica Speciation, Fouling, Control and Maximum Reduction", Desalination, 151, 67-73 (2003).
4. R.Y. Ning, T.L. Troyer and R.S. Tominello, "Chemical Keys to Optimal Reverse Osmosis Processes", Ultrapure Water, September, 42-44 (2002).
5. R.Y. Ning and J.P. Netwig, "Complete Elimination of Acid Injection in Reverse Osmosis Plants", Desalination, 143, 29-34 (2002).
6. R.Y. Ning, "Antiscalants That Permit Operation of RO Systems at High pH Levels", Ultrapure Water, September, 18-21 (2001).
7. R.Y. Ning, "Making an Ideal Process for Pure Water by Reverse Osmosis", Water Conditioning & Purification, September (2000).
8. R.Y. Ning, "Operational Characteristics of Reverse Osmosis Process Chemistry", Ultrapure Water, April, 39-42 (1999).
9. R.Y. Ning, "Reverse Osmosis Process Chemistry Relevant to the Gulf", Desalination, 123, 157-164 (1999).
10. R.Y. Ning and P.T.L. Shen, "Observations From Analysis of Reverse Osmosis Membrane Foulants", Ultrapure Water, April, 37-40 (1998).
11. R.Y. Ning and D. Stith, "The Iron, Silica and Organic Polymer Triangle", Ultrapure Water, March, 30-32 (1997).
12. R.Y. Ning, "A Paradigm Shift from Prepurification of Membrane Feedstreams to Minimal Chemical Intervention", Amer. Membr. Tech. Assoc. 2003 Annual Symposium, Westminster, CO, August 3-5 (2003).
13. R.Y. Ning, "Sustaining the Production of Pure Water in Reverse Osmosis Plants for First Use or Reuse", Annual Water Technologies Convention, AWT, Phoenix, AZ, September 17-20 (2003).
14. R.Y. Ning, T.L. Troyer and R.S. Tominello, "Chemical Control of Colloidal Fouling of Reverse Osmosis Systems", World Congress on Desalination and Water Reuse, Intern. Desal. Assoc., Bahamas, Sept. 28-Oct.3, 2003.
15. W. Varnava, M. Silbernagel, T. Kuepper and M. Miller, "Reverse Osmosis Element Preservation Study", Proceedings of Biennial Conf., Amer. Desalting Assoc., 308-327, August (1996).
16. C.L. Netwig and D.L. Kronmiller, U.S. Patent No. 5,250,118 (1993).

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