A Review of Wastewater Treatment by Reverse Osmosis

Michael E. Williams, Ph.D., P.E,
Williams Engineering Services Company, Inc.

Since the development of the first practical cellulose acetate membranes in the early 1960's and the subsequent development of thin-film, composite membranes, the uses of reverse osmosis have expanded to include not only the traditional desalination process but also a wide variety of wastewater treatment applications. Several advantages of the RO process that make it particularly attractive for dilute aqueous wastewater treatment include: (1) RO systems are simple to design and operate, have low maintenance requirements, and are modular in nature, making expansion of the systems easy; (2) both inorganic and organic pollutants can be removed simultaneously by RO membrane processes; (3) RO systems allow recovery/recycle of waste process streams with no effect on the material being recovered; (4) RO membrane systems often require less energy and offer lower capital and operating costs than many conventional treatment systems; and (5) RO processes can considerably reduce the volume of waste streams so that these can be treated more efficiently and cost effectively by other processes such as incineration (Cartwright, 1985; Sinisgalli and McNutt, 1986; Cartwright, 1990; McCray et al., 1990; Cartwright, 1991; Williams et al., 1992). In addition, RO systems can replace or be used in conjunction with others treatment processes such as oxidation, adsorption, stripping, or biological treatment (as well as many others) to produce a high quality product water that can be reused or discharged.

Applications that have been reported for RO processes include the treatment of organic containing wastewater, wastewater from electroplating and metal finishing, pulp and paper, mining and petrochemical, textile, and food processing industries, radioactive wastewater, municipal wastewater, and contaminated groundwater (Slater et al., 1983a; Cartwright, 1985; Ghabris et al, 1989; Williams et al., 1992). Table 1 lists RO and nanofiltration applications along with selected references. A review of RO and nanofiltration wastewater treatment follows; a thorough discussion of the application of RO membranes to seawater and brackish water desalination can be found in Williams et al. (1992).

RO Separation of Organic Pollutants from Wastewater

Many studies have been performed on the separation of organics and organic pollutants by RO membranes, and these studies have identified some of the unique aspects associated with organic separation. Sourirajan (1970) and Sourirajan and Matsuura (1985) have compiled separation and flux data of cellulose acetate membranes for a large number of organic compounds, including many organic pollutants. They found that organic separation can vary widely (from <0% to 100%) depending on the characteristics of the organic (polarity, size, charge, etc.) and operating conditions (such as feed pH, operating pressure, etc.). In an early study, Anderson et al. (1972) reported some of the factors influencing separation of several different organics (including acetone, urea, phenol, 2,4-dichlorophenol, nitrobenzene) by cellulose acetate membranes. Rejections varied considerably for the different solutes, and rejections of ionizable organics were greatly dependent on degree of dissociation; nonionized and hydrophobic solutes were found to be strongly sorbed by the membranes and exhibited poor rejection. Duvel and Helfgott (1975) also found organic separations varied with molecular size and branching; they postulated organic separation was also a function of the solute's potential to form hydrogen bonds with the membrane.

Table 1. Selected Wastewater Applications of Reverse Osmosis.

Application	Species Removed	Reference
Reverse Osmosis		
Seawater, Brackish Water Desalination	Various Salt Species	Williams et al. (1992)
Organic Pollutants Removal	Various organics	Sourirajan (1970); Anderson et al. (1972); Shuckrow et al. (1981); Kurihara et al. (1981); Lynch et al. (1984); Sourirajan and Matsuura (1985); Pusch et al. (1989)
	Herbicides, pesticides	Edwards and Schubert (1974); Chian et al. (1975)
	Polar organics	Fang and Chian (1976); Koyama et al. (1982)
	Phenolic compounds	Koyama et al. (1984); Bhattacharyya et al. (1987); Bhattacharyya and Madadi (1988); Williams et al. (1990); Bhattacharyya and Williams (1992a)
	PAH compounds	Light (1981); Bhattacharyya et al. (1987)
	Amines, chlorinated hydrocarbons	Light (1981) Rickabaugh et al. (1986); Cheng et al. (1991); Bhattacharyya and Williams (1992a)
Electroplating and Metal-finishing Rinse Water Treatment	Nickel	McNulty et al. (1977); Spatz (1979); Robison (1983)

Table 1. Selected Wastewater Applications of Reverse Osmosis (continued).

Application	Species Removed	Reference
Electroplating and Metal-finishing Rinse Water Treatment	Nickel, chromium, gold	Imasu (1985)
	Aluminum, phosphoric acid	Thorsen (1985)
	Various metals	Davis et al. (1987)
	Cadmium	Slater et al. (1987a)
Pulp and Paper Processing Effluent Treatment	Spent sulphite liquor components	Glimenius (1980); Olsen (1980); Paulson and Spatz (1983); Jönsson and Wimmerstedt (1985)
	Wash water components	Hart and Squires (1985)
	Bleach plant effluent compounds	Dorica et al. (1986); Simpson and Groves (1983); Jönsson and Wimmerstedt (1985); Ekengren et al. (1991)
Food Processing Effluent Treatment	Meat processing COD	Hart and Squires (1985); Gekas et al. (1985)
	Olive mills COD, TDS	Canepa et al. (1988); Anonymous (1988a)
	Various contaminants	Mohr et al. (1989)

Table 1. Selected Wastewater Applications of Reverse Osmosis (continued).

Application	Species Removed	Reference
Radioactive Processing Effluent Treatment	Radionuclides	Ebra et al. (1987)
	Uranium conversion process effluent	Hsiue et al. (1989)
	Various uranium species	Chu et al. (1990); Garret (1990)
	Uranium nitrate	Prabhakar et al. (1992)
Other Wastewater Treatment		
Blast-Furnace Scrubber Water	TDS	Terril and Neufeld (1983)
Coal Mining Drainage	TDS	Hart and Squires (1985)
Cooling Tower Blowdown	TDS	Schutte et al. (1987); Bryant et al. (1987)
Fuel Processing Wastewaters	TDS, COD, organics	Bhattacharyya et al. (1984); Siler and Bhattacharyya (1985); McCray and Ray (1987); Krug and Attard (1990)
Evaporator Condensates	TOC	Lyandres et al. (1989)
Ammonium Nitrate/ Explosive Manufacturing Wastewater	Ammonium nitrate	Hays et al. (1988); Davis et al. (1990)

Table 1. Selected Wastewater Applications of Reverse Osmosis (continued).

Application	Species Removed	Reference
Textile Dyehouse Effluents	Color, organics, TDS	Treffry-Goatly et al. (1983); Slater et al. (1987b); Calabro et al. (1990); Gaeta and Fedele (1991)
Contaminated Water Supply Treatment		
Leachates	TOC (1977)	Chian and De Walle
	TDS, COD	Slater et al. (1983b)
	Alkalinity, COD, TDS, NH_3	Kinman and Nutini (1990)
	Heavy metals, organics, TOC	Bhattacharyya and Kothari (1991)
	TOC, nitrate, metals	Stürken et al. (1991)
Drinking Water	Agricultural chemicals	Chian et al. (1975); Johnston and Lim (1978); Regunathan et al. (1983); Baier et al. (1987); Fronk (1987)
	Humic, fulvic materials	Nusbaum and Riedinger (1980); Odegaard and Koottatep (1982); Bhattacharyya and Williams (1992a)
	Radium, various contaminants, color	Sorg et al. (1980) Sorg and Love (1984); Taylor et al. (1987) Tan and Sudak (1992)

Table 1. Selected Wastewater Applications of Reverse Osmosis (continued).

Application	Species Removed	Reference
Municipal	TDS, organics Wastewater	Cruver (1976); Fang and Chian (1976); Lim and Johnston (1976); Tsuge and Mori (1977)
	TDS, TOC	Stenstrom et al. (1982)
	TDS, organics (at Water Factory 21)	Richardson and Argo (1977); Allen and Elser (1979); Argo and Montes (1979); Nusbaum and Argo (1984); Reinhard et al. (1986)
	TDS, TOC, fecal coliform	Suzuki and Minami (1991)
Nanofiltration		
Contaminated Drinking Water Treatment	Color, TOC, hardness, TDS, THMFP	Conlon (1985); Eriksson (1988); Cadotte et al. (1988); Dykes and Conlon (1989); Conlon and McClellan (1989); Watson and Hornburg (1989); Lange et al. (1989); Amy et al. (1990); Conlon et al. (1990); Tan and Amy (1991)
	Agricultural chemicals	Taylor et al. (1989b); Duranceau et al. (1992)
Wastewater Treatment		
Wood Pulping Process Wastewater	Color, organics	Bindoff et al. (1987); Ikeda et al. (1988)

Table 1. Selected Wastewater Applications of Reverse Osmosis (continued).

Application	Species Removed	Reference
Wastewater Treatment		
Textile Mill Effluents	Hardness, color, organics	Simpson et al. (1987); Perry and Linder (1989); Gaeta and Fedele (1991)
Food Processing Effluents	COD	Ikeda et al. (1988); Cadotte et al. (1988); Anonymous (1988b)
Other Wastewaters	Cadmium, nickel	Bhattacharyya et al. (1989)
	Various organic pollutants	Williams et al. (1990); Rautenbach and Gröschl (1990b); Dyke and Bartels (1990); Bhattacharyya and Williams (1992a)
	Uranium species	Chu et al. (1990)

COD: Chemical Oxygen Demand
TDS: Total Dissolved Solids
THMFP: Trihalomethane Formation Potential
TOC: Total Organic Carbon

Edwards and Schubert (1974) reviewed some of the early separation results of herbicides and pesticides with RO membranes. They also conducted studies with the herbicide 2,4-D and found separations were <51%. It was noted that solute adsorption could occur on the cellulose acetate membranes. Fang and Chian (1976) conducted studies on the separation of several polar organic compounds with various functional groups using cellulose acetate and several other types of membranes. This study found that the organic rejection varied considerably not only with solute but also with membrane type. Chian et al. (1975) reported high rejections (>99%) for several pesticides with cellulose acetate and a composite membrane; however, significant adsorption of the pesticides on the membranes was noted. Shuckrow et al. (1981) also listed cellulose acetate rejections of several different organics; rejections were poor to moderate (such as only 10% for methylene chloride, up to 73% for acenapthene).

