

## PRINCIPLES AND PRACTICES OF REVERSE OSMOSIS

**O.J. Morin**

*Black and Veatch, Florida, USA*

**Keywords :** Acidity, Alkaline scale, Anion, Anionic, Antiscalant, Aquifer, Avogadro's number, Brackish water, Buffer, Caustic soda, EDTA, Colloid, Hydrophilic

### Contents

1. Introduction
  - 1.1. General
  - 1.2. Purpose
  - 1.3. Reference Design
2. Theory
  - 2.1. Reverse Osmosis
3. Basic Water Chemistry
  - 3.1. Introduction
  - 3.2. Water Analysis
  - 3.3. Test Methods
4. Process Considerations
  - 4.1. Introduction
  - 4.2. Process Characteristics
5. Pretreatment
  - 5.1. Fouling
6. Process Design
  - 6.1. Design Procedure
  - 6.2. Water Analysis
  - 6.3. Blending
  - 6.4. Recovery
  - 6.5. Number of Stages
  - 6.6. Flux Rate
  - 6.7. Operating Pressure
7. Posttreatment
  - 7.1. Introduction
  - 7.2. Finished Water Quality Goals
  - 7.3. Degassification
  - 7.4. Blending
  - 7.5. Chemical Treatment
  - 7.6. Disinfection
8. Brine Disposal
  - 8.1. Introduction
  - 8.2. Brine Classification
  - 8.3. Sewer Systems
  - 8.4. Deep Well Injection
  - 8.5. Surface Water Disposal
  - 8.6. Solar Evaporation Ponds
  - 8.7. Zero (Liquid) Discharge

## 9. Auxiliary Equipment

### 9.1. Pumps

### 9.2. Energy Recovery Equipment

### 9.3. Interstage Pumping

### 9.4. Piping and Valves

### 9.5. Controls

## 10. Operation and Maintenance

### 10.1. Introduction

### 10.2. Data Collection and Reporting

### 10.3. Data Normalization and Evaluation

### 10.4. Membrane Cleaning

### 10.5. Trouble Shooting

### 10.6. Startup Procedure

### 10.7. Shutdown Procedure

### 10.8. Preventive Maintenance

## 11. Costs

### 11.1. Introduction

### 11.2. Process Considerations

### 11.3. Capital Cost

### 11.4. Operating Costs

## Bibliography and Suggestions for further study

## 1. Introduction

### 1.1. General

The treatment of fresh or brackish waters can be accomplished using the following processes:

- Direct filtration (i.e., sand, dual, or mixed media)
- Microfiltration
- Ultrafiltration
- Reverse osmosis
- Electrodialysis

The type of filtration used for treatment will depend upon the water quality to be treated and the product water quality goals. For example, if the feed water to be treated is high in inorganics and the product water must meet the Safe Drinking Water Act (SDWA) requirements, the treatment process used must have the capability to remove minerals. If the water to be treated is low in inorganics but high in some other constituent, say turbidity, direct or membrane filtration would be used as the treatment process. Figure 1 shows the removal capabilities of each of these processes. It indicates that the ultrafiltration (UF) and microfiltration (MF) processes can be used to remove suspended solids, bacteria, giardia, and others. The reverse osmosis (RO) process can effectively remove all organics, inorganics, biological contaminants, and color. Figure 1 indicates that the RO process can remove low molecular weight volatile organics. This is not necessarily true. The ability of low molecular weight molecules to pass through the membranes will depend upon a number of factors including the pore size of the

membrane and the make-up of the molecule itself. For example, volatile organics of long-chain molecules are generally removed by RO. The RO process does not remove gases. Carbon dioxide, hydrogen sulfide, and others will pass through the membrane. The electro dialysis (ED) process is only effective in the removal of charged particles. These are the commonly known constituents such as calcium, magnesium, chloride, etc. The ED process does not remove the other constituents shown in Figure 1.

