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Water Supply Development for Membrane Water Treatment Facilities

Thomas M. Missimer

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With a description of the membrane process design
by

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To my grandfather, Jacob M. Missimer, Sr. (1907–   ),
who taught us the meaning of work ethic by example.

Preface

Drinking water quality has become a subject of great public concern over the past 10 years. As sources of good quality water have become depleted, and the discovery of cancer-causing compounds in treated water has occurred, it has become necessary to use new technology to treat water to acceptable standards for human consumption. Membrane technology will be the treatment technology of preference in the future because it is both cost-competitive with conventional treatment methods and produces potable water that meets all primary and secondary drinking water standards. Membrane technology can be used to desalinate nearly any quality of water ranging from brackish to seawater to create water supplies from previously unusable sources.

There are currently some manuals available for the design of membrane treatment plants and the membrane process design. However, there is no comprehensive text oriented toward the development of water sources for membrane treatment facilities. If the water supplies are not designed with knowledge of the membrane process, errors commonly occur that cause the unnecessary waste of both construction and operating monies. The purpose of this book is to provide the knowledge necessary to design an efficient feedwater supply for any type of membrane treatment facility. The information provided in this text was accumulated over a period of about 20 years of experience in the design of water supplies and from the experience of system operators throughout the world as communicated to the author.

This book is written using terminology that should be understandable to engineers, hydrogeologists, utility directors, water treatment plant operators, and various other professionals involved in the water treatment industry. The book is organized into seven sections, each covering a single aspect of design and operation of membrane facilities. Section 1 contains a summary of current uses of membrane water treatment technology. Section 2 is a summary of how the membrane process works in terms of the physics and chemistry of the water and the process. There is an explanation of the sensitivities of membrane systems to various ions and compounds. Section 3 covers the design aspects of surface water sources including the type of source and the corresponding infrastructure design. Section 4 is a comprehensive treatment of groundwater supply development including information on wellfield design, production well design, operations, and problem solutions. Section 5 covers the new concept of aquifer storage and recovery as applied to making membrane treatment facilities more efficient. Section 6 is a discussion of concentrate disposal (wastewater) from membrane treatment facilities. Section 7 contains the operational and design histories of three membrane treatment facility wellfields located at Sanibel Island, Florida; Cape Coral, Florida; and Dare County, North Carolina. The book is subdivided into these subject areas so that any professional involved in the design or operation of a membrane treatment facility can easily find the information desired based on the type of raw water source or the problem encountered.

The author gratefully acknowledges the critical reviews made by distinguished engineers, hydrogeologists, chemists, and water treatment plant operators on all chapters of this book. Section 1 was reviewed by Mr. Ian Watson of Boyle Engineering Corporation and Mr. W. Kirk Martin of ViroGroup, Inc. Section 2 was reviewed by Mr. Lloyd E. Horvath of ViroGroup, Inc. Section 3 was reviewed by Mr. Donald Hornberg of Water Consultants International, Mr. Lloyd E. Horvath of ViroGroup, Inc., and Mr. Ian Watson of Boyle Engineering Corporation. Section 4 was reviewed by Dr. Charles Walker, Mr. Brian Peck, Mr. Akin Owosina, Mr. Dan Acquaviva, and Mr. W. Kirk Martin of ViroGroup, Inc., and Mr. Richard Derowitsch of the Island Water Association, Inc. Section 5 was reviewed by Dr. Charles Walker and Mr. W. Kirk Martin of ViroGroup, Inc. Section 6 was reviewed by Mr. William J. Conlan of Camp, Dresser & McKee, Inc. and Mr. Ian Watson of Boyle Engineering Corporation. Section 7 was reviewed by Dr. Charles Walker and Mr. W. Kirk Martin of ViroGroup, Inc., Mr. Richard Derowitsch of the Island Water Association, Inc., Mr. David D. Kuyk and Mr. Steven K. Kiss of the City of Cape Coral, Florida, and Mr. Robert Oreskovitch of Dare County, North Carolina.