Several studies have compared organic rejections of cellulose acetate with other membranes, and many of these have indicated that aromatic polyamide and composite membranes usually have organic rejections greater than those of cellulose acetate membranes. Kurihara et al. (1981) listed several organic rejections of the Toray composite membrane PEC-1000 (polyfuran); most rejections were high, including 97% for acetone and 99% for phenol. Koyama et al. (1982) and Koyama et al. (1984) reported separation results for several polar organic solutes (alcohols, phenols, carboxylic acids, amines, and ketones) and various phenolic derivatives for a composite membrane. They found that the main factors affecting rejection included molecular weight, molecular branching, polarity, and degree of dissociation for ionizable compounds. Lynch et al. (1984) compared cellulose acetate and thin-film, composite membrane (FilmTec FT30, a crosslinked aromatic polyamide) separations with a wide variety of organic pollutants. The composite membrane rejections (greater than 90% for most of the organics studied) and water fluxes were substantially better than the cellulose acetate membrane; however, adsorption of some of the organics on the membranes was noted. Light (1981) studied dilute solutions of polynuclear aromatic hydrocarbons (PAHs), aromatic amines, and nitrosamines and found rejections of these compounds to be over 99% for polyamide membranes. Rickabaugh et al. (1986) also indicated polyamide membrane rejections of chlorinated hydrocarbons (>95%) were much greater than those of cellulose acetate membranes.

Bhattacharyya et al. (1987) and Bhattacharyya and Madadi (1988) investigated rejection and flux characteristics of FT30 membranes for separating various pollutants (PAHs, chlorophenols, nitrophenols) and found membrane rejections were high (>98%) for the organics under ionized conditions. They also found substantial water flux decline occurred even for dilute (< 50 mg/L) solutions of nonionized organics and observed significant organic adsorption on the membrane in some cases. Pusch et al. (1989) reported separation results for several different membranes (four composite and two asymmetric) for a variety of single and multicomponent organic solutions, including many organic pollutants. Rejections varied from only 25% up to >99% depending on the solute, but generally the composite membrane rejections were higher.

Williams et al. (1990) and Bhattacharyya and Williams (1992a) investigated FT30 membranes with ozonation as a feed pretreatment to remove chlorophenols and chloroethanes and reduce declines in water flux caused by the organics. Feed TOC rejections of ozonation intermediates were 80% to 96%, and overall removals of >99.8% were found for the model pollutant compound 2,4,6-trichlorophenol. Batch adsorption experiments and material balances indicated that nonionized chloro- and nitrophenols could strongly adsorb on the membrane. Rautenbach and Gröschl (1990a) also discussed that while high separations of organics could be achieved by RO membranes, significant decreases in water flux could occur even when only traces of organics were present. They indicated these flux declines could be caused by organic sorption on the membranes.

Saavedra et al. (1991) considered the use of polyamide membranes for the treatment of a phenol production waste stream; the stream contained organic acid salts and organic peroxides. While the organic salts were highly removed (>94%), the peroxides were poorly rejected. Studies with the peroxides indicated that some of these could cause significant water flux drop.

Bhattacharyya et al. (1991) reported separation results for a wastewater containing tributyl phosphate, metal salts (Na^+, NO_3^{2-}, Fe^{3+}, Al^{3+}, etc.), and metal hydroxide precipitates. Tributyl phosphate and metals rejections were high (91% to 99%). Declines in water flux were caused by osmotic pressure of the metal salts, tributyl phosphate adsorption, and enhancement of precipitate fouling of the membrane caused by tributyl phosphate adsorption on the precipitate. Cheng et al. (1991) reported the effects of dilute solutions of the halocarbons $CHCl_3$, $CHBr_3$, and CCl_4 on the performance of DuPont cellulose acetate, polyamide, and thin-film composite membranes. The halocarbons were mostly poorly rejected (5% to 83%) by the three membranes; however, these caused water flux drops of up to 31%. The results indicated that water flux drop was caused by halocarbon adsorption.

RO Treatment of Industrial Wastewater

Electroplating and Metal-Finishing Process Wastewaters

In most cases, process wastewaters from the electroplating and metal-finishing industries must be treated to remove heavy metals before being discharged. Reverse osmosis is ideal for this wastewater treatment for many of these operations since it allows both recovery of the heavy metals and reuse of the product water in the process. The RO process has been used in the treatment and recovery of wastewater containing nickel, acid copper, zinc, copper cyanide, chromium, aluminum, and gold (Schrantz, 1975; Sato et al., 1977; Kamizawa et al., 1978; Cartwright, 1985).

McNulty et al. (1977) reported high rejections of nickel and total solids from electroplating bath rinse water. Spatz (1979) discussed the use of RO in the nickel plating industry to recover nickel from nickel plating bath rinse water. In this process the permeate was recycled as rinse water, and the concentrate was recycled back to the plating bath. This allowed 97% recovery of the rinse water, and nickel consumption was significantly reduced. Robison (1983) also discussed the use of a RO process to recover nickel from plating rinse water; recycle of the permeate and nickel concentrate resulted in substantial savings for the plating operation.

Imasu (1985) reported on the use of cellulose acetate and polyamide (FT30) membranes at three Japanese plating shops with nickel, chromium, and gold plating lines. Up to 80% water recoveries with high metal and TDS (>95%) rejections were possible, and the product water was recycled. The RO processes were found to be cost-effective in treating the wastewaters, and the compact nature of the RO system made it highly desirable to the customers because of space limitations.

Thorsen (1985) discussed the RO treatment of effluent from an electrolytic polishing process for aluminum products. The streams contained phosphoric acid and aluminum from rinse water. DDS HR-98 membranes allowed 96% to 98% acid recovery (up to an acid concentration of 20%) and produced permeate water suitable for reuse. The membranes appeared to be stable to the feed even at the low pH values (0.9 to 1.0) found at high recoveries.

Davis et al. (1987) discussed two case histories of heavy metal wastewater treatment using RO membranes. In the first case, spiral-wound polyamide membranes allowed 75% water recovery with TDS rejections of >99% for a heavy metal-containing wastewater. Scaling and fouling were reduced by pretreatment and periodic cleaning. In the second case, rinse water effluents from a metal forming facility were treated. Polyamide membranes gave rejections over 99% for calcium, cadmium, chromium, copper, iron, magnesium, manganese, molybdenum, nickel, and tungsten and up to 90% recovery of the effluent as purified water suitable for reuse in the plant was found to be possible. It was noted subsequent treatment to recover molybdenum for reuse in the facility was also possible. The RO system was determined to be a cost-effective alternative to evaporation.

Slater et al. (1987a) reported on the use of RO membranes to remove cadmium from metal processing wastewaters. The FT30 membranes used had cadmium rejections of >99.5% in most cases and produced a high quality product water suitable for reuse. Rejections of other metals (zinc, silver, copper, nickel, and tin) and overall conductivity were >97% even at water recoveries up to 75%, and water fluxes remained at reasonably high levels. It was concluded that the RO could be an efficient and cost-effective process for treatment of the wastewater.

Pulp and Paper Processing Wastewaters

The use of RO membranes in combination with other processes to treat wastewaters in the pulp and paper industry has also been investigated. Morris et al. (1972) and Wiley et al. (1978) conducted early studies with pulp and paper wastewaters. Glimenius (1980) and Olsen (1980) outlined the use of RO to concentrate spent sulphite liquor (SLL, which consists of lignosulfates and other organics as well as various inorganics) containing wastewater before it was sent to an evaporator, resulting in lower energy costs for the evaporator. Paulson and Spatz (1983) also detailed the use of RO and ultrafiltration/RO processes to concentrate SLL wastes before further treatment by evaporation. In the process RO membranes concentrated solids from less than 2% to 10%; it was noted that this preconcentration would greatly reduce evaporator costs because of reduced volume to be treated. High rejections of solids (>95%), BOD (88%), and COD (>96%) were reported for short-term tests. Ultrafiltration treatment prior to a high pressure RO membrane was reported to allow even further preconcentration prior to evaporation. It was pointed out that RO processes would also produce an excellent quality water for reuse in the pulping process. Chakravorty and Srivastava (1987) and Chakravorty (1989) also reported good separation results for an ultrafiltration/reverse osmosis process for pulp and paper mill effluents.

Jönsson and Wimmerstedt (1985) discussed the use of RO concentration prior to SLL evaporation, concentration of weak black liquor by RO, and the use of RO to treat bleach effluent; rejections of both organics and inorganics in these effluents were >90%. They also reported the use of PCI ZF99 tubular membranes to treat waste paper white water. For these membranes rejections of TDS (99.4%) and COD (>99.8%) were found to be good even at high water recoveries (up to 95%). Hart and Squires (1985) indicated ZF99 membranes gave high rejections of lignin, TOC, sugars, and color in wash waters, making the permeate suitable for reuse; however, periodic membrane cleanings were required to restore water flux of the membranes. Simpson and Groves (1983) and Ekengren et al. (1991) have reported some success in the use of membranes to treat bleach plant effluent. The ultrafiltration and RO processes used gave high removals of inorganics, COD, and chloroorganic compounds. Dorica et al. (1986) also studied the use of ultrafiltration and RO processes to minimize discharges of chlorinated organics and other pollutants in bleach plant effluents. Reverse osmosis membranes completely removed color and 95% to 99.8% of organics, chloride, and organic chlorine for water recoveries of 75% to 85%; feeds consisted of ultrafiltration filtrate of caustic extraction effluent and effluent from a chlorination stage.

Food Processing Wastewaters

Reverse osmosis also has been used to treat food processing wastewaters so that these could be discharged or recycled; in many cases it was indicated a concentrate stream rich in nutrients was produced. Hart and Squires (1985) discussed the use of ZF99 tubular membranes to concentrate slaughter house effluent rich in COD, and Gekas et al. (1985) also reported on the use of a RO system to treat meat processing wastewaters. Canepa et al. (1988) studied treatment of olive mills wastewater containing high total solids and COD with a combination ultrafiltration/RO process. For the RO membranes rejections of TDS were >99% and COD were 93% for water recoveries of 70%. The permeate was suitable for recycle. The use of an ultrafiltration/RO process to reduce effluents from olive canning operations and allow recycling of processing water has also been reported (Anonymous, 1988a). Mohr et al. (1989) discuss several uses of RO in wastewater treatment in the food industry, including for concentration of whey, fruit processing waters, and stillage waters.

Radioactive Processing Wastewaters

Because of high rejection of inorganic compounds, RO membranes have been studied for treatment of radioactive effluents. Ebra et al. (1987) described a treatment facility that included RO processes to remove low levels of radionuclides and hazardous chemicals prior to discharge. Hsiue et al. (1989) reported on the use of RO membranes to treat uranium conversion process effluent containing toxic, corrosive, and radioactive compounds. The FT30 membranes studied had rejections of uranium ≥99.5% for water recoveries up to 70%, and the results indicated that the treated effluent would meet regulatory discharge standards. Chu et al. (1990) used a three stage process consisting of nanofiltration, reverse osmosis, and precipitation to treat uranium effluents. The process removed both soluble and suspended uranium species; it was found that 95% uranium recovery was possible, and the treated effluent met environmental standards. The RO membranes (FT30) gave uranium rejections of >99%. Prabhakar et al. (1992) indicated cellulose acetate membranes could effectively remove 99% of uranium from effluents containing uranium nitrate when the uranium was complexed with EDTA. Garret (1990) also studied removal of uranium and other radioactive elements by RO membranes.

