

Cost Effective RO and NF Systems: Importance of O&M Considerations in Design, Procurement and Manufacturing

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Abstract

The use of membrane water treatment technologies (i.e., reverse osmosis (RO) and nanofiltration (NF)) has often been viewed as costly in comparison to conventional water treatment processes. Water suppliers have generally only pursued membrane technology as a treatment option when high quality, fresh water resources have been utilized to their full extent. Faced with the perception of RO and NF as costly treatment options, many Owners and Engineers are inclined to select RO and NF system equipment based on the lowest capital cost. However, this strategy often does not result in the lowest annualized cost. Based on an overall view of the cost to produce water, the single most significant expense over the life of a plant is the operation and maintenance (O&M) cost. Designing, procuring and fabricating membrane treatment plants with this fact in mind will ensure engineers, owners and end users obtain the best value in their membrane treatment systems.

This paper will present a review of the major components of membrane systems with a view toward evaluating the O&M impacts. Beginning with an initial assessment of raw water quality and desired finished water quality, the selection between RO vs. NF will be evaluated considering both capital and O&M implications based on raw water blend options and feed pressure differences. Specific components within the membrane system will be addressed including pre-treatment, physical and chemical; membrane selection, square footage and physical configurations; high pressure pump type, and pump and motor efficiencies; use of variable frequency drives on high pressure pumps; and general materials of construction and valve selection. The importance of proper hydraulic design and flow balancing will be discussed, with particular emphasis on the application of new multi-port vessels and their impact on the O&M of a plant. Misapplication of this new development in the membrane industry can significantly affect the life-cycle cost of a plant through several means including increased high pressure pumping energy and shortened membrane life as a result of inadequate cleaning access. Other topics will be addressed including energy recovery and instrumentation and controls issues. Finally a brief discussion on alternative procurement methods will present the reader with ideas on obtaining a system designed to provide the user with the lowest life cycle cost membrane plant. Specific information developed from the authors' personal experience in the industry will be incorporated in the discussions.

Benefits of Valued-Added Engineering Services for the Reverse Osmosis Industry

The amount of engineering effort as well as the project aspects to which this effort is applied significantly impacts the capital and O&M costs of a membrane treatment facility. As with conventional water treatment facilities, the larger the facility, the greater the opportunity to significantly leverage engineering effort into cost savings. For membrane facilities, significant savings through customized designs are often obtainable at facility sizes greater than a few hundred gallons per minute. In addition, focusing the engineering effort on areas most sensitive to site-specific savings is key to optimizing the benefits of engineering. For example, developing an integrated approach to pretreatment, recovery efficiency, and by-product disposal is far more likely to realize significant savings than the same level of effort spent detailing skid assembly procedures.

To make the best decision regarding engineering services procurement, Owners must understand and consider the types of services that are available and relative merits of each. Engineering services can be separated into two basic categories:

- Commodity Engineering Approach
- Custom Engineering Approach

Commodity Engineering involves the use of a pre-packaged approach to membrane plant design. Treatment plant design plans and specifications are re-used in a fashion that is sometimes referred to as a “rubber stamp” approach. Potential benefits to this type of approach include:

- Owners often pay less for commodity engineering services,
- Capital costs are well understood,
- For small applications, capital costs are potentially minimized due to a generic application of desalting technologies, and
- Engineers may maximize their profits by use of one design for repeated applications.

In contrast, Custom Engineering takes a more holistic approach to each project, recognizing the unique nature of each project and how costs are controlled by accounting for both capital and O&M costs. The most significant component of cost for desalting over the life a project is the O&M component, and as such, protecting the Owner’s interest must involve an examination of the O&M component of desalting facility. With the O&M component minimized, capital costs are assessed and life cycle costs can be optimized through an iterative process that involves re-evaluating costly capital components that were used to minimize O&M.

Benefits of the Custom Engineering approach include:

- Owners’ long-term interests are protected by an accounting for the O&M component of desalting processes,
- The unique nature of each project is recognized and reflected in the design of the desalting process in a manner that controls life cycle costs that include both capital and O&M costs,
- Application of innovative, yet reliable technologies are encouraged to reduce both capital and O&M costs, and

- Engineers experienced in Custom Engineering are better equipped to respond to a variety of project conditions since they are frequently required to re-think desalting processes in terms of each circumstance as an individual case.

Owners often focus on the “sticker” price of the project in terms of the capital cost and cost for engineering services. The benefits of a Custom Engineering approach is the ability to consider the value of supplemental engineering relative to project cost. For both Custom Engineering and life-cycle cost analysis, the owner needs to appreciate that the capital cost may be higher, but over the long-term the impact on rate-payers is lower. Additionally the quality of the end product is superior and the Owner and consumer will be happier with the end result. The “value-added” to a project through the Custom Engineering approach is a membrane facility that is more economical over the life of the project.

Raw Water Quality/ Process Design Evaluation

The first step in evaluating the application of membrane technology involves reviewing the raw water quality with relation to the desired finished water quality. At this point there may be two different approaches considered. The first approach would involve trying to tailor the RO permeate quality to match the desired finished water quality. In seawater or high brackish water supply systems this is generally the required approach. All water produced is treated through the membrane system. In a low brackish or softening application there is another alternative. This would involve treating the raw water to a high level of purity, enabling blending of the permeate with raw water to reduce the quantity of water that must be treated by the membrane system. There are advantages and disadvantages to each approach and a cost analysis should be performed to weigh the cost impacts.