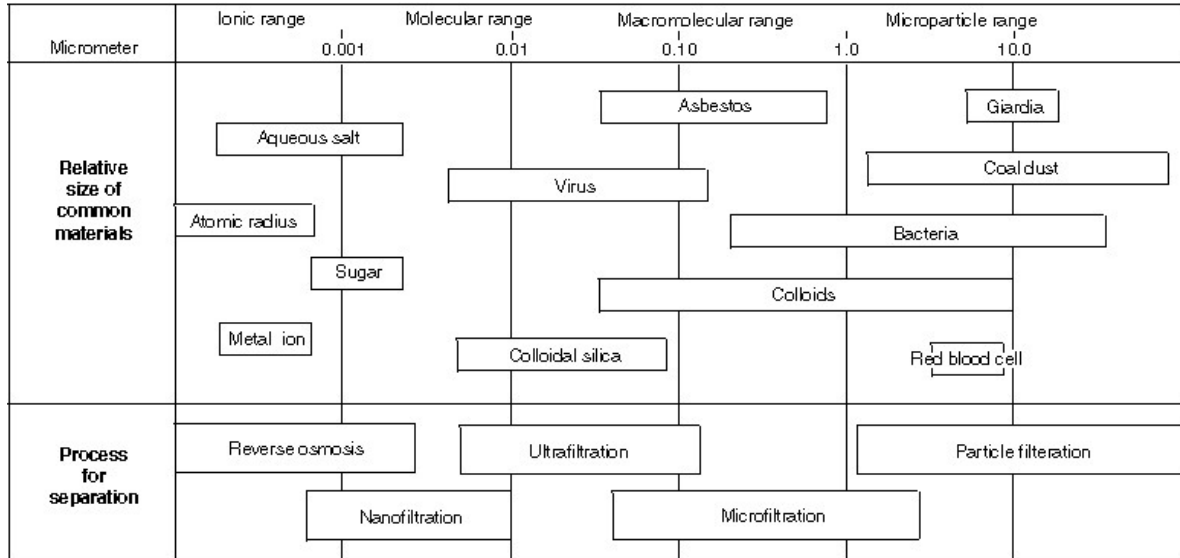


Figure 1. Filtration spectrum.

Each of these treatment processes has its own advantages and disadvantages. Thus, the selection of a process can only be accomplished by performing a detailed study that evaluates and compares the technical and cost aspects of each.

## 1.2. Purpose

The purpose of this chapter is to present the basics of the RO process. The items to be discussed include:

- Theory
- Process design
- Equipment considerations
- Pre- and post-treatment
- Concentrate disposal
- Equipment types
- Operation and maintenance aspects
- Costs

In addition to these subjects, this manual also includes a discussion of basic water chemistry aspects. This information shows how the chemistry of water applies to the RO treatment process.

### 1.3. Reference Design

Process item	Reverse osmosis
Recovery (%)	85
Number of stages	3
Number of trains	1
Flows: gal min <sup>-1</sup> (l min <sup>-1</sup> )	
Raw water	4000 (15 141)
Feed water	3516 (13 310)
Bypass	483 (1828)
Product	2989 (11 315)
Brine	520 (1968)
Finished water	3472 (13 142)
Pressures: psig (kPal)	
Feed water	230 (417)
By-pass	15 (27)
Product	15 (27)
Brine	191 (346)
Concentrations (mg l <sup>-1</sup> )	
Feed water	2000
By-pass	2000
Product	133.5
Brine	12549
Finished water	393

Table 1. Reference designs - technical characteristics.