RO Treatment of Other Wastewaters

Reverse osmosis has also been applied to a variety of other wastewaters. Terril and Neufeld (1983) used RO membranes to remove contaminants (calcium, magnesium, zinc, sulfate, chloride, ammonia and others) in blast-furnace scrubber water, allowing recycle of the product water. Hart and Squires (1985) discussed the use of RO to treat coal mining drainage (containing mostly sodium salts); TDS removals from the permeate were high. Sinisgalli and McNutt (1986) described a process in which RO was integrated with other treatment systems to remove contaminants from a complex industrial wastewater; this wastewater contained contaminants from semiconductor manufacturing lines and plating baths as well as cooling tower blowdown and other facility wastewaters. The treatment process allowed recycle of the product water, reduced operating costs, and compliance with environmental regulations. Reverse osmosis has also been used to demineralize cooling tower blowdown in the power generation industry (Schutte et al., 1987; Bryant et al., 1987).

Bhattacharyya et al. (1984) used FT30 and DuPont B9 (polyamide) membranes to remove contaminants from biotreated coal-liquefaction wastewater. TDS rejections were >77%, and the membranes removed 94% to 98% of the organics and 100% of the color present. Siler and Bhattacharyya (1985) reported on the use of RO membranes to treat oil shale retorting wastewaters containing organics (aliphatic acids and phenolics), inorganics (NH_3, S^{2-}, Cl^-, alkalinity), color, odor, oils, and suspended solids. Rejections with and without various pretreatment by activated carbon, filtration, etc. (which greatly affected flux) ranged from 60% to 94% for conductivity and 75% to 88% for TOC. McCray and Ray (1987) used a RO system to treat process condensate wastewater from a synfuel process which contained high concentrations of organics (phenols, oils and greases, carboxylic acids, cyclic hydrocarbons, etc.) and inorganics such as ammonia, sulfides, carbonates, cyanides, and heavy metals. Studies at high pH indicated contaminants were rejected >95% and fluxes could be maintained at acceptable levels even for water recoveries up to 80%. Krug and Attard (1990) conducted studies using ultrafiltration followed by RO for the treatment of oily wastewater; oil removals greater than 96% were found.

Lyandres et al. (1989) used RO membranes (FT30 and PEC-1000) to treat evaporator condensates from a hazardous waste treatment facility; the condensate contained light organic compounds (mostly carboxylic acids and amines) and small amounts of inorganics. Both membranes removed more than 98% of TOC. Hays et al. (1988) and Davis et al. (1990) have discussed the use of RO membranes to remove and recover ammonium nitrate from manufacturing and explosive manufacturing effluents; ammonium nitrate removals of >87% were found. Reverse osmosis membranes have also been used with some success in the treatment of textile dyehouse effluents (Treffry-Goatly et al., 1983; Slater et al., 1987b; Calabro et al., 1990; Gaeta and Fedele, 1991). Reverse osmosis allows recovery of dyes and auxiliary chemicals and recycle of the product water as rinse water, minimizing discharge of pollutants.

RO Treatment of Contaminated Water Supplies

Leachates

Several studies have been conducted on the treatment of landfill leachates with RO processes. Chian and De Walle (1977) found RO membranes could be used to remove >91% of TOC from sanitary landfill leachate. Slater et al. (1983b) discussed the use of tubular cellulose acetate membranes to treat industrial landfill leachates and found TDS removals of 98% and COD removals of 68%. Water recoveries of up to 75% were possible without significant fouling. McArdle et al. (1987) indicated that RO membranes could be used as a treatment technology for leachate from hazardous waste land disposal facilities. Rautenbach and Ingo (1988) discussed treatment problems of landfill drainage at high water recovery rates. Kinman and Nutini (1990) also described RO treatment of landfill leachate; removals of 94.5% alkalinity, 97% COD, 97% total solids, 92.1% volatile solids, and 96.6% ammonia were reported. Stürken et al. (1991) and Peters (1991) also indicated RO membranes could remove 98% of COD, TOC, and ammonium ions, 96% of nitrate, and heavy metals. Bhattacharyya and Kothari (1991) used FT30 membranes to treat soil-wash leachates so that the treated water could be recycled back to the soil-washing step. The leachate contained heavy metals and organic contaminants. TOC rejections as high as 80-85% and heavy metal (Pb, Zn, Ni, Cu) rejections of 94% to 98% were found. However, water flux decreases of up to 33% were noted. The effects of addition of EDTA or surfactant and feed preozonation were also investigated; feed preozonation substantially improved membrane water flux. Specific organic rejections included >98% for pentachlorophenol and 2,4-dinitrophenol, >97% for ethylbenzene, >81% for xylene, and >90% for chloroaniline. Lepore and Ahlert (1991) reported the treatment of landfill leachates containing organic acids; they found good separations of volatile fatty acids, and TDS was removed sufficiently to allow discharge of the product water.

Contaminated Drinking Water

The ability of RO membranes to remove both inorganic and organic compounds have made these attractive for the treatment of contaminated drinking water supplies (AWWA, 1992). Reverse osmosis processes can simultaneously remove hardness, color, many kinds of bacteria and viruses, and organic contaminants such as agricultural chemicals and trihalomethane precursors. Eisenberg and Middlebrooks (1986) reviewed RO treatment of drinking water sources, and they indicated RO could successfully remove a wide variety of contaminants. Chian et al. (1975) and Johnston and Lim (1978) studied several agricultural chemicals which can contaminate water supplies and found removals were good; however, these adsorbed on the membranes studied. Regunathan et al. (1983) reported good removals of the pesticides endrin and methoxychlor as well as trihalomethanes (THMs) with an RO-adsorption system. Nusbaum and Riedinger (1980), Odegaard and Koottatep (1982), and Bhattacharyya and Williams (1992a) reported that humic and fulvic materials, which are THM precursors, were highly removed by RO membranes. Clair et al. (1991) also found excellent removals (>95%) of dissolved organic carbon from natural waters using FT30 membranes.

Sorg et al. (1980) showed that a RO system could effectively remove radium from contaminated water. Sorg and Love (1984) conducted studies with actual groundwater in which only a few of the pollutants being studied were spiked; several different commercial membranes were studied. Most inorganics were highly (>90%) rejected while organic rejection depended upon the organic and membrane studied. Baier et al. (1987) studied removal of several agricultural chemicals from groundwater using several different membranes. Rejections ranged from 0% to >94% for the different compounds and membranes studied; pilot plant experiments indicated water fluxes could be maintained over long terms with periodic cleaning. Fronk (1987) investigated RO removal of over twenty VOCs and pesticides using several different RO membranes. Average organic removals were 80%. The study indicated that RO could be used to effectively remove both inorganics and organics from drinking water supplies. Taylor et al. (1987) found that RO membranes could be used to remove 96% of DOC, 97% of color, 97% of trihalomethane formation potential (THMFP), and 96% of total hardness. Tan and Sudak (1992) examined several RO membranes and found all were capable of acceptably removing color from groundwater even over long operating periods.

Municipal Wastewater

The application of RO membranes to the treatment of municipal wastewater has also had some success. Reverse osmosis can remove dissolved solids which cannot be removed by biological or other conventional municipal treatment processes. In addition, RO membranes can also lower organics, color, and nitrate levels. However, extensive pretreatment and periodic cleaning are usually needed to maintain acceptable membrane water fluxes. Early studies (Cruver, 1976; Fang and Chian, 1976; Lim and Johnston, 1976) showed that high removals of TDS and moderate removals of organics could be achieved. Tsuge and Mori (1977) showed that tubular membranes (with a substantial pretreatment system) could remove both inorganics and organics from municipal secondary effluent and produce water meeting drinking water standards. Stenstrom et al. (1982) studied municipal wastewater treatment over a 3 year period using tubular cellulose acetate membranes. TDS rejections were 81%, and TOC rejections were >94%, making the permeate suitable for reuse. However, feed pretreatment was necessary to maintain high water flux levels.

Richardson and Argo (1977), Allen and Elser (1979), Argo and Montes (1979), Nusbaum and Argo (1984), and Reinhard et al. (1986) have discussed municipal wastewater treatment at a large scale plant (Water Factory 21, Orange County, California). The feed to the plant consisted of secondary effluent, and the process was composed of a variety of treatment systems, including RO membranes (several different types) with a 5 MGD capacity. The process reduced TDS and organics to levels that allowed the effluent to be injected into groundwater aquifers used for water supplies. Suzuki and Minami (1991) reported studies on use of several RO membranes to treat secondary effluent containing various salts and dissolved organic materials. TDS rejections of up to 99% and TOC rejections as high as 90% were found possible, and fecal coliform group rejections were >99.9%. Losses in water flux over time were noted but could be partially restored by periodic cleaning.

Nanofiltration Applications

Nanofiltration (or "loose RO") membranes, which have high water fluxes at low pressures, are a recent development that have made possible new applications in wastewater treatment. Nanofiltration membranes are often charged (usually negatively-charged), and, as a result, ion repulsion is the major factor in determining salt rejection. For example, more highly charged ions such as SO_4^{2-} are rejected by most nanofiltration membranes to a greater extent than monovalent ions such as Cl^-. These membranes also reject organic compounds with molecular weights above 200 to 500. These properties have made possible some interesting new applications in wastewater treatment, such as selective separation and recovery of pollutants that have charge differences, separation of hazardous organics from monovalent salt solutions, and membrane softening to reduce hardness and trihalomethane precursors in drinking water sources (Eriksson, 1988; Cadotte et al., 1988; Williams et al., 1992).

Nanofiltration of Contaminated Drinking Water Supplies

Nanofiltration membranes, although a relatively recent development, have attracted a great deal of attention for use in water softening and removal of various contaminants from drinking water sources. Nanofiltration (NF) processes can reduce or remove TDS, hardness, color, agricultural chemicals, and high molecular weight humic and fulvic materials (which can form trihalomethanes when chlorinated). In addition, NF membranes typically have much higher water fluxes at low pressures when compared with traditional RO membranes used for this application.

Conlon (1985) reported that FilmTec NF50 membranes could effectively remove color (96%) and TOC (84%), reduce hardness and TDS, and lower trihalomethane formation potential (THMFP) to below regulatory levels. Eriksson (1988) and Cadotte et al. (1988) also indicated that NF membranes (such as FilmTec NF40, NF50, and NF70) could be used to reduce TDS, hardness, color, and organics. Dykes and Conlon (1989), Conlon and McClellan (1989), Watson and Hornburg (1989), and Conlon et al. (1990) have also identified NF as an emerging technology for compliance with THM regulations and for control of TDS, TOC, color, and THM precursors.