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Thomas M. Missimer
Fort Myers, Florida
May 1993

The Author

Thomas M. Missimer is the President and Principal Hydrogeologist of Missimer International, Inc., a groundwater and environmental consulting firm. Mr. Missimer received his M.S. in geology at Florida State University in 1973 and a B.A. in geology from Franklin & Marshall College in 1972. He is currently completing his Ph.D. in marine geology and geophysics at the Rosenstiel School of Marine and Atmospheric Science, University of Miami. Mr. Missimer began his professional career with the U.S. Geological Survey as a hydrologist in 1973. In 1975, he left the U.S. Geological Survey to become a Research Associate at the University of Miami where he remained for one academic year. In May 1976, he co-founded Missimer & Associates, Inc. He served as President of Missimer & Associates, Inc. until May 1991. Mr. Missimer co-founded Missimer International, Inc. in December, 1993.

Mr. Missimer has published numerous papers in technical journals and chapters in books. His project and research experience includes the analysis, permitting, and design of many public water supply wellfields, hydrogeologic analysis and modeling, and environmental auditing. In 1991, he was given the Best Paper Presentation Award at the World Conference on Desalination and Water Reuse by the International Desalination Association. Florida Governor Lawton Chiles appointed Mr. Missimer to the State Board of Professional Geologists for a 4-year term beginning in December 1991.

Mr. Missimer has served on numerous governmental advisory committees. He was elected Chairman of the Earth and Planetary Sciences section of the Florida Academy of Sciences in 1976 and 1977. He served on the national steering committee on environmental site assessments for the Association of Groundwater Scientists and Engineers. He is a member of many professional societies including the Geological Society of America, the American Water Works Association, and the Americal Desalting Association.

Ian C. Watson

Ian C. Watson is one of the foremost authorities in the world on the subject of membrane water treatment process design. He is a Principal Chemical Engineer and Director of Membrane Process Engineering with Boyle Engineering Corporation.

Mr. Watson has a degree in Chemical Engineering from Neath College of Technology, South Wales, Great Britain. He was formerly founder and President of Rostek Services, Inc.

Mr. Watson has been the principal designer of the process engineering for many of the world's largest membrane treatment facilities. Some of these facilities include: the City of Fort Myers, Florida membrane softening plant (12 MGD; 45,425 m^3/day), Collier County, Florida membrane treatment plant (12 MGD; 45,425 m^3/day), Sarasota County, Florida electrodialysis reversal brackish water plant (12 MGD; 45,425 m^3/day), and numerous others. He has been responsible for numerous innovations in membrane technology including: the use of a programmable controller as the primary control device in an RO plant for the first time (Sanibel, Florida), first plant to exceed 75% recovery in two standard length stages (Sanibel, Florida), largest low pressure RO plant in the world at the time of 7 MGD (26,498 m^3/day), and the first application of variable frequency drives for RO feed pump discharge pressure control (Dare County, North Carolina).

For his work in membrane treatment process design, Mr. Watson received an ACEC Honor Award for Excellence in Engineering for a 3.8 MGD (14,385 m^3/day) EDR plant at Suffolk, Virginia and was named "Water Man of the Year" by the Americal Desalting Association in 1990.

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Water Supply Needs and Changing Technology

Chapter 1

Population Growth and Freshwater Supply Depletion

Water is a fundamental requirement for all living things on the earth. Prior to the evolution of man, the balance between the population of living flora and fauna and the environment was controlled by climate and changes in water supply. When one area changed from a tropical rain forest to a desert, the plant and animal population either moved or became extinct. When pollution of surface water sources occurred from natural processes such as volcanic eruptions, dust storms, or natural oil seeps, the living biota dependent on that particular water source either moved or died.