Alternative 1: Tailor Membrane Treatment to Finished Water Quality

Advantages

100% treatment through membranes
Simple, one-process operation
Lower pressure operation
May have lower energy costs
Concentrate is less “concentrated”

Disadvantages

Typically more costly
Higher membrane replacement costs
Consumes more raw water
Produces more concentrate
May require bigger footprint

Alternative 2: High Level Treatment, Maximum Blending

Advantages

Reduce size of R/O treatment system
Reduce amount of raw water required
Reduce amount of concentrate produced
Reduce amount of chemicals used
Usually saves money

Disadvantages

Lose 100% membrane barrier
May require by-pass treatment process
System less adaptable to future regulations
May require more post-treatment chemicals
Concentrate is more “concentrated”

The considerations are many when comparing high level RO treatment with blending versus membrane softening or lower level treatment with no blending. The membrane softening process may or may not use less energy because even though it will operate at a lower pressure more feedwater will have to be pumped. Raw water by-pass may be desired, however, the raw water may contain constituents that make it undesirable for blending, such as iron. In this case it may be cost-effective to treat only the by-pass water with conventional iron removal processes. This may allow the amount of raw water blending permissible to be increased. The treatment of 100% of the produced water through membranes is advantageous for virus and bacteria removal credit, otherwise the by-pass water will still have to meet the requirements as applied to a water characterized as a surface water or a groundwater under the direct influence of a surface water. Planning for 100% membrane treatment will enable the plant to be more flexible in accommodating future regulations. For example, an ion such as arsenic that is currently not regulated may be present in the raw water blend. It may become regulated in the future, negating the ability to blend, then the RO system capacity would have to be increased or additional treatment processes would have to be installed on the by-pass stream. When evaluating blend options, less tangible constituents such as taste, odor and particularly color should also be taken into consideration.

Concentrate disposal requirements may also be important to the evaluation. The high level RO treatment will produce less concentrate volume, however, it will be of worse (more concentrated) quality. Basically the “waste load” of dissolved solids to be disposed of will be the same either way, the engineer must evaluate whether the disposal requirements more easily accommodate higher volume or higher concentrations.

The amount of chemicals required can vary site-specifically. Typically a high level RO treatment process will require higher pre-treatment chemical dosages as a result of rejecting more ions and producing a more scale-forming concentrate. However the membrane softening process, while requiring a lower scale inhibitor dosage and possibly no acid feed, will have a higher feedwater flow that the chemicals must be injected into. The post-treatment analysis will demonstrate that although the high level RO permeate will be more pure and will require more post-treatment, blending with raw water is a very effective way to provide alkalinity and buffering and raise the pH to an acceptable level, thus reducing the amount of post-treatment chemicals required.

In summary, the evaluation of whether to consider producing the highest quality permeate feasible and blending with raw water, versus producing a custom-tailored, 100% RO permeate finished water is complicated. It is the first step in applying the value-added engineering principles previously discussed. Making this important decision based on thorough evaluation and careful study will pay off through the life of the plant.

Benefits of Pilot Studying

One of the primary decisions that must be made when initially considering a membrane system is whether or not to perform a pilot study on the potential water source. There are several factors to consider:

- the cost of the study versus the capacity and expected cost of the plant,
- if any existing users have experience with membrane treatment of the source water,

- if preliminary analysis indicates any particularly troublesome constituents may be present in the raw water,
- if concentrate disposal methods must be evaluated,
- if the end users are not familiar with or skeptical about the process

There is an economy of scale to consider when evaluating pilot studying. A thorough pilot study using a comprehensive, properly-sized pilot, running for an adequate length of time (typically at least 2000 hours on a groundwater – longer on a surface water), will typically cost about \$75,000 to \$150,000. Obviously this would not be considered for a small system that was only likely to cost about \$100,000. On the other hand, this is a small sum of money to invest to obtain invaluable O&M data for optimizing a 40 MGD plant that could cost \$160 million. In fact it is common for a full-scale pilot unit to be purchased by an end-user contemplating a large plant. The pilot unit will be continually useful throughout the life of the plant to test different membranes, pre-treatment chemicals, cleaning schemes, etc. An unexpected benefit that has often been realized from a pilot study is a change in attitude toward the technology from negative operators and customers. Operators that may have been resistant to the technology due to opinions that it was difficult or expensive have completely changed their views after running a well-designed pilot study. Also customers can become fans of the technology if a small post-treatment system is set up with the pilot permitting the production of actual drinking water from the unit which is made available to the end-user. Several utilities have done this as a successful public relations technique.

The benefit of the full-scale pilot, which incorporates full-length, six or seven element vessels, is in its ability to simulate full-scale design conditions and recoveries without requiring concentrate recycle. Recycling the concentrate to achieve higher recoveries may affect the projected results by introducing a feedwater that includes already super-saturated fluid and, thus, does not exactly match the design feedwater. Therefore, the most useful data is obtained from a full-scale pilot. Membrane screening can be performed in a single element pilot, but a single element pilot cannot provide accurate design and operational information. It is important that the pilot unit be comprehensively instrumented, durable, and designed for flexibility of operation. A low pressure booster pump should be included, in case the raw water is not under adequate pressure for the cartridge filter pretreatment. A high quality, stainless steel high pressure pump should be supplied to provide the RO feed pressure. A variable frequency drive and a feed control valve are recommended to provide maximum flexibility in controlling feed pressure. Sample locations should be installed on all flow streams. Instrumentation must include flow measurement, pressure measurement, feed pH, and feed and permeate conductivity. The unit should be designed to test any manufacturers' membrane softening or reverse osmosis elements. It is ideal if the unit has a modem and data logger. It also may be desirable for the pilot to have an interstage booster pump with variable frequency drive. An amp meter can be invaluable for predicting energy consumption. There are innumerable benefits to be realized from performing a pilot study that can recoup the cost of the study many times over. Additional benefits will be mentioned throughout this paper.