Clifford et al. (1988) discussed the use of NF70 membranes for contaminated groundwater treatment. Removals included 91% for radium-226 and 87% for TDS. Taylor et al. (1989a) reported that NF70 membranes could allow control of THM formation, DOC, and TDS and produce a high quality product water from an organic contaminated groundwater; they indicated costs of a NF process would be competitive with conventional treatment processes which do not control THMFP. Lange et al. (1989) also suggested that NF treatment would be a reliable method of meeting existing and future THM limits compared to chemical treatment alternatives.

Amy et al. (1990) used NF70 membranes to remove dissolved organic matter from both groundwater (recharged from secondary effluent) and surface water in order to reduce THM precursors; they found that the process was effective in reducing the organics as well as conductivity in both water sources. Tan and Amy (1991) showed that NF membranes could remove >88% of color, 51% of TOC, 46% of TDS, and 79% of THMFP from a contaminated water supply.

Duranceau et al. (1992) and Taylor et al. (1989b) have reported on the use of NF70 membrane separation of several agricultural chemicals spiked in groundwater. Ethylene dibromide and dibromochloropropane removals averaged 0% and 32%, respectively, while the remaining organics (chlordane, heptachlor, methoxychlor, and alachlor) were 100% removed. Rejections of TDS were 85% and THMFP were 95%. However, it was also indicated that some of the organics adsorbed on the membrane.

Nanofiltration of Wastewater

Nanofiltration has also been used to remove both organics and inorganics in various wastewaters. Bindoff et al. (1987) reported the use of NF membranes to remove color-causing compounds from effluent containing lignins and high salt concentrations in a wood pulping process. Color removals were >98% at water recoveries up to 95% while the inorganics were poorly rejected, allowing the use of low operating pressures (since $\Delta\pi$ was small). Ikeda et al. (1988) indicated NF could give high separations of color-causing compounds such as lignin sulphonates in paper pulping wastewaters. Afonso et al. (1992) found NF removal (>95%) of chlorinated organic compounds from alkaline pulp and paper bleaching effluents with high water fluxes. Simpson et al. (1987) reported the use of NF membranes to remove hardness and organics in textile mill effluents; Gaeta and Fedele (1991) also indicated high water recoveries (up to 90%) from textile dye house effluent could be achieved with NF membranes. Perry and Linder (1989) discussed the recovery of low molecular weight dyes from high salt concentration effluent. Ikeda et al. (1988) and Cadotte et al. (1988) reported the use of NF membranes in the treatment of food processing wastewaters. Some specific uses included the desalting of whey and the reduction of high BOD and nitrate levels in potato processing waters (Anonymous, 1988b).

Bhattacharyya et al. (1989) used NF40 membranes to selectively separate mixtures of cadmium and nickel. Williams et al. (1990) and Bhattacharyya and Williams (1992a) examined NF40 membranes with and without pretreatment by feed preozonation to study removal of various chlorophenols and chloroethanes. TOC rejections up to 90% were possible with ozonation pretreatment. Rautenbach and Gröschl (1990b) also discussed the separation results of several organics (ranging from methanol to ethylene glycol) by various NF membranes. Chu et al. (1990) detailed the use of NF in a process for treating uranium wastewater; NF40 uranium rejections were 97% to 99.9%. Dyke and Bartels (1990) discussed the use of NF membranes to replace activated carbon filters for the removal of organics from offshore produced water containing residual oils. The produced waters contained ~1000 mg/L soluble organics (mostly carboxylic acids) and high inorganic concentrations (~15,000 mg/L Na^+ and ~25,000 mg/L Cl^- as well as other dissolved ions). Organic rejections were suitable to meet discharge standards while inorganic rejections were low (<20%), allowing operation at low pressures.

A Review of Wastewater Treatment by Reverse Osmosis
Michael E. Williams, Ph.D., P.E.
Williams Engineering Services Company, Inc.
http://www.wescinc.com
Publication Date: March 2, 2003.

REFERENCES AND OTHER ARTICLES OF INTEREST

Afonso, M., Geraldes, V., Rosa, M., and De Pinho, M., "Nanofiltration Removal of Chlorinated Organic Compounds from Alkaline Bleaching Effluents in a Pulp and Paper Plant", *Water Research, 26,* 1639 (1992).

Allegrezza, A., "Commercial Reverse Osmosis Membranes and Modules", in Reverse Osmosis Technology, B. Parekh, ed., pp. 53-120, Marcel Dekker, Inc., New York (1988).

Allen, P., and Elser, G., "They Said it Couldn't be Done - the Orange County, California Experience", *Desalination, 30,* 23 (1979).

Aminabhavi, T., Aithal, U., and Shukla, S., "An Overview of the Theoretical Models Used to Predict Transport of Small Molecules through Polymer Membranes", *Journal of Macromolecular Science - Reviews in Macromolecular Chemistry and Physics, C28,* 421 (1988).

Aminabhavi, T., Aithal, U., and Shukla, S., "Molecular Transport of Organic Liquids through Polymer Films", *Journal of Macromolecular Science - Reviews in Macromolecular Chemistry and Physics, C29,* 319 (1989).

Amy, G., Alleman, B., and Cluff, C., "Removal of Dissolved Organic Matter by Nanofiltration", *Journal of Environmental Engineering, 116,* 200 (1990).

Anderson, J., Hoffman, S., and Peters, C., "Factors Influencing Reverse Osmosis Rejection of Organic Solutes from Aqueous Solution", *The Journal of Physical Chemistry, 76,* 4006 (1972).

Anonymous, "NFPA uses RO/UF System to Help Olive Canners Reduce Effluents", *Food Technology, 42,* 129 (1988a).

Anonymous, "Membrane Technology Provides Solution for Process Discharge", *Food Engineering, 60,* 124 (1988b).

Applegate, L., "Membrane Separation Processes", *Chemical Engineering,* 64 (June 11, 1984).

Argo, D., and Montes, J., "Wastewater Reclamation by Reverse Osmosis", *Journal WPCF, 51,* 590 (1979).

Arthur, S., "Structure-Property Relationship in a Thin Film Composite Reverse Osmosis Membrane", *Journal of Membrane Science, 46,* 243 (1989).

Avlonitis, S., Hanbury, W., and Hodgkiess, T., "Chlorine Degradation of Aromatic Polyamides", *Desalination, 85,* 321 (1992).

AWWA Membrane Technology Research Committee, "Committee Report: Membrane Processes in Potable Water Treatment", *Journal AWWA,* 59 (January 1992).

Back, S., "Prediction of Concentration Polarization and Flux Behavior of Reverse Osmosis Membrane Systems by Numerical Analysis Techniques", M.S. Thesis, D. Bhattacharyya, Director, Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky (1987).

Baier, J., Lykins, Jr., B., Fronk, C., and Kramer, S., "Using Reverse Osmosis to Remove Agriculture Chemicals from Groundwater", *Journal AWWA,* 55 (August 1987).

Baker, R., "Membrane and Module Preparation" in *Membrane Separation Systems,* Vol. 2, US DOE Report, DOE/ER/30133-H1 (1990).

Baranowski, B., "Non-equilibrium Thermodynamics as Applied to Membrane Transport", *Journal of Membrane Science, 57,* 119 (1991).

Bartels, C., "A Surface Science Investigation of Composite Membranes", *Journal of Membrane Science, 45,* 225 (1989).

Bhattacharjee, C., and Bhattacharya, P., "Prediction of Limiting Flux in Ultrafiltration of Kraft Black Liquor", *Journal of Membrane Science, 72,* 137 (1992a).

Bhattacharjee, C., and Bhattacharya, P., "Flux Decline Behavior with Low Molecular Weight Solutes During Ultrafiltration in an Unstirred Batch Cell", *Journal of Membrane Science, 72,* 149 (1992b).

Bhattacharyya, D., Jevtitch, M., Ghosal, J.K., and Kozminski, J., "Reverse-Osmosis Membrane for Treating Coal-Liquefaction Wastewater", *Environmental Progress, 3,* 95 (1984).

Bhattacharyya, D., and Cheng, C., "Separation of Metal Chelates by Charged Composite Membranes", in *Recent Developments in Separation Science, 9,* N. Li, ed., p. 707, CRC Press, Boca Raton, FL (1986).

Bhattacharyya, D., Jevtitch, M., Schrodt, J., and Fairweather, G., "Prediction of Membrane Separation Characteristics by Pore Distribution Measurements and Surface Force-Pore Flow Model", *Chemical Engineering Communications, 42,* 111 (1986).

Bhattacharyya, D., Barranger, T., Jevtitch, M., and Greenleaf, S., "Separation of Dilute Hazardous Organics by Low Pressure Composite Membranes", *EPA Report,* EPA/600/87/053 (1987).

Bhattacharyya, D., and Madadi, M.R., "Separation of Phenolic Compounds by Low Pressure Composite Membranes: Mathematical Model and Experimental Results", *AIChE Symposium Series, 84,* No. 261, 139 (1988).

Bhattacharyya, D., Adams, R., and Williams, M., "Separation of Selected Organics and Inorganic Solutes by Low Pressure Reverse Osmosis Membranes", in *Biological and Synthetic Membranes,* D. Butterfield, ed., Alan R. Liss, New York (1989).

Bhattacharyya, D., Back, S., and Kermode, R., "Prediction of Concentration Polarization and Flux

Behavior in Reverse Osmosis by Numerical Analysis", *Journal of Membrane Science, 48,* 231 (1990).

Bhattacharyya, D., Deshmukh, R., and Williams, M., "Flux Drop and Separation Characteristics of Hazardous Organics and Organic-Metal Systems for Thin Film Composite Membranes", Paper Presented at Fourth National Meeting of the North American Membrane Society, May 29-31, 1991, San Diego, California.

Bhattacharyya, D., and Kothari, A., "Separation of Hazardous Organics by Low Pressure Membranes: Treatment of Soil-Wash Rinse-Water Leachates", *EPA Report,* Cooperative Agreement No. CR814491, Submitted 1991.

Bhattacharyya, D., and Williams, M., "Separation of Hazardous Organics by Low Pressure Reverse Osmosis Membranes - Phase II, Final Report", *EPA Report,* EPA/600/2-91/045 (1992a).

Bhattacharyya, D., and Williams, M., "Introduction and Definitions - Reverse Osmosis", in *Membrane Handbook,* W. Ho and K. Sirkar, eds., pp. 265-268, Van Nostrand Reinhold, New York (1992b).

