POU Reverse Osmosis Performance and Sizing

(Excerpted from WQA's Online Knowledge Base)

Reverse Osmosis Performance Factors

Factors that can affect a reverse osmosis system's performance include temperature, operating pressure, back pressure, the equilibrium effect/TDS creep, percent recovery, and, of course, the RO membrane's permeate production and percent rejection ratings.

Temperature

Water temperature is a major factor in determining the RO production rate because it increases or decreases the viscosity of water. Colder feedwater has higher viscosity (thicker water) and requires more pressure to push it through the membrane. The higher pressure requirement slows down production rate. Warmer water has lower viscosity (thinner water), which requires less pressure to push it through the membrane, increasing the production rate. For predicting a more exact production rate at higher or lower temperatures, refer to a temperature conversion chart from the manufacturer of the particular membrane being used. As an estimate, the permeate flow rate can be expected to increase 3% for every 1 $^{\circ}$C increase in temperature.

Increased temperature also increases the rate of salt passage across the membrane by about 6% for every 1 $^{\circ}$C as a result of the thermodynamic energy increase to the salt diffusion process.

To convert $^{\circ}$C to $^{\circ}$F, use the formula below.

$^{\circ}$C x 1.8 + 32 = $^{\circ}$F

To reduce sources responsible for temperature variance in POU/POE applications, avoid installing the RO system too close to a hot water line; the distance varies depending on whether the system is installed as POU or whole house.

Differential Pressure

The required operating pressure for a reverse osmosis system will be provided by the manufacturer. The actual operating pressure available for a given installation, known as the differential pressure or the net driving pressure, will be the difference between the forward pressure (feedwater pressure) provided by the distribution system and the osmotic pressure. In POU air-on-water applications, the pressurized storage tank will also back pressure, roughly equal to the air pre-charge on the tank.

In some private well applications, the well pump pressure is too low compared to the back pressure and a booster pump may be required. To determine if a booster pump is needed, use the formula below to calculate differential pressure at the membrane.

Differential pressure = Feedwater pressure – (osmotic pressure + storage tank back pressure)

Low differential pressure can negatively affect both water quality and quantity. If the water supply pressure is too low it might not provide the water production rate required for the customer's needs. Also, it might not provide adequate permeate water quality with sufficiently reduced contaminants.

If the pressure is too high the water can bypass the membrane (as bleed-through or channeling around the membrane). A restrictor could be used to correct for this situation.

Generally speaking, the pressure from a municipal source should be sufficient for the RO to operate properly. Pressure in private wells can be problematic.

In some cases, where RO treatment is needed both for a faucet and an application such as an ice maker that requires higher permeate pressure, a delivery pump may be needed to increase pressure in the distribution line to the ice maker.

Osmotic Pressure

Osmotic pressure is related to the natural process of osmosis, where water flows through a semipermeable membrane from the side with a lower concentration of dissolved solids to the side with a higher concentration of dissolved solids. The reverse osmosis process has to overcome osmotic pressure to operate. Osmotic pressure depends on the total dissolved solids in the feed water (the higher the TDS level, the greater pressure required) and is often estimated as 1 psi for every 100 mg/L TDS. While this estimate is not an exact value for all possible combinations of water constituents, it is sufficient for calculations of performance. In critical, health-related or manufacturing applications, RO systems should be pilot tested to ensure proper operation.

Back Pressure

Back pressure is created by the filling of the storage (or "pressure") tank. The RO system's performance depends on the pressure tank's ability to exert pressure on the water stored in the tank to deliver it from the tank to either the faucet or the distribution system. In air-on-water systems, the tank contains a pre-charged air bladder that compresses as water fills the tank. When the air can no longer be compressed, no additional water can enter the tank. The more air that is in the tank, the less water the tank can store.

As the tank fills and the bladder is compressed, a backward pressure is exerted on the RO membrane, reducing the available operating pressure. Once the differential pressure is decreased to the limit corresponding to the shut-off pressure, the auto shut-off mechanism turns off the RO water production.

In some systems, the RO continues to process water but the permeate is sent to waste. WQA strongly recommends that all residential RO systems use a functioning auto shut-off mechanism to reduce wasted water. However, some health-critical applications may be more sensitive to TDS creep, requiring

that the water treatment professional properly evaluate the effects of TDS creep on final storage tank water quality.

Storage tanks have a valve that allows for the air pressure to be set. Typically, pressure is set between 5 and 10 psi (0.34 to 0.68 atm). Several trials may be needed to determine the optimum setting that provides sufficient permeate delivery pressure to the point of use while allowing enough space in the tank to accumulate the appropriate volume of water to meet the customer's usage patterns.

Storage tank back pressure is a key factor when troubleshooting RO performance.