Raw Water Supply and Transmission

Once the general treatment process idea is developed the single most important factor in predicting the successful operation of a membrane plant is the condition of the raw water supply. A membrane plant can be superbly designed, perfectly fabricated, and flawlessly operated, however, if the raw water supply is not suitable for membrane treatment due to particulate or biological contamination, the plant will be fraught with problems and operation and maintenance costs will increase exponentially. Therefore, the Owner is encouraged to commit adequate time and resources to developing and designing the raw water supply and membrane pre-treatment systems. The first step is performing thorough hydrogeological studies of the proposed water source if it is a groundwater. For surface water sources the water quality review must cover an entire year as quality and temperature can vary seasonally. Listed below is a summary of the minimum constituents that must be known for membrane treatment evaluation.

Table 1
Recommended Minimum Water Quality Analysis for Design

Parameter
Calcium
Magnesium
Sodium
Potassium
Ammonia
Strontium
Barium
Iron
Manganese
Carbonate
Bicarbonate Alkalinity
Sulfate
Chloride
Nitrate
Fluoride
Silica
Carbon Dioxide
Hydrogen Sulfide
Total Dissolved Solids
Temperature
pH
Silt Density Index

Proper well and wellhead piping design is also important. Several points to consider when designing raw water supply and transmission systems are presented below. An important factor in groundwater supply sources is keeping the source anaerobic. There are dissolved ions such as

hydrogen sulfide and iron that are in solution in an anaerobic groundwater. In solution these constituents do not pose a problem to the membrane system. It is very important that air is not then mixed with the water, either in the well, the raw water transmission piping or the pre-treatment. If air mixes with the water then the hydrogen sulfide will convert to elemental sulfur and dissolved metals will precipitate out and become foulants to the membrane system (1). An even more troublesome side effect of allowing air to contact a naturally anaerobic groundwater stems from the rapid increase in biological activity. A study was performed in the Netherlands by the Overijssel Water Supply Company and Kiwa Research and Constituency on a water supply that was a high iron anaerobic groundwater. Membrane pilot studies were performed on the water. The studies compared operation with direct membrane treatment and membrane treatment following aeration and filtration pre-treatment. The studies concluded that the direct anaerobic treatment was far less susceptible to particulate and biological fouling than the aerobically pre-treated water (2).

Summary of Recommendations for Raw Water Supply

- Groundwater Wells
 - proper design – screen sizing, gravel pack selection
 - minimize particulate withdrawal
 - casing and grout integrity
 - reduce aeration
 - isolate aquifer
 - proper materials of construction
 - preferably non-ferrous
 - minimize biological contamination
- Surface Water Intakes
 - evaluate seasonal variation by studying source for one year
 - physical and chemical variations
 - location and elevation of intake
 - minimize source water variation
 - “modified intake” design, ie beach wells, bank filtration
 - provides some pre-filtration

Groundwater Pumping and Piping Recommendations – for minimizing aeration

- recommend submersible pumps, provide adequate pressure including pretreatment losses
- consider VFD's on the well pumps
- incorporate foot valves
- design wellhead piping with tee for flushing
- stainless, FRP or flexible pump column
- stainless, FRP or PVC raw water piping
- preferably no automatic air relief valves
- consider building in pigging facilities
- flush new pipelines at design flow

Even a well-designed water supply system will need periodic maintenance, i.e. flushing, periodic disinfection, and possibly occasional well rehabilitation. The facilities should be designed with

adequate isolation valves, access for pulling pumps, means of diverting disinfection flushing water so chlorinated water is not directed to the RO plant, etc (1). The operation and maintenance of the supply system should be monitored and maintained as carefully as the RO system. The most significant problems a RO system experiences can most often be traced to problems in the raw water supply system, particularly bio-fouling problems.

Physical Pre-treatment Facilities

The physical pre-treatment facilities addressed will be limited within the scope of this paper to those facilities typically found on conventional groundwater RO systems. The first process is a sand separator. It is not uncommon for wells to occasionally pump sand. Sand can quickly load a cartridge filter and is certainly detrimental to the membranes. A sand separator is an excellent way to eliminate this possible loading on the cartridge filters. They require little maintenance compared to expensive, labor intensive cartridge filters. If designed properly and built out of the proper materials of construction they should not aerate the water or contribute metals or other contaminants. They typically run off the head pressure from the raw water supply, therefore make sure the raw water supply design pressure is adequate to accommodate sand separators, should they be desired initially or in the future. They can be installed at individual wells, useful if only certain wells seem to be producing sand, or they can be installed at the head of the RO plant.

The industry standard for RO pretreatment is the cartridge filter. This an ASME designed pressure-rated housing, usually stainless steel, that contains numerous disposal filter elements. The filter elements are usually string-wound polypropylene or melt blown elements, 2 ½" in diameter by 30" or 40" long. They can have ratings from 1 to 20 microns, usually about 5 micron is used in the RO industry. The elements have a core that slips over a guide and is held in place against a seat plate for filtration integrity. The filter elements have widely varying efficiencies, and thus widely varying costs. An inexpensive, low efficiency filter can allow a significant quantity of material to by-pass. Although the filter elements have a depth/storage capacity, they are not designed for heavy loadings. The cartridge filter is in place as a "last line of defense" to protect the membranes and RO feed pumps from occasional upsets or particulate matter that may enter the raw water feed from a line break or other maintenance. The elements are relatively expensive to replace and change-outs are very labor intensive. For example, a housing rated for 1 MGD flow could contain forty to fifty 40" individual cartridge filter elements, each filter element could cost \$5 to \$10 a piece.