The emergence of man on the earth has had a pronounced effect on the natural order of succession and on fundamental changes in the supply of water with time. Thousands of years ago, when the human population was relatively small, population concentrations occurred adjacent to sources of water supply, which were predominantly rivers and streams. The earliest users of groundwater were perhaps nomadic tribes of the Middle East, who utilized hand dug wells, or perhaps one of the Chinese cultures that constructed wells by jetting bamboo into loosely consolidated sediment. Regardless of which source of water was used by ancient populations, when the source of water failed, the population either moved or died. Therefore, the natural system of the earth still maintained control over the numbers and locations of human population centers.

As the population of the earth grew and the early population centers became the ancient nuclei of modern cities, water supply was still a major factor limiting growth. With a decline in water supply or contamination of the water supply with waste, the population centers were ridden with disease, or mass migration occurred. The real carrying capacity of a given population center was related more to water supply than any other factor.

A major change in the demographics of the population occurred when the water supplies were artificially supplemented by transporting water to population centers. Perhaps credit for the engineering of the first major water supply infrastructure should go to the Romans for construction of the aqueduct system. From the founding of the city of Rome in about 754 B.C. until 313 B.C., the water supply for the city was obtained from the Tiber River, springs, or local wells (Frontinus, 97 A.D.; Herschel, 1973). Under the leadership of M. Valerius Maximus and P. Decius Mus, water was first brought into the city via the Appian Aqueduct.

Upon acquisition of knowledge on how to bring water supplies to a fixed population, the natural "carrying capacity of the earth" to limit the size of population centers on the basis of water supply would be forever altered. Growth of population centers would become limited only by the ability to mass transfer water or by water treatment economics.

Perhaps the most important advancement in water supply technology after the invention of the mass transfer of water was water treatment to prevent disease. Water treatment technology of a "conventional nature" was used beginning in the late 1800s to the present day with only minor changes in the processes. Conventional water treatment processes were capable of converting only freshwater into potable water. The most important advancement in water treatment in the last 50 years was the ability to economically desalt water to produce potable freshwater from either brackish or seawater sources. The dawn of the desalination age rendered the concept of population carrying capacity based on water supply as obsolete. The primary potable water supply limitation of the 21st century will be that of fundamental economics and not raw water supply.

Chapter 2

Membrane Water Treatment and Technology Improvement

CONTENTS

INTRODUCTION

Reverse osmosis is the process of forcing water through a semipermeable membrane against the natural osmotic gradient (Merten, 1966; Belfort, 1984; Rautenbach and Albrecht, 1989). When water is forced through the membrane, a large percentage of the dissolved salts and other material in the water are removed from the water with the permeate being relatively pure water. The first reverse osmosis membranes were constructed of cellulose acetate at the University of Florida in 1959. Over the 34-year period since the first membrane desalination experiments were completed, numerous technical advances have been made in the membrane materials and in the efficiency of the process in terms of reduced pressure and increased potable water production rates. There are currently membranes available that can be used to treat a wide range of water quality types from organic-laden freshwater to hypersaline seawater.

Membrane-process water treatment has become increasingly more important as the result of major declines in the availability of economically treatable freshwater. The lack of resource availability in conjunction with more stringent potable water quality standards has altered the historical approach to the development and treatment of public water supplies. The cumulative capacity of all land-based desalination plants larger than 100 m^3/day (26,420 gpd) has increased from near 0 in 1959 to over 15 million m^3/day (3.96 billion gpd) in 1991 (Wangnick Consulting Engineers, 1992). Of this total capacity, about 18% of the water is treated by the reverse osmosis or membrane treatment process.

Reverse osmosis water treatment has been shown to be an economic method of desalting water when necessary or removing large organic molecules that are precursors to the formation of carcinogenic compounds during conventional disinfection. Four general areas of membrane treatment applications are being rapidly pursued: (1) desalination of brackish water or seawater in the coastal zone or on islands, (2) desalination of various waters in the desert or interior locations, (3) the removal of organic compounds in the treatment of highly colored surface water or groundwater, and (4) special water treatment projects, such as domestic wastewater recycling and various industrial or agricultural applications. As technology improves and the cost of membrane water treatment declines, large scale application of this process may be used to provide water for agriculture or major industries.