Bhattacharyya, D., and Williams, M., "Theory - Reverse Osmosis", in *Membrane Handbook,* W. Ho and K. Sirkar, eds., pp. 269-280, Van Nostrand Reinhold, New York (1992c).

Bhattacharyya, D., Williams, M., Ray, R., and McCray, S., "Reverse Osmosis", in *Membrane Handbook,* W. Ho and K. Sirkar, eds., pp. 263-390, Van Nostrand Reinhold, New York (1992).

Bindoff, A., Davies, C., Kerr, C., and Buckley, C., "The Nanofiltration and Reuse of Effluent from the Caustic Extraction Stage of Wood Pulping", *Desalination, 67,* 453 (1987).

Bitter, J., *Transport Mechanisms in Membrane Separation Processes,* Plenum Press, New York (1991).

Brian, P., "Mass Transport in Reverse Osmosis", in *Desalination by Reverse Osmosis,* U. Merten, ed., pp. 161-202, MIT Press, Cambridge, MA (1966).

Bryant, T., Stuart, J., Fergus, I., and Lesan, R., "The Use of Reverse Osmosis as a 35,600 m^3/day Concentrator in the Wastewater Management Scheme at 4640 MW Bayswater/Liddel Power Station Complex - Australia", *Desalination, 67,* 327 (1987).

Bummer, P., and Knutson, K., "Infrared Spectroscopic Examination of the Surfaces of Hydrated Copoly(ether-urethane-ureas)", *Macromolecules, 23,* 4357 (1990).

Burghoff, H., and Pusch, W., "Thermodynamic and Mechanistic Characterization of Water Sorption in Homogeneous and Asymmetric Cellulose Acetate Membranes", *Journal of Applied Polymer Science, 20,* 789 (1976).

Burghoff, H., Lee, K., and Pusch, W., "Characterization of Transport Across Cellulose Acetate

Membranes in the Presence of Strong Solute-Membrane Interactions", *Journal of Applied Polymer Science, 25,* 323 (1980).

Cabasso, I., "Membranes", in Encyclopedia of Polymer Science and Engineering, Vol. 9, pp. 509-579, John Wiley & Sons, Inc., New York (1987).

Cadotte, J., King, R., Majerle, R., and Petersen, R., "Interfacial Synthesis in the Preparation of Reverse Osmosis Membranes", *Journal of Macromolecular Science-Chemistry, A15,* 727 (1981).

Cadotte, J., Forester, R., Kim, M., Petersen, R., and Stocker, T., "Nanofiltration Membranes Broaden the Use of Membrane Separation Technology", *Desalination, 70,* 77 (1988).

Calabro, V., Pantano, G., Kang, M., Molinari, R., and Drioli, E., "Experimental Study on Integrated Membrane Processes in the Treatment of Solutions Simulating Textile Effluents. Energy and Exergy Analysis", *Desalination, 78,* 257 (1990).

Canepa, P., Marignetti, N., Rognoni, U., and Calgari, S., "Olive Mills Wastewater Treatment by Combined Membrane Processes", *Water Research, 22,* 1491 (1988).

Cartwright, P.S., "Membranes Separations Technology for Industrial Effluent Treatment - A Review", *Desalination, 56,* 17 (1985).

Cartwright, P.S., "Membranes for Industrial Wastewater Treatment - a Technical/Application Perspective", Paper Presented at the 1990 International Congress on Membranes and membrane Processes, August 20-24, 1990, Chicago, Illinois.

Cartwright, P.S., "Zero Discharge/Water Reuse - The Opportunities for Membrane Technologies in Pollution Control", *Desalination, 83,* 225 (1991).

Chakravorty, B., and Srivastava, A., "Application of Membrane Technologies for Recovery of Water from Pulp and Paper Mill Effluents", *Desalination, 67,* 363 (1987).

Chakravorty, B., "Effluent Treatment by Membrane Technology - Opportunities and Challenges", in Biological and Synthetic Membranes, D. Butterfield, ed., Alan R. Liss, New York (1989).

Cheng, R., Glater, J., Neethling, J.B., and Stenstrom, M.K., "The Effects of Small Halocarbons on RO Membrane Performance", *Desalination, 85,* 33 (1991).

Cheryan, M., Ultrafiltration Handbook, Technomic Publishing Co., Inc., Lancaster, PN (1986).

Chian, E., Bruce, W., and Fang, H., "Removal of Pesticides by Reverse Osmosis", *Environmental Science and Technology, 9,* 364 (1975).

Chian, E., and De Walle, F., "Evaluation of Leachate Treatment: Volume II, Biological and Physical-Chemical Processes", *EPA Report,* EPA-600/2-77-186b (1977).

Chu, M., Tung, C., and Shieh, M., "A Study on Triple-Membrane-Separator (TMS) Process to Treat

Aqueous Effluents Containing Uranium", *Separation Science and Technology, 25,* 1339 (1990).

Clair, T., Kramer, J., Sydor, M., and Eaton, D., "Concentration of Aquatic Dissolved Organic Matter by Reverse Osmosis", *Water Research, 25,* 1033 (1991).

Clifford, D., Vijjeswarapu, W., and Subramonian, S., "Evaluating Various Adsorbents and Membranes for Removing Radium from Groundwater", *Journal AWWA,* 94 (July 1988).

Conlon, W., "Pilot Field Test Data for Prototype Ultra Low Pressure Reverse Osmosis Elements", *Desalination, 56,* 203 (1985).

Conlon, W., and McClellan, S., "Membrane Softening: A Treatment Process Comes of Age", *Journal AWWA,* 47 (November 1989).

Conlon, W., Hornburg, C., Watson, B., and Kiefer, C., "Membrane Softening: The Concept and its Application to Municipal Water Supply", *Desalination, 78,* 157 (1990).

Connell, P., and Dickson, J., "Modeling Reverse Osmosis Separations with Strong Solute-Membrane Affinity at Different Temperatures Using the Finely Porous Model", *Journal of Applied Polymer Science, 35,* 1129 (1988).

Crank, J., *The Mathematics of Diffusion,* Clarendon Press, Oxford (1967).

Cruver, J., "Waste-treatment Applications of Reverse Osmosis", *Transactions ASME,* 246 (February 1976).

Davis, G., Paulson, D., Gosik, R., and Van Riper, G., "Heavy Metals Contaminated Waste Water Treatment with Reverse Osmosis - Two Case Histories", Paper Presented at AIChE New York Annual Meeting, November 15-20, 1987, New York.

Davis, G., Paulson, D., and Delebo, J., "Membrane Selection and Optimal Ammonium Nitrate Chemistry for Reverse Osmosis Treatment of Explosives Wastewater", Paper Presented at the 1990 International Congress on Membranes and Membrane Processes, August 20-24, 1990, Chicago, Illinois.

Deshmukh, R., "Adsorption of Selected Organics on Reverse Osmosis Membranes and its Effect on Membrane Separation Characteristics", M.S. Thesis, D. Bhattacharyya, Director, Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky (1989).

Dickson, J., "Fundamental Aspects of Reverse Osmosis", in *Reverse Osmosis Technology,* B. Parekh, ed., pp. 1-51, Marcel Dekker, Inc., New York (1988).

Dorica, J., Wong, A., and Garner, B.C., "Complete Effluent Recycling in the Bleach Plant with Ultrafiltration and Reverse Osmosis", *Tappi Journal, 69,* 122 (1986).

Doshi, M., "Modeling of Reverse Osmosis Membrane Devices", in *Reverse Osmosis Technology,* B.

Parekh, ed., pp. 121-139, Marcel Dekker, Inc., New York (1988).

Dresner, L., "Some Remarks on the Integration of the Extended Nernst-Planck Equations in the Hyperfiltration of Multicomponent Solutions", *Desalination, 10,* 27 (1972).

Dresner, L., and Johnson, J., "Hyperfiltration (Reverse Osmosis)" in *Principles of Desalination,* 2nd Ed., K. Spiegler and A. Laird, eds., pp. 401-560, Academic Press, Inc., New York (1980).

Duranceau, S., Taylor, J., and Mulford, L., "SOC Removal in a Membrane Softening Process", *Journal AWWA,* 68 (January 1992).

Duvel, W., and Helfgott, T., "Removal of Wastewater Organics by Reverse Osmosis", *Journal WPCF, 47,* 57 (1975).

Dyke, C., and Bartels, C., "Removal of Organics from Offshore Produced Waters Using Nanofiltration Membrane Technology", *Environmental Progress, 9,* 183 (1990).

Dykes, G., and Conlon, W., "Use of Membrane Technology in Florida", *Journal AWWA,* 43 (November 1989).

Ebra, M., Piper, D., Poy, F., and Siler, J., "Decontamination of Low-level Process Effluents by Reverse Osmosis", Paper Presented at Summer National Meeting of AIChE, August 16-19, 1987, Minneapolis, Minnesota.

Edwards, V., and Schubert, P., "Removal of 2,4-D and other Persistent Organic Molecules from Water Supplies by Reverse Osmosis", *Journal AWWA,* 610 (October 1974).

Eisenberg, T., and Middlebrooks, E., *Reverse Osmosis Treatment of Drinking Water,* Butterworth, Boston (1986).

Ekengren, O., Burhem, J., and Filipsson, S., "Treatment of Bleach-Plant Effluents with Membrane Filtration and Sorption Techniques", *Water Science and Technology, 24,* 207 (1991).

Eriksson, P., "Nanofiltration Extends the Range of Membrane Filtration", *Environmental Progress, 7,* 58 (1988).

Fang, H., and Chian, E., "Reverse Osmosis Separation of Polar Organic Compounds in Aqueous Solution", *Environmental Science and Technology, 10,* 364 (1976).

Faust, S., and Aly, O., *Adsorption Processes For Water Treatment,* Butterworths, Boston (1987).

Ferguson, P., "The First Decade of Commercial Reverse Osmosis Desalting 1968-1978", *Desalination, 32,* 5 (1980).

Forgach, D., Rose, G., Luteneske, N., "Characterization of Composite Membranes by Their Non-equilibrium Thermodynamic Transport Parameters", *Desalination, 80,* 275 (1991).

Fronk, C., "Removal of Low Molecular Weight Organic Contaminants from Drinking Water Using Reverse Osmosis Membranes", *EPA Report,* EPA/600/D-87/254 (1987).

Gaeta, S., and Fedele, U., "Recovery of Water and Auxiliary Chemicals from Effluents of Textile Dye Houses", *Institution of Chemical Engineers Symposium Series, 3,* 183 (1991).

Gao, S., and Bao, Q., "Determination of Interfacial Parameters of Cellulose Acetate Membrane Materials by HPLC", *Journal of Liquid Chromatography, 12,* 2083 (1989).

