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# MEMBRANE TECHNOLOGIES FOR

# USE ON PRODUCED WATER

by

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for

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# INTRODUCTION

Produced water, the water brought to the surface with oil or gas, contains chemical contaminants from the formation, the hydrocarbon product, injection water, and chemicals added during the production and treatment processes. These contaminants include suspended solids, oils, as well as other organic compounds, salts, and possibly naturally occurring radioactive materials.

The specific kinds and concentrations vary considerably from one location to another, and even within a formation.

Produced water is by far the largest volume byproduct associated with oil and gas exploration. 15 to 20 billion barrels (630 to 840 billion gallons) of produced water are generated annually in the U.S.

# BACKGROUND

In order to address treatment technologies, it is essential to understand the nature of produced water contaminants, which can be categorized into five classes as follows:

**Water Contaminants**

| Class | Examples |
|-------|----------|
| Suspended solids | Dirt, clay, colloidal materials, silt, dust, insoluble metal oxides and hydroxides |
| Dissolved organics | Hydrocarbons (emulsified and/or dissolved), synthetic organic chemicals, humic acids, fulvic acids |
| Dissolved ionics (salts) | Sodium chloride, heavy metals, silica, arsenic, nitrate, chloride, carbonates |
| Microorganisms | Bacteria, viruses, protozoan cysts, fungi, algae, molds, yeast cells |
| Gases | Hydrogen sulfide, methane, sulfur dioxide, carbon dioxide, natural gas |

Because of the extremely high concentration of hydrocarbons in produced water, they deserve special mention.  Also, they can exist as free oils or emulsified oils.  In addition, chemical additives used in drilling and production may also be in the water, including:

- o Corrosion inhibitors
- o Scale inhibitors
- o Biocides
- o Emulsion breakers
- o Coagulants and flocculants
- o Others

A plethora of choices is available for removal of oily waste, as listed below:

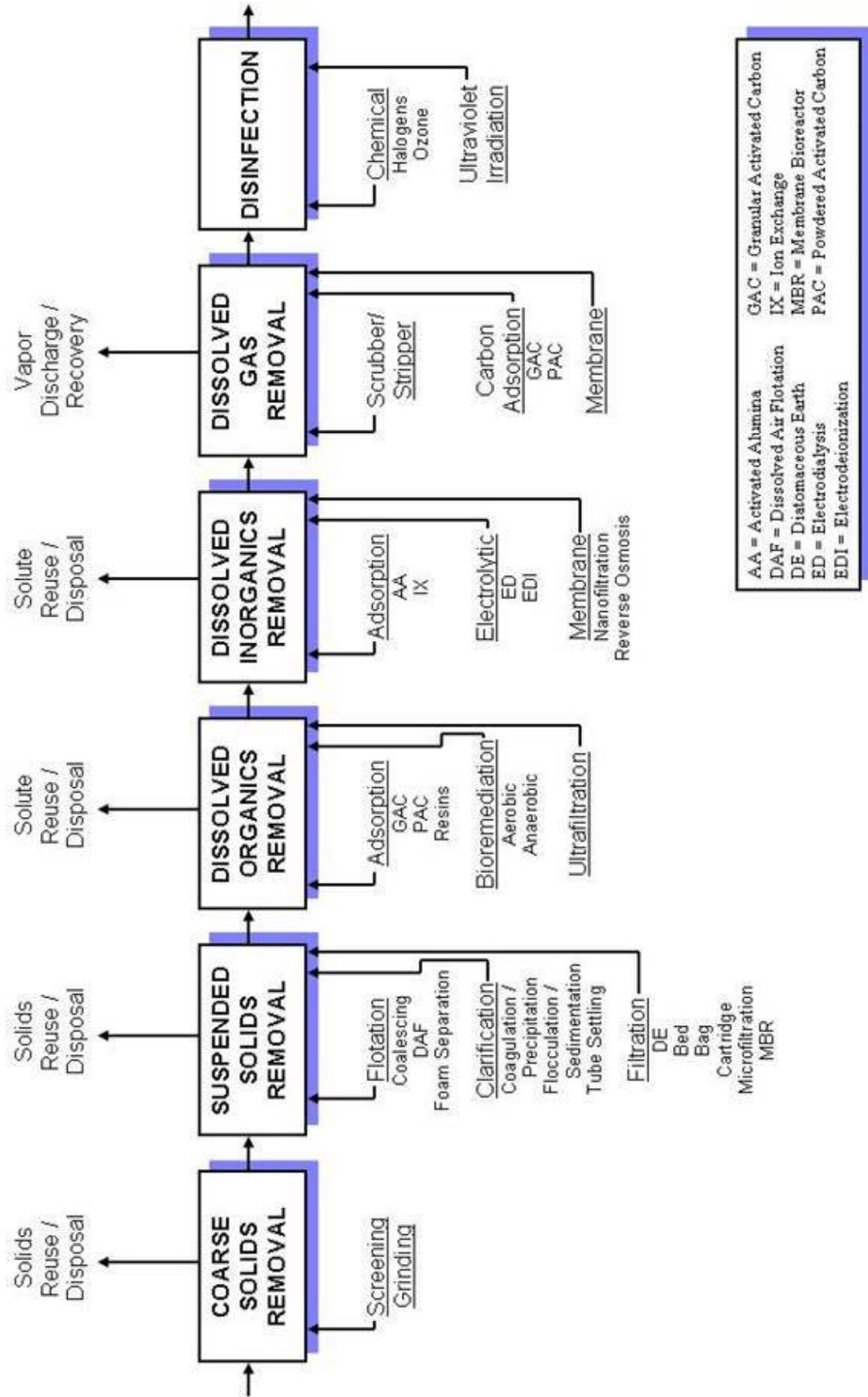**Primary Oil / Water Separation Technologies**

| Separator Type | Technology | Oil Droplet Size Removal (microns) |
|---|---|---|
| API Separator | Gravity | >150 µm |
| CPI / TP Separator | Gravity with Coalescer | >50 µm |
| DGF / IGF Gas Flotation | Gas Flotation | >20 µm |
| De-Oiling Hydrocyclones | Centrifugal Force | >10 µm |
| Coalescing Media Filtration | Adsorption | >2 µm |
| Adsorption Media Filtration | Adsorption | <2 µm |
| Microfiltration Technology | Barrier | <1 µm (emulsified oil) |
| Ultrafiltration Technology | Barrier | soluble oil |

## TREATMENT TECHNOLOGIES

The arsenal of treatment technologies available today for industrial wastewater treatment is extensive, and some may be appropriate for treatment of produced water to allow reinjection or reuse in other applications.