Percent Recovery

Percent recovery is the term used to describe how much water a unit can produce vs. the volume of raw water it's fed. The percent recovery at which a membrane is operated will directly affect the quality and quantity of permeate; as the recovery is increased, so is the TDS concentration of the permeate as it exits the membrane. Thus, increasing the percent recovery decreases the water quality.

Equilibrium Effect/TDS Creep

When the storage tank is full and the feed water is shut off, the diffusion of ions continues through the membrane into the product water. The typical result is a higher TDS concentration when the water is first drawn (e.g., morning use) due to lack of pressure from a system that sat idle. The water quality should improve after 5-10 minutes of use. If the RO is applied for the reduction of health-related contaminants, customers may be counseled to discard the first several glasses of water.

Permeate Production

Permeate production is related to the RO membrane's rating. For example, a 25 gal/day membrane can make about one gallon of purified water per hour, when operated at the same conditions the manufacturer used to rate the system. If the storage tank on that system can hold 3 gallons of water and the end-user needs to draw 4 gallons all at once, the system will be able to supply 3 gallons immediately and will require an additional hour to produce the 4th gallon.

Percent Rejection

If removing TDS or a health-related contaminant, it's important to know how well the RO membrane rejects that contaminant. The percentage of the feed water contaminant concentration that is prevented from passing through the membrane with the permeate is known as the percent rejection, or

% rejection. An RO membrane's % rejection depends on the manufacturer and operating conditions. Most manufacturers will have their own charts with % rejection ratings.

RO Membrane Functionality

To better understand how an RO membrane functions, two equations are useful. These equations describe the transport of water and dissolved minerals from the feed to the permeate side of the membrane.

Water transport through the membrane is a function of differential pressure, and can be stated as follows:

$J_W = K_W(\Delta P - \Delta \pi)$

where:

J_W = rate of water passage through the membrane.

K_W = permeability coefficient for water for a particular membrane, thus area and thickness are included.

P = pressure.

π = osmotic pressure.

Membranes also permit some salt passage. This process is described mathematically as follows:

$J_S = K_S \Delta C$

where:

J_S = rate of salt passage through the membrane.

K_S = permeability coefficient for salt for a particular membrane, thus area and thickness are included.

C = salt concentration.

From this expression salt transport is independent of system differential pressure.

The most important facts to remember about these equations are:

1. Water passage is a function of differential pressure. The rate of water passage through the membrane is dependent on the difference between the pressure applied (feedwater pressure), the osmotic pressure, and the storage tank backpressure. The applied pressure will decrease as pressure in the storage tank increases (and pushes back). This means the water flow will slow down.

2. Salt passage is a function of differential concentration. Salt passage (i.e. % rejection) is dependent on the difference in concentration of the dissolved substances on the different sides of the membrane.

3. Water quality will degrade as the water flow through the membrane slows down ("TDS creep"). "[As stated above,] the rate of salt passage through the membrane is not a function of pressure, whereas the water flow rate is. Therefore, a lower concentration of salts will result on the pure water side of the membrane if higher pressures are utilized on the concentrated solute (dissolved solids) side of the membrane. This is due to the greater dilution of the salt flow by the increased permeate flow rate." (Byrne, W., Reverse Osmosis: A Practical Guide for Industrial Users, 2nd ed., Tall Oaks Publishing, Littleton, CO, 2002, pg. 20.)

Conversely, when the storage tank fills, the tank pressure exerted on the RO system increases, reducing the net driving pressure (another term for differential pressure) and slowing down the rate of water passage. As the rate of water passage slows down, the level of dilution of the salt flow decreases, resulting in higher concentrations of salts on the pure side of the membrane. This phenomenon is called "TDS creep."

TDS creep is the appearance of salt in RO product water which sometimes occurs as a result of the reduction of differential pressure across the membrane as can occur when the RO unit has been shut down for a period of time. Water will cease to permeate through the membrane when there is insufficient differential water pressure across the membrane; however, TDS permeates through the membrane as a function of the TDS concentration difference across the membrane.

Methods for reducing TDS creep are explained in the WQA Online Knowledge Base article, *Reverse Osmosis Systems and Operation*.

RO Membrane Performance: Calculating Percent Rejection

The percent rejection of contaminants can be calculated for an installed RO membrane by comparing the concentrations of a specific contaminant in both the source water and permeate. This calculation can serve as a check of actual performance under the customer's specific conditions.

Here's the generic formula:

% Rejection = (contaminant concentration in feed water - contaminant concentration in permeate) ÷ contaminant concentration in feed water x 100

Be sure to use the same units of measurement, e.g., ppm or mg/L for contaminant concentration in the feed water and in the permeate.

Using % Rejection Estimates to Calculate Concentration of Contaminants in Product Water

If the RO system is being used to address a specific contaminant that may be harmful to the customer's health, then it is useful to estimate to what concentration the system is capable of reducing the contaminant.