Important design considerations for the cartridge filters include adequately sizing the inlet and outlet nozzles to minimize headloss, uneven filter element loading, and hydraulic "short-cutting". Well designed internal structural elements are critical. The filters are only as good as the seating and sealing mechanisms are at maintaining the filtration integrity. Of great importance is generous drain sizing. There must be separate clean and dirty water drains, sized large enough to get thorough flushing after an element change-out. For example, 2" drains minimum on a 1 MGD rated filter housing. The drains should be piped separately to a free-flowing disposal point, open to atmosphere. A specific procedure should be followed during filter changes to minimize the possibility of by-passing dirt to the membrane system. It is remarkably common to

match spikes in RO feed pressure increases to cartridge filter change schedules, indicating that dirt is allowed to remain in the housing during change-outs and is then directly pumped to the membranes when the system is started back up. Following the right procedure when changing filters and thoroughly flushing the housings through generously-sized drains would eliminate these problems. There are two primary housing design configurations, vertical and horizontal. The horizontal design is more popular for large systems for ease of access. It is also advantageous because the clean water outlet is not on the bottom of the unit, therefore, it is less likely for dirt to by-pass during change-outs. It is usually more costly than the vertical configuration due to the additional structural elements required to support the filter elements. The filters should be designed for a conservative loading rate for optimum filter life. A design rate of 3.5 to 5 gpm per 10-inch length of filter is a good rule of thumb. This rate can be calculated based on all filters in service, although it is commonly specified to be calculated with one filter out of service. It is not usually a problem to allow the remaining filters to operate at a slightly higher rate while one filter is out of service for filter change-out, as long as there are three or more filters total. The period of time a filter is down for change-out is typically minimal, a few hours every few months. This is quite different than a conventional filter system where one filter is backwashing maybe a quarter of the operational time. This is why it is common for engineers to specify the design loading rate with one filter out of service, when it really may not be necessary for a cartridge filter.

Most of the cartridge filter manufacturers will publish the differential pressure the elements may withstand before they need to be changed. It is typically between 10 and 20 psi. The engineer should make sure the raw water supply pressure is adequate to accommodate the maximum differential pressure loss through the filters. It is an unnecessary waste of money to have to change filters more often than actually required because the raw water supply pressure cannot accommodate the differential head loss.

Another physical pre-treatment process occasionally used upstream of an RO system is a bag filter. Bag filters have not been commonly used in membrane pre-treatment, but can be a useful and cost-effective pre-treatment device. Bag filters can be useful when installed upstream of cartridge filters. They can perform as a “roughing filter” if the particulate loading on the cartridge filters is higher than desirable, but cannot be prevented or accommodated through other means. The bag filters have a higher dirt holding capacity than the cartridge filters and are less expensive and quicker to change out than cartridge filters. The bag filter housings look similar to the cartridge filter housings but they are always vertical. The filters are about 8” diameter and usually 20” or 30” long. It is not recommended to use bag filters alone as a RO pre-treatment because they have a much lower efficiency than the cartridge filters and will allow too much material to by-pass. Installing a 20 micron bag filter upstream of a 5 micron cartridge filter, for example, can be a cost effective pre-treatment scheme that lowers operation and maintenance costs significantly and increases membrane life and decreases membrane cleaning frequency.

Pre- and Post-Treatment Chemical Feed

Most membrane plants incorporate several chemical feed systems, typically, scale inhibitor and acid pre-treatment and caustic post-treatment, as a minimum. Disinfectants, fluoride, and

distribution system corrosion inhibitors are usually present as well, but are site-specific and not specifically related to the membrane process and therefore will not be addressed in this paper.

Scale inhibitor and acid pre-treatment is required to prevent calcium carbonate and sparingly soluble salts from scaling within the membrane system. Scaling may be controlled physically by lowering the RO process recovery so the solubility product is not exceeded. However, it is more cost-effective to control scaling chemically. Typically, calcium carbonate scaling is controlled by adjusting the feed water pH such that the concentrate Langlier Saturation Index (LSI) remains negative if a scale inhibitor is not also used, or to about 1.8 if a scale inhibitor is used. The LSI has been used since the beginning of the membrane treatment industry as a qualitative measure of calcium carbonate precipitation potential. Most of the membrane manufacturers' design projection software also calculates concentrate LSI (along with other indices) as an indication of scale potential. Unfortunately it is not the most accurate indication of scale formation potential as it relates to an RO system. A more accurate indication of scale potential may be the Calcium Carbonate Precipitation Potential (CCPP) index as described in the an AWWA Journal article published February 1983 by Rossum and Merrill titled "*An Evaluation of the Calcium Carbonate Saturation Indices*". This article describes how the LSI often gives the appearance of over-saturated conditions when the water may actually be under-saturated. The article states that the CCPP is a better indicator of a water's potential to deposit calcium carbonate. The CCPP can be calculated using the Rothberg, Tamburini, and Winsor model available from AWWA.

As an example, two different waters were compared that both exhibited a similar concentrate LSI. A high calcium and alkalinity water had a concentrate LSI of 2.8. The other water had virtually no calcium but a concentrate LSI of 2.6. Both would seem to be scaling waters requiring pH reduction and scale inhibitor addition. The CCPP for the high calcium and alkalinity water was over 1000 mg/l as CaCO_3 , the CCPP for the low calcium water was less than 24 mg/l as CaCO_3 . The low calcium water RO system has been operating successfully for several years with no pH reduction and minimal scale inhibitor injection. It has not required cleaning once. Therefore, it is important to consider more than just the LSI when optimizing chemical dosage and feed system designs. A great deal of operational funds are probably wasted due to over-feeding and unnecessary chemical injection.

The next step in improving O & M costs for chemical systems involves the physical design of the feed facilities. The injection piping should be designed to permanently include a calibration column to make it easy for the operator to check the chemical injection rate regularly. This is primarily important for chemicals that do not provide continuous feedback related to their injection rate – that is, it is not necessary on acid or caustic because pH adjustment immediately indicates the chemical is being injected in the required amount. In fact, it is not desirable to have calibration columns installed on acid or caustic systems as these are dangerous chemicals and the systems should be designed to minimize handling and the potential for leaks. Systems such as scale inhibitor feed should definitely include calibration columns as there is no way to immediately tell if the chemical is being injected properly.