These technologies are summarized in the illustration below:

# INDUSTRIAL WASTEWATER TREATMENT

**COARSE SOLIDS REMOVAL**
- Solids Reuse / Disposal
- Screening
- Grinding

**SUSPENDED SOLIDS REMOVAL**
- Solids Reuse / Disposal
- Flotation
  - Coalescing
  - DAF
  - Foam Separation
- Clarification
  - Coagulation / Precipitation
  - Flocculation / Sedimentation
  - Tube Settling
- Filtration
  - DE
  - Bed
  - Bag
  - Cartridge
  - Microfiltration
  - MBR

**DISSOLVED ORGANICS REMOVAL**
- Solute Reuse / Disposal
- Adsorption
  - GAC
  - PAC
  - Resins
- Bioremediation
  - Aerobic
  - Anaerobic
- Ultrafiltration

**DISSOLVED INORGANICS REMOVAL**
- Solute Reuse / Disposal
- Adsorption
  - AA
  - IX
- Electrolytic
  - ED
  - EDI
- Membrane
  - Nanofiltration
  - Reverse Osmosis

**DISSOLVED GAS REMOVAL**
- Vapor Discharge / Recovery
- Scrubber / Stripper
- Carbon Adsorption
  - GAC
  - PAC
- Membrane

**DISINFECTION**
- Chemical
  - Halogens
  - Ozone
- Ultraviolet Irradiation

AA = Activated Alumina
DAF = Dissolved Air Flotation
DE = Diatomaceous Earth
ED = Electrodialysis
EDI = Electrodeionization

GAC = Granular Activated Carbon
IX = Ion Exchange
MBR = Membrane Bioreactor
PAC = Powdered Activated Carbon

membrane surface, and because the system is pressurized, water is forced through the membrane and becomes "permeate".  The relatively high flow rate of the bulk solution across the surface minimizes the accumulation of particulate matter on the surface and facilitates continuous operation of the system.  Conventional and Crossflow filtration are illustrated below.
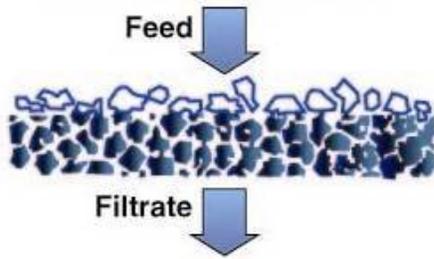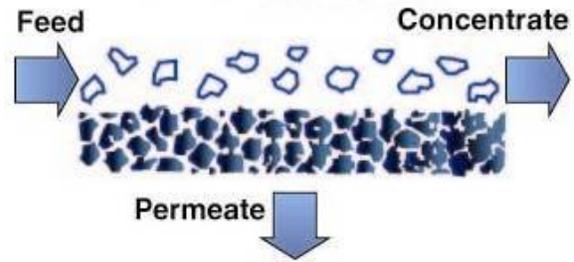


**Conventional vs. Crossflow Filtration**

*Microfiltration (MF)* is utilized to remove submicron suspended materials on a continuous bases. Generally, microfiltration involves the removal of particulate, or, suspended materials ranging in size from approximately 0.01 to 1 microns (100 to 10,000 angstroms). By definition, microfiltration does not remove dissolved materials. Microfiltration is illustrated below.
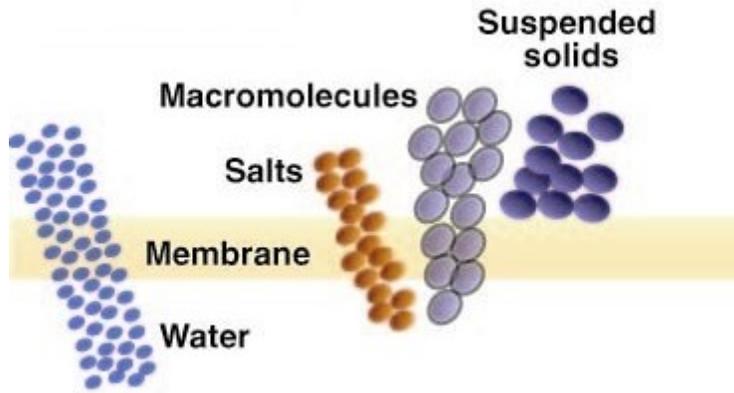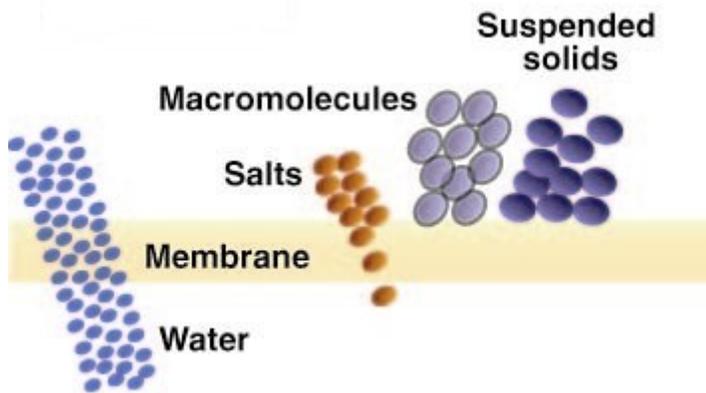


**Microfiltration**

*Ultrafiltration (UF)* is used to separate dissolved, non-ionic materials typically smaller than 0.01 micron (100 angstroms). The removal characteristics of UF membranes can be described in terms of "molecular weight cutoff" (MWCO), the maximum molecular weight of compounds that will pass through the membrane pores. MWCO terminology is expressed in Daltons. Basically, ultrafiltration is used to remove dissolved organic contaminants, while suspended solids are removed by microfiltration. Ultrafiltration technology is illustrated below.
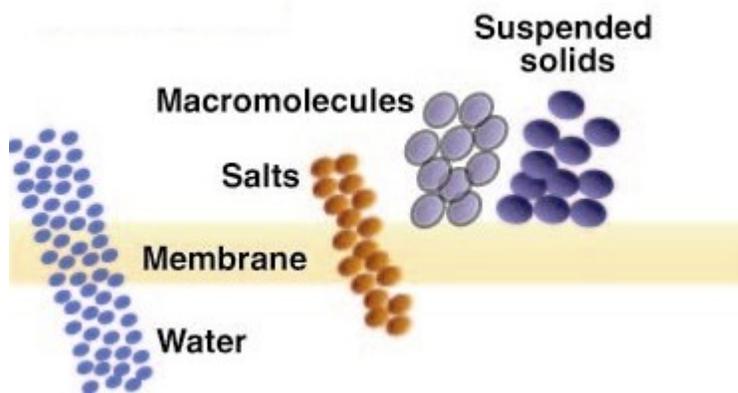


**Ultrafiltration**

*Nanofiltration (NF)*   This is an intermediate process between ultrafiltration and reverse osmosis. The molecular weight cut-off (MWCO) properties of nanofiltration membranes are in the range of 400 to 800 Daltons (<10 angstroms).  Ionic rejections vary based on the valence of the salts; multivalent salts such as magnesium sulfate ($MgSO_4$) are rejected as much as 99%, while monovalent salts such as sodium chloride (NaCl) may have rejections as low as 10%. Nanofiltration is depicted below.