The chart below shows the nominal rejection performance of the two most common types of membranes for dozens of contaminants.

DRINKING WATER CONTAMINANTS AND THEIR CONTROL WITH REVERSE OSMOSIS WATER TREATMENT

Nominal Rejection Performance for Reverse Osmosis Membranes at 60 psi Net Pressure and 77°F[1]

Inorganic Contaminant	CTA* Rejection	TFC* Rejection
Sodium	85–90%	90–98%
Calcium	90–95%	93–99%
Magnesium	90–95%	93–99%
Potassium	85–90%	90–98%
Iron[2]	90–95%	93–99%
Manganese[2]	90–95%	93–99%
Aluminum	90–95%	93–99%
Copper	90–95%	93–99%
Nickel	90–95%	93–99%
Zinc	90–95%	93–99%
Strontium	90–95%	93–99%
Cadmium	90–95%	93–99%
Silver	90–95%	93–99%

Inorganic Contaminant (cont.)	CTA* Rejection	TFC* Rejection
Mercury	90–95%	93–99%
Barium	90–95%	93–99%
Chromium	90–95%	93–99%
Lead	90–95%	93–99%
Chloride	85–95%	90–98%
Bicarbonate	85–90%	90–98%
Nitrate3	40–50%	85–95%
Fluoride	85–90%	90–98%
Phosphate	90–95%	93–99%
Chromate	85–90%	90–98%
Cyanide	85–90%	90–98%
Sulfate	90–95%	93–99%
Boron	30–40%	55–80%
Arsenic[3+]	60–70%	70–80%
Arsenic[5+]	85–90%	93–99%
Selenium	90–95%	93–99%
Radioactivity	90–95%	93–99%

Biological & Particulate Contaminants[4]	CTA* Rejection	TFC* Rejection
Bacteria	>99%	>99%
Protozoa	>99%	>99%
Ameobic Cysts	>99%	>99%
Giardia	>99%	>99%
Asbestos	>99%	>99%
Sediment/Turbidity	>99%	>99%

Organic Contaminants	CTA* Rejection	TFC* Rejection
Organic molecules with a molecular weight >300	>90%	>99%

*CTA—Celulosic Membrane

*TFC—Thin Film Composite Membrane

[1]This table of nominal rejection performance is for the two types of membranes used in drinking water systems operating at a net pressure (feed pressure less back pressure and osmotic pressure) of 60 psi and 77°F water temperature. The actual performance of systems incorporating these membranes may be less due to changes in feed pressure, temperature, water chemistry, contaminant level, net pressure on membrane, and individual membrane efficiency. Countertop RO drinking water systems produce better overall rejection performance than undercounter systems due to maximizing of net pressure on membrane.

[2]While iron and manganese are effectively removed by the membrane, they also can easily foul its surface with deposits even at low concentrations. Generally, iron and manganese should be removed by other water treatment methods prior to RO treatment.

[3]Nitrate removal depends on factors such as pH, temperature, net pressure across membrane, and other contaminants present.

[4]While reverse osmosis membranes theoretically remove virtually all known microorganisms, including virus, they cannot offer foolproof protection when incorporated into a consumer drinking water system. Potential seal leaks and manufacturing imperfections may allow some microorganisms to pass into the treated water. Therefore, small home RO drinking water systems should never be used as a primary means of removing biological contamination to make a water supply fit for consumption.

[5]The degree of rejection of organic molecules less than molecular weight (MW) 300 depends on the size and shape of the molecule. Activated carbon is always incorporated along with reverse osmosis to insure complete removal of these lower molecular weight organic contaminants.

Given a feed water analysis and this chart of rejection, you can estimate the concentration of contaminant in the product water.

Here's the formula:

Concentration of contaminant in permeate =

[concentration of contaminant in feed water x 1-(Percent Rejection ÷ 100)]

Note that this provides an estimate of performance. If the RO system is being used to remove contaminants that could negatively impact health, the calculations should be checked by actual analysis of the product water.

Being able to estimate the concentration of a contaminant in the product water using the RO's % rejection rating is useful if an analysis of a private water supply shows concentrations of a regulated contaminant is above the USEPA MCL or the regulated regional level. The calculation provides a way to check if the RO system can sufficiently reduce the concentration (use the % rejection).

Disclaimer for contaminants with health effects: A water analysis from a certified laboratory is strongly recommended before any treatment is specified.

Specifying an RO System

Several factors need to be considerations when selecting a POU reverse osmosis system: the customer's capacity requirement (i.e. water usage), the daily production capacity of the system, and the percent rejection for specific contaminants in the source water.