A big step in improving the O & M costs of a membrane plant is in simplifying the design and operation in general. The chemical feed systems are areas that can often be simplified for improved O & M. Even on large plants the simplest and most effective way to control certain

chemical feed systems, especially the scale inhibitor system, is to basically design for one chemical pump per RO train (assuming a train operates at constant flow and recovery). This makes operation so much easier than having flow controllers and PID loops. Also the pumps are simpler and easier to maintain, and the chemical injection and daily usage is more intuitive and easier for the operator to observe and track and note if there are any problems. Acid and caustic systems are usually pH controlled.

Designing the chemical systems to be close to the injection point improves O & M because there is less piping to maintain and this minimizes potential for leaks. Arranging for the injection points to be above-grade and easily accessible rather than down in a trench is also a good idea. They are safer to maintain and more likely to be maintained if the injectors are visible and accessible. Most importantly, placing the injectors higher than the day tanks prevents siphoning.

RO Skid Considerations

Feed pumps.

The most common type of pump used as a membrane feed pump is the vertical turbine can pumps. These pumps generally have the highest efficiencies at specific points. RO skids operate best at a fixed flow and recovery, therefore, the feed pump does not have to be efficient at a wide flow range. The only variation the pump must be able to accommodate is an increase in operating pressure over time as the membranes foul or water quality or temperature changes. This pressure variation over time can be most effectively managed through the use of variable frequency drives (VFD's) on the RO feed pumps. Because the expected increase in feed pressure is generally gradual over a period of many years, the pump would have to be throttled initially, wasting a great deal of energy over the years. VFD's allow the speed of the pump to be turned down during initial operation, increasing over time. Horizontal ANSI-type pumps are sometimes used as feed pumps, but they generally have lower efficiencies and rather under-sized suction and discharge connections causing excessive headloss and requiring higher feed pressure, larger horsepower motors and higher energy consumption. For example, on a system recently under design in South Carolina, an evaluation of vertical turbine can pumps versus ANSI pumps indicated that the ANSI pump selection would have to be 100 hp while the vertical turbine pump selection could be only 75 hp, a significant cost and energy savings.

The ANSI pumps may be easier to install as they do not require a sub-surface intake can, however, they take up more floor space and may require more complicated connecting piping. Other types of pumps are available such as in-line pumps like Torpedo pumps. These are useful if there are severe space constraints as they often fit right on the RO skid. However, they are not operator-friendly as they are sealed like submersible well pumps and are quite cumbersome to access for repair or maintenance.

Membrane skid frame.

The membrane skid frame material can be painted or coated steel, aluminum, stainless steel or fiberglass. The material of choice for most municipal systems is fiberglass. Painted steel frames will generally corrode as the paint or coating is chipped or damaged. Aluminum will corrode also in adverse conditions. Stainless steel frames are usually good if made out of 316 stainless,

however, most are made out of 304 stainless which will ultimately show surface corrosion. They are also quite expensive and difficult to modify or retrofit. Fiberglass structural shapes are readily available and relatively easy to work with. The material comes in the same shapes as structural steel shapes. Properly designed and fabricated frames can be as strong as steel. The real beauty of the fiberglass frames is they will never rust. It is recommended the fiberglass be painted for aesthetics as well as ease of maintenance and to minimize water absorption. But even if the paint is scratched or damaged, the structural material underneath will never corrode. Skids of all sizes can be built from fiberglass, from small pilot units to 40 MGD + plants.

Hydraulic Design

Correct hydraulic design is the key to a low maintenance, efficient membrane treatment system. With proper hydraulic design, all parts of the system will be evenly loaded, there will not be excessive headloss or short-circuiting. The lower the operating pressure of the system the more important good hydraulic balance is. Likewise piping must not be oversized either. Too low of a velocity or stagnant areas in a seawater or high brackish systems can lead to crevice corrosion in the stainless piping.

There are two aspects to hydraulic design: one is the design of the piping to and from the membrane system, the other is the hydraulic design through the membrane system. The hydraulic design to and from the system should consider both current and future operating conditions, potential variations in recovery, and thus changes in feed and concentrate flows. The design should also consider the operating pressure of the streams, i.e., the permeate leaves the skid at a very low pressure and therefore the piping should be more conservatively designed for lower velocities and headloss than the high pressure feed, interstage and concentrate piping. The flow distribution of permeate as produced from each stage of a multi-stage system is what is meant by “the hydraulic balance through the membrane system”. This is a function of the array sizing and interstage balance control, usually either first stage permeate throttling (or backpressure) or interstage booster pumping. These balance control measures will be discussed subsequently. It is important to note that maintaining balance throughout the skid will prolong membrane life and may reduce membrane cleaning frequencies by minimizing overloading of the lead elements in the first stage of the system.

Good hydraulic design is absolutely crucial in considering cleaning effectiveness. Cleanings must be performed at low pressures and high velocities to be effective. The piping should always be designed to allow cleanings by stage. Never should cleaning flow be forced from one stage through another; then a foulant that may have been fairly easily removed from the first stage elements will be forced into the second stage, never to be removed because the velocity is not high enough. The proper design cleaning flows will almost always be higher than the actual operating flows and therefore will govern the hydraulic design. Piping and pressure vessel port sizing should always take into account the cleaning flow requirements. Generously sized cleaning connections should be placed throughout the skid for access by individual stage. The connections should be placed upstream of restrictions such as control valves. If the system incorporates an interstage boost pump there should be cleaning connections upstream and downstream of the pump so that the cleaning solution does not have to flow through the pump. The pump would be a restriction and most cleaning solutions are quite corrosive, which would not be good for the pump either. Cleanings are one of the most expensive elements of an RO

systems' O & M costs. They are chemical and labor intensive. Disposal of spent cleaning solution is a major hassle. Additionally cleanings use up a lot of permeate. And worst of all, a plant is not producing water while it is undergoing a cleaning. Therefore, it is of the utmost importance that cleanings be minimized, and when they are performed they are absolutely as effective as possible.