**Nanofiltration**

*Reverse Osmosis* is best understood by first defining the phenomenon of osmosis, the natural passage of water through a semipermeable membrane from a water supply of low salts concentration (high energy) to a region of high salts concentration (low energy).  By applying pressure to the high salts concentration side and overcoming the natural osmotic pressure ($\pi$), water is forced back through the membrane.  This is reverse osmosis.  Illustrations of osmosis and reverse osmosis follow.

This process will remove almost all dissolved organic (non-ionic) solids with molecular weights above approximately 100 Daltons, as well as a high percentage of ionic materials.  Because reverse osmosis membranes are not perfect (they will typically remove 95-99% of the ionic contaminants), for high purity water production, they are usually used as pretreatment to a final "polishing" resin deionization or electrodeionization step.
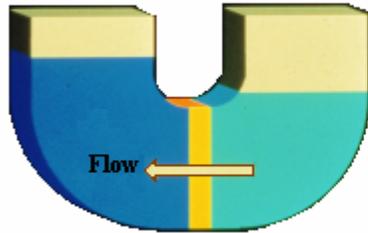
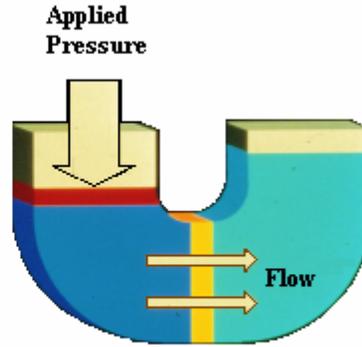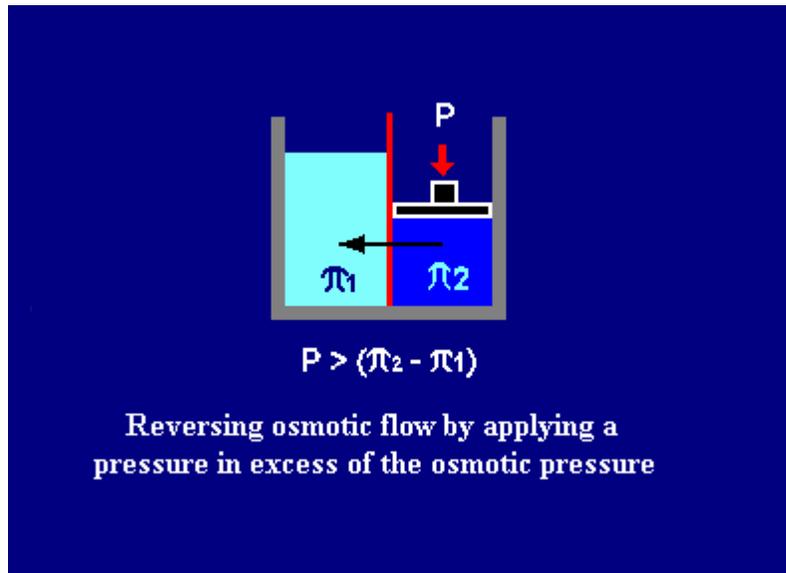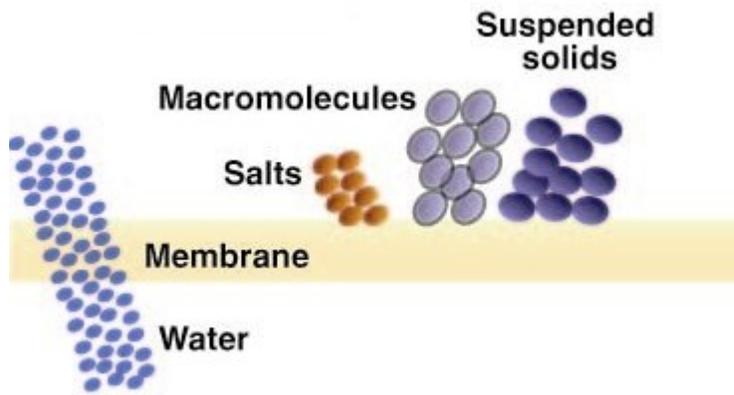**Reverse Osmosis**



**Reverse Osmosis**

**Reverse Osmosis**

In particular, membrane technologies possess certain advantages that make them unique when compared to other solid/liquid separation operations. These include:

► Continuous process, resulting in automatic and uninterrupted operation
► Low energy utilization involving neither phase nor temperature changes
► Modular design – no significant size limitations
► Minimal moving parts with low maintenance requirements
► No effect on form or chemistry of contaminants
► Discrete membrane barrier to ensure physical separation of contaminants
► No chemical addition requirements to effect separation

The following summarizes the various properties and other features of membrane technologies.

## Membrane Technologies Comparison Chart

| Feature | Microfiltration | Ultrafiltration | Nanofiltration | Reverse Osmosis |
|---|---|---|---|---|
| Polymers | Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride, Polytetrafluoroethyliene | Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride | Thin film composites, Cellulosics | Thin film composites, Cellulosics |
| Pore Size Range (microns) | 0.1 - 1.0 | 0.001 - 0.1 | 0.0001 - 0.001 | <0.0001 |
| Molecular Weight Cutoff Range (Daltons) | >100,000 | 1,000 - 100,000 | 300 - 1,000 | 50 - 300 |
| Operating Pressure Range | <30 | 20 - 100 | 50 - 300 | 225 - 1,000 |
| Suspended Solids Removal | Yes | Yes | Yes | Yes |
| Dissolved Organics Removal | None | Yes | Yes | Yes |
| Dissolved Inorganics Removal | None | None | 20-95% | 95-99+% |
| Microorganism Removal | Protozoan cysts, algae, bacteria* | Protozoan cysts, algae, bacteria*, viruses | All* | All* |
| Osmotic Pressure Effects | None | Slight | Moderate | High |
| Concentration Capabilities | High | High | Moderate | Moderate |
| Permeate Purity (overall) | Low | Moderate | Moderate-high | High |
| Energy Usage | Low | Low | Low-moderate | Moderate |
| Membrane Stability | High | High | Moderate | Moderate |

*Under certain conditions, bacteria may grow through the membrane.*

*Membrane Device Configurations*

In an effort to package the membrane as economically as possible and minimize fouling, a number of membrane device configurations have been developed over the years. The devices (elements or modules) in common use today are as follows and are illustrated below:

- Plate and Frame
- Tubular
- Hollow (Capillary) Fiber
- Spiral Wound
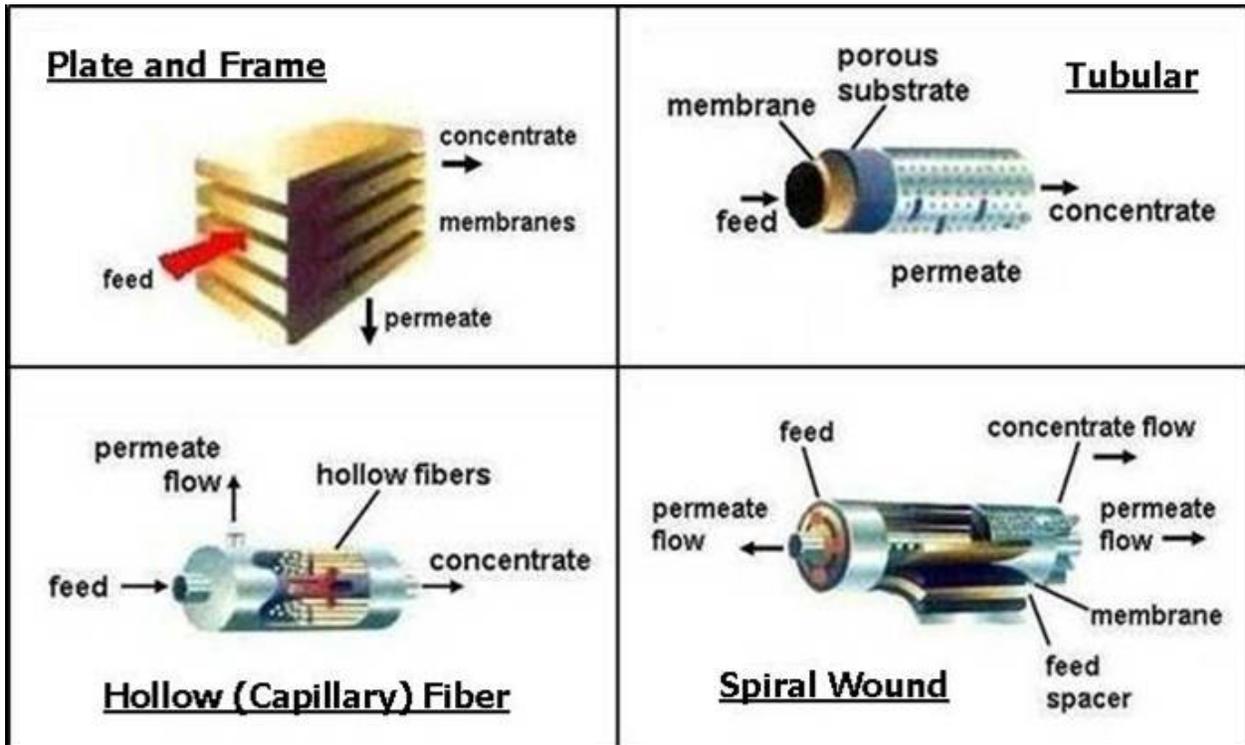


**Membrane Device Configurations**

From the perspective of cost and convenience, it is beneficial to pack as much membrane area into as small a volume as possible. This is known as "packing density". The greater the packing density, the greater the membrane area enclosed in a certain sized device, and generally the lower its cost. The downside of the high packing density membrane elements is their greater propensity for fouling. The following table compares the element configurations with regard to their packing densities and fouling resistance.
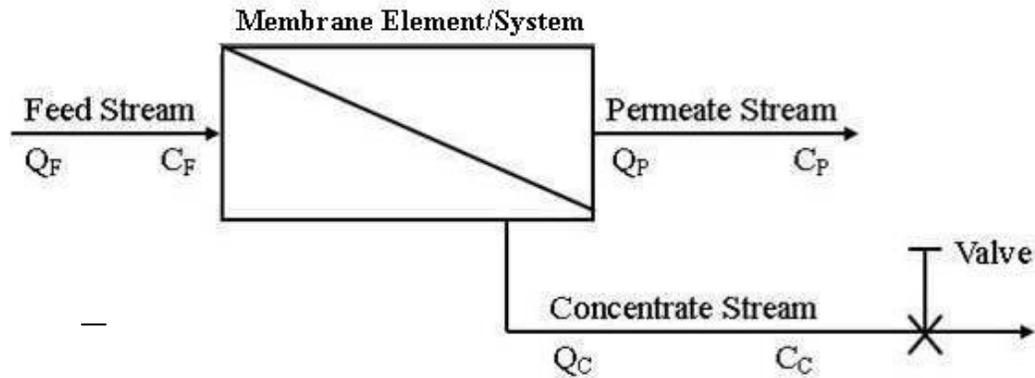
**Membrane Element Configuration Comparison.**

| Element Configuration | Packing Density * | Fouling Resistance ** |
|---|---|---|
| Plate & Frame | Low | High |
| Hollow (Capillary) Fiber | Medium | High |
| Tubular | Low | High |
| Spiral Wound | Medium | Moderate |

*Membrane area per unit volume of element*
*** Tolerance to suspended solids*

A complete membrane processing system is illustrated below. In terms of function, it could also represent a single membrane element.

**Membrane Element/System**

Feed Stream $Q_F$ $C_F$

Permeate Stream $Q_P$ $C_P$

Valve

Concentrate Stream $Q_C$ $C_C$

$Q_F$ - Feed Flow Rate
$C_F$ - Solute Concentration in Feed
$Q_P$ - Permeate Flow Rate
$C_P$ - Solute Concentration in Permeate
$Q_C$ - Concentrate Flow Rate
$C_C$ - Solute Concentration in Concentrate

$$Recovery = \frac{Q_P}{Q_F} \times 100$$

(Expressed as Percent)

TDS = Total Dissolved Solids: Usually considered the total of the ionic contaminants (salts) in solution.

mg/L (milligrams per liter) is the same as ppm (parts per million)

**Membrane System Schematic**

Note that the "feed" stream enters the system (or membrane element), and as the stream passes along and parallel to the surface of the membrane under pressure, a percentage of the water is forced through the membrane polymer producing the "permeate" stream. Contaminants are prevented from passing through the membrane based on the polymer characteristics. This contaminant-laden stream exits the membrane system (or element) as the "concentrate" stream, also known as the "brine" or "reject".