Garcia, A., and Medina, G., "Predicting Membrane Performance by Dimensional Analysis", *Transactions of the ASAE, 32,* 2059 (1989).

Garret, L., "Reverse Osmosis Application to Low-level Radioactive Waste", *DOE Report,* WHC-SA-0993 (1990).

Gekas, V., Hallstrom, B., and Tragardh, G., "Food and Dairy Applications: The State of the Art", *Desalination, 53,* 95 (1985).

Gekas, V., and Hallstrom, B., "Mass Transfer in the Membrane Concentration Polarization Layer under Turbulent Cross Flow", *Journal of Membrane Science, 30,* 153 (1987).

Gekas, V., "Terminology for Pressure-Driven Membrane Operations", *Desalination, 68,* 77 (1988).

Ghabris, A., Abdel-Jawad, M., and Aly, G., "Municipal Wastewater Renovation by Reverse Osmosis, State of the Art", *Desalination, 75,* 213 (1989).

Glaves, C., and Smith, D., "Membrane Pore Structure Analysis Via NMR Spin-Lattice Relaxation Experiments", *Journal of Membrane Science, 46,* (1989).

Glimenius, R., "Membrane Processes for Water, Pulp and Paper, Food - State of the Art", *Desalination, 35,* 259 (1980),

Greenleaf, S., "Reverse Osmosis Separation of Selected Hazardous Organics in a Continuous System", M.S. Thesis, D. Bhattacharyya, Director, Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky (1987).

Han, M., "Cellulose Acetate Reverse Osmosis Membranes: Effects of Casting Variables on Membrane Pore Structure and Transport Properties", M.S. Thesis, D. Bhattacharyya, Director, Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky (1989).

Han, M., and Bhattacharyya, D., "Characterization of Reverse Osmosis Cellulose Acetate Membranes by Gas Adsorption Method: Effect of Casting Variables and Chlorine Damage", *Journal of Membrane Science, 62,* 325 (1991).

Hance, D., "Polymeric Membranes: Pore Structure Characteristics by Gas Adsorption and

Membrane Separation Prediction by Surface Force-Pore Flow Model", M.S. Thesis, D. Bhattacharyya, Director, Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky (1987).

Hart, O.O., and Squires, R.C., "The Role of Membrane Technology in Industrial Water and Wastewater Management", *Desalination, 56,* 69 (1985).

Hays, D., Miget, M., Motilall, M., and Davis, G., "Recovery of Ammonium Nitrate by Reverse Osmosis", *Osmonics Report,* Osmonics, Inc., Minnetonka, Minnesota (1988).

Heyde, M., Peters, C., and Anderson, J., "Factors Influencing Reverse Osmosis Rejection of Inorganic Solutes from Aqueous Solution", *Journal of Colloid and Interface Science, 50,* 467 (1975).

Hindmarsh, A., "LSODE and LSODI, Two New Initial Value Ordinary Differential Equation Solvers", *ACM-SIGNUM Newsletter, 15,* 10 (1980).

Hsiue, G., Pung, L., Chu, M., and Shieh, M., "Treatment of Uranium Effluent by Reverse Osmosis Membrane", *Desalination, 71,* 35 (1989).

Ikeda, K., Nakano, T., Ito, H., Kubota, T., and Yamamoto, S., "New Composite Charged Reverse Osmosis Membrane", *Desalination, 68,* 109 (1988).

Imasu, K., "Wastewater Recycle in the Plating Industry using Brackish Water Reverse Osmosis Elements", *Desalination, 56,* 137 (1985).

Jeffrey, G., and Saenger, W., *Hydrogen Bonding in Biological Structures,* Springer-Verlag, New York, 1991.

Jevtitch, M., "Reverse Osmosis Membrane Separation Characteristics of Various Organics: Prediction of Separation by Surface Force-Pore Flow Model and Solute Surface Concentration by Finite Element Method", Dissertation, D. Bhattacharyya, Director, Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky (1986).

Jiang, J., Mingji, S., Minling, F., and Jiyan, C., "Study of the Interaction Between Membranes and Organic Solutes by the HPLC Method", *Desalination, 17,* 107 (1989).

Jiang, J., and Jiayan, C., "Study on Interactions between PBIL Membranes and Organic Solutes", *Desalination, 78,* 389 (1990).

Johnston, H., and Lim, H., "Removal of Persistent Contaminants from Municipal Effluents by Reverse Osmosis", *Report 85,* Ontario Mining Environmental, Ontario (1978).

Jönsson, A., and Wimmerstedt, R., "The Application of Membrane Technology in the Pulp and Paper Industry", *Desalination, 53,* 181 (1985).

Jonsson, G., and Boesen, C., "Water and Solute Transport Through Cellulose Acetate Reverse Osmosis Membranes", *Desalination, 17,* 145 (1975).

Jonsson, G., "Overview of Theories for Water and Solute Transport in UF/RO Membranes", *Desalination, 35,* 21 (1980).

Jonsson, G., and Benavente, J., "Determination of Some Transport Coefficients for the Skin and Porous Layer of a Composite Membrane", *Journal of Membrane Science, 69,* 29 (1992).

Kamizawa, C., Masuda, H., Matsuda, M., Nakane, T., and Akami, H., "Studies on the Treatment of Gold Plating Rinse by Reverse Osmosis", *Desalination, 27,* 261 (1978).

Kedem, O., and Katchalsky, A., "Thermodynamic Analysis of the Permeability of Biological Membranes to Non-Electrolytes", *Biochim. Biophys. Acta, 27,* 229 (1958).

Kesting, R., and Eberlin, J., "Semipermeable Membranes of Cellulose Acetate for Desalination in the Process of Reverse Osmosis. IV. Transport Phenomena Involving Aqueous Solutions of Organic Compounds", *Journal of Applied Polymer Science, 10,* 961 (1966).

Kesting, R., *Synthetic Polymeric Membranes: A Structural Perspective,* Wiley-Interscience, New York (1985).

Kesting, R., "The Four Tiers of Structure in Integrally Skinned Phase Inversion Membranes and Their Relevance to the Various Separation Regimes", *Journal of Applied Polymer Science, 41,* 2739 (1990),

Kim, J., Reucroft, P., Taghiei, M., Pradhan, V., and Wender, I., *American Chemical Society, Division of Fuel Chemistry, 37,* 756 (1992).

Kinman, R., and Nutini, D., "Treatment of Landfill Leachate Using Reverse Osmosis", Paper Presented at the 1990 International Congress on Membranes and Membrane Processes, August 20-24, 1990, Chicago, Illinois.

Koo, J., Petersen, R., and Cadotte, J., "ESCA Characterization of Chlorine-Damaged Polyamide Reverse Osmosis Membrane", *Polymer Preprints, 27,* 391 (1986).

Koros, W., Fleming, G., Jordan, S., Kim, T., and Hoehn, H., "Polymeric membrane materials for solution-diffusion based permeation separations", *Progress in Polymer Science, 13,* 339 (1988).

Kothari, A., "Concentration and Purification of Hazardous Wastes by Low Pressure Composite Membranes: Treatment of Soil-Wash Rinse Water Leachates", M.S. Thesis, D. Bhattacharyya, Director, Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky (1991).

Koyama, K., Nishi, T., Hashida, I., and Nishimura, M., "The Rejection of Polar Organic Solutes in Aqueous Solution by an Interpolymer Anionic Composite Reverse Osmosis Membrane", *Journal of*

Applied Polymer Science, 27, 2845 (1982).

Koyama, K., Kimura, E., Hashida, I., and Nishimura, M., "Rejection of Phenolic Derivatives in Aqueous Solution by an Interpolymer Anionic Composite Reverse Osmosis Membrane", *Journal of Applied Polymer Science, 29,* 2929 (1984).

Krug, T., and Attard, K., "Treating Oily Waste Water with Reverse Osmosis", *Water and Pollution Control, 128,* 16 (1990).

Kulkarni, S., Funk, E., and Li, N., "Theory and Mechanistic Concepts", in *Membrane Handbook,* W. Ho and K. Sirkar, eds., pp. 398-407, Van Nostrand Reinhold, New York (1992).

Kurihara, M., Harumiya, N., Kanamaru, N., Tonomura, T., and Nakasatomi, M., "Development of the PEC-1000 Composite Membrane for Single-Stage Seawater Desalination and the Concentration of Dilute Aqueous Solutions Containing Valuable Materials", *Desalination, 38,* 449 (1981).

Lakshminarayanaiah, N., "Transport Phenomena in Artificial Membranes", *Chemical Reviews, 65,* 491 (1965).

Lakshminarayanaiah, N., *Transport Phenomena in Membranes,* Academic Press, New York (1969).

Lange, P., Laverty, P., Edwards, E., and Watson, I., "THM Precursor Removal and Softening - FT. Myers 12 MGD RO Membrane Plant, Florida USA", *Desalination, 76,* 39 (1989).

Le Moël, A., Duraud, J., and Balanzat, E., "Modifications of Polyvinylidene Fluoride (PVDF) Under High Energy Heavy Ion X-Ray and Electron Irradiation Studied by X-ray Photoelectron sepectroscopy", *Nuclear Instruments and Methods in Physics Research, B18,* 59 (1986).

Lepore, J., and Ahlert, R., "Membrane Separation of Organic Acids from Aqueous Salt Solutions", *Waste Management, 11,* 27, 1991.

Light, W., "Removal of Chemical Carcinogens from Water/Wastewater by Reverse Osmosis", in *Chemistry in Water Reuse, Vol. 1,* W.J. Cooper, ed., Ann Arbor Science, Ann Arbor, Michigan (1981).

Lim, M., and Johnston, H., "Reverse Osmosis as an Advanced Treatment Process", *Journal WPCF, 48,* 1820 (1976).

Lloyd, D., and Meluch, T., "Selection and Evaluation of Membrane Materials for Liquid Separations", *ACS Symposium Series No. 269,* Washington, DC (1985).

Loeb, S., and Sourirajan, S., "Sea Water Demineralization by Means of an Osmotic Membrane", *Advances in Chemistry Series, 38,* 117 (1962).

Loeb, S., "The Loeb-Sourirajan Membrane: How it Came About", in *Synthetic Membranes,* A. Turbak, ed., ACS Symposium Series 153, Vol. I, Washington, DC (1981).

Lonsdale, H., Merten, U., and Riley, R., "Transport Properties of Cellulose Acetate Osmotic Membranes", *Journal of Applied Polymer Science, 9,* 1341 (1965).

Lonsdale, H., "The Growth of Membrane Technology", *Journal of Membrane Science, 10,* 81 (1982).