Cleaning System

A significant benefit from pilot studying a membrane application is the ability to predict probable cleaning frequency. The expected cleaning frequency and likely potential foulants should be considered when designing the skids and cleaning system. Membrane system cleanings are always initiated and performed manually, and are – hopefully – quite infrequent. The systems can be designed one of two basic ways:

1. all cleaning system connections can be hard-piped to the skids with valves at the connections, or
2. cleaning piping and on-skid connections can be terminated with plugs and cleaning connections are hooked up manually for each cleaning

The first method has a higher capital cost, but the labor and down-time costs will be less for each cleaning. The second method saves money initially, however, performing the cleanings will take more labor and time. If an Owner has experience on the feed water and thinks cleanings may be very infrequent, a hard piped cleaning system would probably not be cost-effective. However, if it is expected, or piloting demonstrated an expected cleaning frequency of several times a year, a hard-piped cleaning system may be a good investment.

The cleaning system should be sized and the skid-piping and cleaning connections designed to clean the skids at even flow rates. Thus, it is common to clean the first of a two stage system in two separate steps and the second stage in one step. This way the cleaning flow is approximately the same (and the hydraulics can be optimized) because most two stage systems are in a 2:1 ratio. For example, the cleaning system for a 10:5 array would be sized to clean 5 vessels at a time. The first stage piping would be designed to allow 5 vessels of the first stage to be cleaned, then the next five, then the five vessels of the second stage. The cleaning tank should always be designed for a 100 % drain capability so no cleaning solution or dirt remains in the tank between cleanings. A cartridge filter should be incorporated to prevent particulates from being recirculated during cleanings. A mixer is not typically required because the piping should be set up to allow mixing by recirculating the solution using the cleaning pump. This recirculation also heats up the solution but an additional heater may be desired if the water is particularly cold or if biofouling is anticipated to be a large problem. Basic instrumentation should include a temperature probe, a pH probe, a flow meter and a pressure gage. Achieving effective cleanings is a result of the ability to apply the solution at a high flow and a low pressure, this achieves maximum flushing. Specific cleaning instructions are provided by the membrane manufacturers for their particular membranes. Cleaning pumps should either be non-metallic, ie fiberglass or plastic, or stainless steel. Cleaning solutions can range in pH from 2 to 12, at temperatures up to 110°F. The piping and valving materials can generally be PVC as the operating pressures are quite low, generally less than 70 psi.

RO System Piping and Valving

The piping materials of construction may vary depending on the water quality, but generally are the same throughout membrane plants, unless the salinity is very high brackish ($>10,000$ mg/l TDS) or seawater. The low pressure piping is usually schedule 80 PVC. This is used on the inlet piping, RO feed pump suction, the permeate piping and the concentrate piping after the concentrate control valve. Inside the plant the PVC piping should not be painted as it will require more maintenance if it is painted. Piping identification can be made with printed, color-coded plastic labeling. The high pressure piping should be 316 stainless steel, passivated and electropolished after fabrication. The electropolishing provides a bright finish and removes surface impurities (particularly from the welds) that could contribute to surface corrosion eventually. High pressure piping is generally the RO pump discharge piping, interstage and concentrate piping upstream of the concentrate control valve.

Valve sizing is an important part of a good hydraulic design. Even with a VFD on the feed pump a back-up feed control valve is recommended on the discharge of the RO pump. This could be a control valve such as a V-port ball valve or even just a butterfly valve. If there is no VFD and the valve must be used for feed pressure control it should be a high-quality characterized seat valve, V-port or other. If the valve is properly sized it should not cause more than 5 or 10 psi headloss when full open. This is especially important if there is a VFD and it is just a back-up feed control valve. Also, it is important so that it does not create a restriction during pre-and post-flushing. Likewise the concentrate control valve must be carefully sized for hydraulic control without cavitation or excessive noise. If the concentrate control valve is not motor operated, a motorized full-port ball valve should be installed on a by-pass around the concentrate control valve to allow for adequate flushing. If the concentrate control valve is motor operated it should be programmed to go full open during pre- and post-flushes. Thorough post-flushing is critical to minimizing scaling and fouling in a RO system. The scale inhibitor has a short period of effectiveness. If supersaturated concentrate is allowed to sit in an RO system, it will quickly begin to scale. Also the supersaturated concentrate will want to equalize and thus will suck permeate back across the membrane. In a highly saline water this osmotic pressure can be severe enough to cause damage to the membrane surface and the membrane can delaminate from the backing. The post-flush timer should be set upon initial operation of a system by checking the concentrate conductivity versus the raw water conductivity. The system should be flushed until the conductivities are nearly equal. On high salinity systems (usually greater than about 3000 to 4000 mg/l TDS) a permeate post-flush may be recommended instead of a raw water flush.

Pressure vessels.