Several important parameters related to membrane technologies are described below.
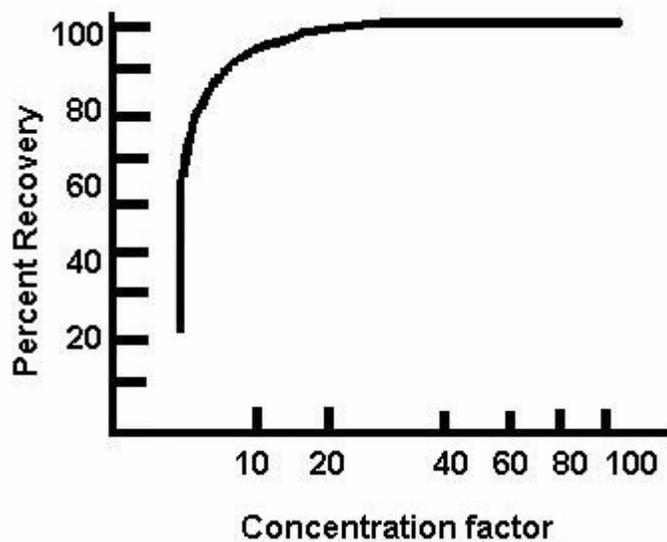
*Recovery*

The percentage of feed flow that passes through the membrane and becomes permeate is known as "recovery" as defined in the previous illustration.  As recovery is increased (to decrease the concentrate volume), the concentration of contaminants in the concentrate stream increases significantly.  This effect is summarized in the table below, and the following graph.

**Effect of Recovery on Concentration**

$$C_c \approx \frac{C_F}{1 - Recovery} = XC_F$$

$$X = \frac{1}{1 - Recovery} = \text{Concentration Factor}$$

| Percent Recovery | Concentration Factor |
|---|---|
| 33% | 1.5 |
| 50% | 2 |
| 67% | 3 |
| 75% | 4 |
| 80% | 5 |
| 90% | 10 |
| 95% | 20 |
| 97.5% | 40 |
| 98% | 50 |
| 99% | 100 |

**Graphic Representation**

The advantage of operating systems at high recoveries is that the volume of concentrate is small and the flow rate of the feed pump is smaller. The potential disadvantages are numerous:

- Higher concentration of contaminants can result in precipitation and greater propensity for fouling.
- In nanofiltration and reverse osmosis applications, the concentrated salts will result in higher osmotic pressure, requiring a higher pressure pump and a more pressure resistant system.
- As higher recoveries reduce the quantity of concentrate to be discharged, the higher concentration of this concentrate stream can itself present discharge problems.

In an ideal RO/NF system, all of the ionic contaminants to be removed are separated by the membrane and exit in the concentrate stream. But in reality, no membrane is perfect in that it rejects 100% of the solute on the feed side; this solute leakage is known as "passage". Expressed as "percent passage", the actual quantity of solute which passes through the membrane is a function of the concentration of solute on the feed side. With reverse osmosis and nanofiltration, the concentration of salts on the feed side is increased, and therefore, the actual quantity of salts passing through the membrane also increases. Many applications demand that, in addition to a minimum concentrate volume, the permeate quality be high enough for reuse. The "catch 22" predicament of permeate quality decreasing as recovery is increased can impose design limitations. Additionally, the increased osmotic pressure resulting as recovery is increased also imposes a design limit. Generally, pumping pressures in excess of 1000psi (68 bar) are impractical for most applications.

*Rejection*

Suspended solids, microorganisms and dissolved organic contaminants are effectively removed by the "sieving" process; that is, contaminants too large to pass through the membrane pores remain in what becomes the concentrate stream.  For dissolved inorganic ("ionic") contaminant removal, the membrane technologies of nanofiltration and reverse osmosis must be employed, and since the pores of the membranes, although smaller than those of the microfiltration and ultrafiltration membranes, are not small enough to physically sieve out these contaminants, a different mechanism applies here.  There is lack of agreement among the experts as to the exact mechanism of this rejection (and even as to whether pores actually exist in these membranes); however, it is known that multivalent salts are rejected to a higher degree than monovalent salts. This characteristic is exploited with nanofiltration membranes which exhibit overall lower salts rejection than reverse osmosis membranes, but remove multivalent salts to a much higher degree than monovalent salts.  These membranes are also known as "softening" membranes because of their ability to remove the divalent hardness ions of calcium and magnesium, with little effect on monovalent ions such as sodium. The "thin film composite" reverse osmosis polymers now on the market have such high salts rejection characteristics that both monovalent and multivalent salts are rejected to almost the same degree.

Following is the simple calculation to determine the salts rejection of an RO or NF membrane:

$$\text{Percent rejection} = \frac{\text{Feed conductivity - permeate conductivity}}{\text{Feed conductivity}} \times 100$$

*Flux*

"Flux " is a fundamental characteristic of all membranes, defined as the permeate rate through a given area of membrane at a specific temperature and pressure.  "Specific flux" is normally expressed as gallons per square foot per day per psi or liters per square meter per hour per bar.

*Osmotic Pressure*

For the process of nanofiltration and reverse osmosis (and to a lesser extent, ultrafiltration), which deal with dissolved salts or polar organics, a property of the solution known as "osmotic pressure" usually becomes the limiting factor in system design. Osmotic pressure is a characteristic of all ionic solutions, and is loosely defined as the resistance of the solvent portion of the solution to passage through the membrane.  The higher the osmotic pressure, the more pressure required to pump water through the membrane.

Osmotic pressure is a function of both the particular solute and its concentration.  A specific test is almost always required to accurately determine osmotic pressure.

As recovery is increased (typically through the use of a flow restrictor or concentrate valve), with the resulting decrease in concentrate flow, the concentration of solute in the concentrate stream increases, resulting in increased osmotic pressure, as described previously.

As a rule of thumb, only dissolved salts (ionic solute) have any significant osmotic pressure, and for estimating, the following can be used:

| Ionic Valence (charge) | $\Delta\pi$/100 ppm Solute |
|---|---|
| Single | 1 psi |
| Multiple | ½ psi |

Examples of salts with single valence (monovalent) are $Na^+$, $Cl^-$, $K^+$, $HCO_3^-$. Salts with multiple valences include $Ca^{2+}$, $SO_4^{2-}$ and $Al^{3+}$.

The following table illustrates osmotic pressures for a number of solutes.

**Typical Osmotic Pressures at 25°C ($\Delta\pi$)**

| Compound | Concentration (mg/L) | Osmotic Pressure (psi) |
|---|---|---|
| NaCl | 35,000 | 398 |
| NaCl | 1,000 | 11.4 |
| $Na_2CO_3$ | 1,000 | 12.8 |
| $Na_2SO_4$ | 1,000 | 6 |
| $MgSO_4$ | 1,000 | 3.6 |
| $CaCl_2$ | 1,000 | 9.7 |
| Sucrose | 1,000 | 1.05 |
| Dextrose | 1,000 | 2.0 |

*Fouling*

Below is a conceptual illustration of an RO membrane process in action. This shows the movement of water through the membrane, and the contaminants typically encountered at the membrane surface.