Lonsdale, H., "The Evolution of Ultrathin Synthetic Membranes", *Journal of Membrane Science, 33,* 121 (1987).

Loudon, G., *Organic Chemistry,* Addison-Wesley, Reading, MA (1984).

Luck, W., "Structure of Water and Aqueous Systems", in *Synthetic Membrane Processes: Fundamentals and Water Applications,* G. Belfort, ed., pp. 21-72, Academic Press, Inc., New York (1984).

Luck, W., "Contributions to the Desalination Membrane Mechanism by Studies of Interactions in Aqueous Solutions and in Polymer Hydration", *Desalination, 62,* 19 (1987).

Lyandres, S., Meardon, J., and Reese, J., "Evaluation of Membrane Processes for the Reduction of Trace Organic Contaminants", *Environmental Progress, 8,* 239 (1989).

Lykins, B., Clark, R., and Fronk, C., "Reverse Osmosis for Removing Synthetic Organics from Drinking Water: A Cost and Performance Evaluation", *EPA Report,* EPA/600/D-88/134 (1988).

Lynch, S., Smith, J., Rando, L., and Yauger, W., "Isolation or Concentration of Organics Substances from Water - An Evaluation of Reverse Osmosis Concentration", *EPA Report,* EPA/600/1-84/018 (1984).

Madadi, M., "Separation of Phenolic Compounds in Water and Water-Alcohol Systems Using Low Pressure Composite Membranes", M.S. Thesis, D. Bhattacharyya, Director, Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky (1987).

Mason, E., and Lonsdale, H., "Statistical-Mechanical Theory of Membrane Transport", *Journal of Membrane Science, 51,* 1 (1990).

Mason, E., "From Pig Bladders and Cracked Jars to Polysulfones: An Historical Perspective on Membrane Transport", *Journal of Membrane Science, 60,* 125 (1991).

Matsuura, T., and Sourirajan, S., "Physicochemical Criteria for Reverse Osmosis Separation of Alcohols, Phenols, and Monocarboxylic Acids in Aqueous Solutions Using Porous Cellulose Acetate Membranes", *Journal of Applied Polymer Science, 15,* 2905 (1971).

Matsuura, T., and Sourirajan, S., "Reverse Osmosis Separations of Phenols in Aqueous Solutions Using Porous Cellulose Acetate Membranes", *Journal of Applied Polymer Science, 16,* 2531 (1972).

Matsuura, T., and Sourirajan, S., "Reverse Osmosis Transport Through Capillary Pores Under the Influence of Surface Forces", *Industrial and Engineering Chemistry Process Design and Development, 20,* 273 (1981).

Matthiasson, E., and Sivik, B., "Concentration Polarization and Fouling", *Desalination, 35,* 59 (1980).

Mattson, M, "Significant Developments in Membrane Desalination - 1979", *Desalination, 28,* 207 (1979).

Mazid, M., "Mechanisms of Transport Through Reverse Osmosis Membranes", *Separation Science and Technology, 19,* 357 (1984).

McArdle, J., Arozarena, M., and Gallagher, W., "A Handbook on Treatment of Hazardous Waste Leachate", *EPA Report,* EPA/600/8-87/006 (1987).

McCray, S., and Ray, R., "Concentration of Synfuel Process Condensates by Reverse Osmosis", *Separation Science and Technology, 22,* 745 (1987).

McCray, S., Wytcherley, R., Newbold, D., and Ray, R., "A Review of Wastewater Treatment Using Membranes", Paper Presented at the 1990 International Congress on Membranes and membrane Processes, August 20-24, 1990, Chicago, Illinois.

McNulty, K., Goldsmith, R., and Gollan, A., "Reverse Osmosis Field Test: Treatment of Watts Nickel Rinse Waters", *EPA Report,* EPA-600/2-77-039 (1977).

Mehdizadeh, H., and Dickson, J., "Theoretical Modification of the Surface Force-Pore Flow Model for Reverse Osmosis Transport", *Journal of Membrane Science, 42,* 119 (1989).

Mehdizadeh, H., Dickson, J., and Eriksson, P., "Temperature Effects on the Performance of Thin-Film Composite, Aromatic Polyamide Membranes", *Industrial and Engineering Chemistry Research, 28,* 814 (1989).

Mehdizadeh, H., and Dickson, J., "Solving Nonlinear Differential Equations of Membrane Transport by Orthogonal Collocation", *Computers in Chemical Engineering, 14,* 157 (1990).

Mehdizadeh, H., "Modeling of Transport Phenomena in Reverse Osmosis Membranes", Dissertation, J. Dickson, Director, Department of Chemical Engineering, McMaster University, Hamilton, Ontario, Canada (1990).

Mehdizadeh, H., and Dickson, J., "Modelling of Temperature Effects on the Performance of Reverse Osmosis Membranes", *Chemical Engineering Communications, 103,* 99 (1991).

Merten, U., "Transport Properties of Osmotic Membranes", in *Desalination by Reverse Osmosis,* U. Merten, ed., pp. 15-54, MIT Press, Cambridge, Mass. (1966).

Mitlin, V., and Bromberg, L., "Analysis of Diffusion through Composite Membranes - I. Mathematical Development", *Chemical Engineering Science, 47,* 695 (1992).

Mohr, C., Engelgau, D., Leeper, S., and Charboneau, B., *Membrane Applications and Research in Food Processing,* Noyes Data Corporation, Park Ridge, NJ (1989).

Morris, D., Nelson, W., and Walraver, G., "Recycle of Papermill Waste Waters and Applications of Reverse Osmosis", *EPA Report,* EPA-12040 FUB 01/72 (1972).

Muldowney, G., and Punzi, V., "A Comparison of Solute Rejection Models in Reverse Osmosis Membranes for the System Water-Sodium Chloride-Cellulose Acetate", *Industrial and Engineering Chemistry Research, 27,* 2341 (1988).

Murphy, A., "Cellulose Acetate: Interactions with Aqueous Phenol and a Transition Temperature of About 20 C", *Journal of Applied Polymer Science, 43,* 817 (1991).

NAG, "D03-Partial Differential Equations", in *The NAG Fortran Library Manual, Mark 15,* The Numerical Algorithms Group Limited, Oxford, United Kingdom (1991).

Nakatsuka, S., and Michaels, A., "Transport and Separation of Proteins by Ultrafiltraion through Sorptive and Non-sorptive Membranes", *Journal of Membrane Science, 69,* 189 (1992).

Nusbaum, I., and Riedinger, A., "Water Quality Improvement by Reverse Osmosis", in *Water Treatment Plant Design,* R. Sanks, ed., Ann Arbor Science, Ann Arbor, Michigan (1980).

Nusbaum, I., and Argo, D., "Design, Operation, and Maintenance of a 5-mgd Wastewater Reclamation Reverse Osmosis Plant", in *Synthetic Membrane Processes: Fundamentals and Water Applications,* G. Belfort, ed., Academic Press, New York (1984).

Odegaard, H., and Koottatep, S., "Removal of Humic Substances from Natural Waters by Reverse Osmosis", *Water Research, 16,* 613 (1982).

Olsen, O., "Membrane Technology in the Pulp and Paper Industry", *Desalination, 35,* 291 (1980).

Paulson, D., and Spatz, D., "Reverse Osmosis/Ultrafiltration Membrane Applied to the Pulp and Paper Industry", *Proceedings of the Technical Association of the Pulp and Paper Industry, 1983 International Dissolving and Specialty Pulps Conference, 51,* TAPPI Press, Atlanta (1983).

Perry, M., and Linder, C., "Intermediate Reverse Osmosis Ultrafiltration (RO UF) Membranes for Concentration and Desalting of Low Molecular Weight Organic Solutes", *Desalination, 71,* 233 (1989).

Peters, T., "Desalination and Industrial Waste Water Treatment with the ROCHEM Disc Tube Module DT", *Desalination, 83,* 159 (1991).

Petersen, R., and Cadotte, J., "Thin Film Composite Reverse Osmosis Membranes", in *Handbook of*

Industrial Membrane Technology, M. Porter, ed., pp. 307-348, Noyes Publications, Park Ridge, NJ (1990).

Pimentel, G., and McClellan, A., The Hydrogen Bond, W.H. Freeman and Co., San Francisco (1960).

Prabhakar, S., Panicker, S.T., Misra, B.M., and Ramani, M.P.S., "Studies on the Reverse Osmosis Treatment of Uranyl Nitrate Solution", *Separation Science and Technology, 27,* 349 (1992).

Punzi, V., Hunt, K., Muldowney, G., "Comparison of Solute Rejection Models in Reverse Osmosis Membranes. 2. System Water-Sodium Chloride-Asymmetric Polyamide", *Industrial and Engineering Chemistry Research, 29,* 259 (1990a).

Punzi, V., Muldowney, G., and Hunt, K., "Study of Solute Rejection Models for Thin Film Composite Polyamide RO Membranes", *Journal of Membrane Science, 52,* 19 (1990b).

Pusch, W., "Determination of Transport Parameters of Synthetic Membranes by Hyperfiltration Experiments", *Ber. Bunsenges. Phys. Chem., 81,* 269 (1977).

Pusch, W., and Walch, A., "Synthetic Membranes: State of the Art", *Desalination, 35,* 5 (1980).

Pusch, W., "Measurement Techniques of Transport Through Membranes", *Desalination, 59,* 105 (1986).

Pusch, W., Yu, Y., and Zheng, L., "Solute-Solute and Solute-Membrane Interactions in Hyperfiltration of Binary and Ternary Aqueous Organic Feed Solutions", *Desalination, 75,* 3 (1989).

Pusch, W., "Performance of RO Membranes in Correlation with Membrane Structure, Transport Mechanisms of Matter and Module Design (Fouling). State of the Art", *Desalination, 77,* 35 (1990).

Rautenbach, R., and Ingo, J., "Reverse Osmosis for the Separation of Organics from Aqueous Solutions", *Chemical Engineering and Processing, 23,* 67 (1988).

Rautenbach, R., and Albrecht, R., Membrane Processes, John Wiley & Sons, New York (1989).

Rautenbach, R., and Gröschl, A., "Reverse Osmosis of Aqueous-Organic Solutions: Material Transport and Process Design", Paper Presented at the 1990 International Congress on Membranes and membrane Processes, August 20-24, 1990a, Chicago, Illinois.

Rautenbach, R., and Gröschl, A., "Separation Potential of Nanofiltration Membranes", *Desalination, 77,* 73 (1990b).

Rautenbach, R., and Gröschl, A., "Fractionation of Aqueous Organic Mixtures by Reverse Osmosis", Paper Presented at 203rd American Chemical Society National Meeting, April 5-10, 1992, San Francisco, California.