Pressure vessels for membrane treatment systems are usually fiberglass. There are stainless steel and PVC models available also but are not commonly used in the municipal market. The stainless vessels are subject to surface corrosion and denting. The PVC vessels cannot be ASME code rated as is occasionally required on municipal systems. Pressure vessels are available in a variety of pressure ratings. The newest feature of the pressure vessels is called multi-porting. Originally vessels only came with three ports: one for feed, one for concentrate, and one for permeate. The multi-porting option now enables several vessels to be directly connected in series minimizing the stainless manifolding required. The size of the ports is still limited in diameter due to structural constraints of the pressure vessel. A common trend in the industry has been unfortunately to mis-apply the multi-porting ability by connecting too many vessels in

series. The vessel manufacturers' publish guidelines for designing multi-port systems to ensure even hydraulic balance and to prevent excessive headloss (3). These guidelines should be carefully followed by the R/O system designer. The most unfortunate applications of the multi-porting options have actually connected stages in series, thus negating the ability to perform cleanings, isolated by stages. The cleaning flows are greatly restricted by the undersized porting, if cleaning connections are provided at all.

This topic of misapplication of multi-porting provides the perfect example of low capital cost versus O & M considerations. The capital cost may be lowered by reducing the amount of stainless manifolding required, but O & M greatly suffers. The energy costs will be higher as a result of excessive headloss through the ports. The maintenance and cleaning frequency will be greater due to hydraulic imbalance and un-even loading. The cleanings will be far less effective, wasting operation and maintenance funds. And lastly, membrane life is likely to be shorter due to uneven hydraulic loading and ineffective cleaning capability.

Membrane Elements

Membrane elements come in countless variations today from numerous manufacturers. The role of the Engineer is to evaluate and narrow down the options suitable for a particular application. Some of the essentials of membrane design to be considered for their impact on the potential O & M costs of a system include square footage, physical configuration, membrane chemistry and replacement cost. Most manufacturers have three main families of spiral-wound, thin film composite membranes commonly applied in municipal systems: membrane softening (also called nanofiltration), brackish reverse osmosis, and seawater. Of course it is obvious where to apply seawater membranes, but the evaluation between membrane softening elements and reverse osmosis elements can be complicated, as described in the first section of this paper. Additionally there is a new major division developing in the brackish membrane area between standard pressure and ultra-low pressure or energy saving. Most manufacturers now offer a low pressure membrane that has a high specific flux at an RO membrane salt rejection of 99.5% plus. It is becoming popular to evaluate hybrid arrays combining standard pressure and low pressure membranes to obtain a well-balanced system that produces precisely the desired water quality.

Another exciting new development in membrane technology is "fouling-resistant" membranes. These types of membranes are available from several manufacturers both in nanofiltration and reverse osmosis salt rejection ranges. They may be considered "fouling-resistant" based on a wide-variety of design modifications. These could be changes in the surface chemistry or charge; or changes in the physical configuration, such as feed/brine carrier geometry or leaf length. Each type is very different and what may be highly successful on one application could be completely ineffective on another. Some may not actually be more resistant to fouling, but may be easier and more effectively cleaned, thus making them longer lasting. Pilot studying is definitely recommended when considering using one of the new fouling-resistant membranes on a large-scale application.

Interstage Boosting

Interstage boosting is taking the concentrate of the first stage and boosting its pressure before applying it to the second stage. This is desirable for two reasons:

1. The first stage concentrate (which becomes the feed to the second stage) is typically about twice as saline as the raw feed water, and thus has a higher osmotic pressure to overcome to produce permeate.
2. The first stage of membrane systems using the new low-pressure RO membranes will tend to over-produce, leading to an uneven hydraulic balance, more operational problems in the first stage, and potentially shortened membrane life.

Interstage boosting, when properly applied can potentially solve both of these problems.

Interstage boosting can be accomplished with a regular motorized pump, or an energy recovery booster can be used.

The motorized booster is typically a small vertical turbine pedestal-type pump. It must be carefully selected to accommodate a high incoming suction pressure. It is generally fairly low horsepower because it is only providing usually less than 50 psi boost pressure.

There are several different types of energy recovery booster available. They were mostly developed for seawater systems and were used as an additional booster at the head of a seawater system. But several have been adapted for interstage boosting of low pressure brackish systems. The energy recovery devices all use the residual pressure of the concentrate to boost the interstage pressure, either through direct hydraulics or through the coupling of a forward and a reverse running turbine. They vary in efficiency and applicability (5). The higher brackish systems (greater than 2000 mg/l TDS) are more suited to energy recovery booster applications than low pressure or nanofiltration systems, because they have more residual concentrate pressure to recover. The energy boosters are much more expensive than a motorized interstage pump, however, the energy savings can yield a quick payback period depending on the individual application. Energy recovery boosters were incorporated in Marco Island, Florida on a very high TDS system (approximately 10,000 mg/l TDS). Prior to installing the interstage boosters the RO feed pumps were at their maximum limits, the membranes were needing to be replaced due to unacceptable permeate quality, the hydraulic balance between the two stages was extremely poor, and the energy costs to produce water were quite high. The boosters enabled the lowering of the feed pressure from about 400 psi to about 300 psi, production was able to be increased as a result of reducing the load on the feed pumps, the hydraulic balance was greatly improved, the overall permeate quality improved, and the Owner was able to obtain three or four more years of life out of the membranes. Overall the Engineer estimated the interstage boosters saved about \$0.08/kgal in energy costs, in addition to the intangible benefits (5).

Motorized boosters can also save energy over-all because they lower the feed pressure required for the first stage. Additionally they provide the hydraulic balance between the two stages that would otherwise have to be obtained through the use of permeate back-pressure which just increases the overall feed pressure required and energy consumption. A pilot study was performed on an Illinois water that proved that even though the motorized booster was another energy consumer, it lowered the total energy consumption for the system while producing a superior water quality. This indicates that interstage boost should even be considered on membrane softening systems, where an energy recovery booster would never be feasible.