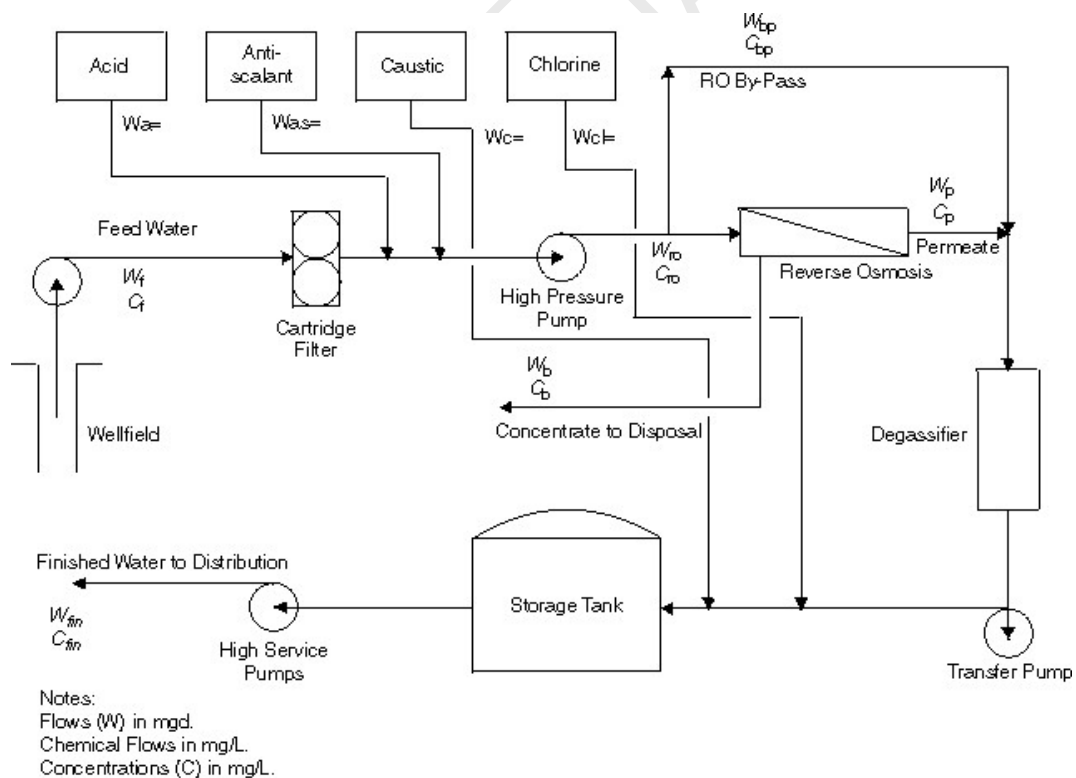


Figure 2. Process flow diagram - reverse osmosis. Flows (W); chemical flows and concentrations in mg l<sup>-1</sup>.

Throughout this discussion, examples are given to assist in the clarification of the discussion. For this purpose, a reference design for the RO system is proposed. This assumes treating a feed water quality of  $2000 \text{ mg l}^{-1}$ , total dissolved solids (TDS). Finished water production capacity is assumed to be  $5.0 \times 10^6 \text{ gal d}^{-1}$ . Figure 2 shows the diagrammatic arrangement of this reference design. Table 1 gives the technical aspects.

## 2. Theory

### 2.1. Reverse Osmosis

In order to understand the term "reverse osmosis", the term "osmosis" must first be understood. To do this, the term "Chemical Potential" is defined first. It is the inequality of the chemical potential between, say, fresh and brackish waters that is the driving force for osmosis. A solution's chemical potential is determined by the following:

- Concentration of salts in the water
- The temperature of the water (expressed in absolute terms)
- The pressure of the solution

The concentration of salts in the water supply has an inverse effect on the chemical potential of the solution, whereas the temperature and pressure have a direct effect. Therefore, at constant temperature and pressure of a solution, increased salt content results in decreased chemical potential. This phenomenon is shown in Figure 3. This figure shows a vessel filled with waters of two different salt concentrations. These are separated by a semi-permeable membrane. A semi-permeable membrane is one that allows the passage of pure water, while preventing the passage of salts. The fresh water side has a higher chemical potential than the saline water side. Thus, pure water will pass through the membrane from the fresh water side to the more saline water side. This is the phenomenon called "osmosis". As the pure water passes to the saline water side, four things occur: (1) the water on the saline side becomes less concentrated; (2) the level of the solution on the saline side increases; (3) the water on the fresh side becomes more concentrated; and (4) the water level on the fresh water side decreases. These occurrences result in increasing the chemical potential of the solution on the saline side of the membrane and decreasing the potential on the fresh water side. The flow of pure water from the fresh to the saline side will continue until a chemical potential equilibrium condition between the two sides is obtained (Figure 4). At this point, the flow of pure water stops. This is called "osmotic equilibrium". It follows that if the pressure on the saline side were now to be increased, the flow could be reversed. That is, flow across the membrane could be directed from the saline side to the fresh water side. This is called "reverse osmosis" (Figure 5). Its occurrence is caused by the increased pressure applied to the saline side. The pressure required to begin flow is termed the "osmotic pressure". If this flow were allowed to continue unchanged, the pressure on the saline side would have to be continually increased because the chemical potential on the fresh water side would continue to increase. Thus, for the RO process to work at constant pressure, the concentration of the saline side must be kept constant. This is done by adding new water (feed water) to the saline side while continually extracting concentrated water from the saline side. This describes RO operation in the actual plant and is shown schematically in Figure 6.