Regunathan, P., Beauman, W., and Kreusch, E., "Efficiency of Point-of-Use Devices", *Journal AWWA, 75,* 42 (1983).

Reid, C., and Breton, E., "Water and Ion Flow Across Cellulosic Membranes", *Journal of Applied Polymer Science, 1,* 133 (1959).

Reid, C., "Principles of Reverse Osmosis", in *Desalination by Reverse Osmosis,* U. Merten, ed., pp. 1-14, M.I.T. Press, Cambridge, Mass. (1966).

Reid, R., Prausnitz, J., and Sherwood, T., *The Properties of Gases and Liquids,* McGraw-Hill Book Co., New York (1977).

Reinhard, M., Goodman, N., McCarty, P., and Argo, D., "Removing Trace Organics by Reverse Osmosis Using Cellulose Acetate and Polyamide Membranes", *Journal AWWA,* 163 (April 1986).

Richardson, N., and Argo, D., "Orange County's 5 MGD Reverse Osmosis Plant", *Desalination, 23,* 563 (1977).

Rickabaugh, J., Clement, S., Martin, J., and Sunderhaus, M., "Chemical and Microbial Stabilization Techniques for Remedial Action Sites", Proceedings of the 12th Annual Hazardous Wastes Symposium, April 1986, Cincinnati, Ohio.

Riley, R., "Reverse Osmosis", in *Membrane Separation Systems, Vol. 2,* US DOE Report, DOE/ER/30133-H1 (1990).

Robison, G., "Recovery Pays Off for Chicago Job Shop Plater", *Products Finishing Magazine* (June 1983).

Ruthven, D., *Principles of Adsorption and Adsorption Processes,* John Wiley & Sons, New York (1984).

Saavedra, A., Bertoni, G., Fajner, D., Sarti, G., "Reverse Osmosis Treatment of Process Water Streams", *Desalination, 82,* 267 (1991).

Sato, T., Imaizumi, M., Kato, O., and Taniguchi, Y., "RO Applications in Wastewater Reclamation for Re-use", *Desalination, 23,* 65 (1977).

Schrantz, J., "Big Savings with Reverse Osmosis and Acid Copper", *Industrial Finishing, 51,* 30 (1975).

Schutte, C., Spencer, T., Aspen, J., and Hanekom, D., "Desalination and Reuse of Power Plant Effluents: From Pilot Plant to Full Scale Applications", *Desalination, 67,* 255 (1987).

Sherwood, T., Brian, P., and Fisher, R., "Desalination by Reverse Osmosis", *Industrial and Engineering Chemistry Fundamentals, 6,* 2 (1967).

Shuckrow, A., Pajak, A., and Osheka, J., "Concentration Technologies for Hazardous Aqueous Waste Treatment", *EPA Report,* EPA-600/2-81-019 (1981).

Siler, J., and Bhattacharyya, D., "Low Pressure Reverse Osmosis Membranes: Concentration and Treatment of Hazardous Wastes", *Hazardous Waste and Hazardous Materials, 2,* 45 (1985).
Simon, G., and Calmon, C., "Experimental Methods for the Determination of Non-Transport Properties of Membranes", *Desalination, 59,* 61 (1986).

Simpson, M., and Groves, G., "Treatment of Pulp/Paper Bleach Effluents by Reverse Osmosis", *Desalination, 47,* 327 (1983).

Simpson, M., Kerr, C., and Buckley, C., "The Effect of pH on the Nanofiltration of the Carbonate System in Solution", *Desalination, 64,* 305 (1987).

Sinisgalli, P., and McNutt, J., "Industrial Use of Reverse Osmosis", *Journal AWWA,* 47 (May 1986).

Slater, C., Ahlert, R., and Uchrin, C., "Applications of Reverse Osmosis to Complex Industrial Wastewater Treatment", *Desalination, 48,* 171 (1983a).

Slater, C., Ahlert, R., and Uchrin, C., "Treatment of Landfill Leachates by Reverse Osmosis", *Environmental Progress, 2,* 251 (1983b).

Slater, C., Ferrari, A., and Wisniewski, P., "Removal of Cadmium from Metal Processing Wastewaters by Reverse Osmosis", *Journal of Environmental Science and Health, A22,* 707 (1987a).

Slater, C., Ahlert, R., and Uchrin, C., "Reverse Osmosis Processes for the Renovation and Reuse of Hazardous Industrial Wastewaters", *Current Practices Environmental Science, 3,* 1 (1987b).

Slejko, F., *Adsorption Technology,* Marcel Dekkar, Inc., New York (1985).

Soltanieh, M., and Gill, W., "Review of Reverse Osmosis Membranes and Transport Models", *Chemical Engineering Communications, 12,* 279 (1981).

Sorg, T., Forbes, R., and Chambers, D., "Removal of Radium 226 from Sarasota County, FL, Drinking Water by Reverse Osmosis", *Journal AWWA, 72,* 230 (1980).

Sorg, T., and Love, Jr., O., "Reverse Osmosis Treatment to Control Inorganic and Volatile Organic Contamination", *EPA Report,* EPA 600/D-84-198 (1984).

Sourirajan, S., *Reverse Osmosis,* Academic Press, New York (1970).

Sourirajan, S., and Matsuura, T., *Reverse Osmosis/Ultrafiltration Principles,* National Research Council of Canada, Ottawa, Canada (1985).

Spatz, D., "A Case History of Reverse Osmosis Used for Nickel Recovery in Bumper Recycling", *Plating and Surface Finishing* (July 1979).

Spiegler, K., and Kedem, O., "Thermodynamics of Hyperfiltration (Reverse Osmosis): Criteria for Efficient Membranes", *Desalination, 1,* 311 (1966).

Stenstrom, M., Davis, J., Lopez, J., and McCutchan, J., "Municipal Wastewater Reclamation by Reverse Osmosis - A 3-year Case Study", *Journal WPCF, 54,* 43 (1982).

Strathmann, H., and Michaels, A., "Polymer-Water Interaction and Its Relation to Reverse Osmosis Desalination Efficiency", *Desalination, 21,* 195 (1977).

Strathmann, H., "Synthetic Membranes and Their Preparation" in *Handbook of Industrial Membrane Technology,* M. Porter, ed., pp. 1-60, Noyes Publications, Park Ridge, NJ (1990).

Stürken, K., Peinemann, K., Ohlrogge, K., and Behling, R., "Removal of Organic Pollutants from Gaseous and Liquid Effluent Streams by Membranes", *Water Science and Technology, 24,* 1 (1991).

Sudak, R., "Reverse Osmosis" in *Handbook of Industrial Membrane Technology,* M. Porter, ed., pp. 260-306, Noyes Publications, Park Ridge, NJ (1990).

Suzuki, M., *Adsorption Engineering,* Elsevier, New York (1990).

Suzuki, Y., and Minami, T., "Technological Development of a Wastewater Reclamation Process for Recreational Reuse: An Approach to Advanced Wastewater Treatment Featuring Reverse Osmosis Membrane", *Water Science and Technology, 23,* 1629 (1991).

Tam, C., Matsuura, T., and Tremblay, A., "The Fractal Nature of Membranes", *Journal of Colloid and Interfacial Science, 147,* 206 (1991).

Tan, L., and Amy, G.L., "Comparing Ozonation and Membrane Separation for Color Removal and Disinfection By-Product Control", *Journal AWWA,* 74 (May 1991).

Tan, L., and Sudak, R., "Removing Color from a Groundwater Source", *Journal AWWA,* 79 (January 1992).

Taylor, J., Thompson, D., and Carswell, J., "Applying Membrane Processes to Groundwater Sources for Trihalomethane Precursor Control", *Journal AWWA,* 72 (August 1987).

Taylor, J., Mulford, L., and Duranceau, S., "Cost and Performance of a Membrane Pilot Plant", *Journal AWWA,* 52 (November 1989a).

Taylor, J., Durancean, S., Mulford, L., Smith, D., and Barrett, W., "SOC Rejection by Nanofiltration", *EPA Report,* EPA/600/2-89/023 (1989b).

Terril, M., and Neufeld, R., "Reverse Osmosis of Blast-Furnace Scrubber Water", *Environmental Progress, 2,* 121 (1983).

Thiel, S., and Lloyd, D., "Frictional and Osmotic Effects in the Pressure Driven Membrane Separation of Dilute Solutions", *Journal of Membrane Science, 50,* 131 (1990).

Thorsen, T., "Recovery of Phosphoric Acid with RO", *Desalination, 53,* 217 (1985).

Treffry-Goatley, K., Buckley, C., and Groves, G., "Reverse Osmosis Treatment and Reuse of Textile Dyehouse Effluents", *Desalination, 47,* 313 (1983).

Tsuge, H., and Mori, K., "Reclamation of Municipal Sewage by Reverse Osmosis", *Desalination, 23,* 123 (1977).

van den Berg, G., and Smolders, C., "Diffusional Phenomena in Membrane Separation Processes", *Journal of Membrane Science, 73,* 103 (1992).

Verschueren, K., *Handbook of Environmental Data on Organic Chemicals,* Van Nostrand Reinhold, New York (1983).

Vinogradov, S., and Linnell, R., *Hydrogen Bonding,* Van Nostrand Reinhold, New York (1971).

Wäsche, M., Lippitz, A., Pinnow, M., and Kunze, R., "An XPS Study of Poly(vinylidene fluoride) Surfaces Irradiated by Low Energy Argon Ions", *Acta Polymerica, 39,* 403 (1988).

Watson, B., and Hornburg, C., "Low-Energy Membrane Nanofiltration for Removal of Color, Organics and Hardness from Drinking Water Supplies", *Desalination, 72,* 11 (1989).

Wiley, A., Dambruch, L., Parker, P., and Dugal, H., "Treatment of Bleach Plant Effluents: A Combined Reverse Osmosis/Freeze Concentration Process", *TAPPI, 61,* 77 (1978).

Williams, M., "Separation and Purification of Dilute Hazardous Organics by Ozonation-Low Pressure Composite Membrane Process", M.S. Thesis, D. Bhattacharyya, Director, Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky (1989).

Williams, M., "Measurement and Mathematical Description of Separation Characteristics of Hazardous Organic Compounds with Reverse Osmosis Membranes", Ph.D. Dissertation, D. Bhattacharyya, Director, Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky (1993).

Williams, M., Deshmukh, R., and Bhattacharyya, D., "Separation of Hazardous Organics by Reverse Osmosis Membranes", *Environmental Progress, 9,* 118 (1990).

Williams, M., Bhattacharyya, D., Ray, R., and McCray, S., "Selected Applications", in *Membrane Handbook,* W.S.W. Ho and K.K. Sirkar, ed., pp. 312-354, Van Nostrand Reinhold, New York (1992).