Calculating Capacity Requirements

Selecting a typical POU RO system requires an estimate of daily water usage (the "capacity requirements"). Knowing the capacity requirements helps you choose an RO membrane with the appropriate production capacity.

Capacity requirements can be calculated based on a number of assumptions. In the United States, the water processing industry uses the following assumptions to standardize the capacity calculation:

- Daily drinking water needs: Each person drinks one gallon (3.8 liters) of water per day
- Daily cooking water needs: Each 4-person household uses a total of two gallons (7.6 liters) of cooking water per day

The resulting formula is:

Total volume per day = [Number of persons in household x 1 gallon (or 3.8 liters) drinking water] + 2 gallons (or 7.6 liters) cooking water

Example:

In a household of four people, the calculation would be:

Total volume per day = [4 people x 1 gallon] + 2 gallons

Total volume per day = 6 gallons (22.8 liters) per day

This standardized calculation also assumes:

- Standard use with no special appliances (i.e. ice maker)

- Soft water

- No chlorine, iron or bacteria

- No more than 500 ppm TDS

- Location under the sink

These assumptions provide a baseline for sizing a 3 or 4-stage under the sink RO system.

Choosing an RO Membrane and Storage Tank

For residential, POU RO systems three options are common, based on the RO membrane rating: 25, 50 and 100 gal/day (95, 190, 379 L/day). The ratings are based on manufacturers' standard testing conditions, which are typically 77 °F (25 °C) and 60 psi. At lower temperatures and line pressures that are typical for private wells production rate will be slower. Production rate decreases approximately 3% for every 1 °C. Refer to manufacturers' specifications for test conditions and factors to determine production rates at the actual operating conditions. Adjusting production rates for operating conditions is especially important for whole-house RO sizing as well as commercial and industrial applications.

A membrane rated at 25 gal/day (95 L/day) produces one gallon (4 L) of drinking water every hour. A membrane rated at 50 gal/day (190 L/day) produces one gallon (4 L) every half hour. A membrane rated at 100 gal/day (379 L/day) produces one gallon (4 L) every 15 minutes.

Standard under sink storage tanks range from 2 to 4 gallons (8 to 15 liters). As the storage tank is emptied, it will refill at the RO membrane's rated production speed. The tank should be matched to the customer's usage patterns to ensure sufficient water volume at peak use, such as during food preparation.

When averaged over 24 hours, each of the three common membrane options more than meets the capacity requirements of a typical four-person household (six gallons per day, or 22.8 Liters). Deciding which membrane to get depends on anticipated usage patterns, which will dictate how quickly the customer needs the storage tank to be refilled after it is emptied. A detailed discussion with the customer is recommended, however, a 50 gal/day (190 L/day) membrane is currently considered a standard choice. Decreasing membrane costs have led to membranes with higher production rates becoming more common.

The capacity requirement calculations become more critical in commercial and industrial applications as improper sizing could result in significant financial losses as processes are put on hold while the storage tank fills. Storage tank sizing also becomes more significant to ensure sufficient water volumes are available to meet peak demand times.

Adjusting for non-standard factors

If an RO system is to be placed into a non-standard setting, adjustments must be made. Non-standard factors include:

- Additional water-using equipment. One must know the type of additional equipment to be fed by the RO system, such as ice machines and ice makers in refrigerators, and the flow rate and pressure demand of each piece of equipment. Inlet pressure requirements for this equipment can often be found in the owner's manual for the appliance. Typical output pressure of an under-the-sink RO system is 10 - 12 psi (0.7 – 0.8 atm). If the appliance pressure requirement is higher, a delivery pump may need to be added. Some appliances require inlet pressure as high as 45 psi (3 atm). Most delivery pumps can pressurize the water up to 60 psi (4 atm). Product water volume may be an additional requirement. If the ice maker runs continuously, a larger storage tank may be needed (e.g. 20 gal/76 L).

- Nonstandard location (e.g., if there's no room under the sink)

- Pressure loss due to friction. At times, the POU RO unit is placed some distance away from the point of use. The distance the water has to travel both horizontally and vertically will impact the final pressure at the point of use. The greater the length of horizontal tubing, the greater the loss of pressure due to friction. If a delivery pump is required it should be placed right after the storage tank.

- Well water source. Due to lower feedwater pressures, well water would likely require a booster pump before the RO system. If the well water is fed into a storage tank and then repressurized, the feedwater pressure after the well water storage tank may be sufficient.

- Inlet water quality. Inlet water quality affects pressure. When TDS concentration is high, the osmotic pressure increases, resulting in a smaller operating pressure available to the RO. Membranes rated for higher production rates operate at lower pressures. A 100 gal/day (379 L/day) or higher rated membrane might be used to compensate for the lower available pressure.

Additional information on application of reverse osmosis for POE/POU treatment is available in the WQA Online Knowledge Base.