Planning and Procurement

In conventional construction projects there are three main parties: the owner, the engineer, and the contractor. In specialized process projects, a specialized system supplier with particular expertise on the process is also usually involved. This party is also called an original equipment manufacturer (OEM). Each of these parties are a necessary and valuable member of the team. The key to obtaining a successful project is organizing the project so that all participants are able to be involved as a valuable element of the team and to be able to contribute in their area of expertise. Alternative procurement methods should be considered to accomplish a successful project that achieves the goal of a cost-effective system designed for long life and low O&M costs. The reasons most often cited for construction difficulties are as follows:

1. Contractors who bid too low
2. Ambiguous contract documents
3. Owner discretionary changes
4. Unrealistic risk taking
5. Failure to deal promptly with changes
6. Poor communication

The latest trend in the effort to reverse this proliferation of problems is called Partnering. Partnering is a thought process wherein the parties of the construction project are encouraged to think of each other as members of the same team, rather than adversaries. Before partnering can really be effective, it is advantageous to set a project up in a manner that will minimize conflict and enhance cooperation and ensure the project is successful. Partnering is basically about building good relationships within the construction project team. As in any relationship, a collective understanding of each party's role lays the groundwork for preventing misunderstandings and developing mutual respect. In construction projects, this understanding can only be ensured by all parties knowing their role in the project. The Owner must be knowledgeable of the desired function of the finished facility, the construction requirements of the project, and the realistic budget and time needed to complete the project. The Engineer must understand the owner's needs and translate them into clear, accurate construction documents. If the project involves special work, as in a desalination facility, the Engineer should be careful to see that the specifications are practical and that they can be met without excessive cost, time delay, or trouble. Unless the Engineer is an expert in the specialized field, it is advisable to make provisions for having a competent sub-consultant review the documents before they are finalized and retain their services throughout the project for shop drawing review and periodic consultation. The contractor, and/or a specialized OEM, bears the obligation of preparing a responsible bid, pointing out conflicts or deficiencies, preferably prior to the bid, if time allows, and constructing the project utilizing the best standards of the industry. The contractor/OEM team is also responsible for dealing with changes fairly, and seeing the project through completion, start-up, training, and remaining accessible throughout the warrantee period and beyond.

Related to the topic of relationships is the issue of trust. Trust is key to all good relationships. Trust is developed over a period of time through open communication and risk taking for the sake of the team and the over-all success of the project. Parties who are aware that their

relationship will be of a short duration are more likely to resist agreement, less likely to communicate freely, or take risks for the benefit of the project. On the other hand, if the parties have had and hope to continue having a long term relationship, cooperation, risk-taking, and honest communication is more likely. The parties may fear that the tables may be turned in the future and they will be endangering future work opportunities. This concept of trust is not only project-specific, it applies to the desalination industry as a whole. The Owner and Engineer will feel more at ease knowing the company responsible for providing their expensive facility is a company that has been involved in the industry for a significant number of years, that has a face or faces they have seen at meetings or conferences numerous times, and will continue to be around to provide service for years to come. If the Engineer spends a great deal of time preparing detailed construction documents to the point that the Engineer and Owner have determined an OEM is not necessary, the thought may be that the Owner will experience over-all project savings by having the complete work constructed by a general contractor under a lower margin than an OEM might command. Obtaining a satisfactory outcome under this arrangement would require intensive oversight and involvement of the Engineer and Owner throughout the project. The Owner is liable to have minimal support after construction completion and during the life of the plant from the general contractor. It is doubtful that much, if any cost savings would be realized, as a general contractor with no desalination experience will be inefficient at detailed fabrication and installation requirements and will not have the long-term relationships with the network of specialty suppliers an experienced OEM will have. Additionally, an experienced OEM will have a knowledgeable technical staff involved during the project, enabling the Owner and Engineer to utilize the resources of their years of experience for the benefit of the project.

Alternative procurement methods should be considered for membrane treatment projects. The types of contracts summarized below may be advantageous for their application to membrane systems.

- Parallel Prime Contractor: Advantages
 - obtain quality work partners (contractor/OEM)
 - OEM has direct communication with owner/engineer
 - each contractor directly accountable to owner
- Parallel Prime Contractor: Disadvantages
 - administration of two contracts
 - careful division of scope is required
 - “finger-pointing” could arise
- Single Prime w/ assigned OEM: Advantages
 - owner and engineer assured of qualified OEM
 - administer only one contract
- Single Prime w/ assigned OEM: Disadvantages
 - communication still goes through GC

- “finger-pointing” could arise with assigned OEM
- Strategic Partnerships: Design/Build
 - involve contractor/OEM in early stages of project
 - long-term involvement encourages team spirit
 - selection process narrowed down to pre-qualified teams

Pre-qualification of OEM

Pre-qualification procedures can be very involved or they can be brief and concise. A complex pre-qualification procedure could involve lengthy technical submittals and interviews with the OEM either at the OEM’s facility or at the owner’s office. At a minimum, a pre-qualification survey should be performed requesting the following information [11]:

- description of company, background, and years of experience in desalination field
- list of installations, including name and address of owner
- any other references the OEM may want to submit
- project descriptions and photographs of installations similar to the project being considered
- resumes for key project personnel
- description of company’s manufacturing facilities, fabrication processes, quality control and testing procedures and installation practices and field services capabilities
- information on major subcontractors the OEM would use

Summary

In conclusion, it is evident the future for desalination technology is bright. It seems almost daily a new report is publicized regarding water supply problems, health concerns or additional water quality regulations. All members of this industry serve to benefit from improving the cost-effective, smooth implementation of high quality projects.

Faced with the perception of RO and NF as costly treatment options, many owners and engineers are inclined to select RO and NF system equipment based on the lowest capital cost. However, this strategy often does not result in the lowest annualized cost. Based on an overall view of the cost to produce water, the single most significant expense over the life of a plant is the operation and maintenance (O&M) cost. Designing, procuring and fabricating membrane treatment plants with this fact in mind will ensure engineers, owners and end users obtain the best value in their membrane treatment systems.

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