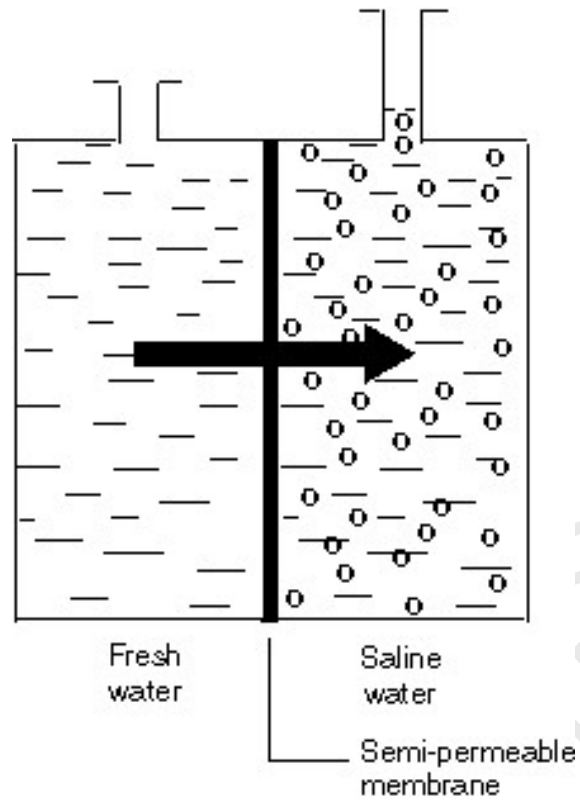


Figure 3. Normal osmosis.

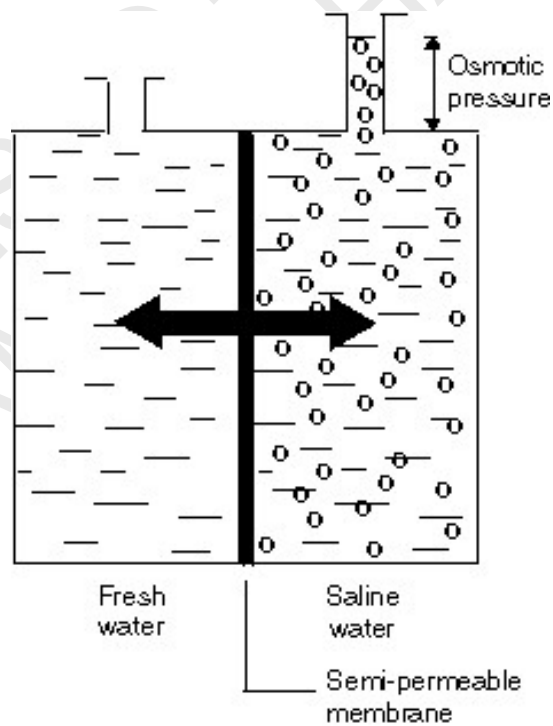


Figure 4. Osmotic equilibrium.