*Source: WQA RO Manual*
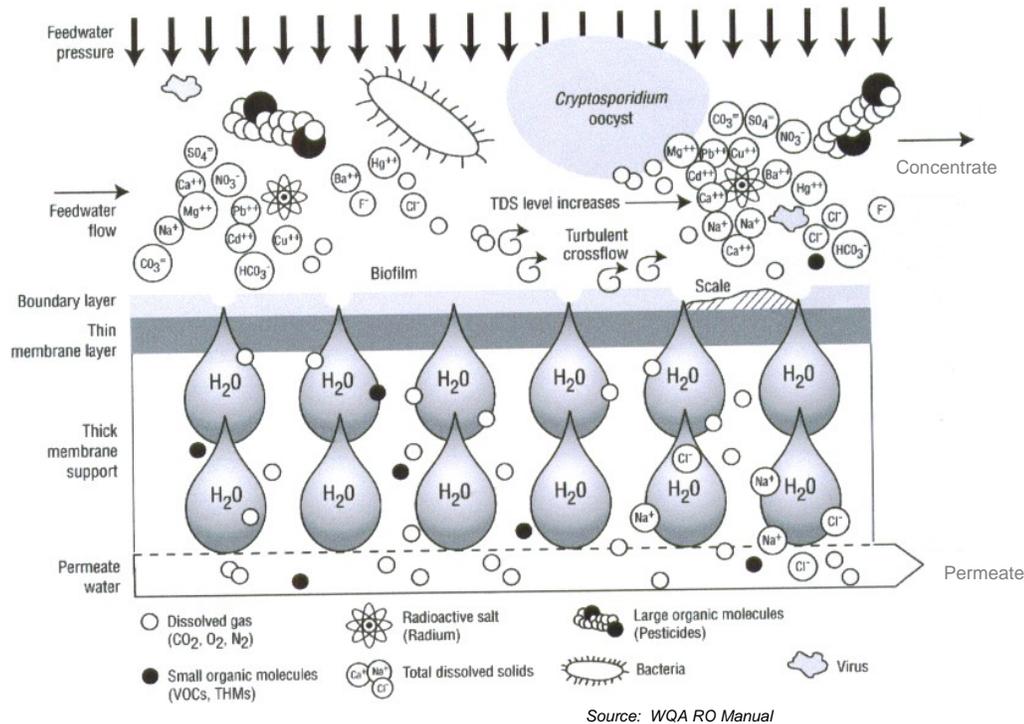
**Cross section of an RO membrane in operation** (not to scale)

Because they all rely on the passage of water through a semi-permeable membrane to effect separation, the membrane surface is subjected to the accumulation of suspended solids or solute – the material intended to be separated or concentrated from the feed stream.

This phenomenon, known as "fouling," is linked to four causes:

1. Plugging - Resulting from particulate material (dirt, sand, etc.) accumulation on the membrane surface.

2. Scaling - As certain dissolved inorganic compounds become more concentrated during processing (usually limited to NF and RO), they exceed their solubility limits and precipitate on the membrane surface (examples include $CaCO_3$, $CaSO_4$, $BaSO_4$).

3. Organic Fouling - Some organic molecules (oils, greases, humic/fulvic acids, surfactants), either naturally occurring or synthetic, coat and plug the membrane pores.

4. Microorganisms - Bacteria, in particular, present a significant fouling problem. As they grow and multiply, they normally produce biofilm, organic films of lypopolysaccharides, to encase and protect the bacteria. These biofilms can cover the membrane surface, resulting in fouling.

The vast majority of membrane element device and system failures occur as the result of membrane fouling.

These mechanisms cause the membrane surface to become coated with fouling materials that build up in layers. As the layer thickness increases, the flow rate across the membrane surface and immediately adjacent to it decreases, thereby encouraging more settling of suspended solids and increasing the fouling layer thickness – a vicious circle.

Membrane fouling cannot be <u>prevented</u>, but can be <u>minimized</u>. The table below summarizes the fouling mechanisms.

## Fouling Summary

| Foulant | Primary Mechanism | Examples |
|---------|-------------------|----------|
| Suspended solids | Insufficient prefiltration | Dirt, clay silt, dust, hydrous metal oxides *e.g.Fe(OH)$_3$* |
| Inorganic salts (scaling) | Concentration effects, Precipitation | $CaCO_3$, $MgCO_3$, $BaSO_4$, $CaSO_4$, $SiO_2$, and other insoluble salts |
| Organics | Adsorption on membrane surface | Oils, grease, surfactants, coagulants, antiscalants, humic and fulvic acids |
| Microorganisms (biofouling) | Adhesion, Adsorption | Bacteria, viruses, protozoan cysts, fungi, algae, molds, yeast cells |

Fortunately, there are a number of approaches available to the system designer and operator which help to minimize the frequency and degree of fouling.

> ► Pretreatment
> ► System Design
> ► Membrane Polymer
> ► Membrane Device Configuration
> ► Chemical Addition
> ► System Operation

## MBR

*Introduction*

A new membrane application deserves special mention, membrane bioreactor (MBR) technology. MBR is particularly unique because it combines one of the newest technologies, pressure-driven membrane separation, with the oldest wastewater treatment technology, biological degradation (bioremediation), the use of naturally occurring bacteria to break down biological and chemical contaminants.

For example, virtually all municipal wastewater treatment plants take advantage of naturally occurring bacteria that break down sewage as part of their normal metabolic activity.

In addition, wastewater from food processing plants, rendering plants, etc., which typically are high in BOD (biochemical oxygen demand) are treated with bioremediation.

There are two distinct biodegradation processes in use today:

> Aerobic
> Anaerobic

Aerobic utilizes air to encourage the activity of aerobic bacteria, whereas, the anaerobic process uses bacteria which only thrive in the absence of air.

In general, the contaminants that are broken down as a result of biodegradation are classified as BOD, or COD (chemical oxygen demand), organic compounds that constitute the food for the bacteria.

The key to effective and efficient biodegradation processes is the creation and maintenance of a healthy population of thriving bacteria, known as the biomass. Typically, the biomass is either suspended in the wastewater in what is called a suspended-growth environment, or attached to a surface, know as fixed-film.

Within the suspended growth category, there are a number of design options including:

- Defused aeration
- Jet aeration
- Surface aeration

Under the fixed-film category, design options include:

- Trickling filters
- Rotating biological contractors
- Submerged biological contractors

MBR involves the utilization of either an MF or UF membrane to treat the water in a bioremediation tank to continuously remove TSS (total suspended solids), BOD, COD and coliform bacteria. This treated water then can be used in many non-critical applications, or can be sent directly to a RO unit for "polishing."

This is another example of the application of membrane technology (MF/UF) as potential pretreatment to membrane technology (NF/RO).