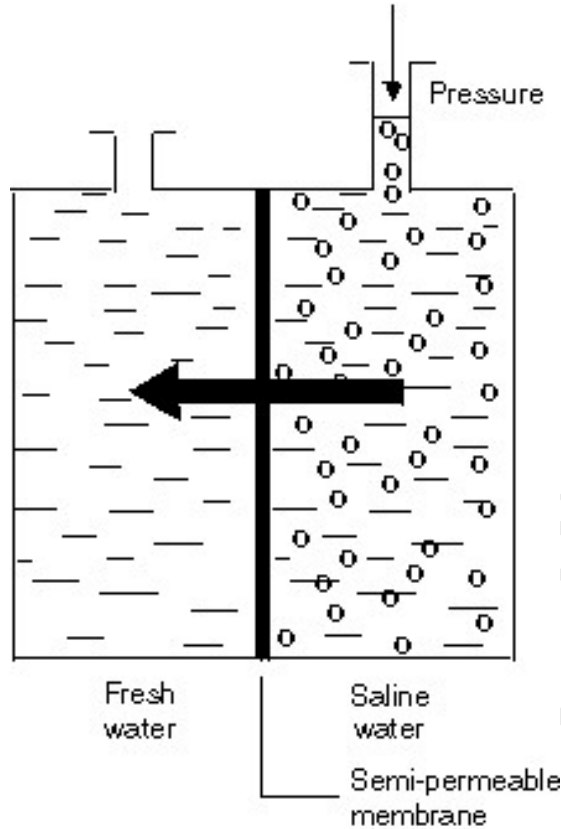


Figure 5. Reverse osmosis.

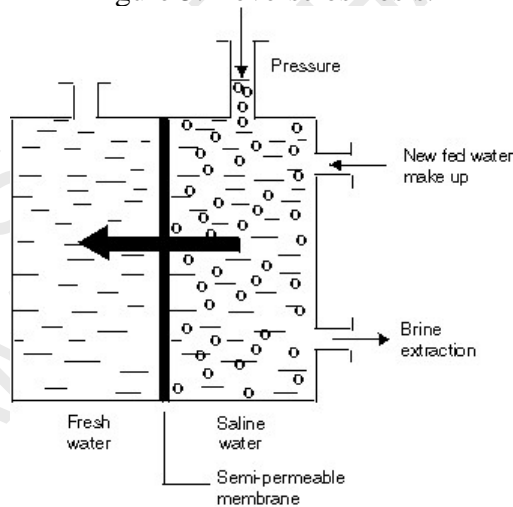


Figure 6. Reverse osmosis process.

### 3. Basic Water Chemistry

#### 3.1. Introduction

The chemistry of water can be thought of as being constructed from the basic building blocks shown in Figure 7. As shown in the box, the dark calcium ion block combines with the white sulfate ion block to produce calcium sulfate ( $\text{CaSO}_4$ ). Similarly, the two hydrogen ions combine with the sulfate ion in the form of sulfuric acid ( $\text{H}_2\text{SO}_4$ ). The

joining of the cations and anions forms compounds that make up the structure of these building blocks.

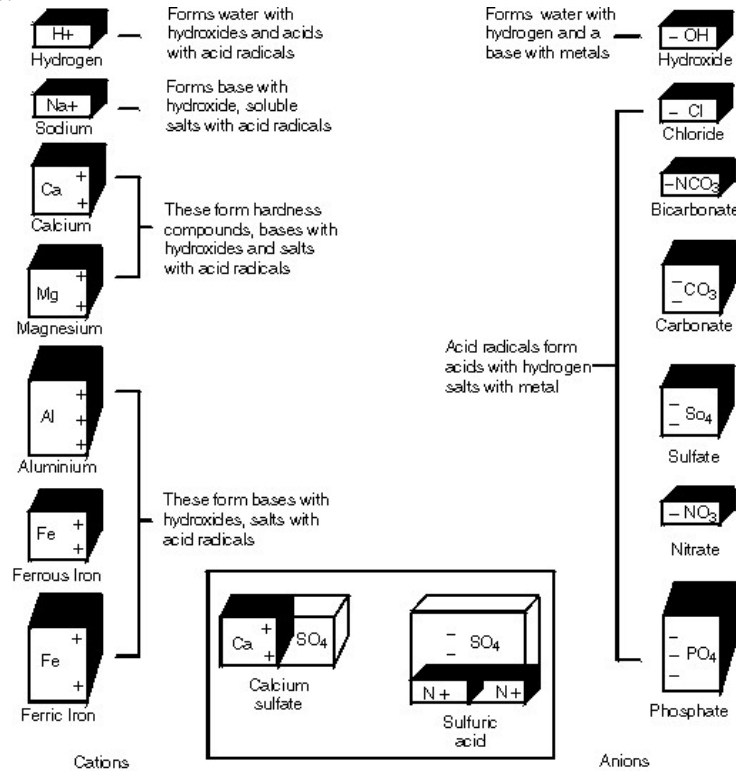


Figure 7. Chemical building blocks.

TO ACCESS ALL THE 96 PAGES OF THIS CHAPTER,  
Visit: <http://www.desware.net/DESWARE-SampleAllChapter.aspx>

#### Bibliography and Suggestions for further study

Andrienne J. and Alardin, F. (2002) Thermal and membrane processes economics: Optimised  
Ayse Asatekin, Adrienne Menniti, Seoktae Kang, Menachem Elimelech, Eberhard Morgenroth, and Anne M. Mayes (2006), Antifouling Nanofiltration Membranes for Membrane Bioreactors from Self-Assembling Graft Copolymers, *Journal of Membrane Science* 285 ,81-89.

Drioli E., Romano M., (2001), Progress and new perspectives on integrated membrane operations for sustainable industrial growth, *Ind. Eng. Chem. Res.* 40 , 1277-1300

H. Mehdizadeh, (2006), Membrane desalination plants from an energy-exergy viewpoint, *Desalination* 191, , 200-209.

J. Koschikowski, M. Wieghaus, M. Rommel: (2003), Solar thermal-driven desalination plants based on membrane distillation, *Desalination*, 295-304, 156

Joseph A. Cotruvo, (2007), World Health Organization Guidance on Desalination for a Safe Water Supply: Health and Environmental Aspects Applicable to Desalination) and Health Factors Related to the



### Composition of Desalinated Water

- Kimura K., Hane Y., Watanabe Y., Amy G., Ohkuma N.,(2004), Irreversible membrane fouling during ultrafiltration of surface water, *Water Res.* 38 (2004) 3431–3441
- Lee S., Cho J., Elimelech M., (2005) , Combined influence of natural organic matter (NOM) and colloidal particles on nanofiltration membrane fouling, *Journal of Membrane Science* 262,27-41
- N. Hilala, H. Al-Zoubia, N.A. Darwishb, A.W. Mohammac, c and M. Abu Arabi (2004) ,A Comprehensive Review of Nanofiltration Membranes." *Desalination* 170 , 281-308.
- Pearce G., (2007),The case of UF/MF pretreatment to RO in seawater applications, *Desalination* 203 , 286-295
- Pilat B.,(2001), Practice of water desalination by electrodialysis, *Desalination* 139 . 385-392
- Pilat B.V.,(2003), Industrial application of electrodialysis reversal systems, *Desalination* 158 , 87-89
- Riemersma M.C., Post J.W.,(2003) Hydraulically optimised design increases productivity and reduces cost, *The International Desalination & Water Reuse* ,13/2, 26-29
- Seacord T.F., Coker S.D., MacHarg J.,(2006) Affordable Desalination Collaboration 2005 results, *The International Desalination & Water Reuse* 16/2 , 10-22
- selection for seawater desalination, *Desalination*, 153, p. 305-311.
- Strathmann H., Giorno L., Drioli E.,(2006), An introduction to membrane science and technology, Publisher CNR Roma,
- Tomi Y. et. al.,(2005), Evolution of RO Membrane for Seawater Desalination, *International Forum on Water Industry Qingdao 2005, China* , 92- 97.
- Turek M.,(2003) Cost effective electrodialytic seawater desalination, *Desalination* 153 , 371-376
- Van der Bruggen, B.; Vandecasteele, C. (2002) Distillation vs. Membrane filtration: overview of process evolutions in seawater desalination. *Desalination* 143, 207-218.
- Villa Sallangos O.L.,(2005),Operating experience at the Dhekelia seawater desalination plant using an innovative energy recovery system, *Desalination* 173 , 91-102
- Zularisam A.W., Ismail A.F., Salim R.,(2006), Behaviours of natural organic matter in membrane filtration for surface water treatment — a review, *Desalination* 194 , 211–231