*Benefits*

Compared to other biological processes, MBR offers the following advantages:
- ♦ High-quality effluent, almost free from suspended solids
- ♦ The ability to partially disinfect without the need for chemicals
- ♦ Complete independent control of HRT (Hydraulic Retention Time) and SRT (Sludge Retention Time)
- ♦ Reduced sludge production
- ♦ Process intensification through high biomass concentrations with MLSS (Mixed Liquor Suspended Solids) up to at least 15,000 mg/L
- ♦ Treatment of recalcitrant organic fractions and improved stability of processes such as nitrification
- ♦ Ability to treat high strength wastes

*Device Configurations*

Although all four membrane device configurations (plate and frame, hollow fiber, tubular and spiral wound) are used, the most widely used today are plate and frame and hollow fiber. Each manufacturer has its own proprietary designs.

*System Design*

As the most common biological treatment is aerobic, typically, air is bubbled into the treatment tank. A very popular MBR approach is to immerse the membrane element in the treatment tank and either allow the hydrostatic head of the solution to provide the driving force or to use a pump to pull the permeate through the membrane (or both). In this case, air bubbles are also directed over the surface of the membrane (air scouring) to reduce fouling. Another design involves pumping water through the membrane system external to the treatment tank, and yet another uses a separate tank for membrane processing downstream of the biological treatment tank. Additional designs and configurations are sure to appear as MBR technology becomes more widely used. The following figures illustrate aerobic MBR applications for both "immersed" and "external" designs.



**Immersed MBR**

**Concentrate**

**Feed**

**Air**

**Diffuser**

**Pump**

**Membrane**

**Permeate**
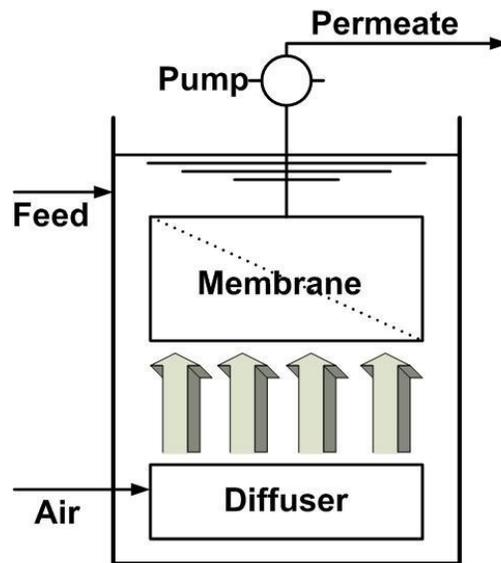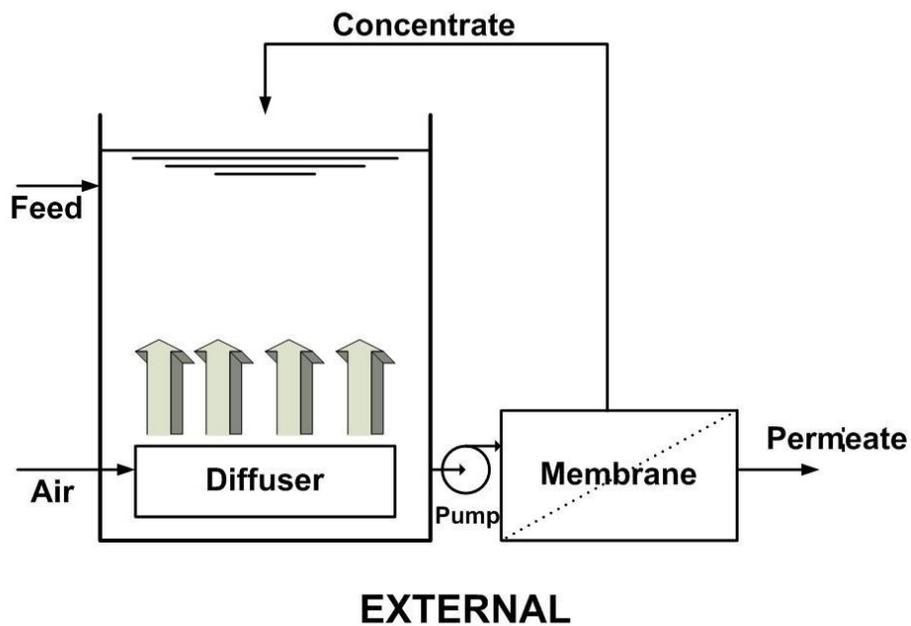
## EXTERNAL

**External MBR**

## WASTEWATER MEMBRANE TESTING

In general, every stream must be tested to develop the following design factors:

- Optimum membrane element configuration
- Total membrane area
- Specific membrane polymer
- Optimum pressure
- Maximum system recovery
- Flow conditions
- Membrane element array
- Pretreatment requirements

The chemical composition of the feedwater can affect the membrane element in a number of ways. The polymer itself (or components of the membrane element) can be degraded by certain chemicals. For example, cellulosic membrane polymers are subject to hydrolysis by high pH, thin film composite polymers are degraded by oxidizing agents such as chlorine, and most of the polymers are affected by chlorinated hydrocarbon solvents in concentrations above 5%. Water chemistry can also contribute to fouling problems – the bane of all membrane systems. Certainly, suspended solids of any kind represent a potential problem, and the configuration of the membrane element plays a major role in its ability to resist fouling.

The most significant feedwater parameters are:
    Total solids content
    Suspended (TSS)
    Dissolved organic (TOC, MBAS, COD, BOD)
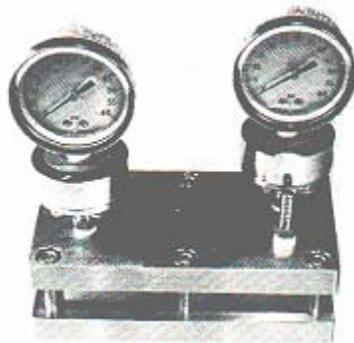    Dissolved inorganic (TDS)

Chemicals of concern include:
    Oxidizing chemicals
    Organic solvents
    Saturated solutes

Other factors include:
    pH
    Operating temperature
    Osmotic pressure as a function of system recovery
    Variation in chemistry as a function of time

To generate the necessary design data, several testing options are available.

**Cell Testing**



**Cell Test Unit**

Cell test devices are available for purchase (or through a consulting engineering firm skilled in the art), which evaluate small sheets of membranes on the stream to be processed. Typically, the sheet is placed between two stainless steel plates, and the test stream pumped across the membrane surface at a selected pressure and flow rate. The permeate is collected and analyzed for degree of separation, possible effect of the stream on the test membrane, and other properties.

The cell test offers a number of *advantages*:

- ✓ Only small areas of membranes are needed; excellent for screening membrane polymer candidates.
- ✓ Can be run on small volumes of test stream.
- ✓ Takes very little time.
- ✓ Unit is simple to operate.

The *disadvantages* of this testing approach are:

- ✓ Cannot obtain engineering design data.
- ✓ Cannot be used for long-term fouling study.
- ✓ Is only useful with membranes available as flat sheet.

The cell test approach is useful as an initial step, primarily to select one or more membrane candidates for further evaluation.

## Applications Testing

An applications test schematic is depicted below.
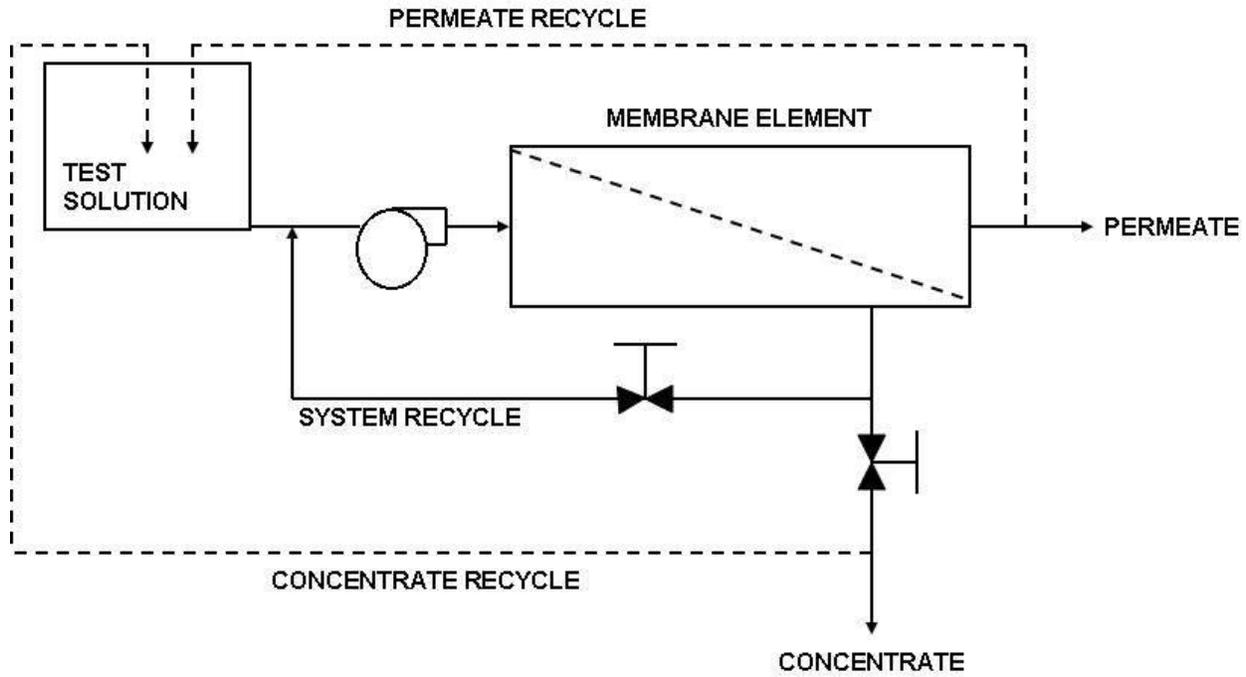


**Applications Test Schematic**

Applications testing utilizes a membrane element in a test unit capable of operating similar to a production unit. Since the data from this testing will be used to scale up the design to full size, it is essential that the membrane element manufacturer supplies an element capable of this scale up.

The applications test equipment should be designed so that very high recoveries can be achieved without compromising the flow rates required to produce turbulent flow, for example. This requires that the pump be capable of not only producing the desired pressure, but also the flow rate to accomplish the minimum crossflow velocity across the membrane surface.

Because the system must be capable of testing at very high recoveries, the concentrate valving must be adjustable to accurately produce extremely low flow rates. This typically involves the assembly of a "valve nest" using micrometer valves. Additionally, the recycle line should be equipped with a diaphragm valve for adjustment of flow and pressure.

The most important feature for application testing equipment is versatility. Different membrane elements have very specific operating parameters, and the equipment must accommodate these.

To cover the entire gamut of membrane technologies, two different pieces of application testing equipment are generally required: one for MF and UF, and the other for NF and RO.

The latter must be capable of pressures up to 1,000 psi (68 bar), and it is virtually impossible to find a single pump capable of supplying the flows and pressures required for all four technologies. For MF and UF applications, a variable speed drive centrifugal pump works fine, although the variable speed feature makes it expensive.

Materials of construction are an important consideration in testing considerations: 316L stainless steel is essential for applications requiring pressures in excess of 60 psi (4 bar); below that, schedule 80 PVC is sufficient. In those applications involving high chloride feedwaters, hastalloy or other chloride resistant alloys are required.

Applications testing is capable of generating complete design data for the full sized system. An applications test can be run on as little as 50 gallons (200L) of test stream, and after setup, can be completed in one hour or less, for each membrane element tested.

A typical applications test is run as follows:

1. To establish "control conditions", high quality water (tap water or water treated with RO or DI) is run into the system at low recovery to minimize any possible contaminant concentration effects, and data recorded.

2. Feedwater is then run into the unit set at low recovery, and after stabilization (usually less than 5 minutes), the following data are taken:

        Pressures
            Prefilter
            Primary (feed)
            Final (concentrate line)
        Flow
            Recycle
            Permeate
            Concentrate
        Temperature (recycle)
        Quality (conductivity)
            Feed
            Permeate
            Concentrate

    The system recovery is then increased incrementally while adjusting the recycle valve to ensure that the correct crossflow velocity is maintained.

3. At the end of the testing, the same quality of water used in the initial control testing is fed into the system under the same conditions to determine possible effects of the feedwater on the membrane element (adsorption, chemical attack, etc.)

At each recovery, in addition to the collection of flow and pressure data, analytical samples should be taken for performance evaluation. Of course, the choice of parameters to be measured depends upon the separation goals of the test. It is unusual for system recoveries to exceed 95%; however, that also depends upon the goals of the testing, and it is possible to run a well designed test unit up to 99% recovery.

Once the optimum conditions have been established, such as operating pressure and maximum system recovery, the normalized performance data will enable the test engineer to determine the total membrane area required for the full sized system.

Application testing provides the following advantages and disadvantages:

*ADVANTAGES*

- ✓ Fast.
- ✓ Provides scale-up data (flow, osmotic pressure as a function of recovery, pressure requirements, etc.).
- ✓ Can provide an indication of membrane stability.

*DISADVANTAGES*

- ✓ Does not reveal long term chemical effects.
- ✓ Does not provide data on long term fouling effects.

**Pilot testing**

Usually this involves placing a test machine (such as that used for the applications test) in the process, and operating continuously on a "side-stream" for a minimum of 30 days.

*ADVANTAGES*

- ✓ Accomplishes all of the functions of the applications test plus provides long term membrane fouling and stability data.

*DISADVANTAGES*

- ✓ Expensive in terms of monitoring and time requirements.

## CONCLUSIONS

Membrane technologies represent core technologies that can be utilized to treat produced water for reinjection or virtually any other reuse application. It is critical that complete comprehensive testing be employed to develop the optimum system design.