COASTAL ZONE AND ISLAND WATER SUPPLIES

The population of the United States and other countries has tended to concentrate in the coastal areas. Although the coastal plain is a desirable place to live, the development of public water supplies is complicated by the proximity to tidal saline waters and the corresponding occurrence of saline water in the groundwater system. In the past, most coastal communities relied upon freshwater occurrences, such as rivers, lakes, natural springs, or shallow aquifers, as the primary water supply sources. Some of these sources were severely affected by seasonal variations in rainfall or extended drought conditions. Fluctuations in rainfall coupled with increased pumpage has caused many coastal aquifers to become progressively more saline with time as the freshwater is replaced by seawater.

Development of membrane technology has created an economic alternative to treat saline water as opposed to the construction of expensive pipelines and reservoirs. A large number of reverse osmosis water treatment facilities have been constructed in various coastal settings in the United States, the Middle East, and in other parts of the world. Some examples of these facilities are given in Table 2.1, and a more complete inventory is maintained by the International Desalination Association (Wangnick Consulting Engineers, 1992). Most of the facilities listed treat either seawater or brackish water obtained from groundwater sources, and one

Table 2.1. **Coastal Zone Examples of Membrane Treatment Facilities**

Location	Water Type	Source	Size (mgd)
City of Cape Coral, FL	Brackish	Groundwater	15.000
City of Sarasota, FL	Brackish	Groundwater	4.500
Indian River County, FL	Brackish	Groundwater	3.000
City of Venice, FL	Brackish	Groundwater	4.000
City of Englewood, FL	Brackish	Groundwater	2.500
Venice Gardens, FL	Brackish	Groundwater	1.500
Acme Improvement District, Palm Beach County, FL	Brackish	Groundwater	1.800
Greater Pine Island Water Association, Lee County, FL	Brackish	Groundwater	0.825
North Beach Water Company (Now Indian River County)	Brackish	Groundwater	1.000
Jeddah 4, Saudi Arabia	Seawater	Surface	15.000

Table 2.2. **Examples of Membrane Treatment Facilities on Islands**

Location	Water Type	Source	Size (mgd)
Island Water Association Sanibel Island, FL	Brackish	Groundwater	3.0
Dare County, NC (Kill Devil Hills)	Brackish	Groundwater	3.0+
Malta	Seawater	Groundwater	6.0+
Florida Keys Aqueduct Authority Key West, FL[a]	Seawater	Groundwater	3.0
Al Dur, Bahrain	Seawater	Groundwater	12.0
Grand Cayman Island, Brittania[b]	Seawater	Groundwater	0.2
Ocean Reef Club, Key Largo, FL	Brackish	Groundwater	1.0

[a]Facility on standby.
[b]Part of use for irrigation.

facility utilizes a surface water intake. The largest constructed potable water supply system utilizing membrane treatment technology in the United States today is the city of Cape Coral, Florida (see Chapter 17 case study).

Reverse osmosis water treatment technology has been used for many years to provide potable water to natural and man-made islands completely surrounded by seawater. Some examples of membrane treatment facilities located on islands are given in Table 2.2. Many of these facilities treat seawater obtained through various types of surface water intake systems or through the groundwater system.

Regardless of the source of water for the coastal or island treatment facilities, the key to the successful operation of a membrane treatment plant is the stability of water quality. Because of the natural dynamics of the coastal zone, where freshwater and seawater tend to mix in both the surface water and groundwater systems, it can be most difficult to develop a water supply source of constant or predictable quality.

The methodology required to minimize feedwater quality problems is fully explained in this book.

INLAND AND DESERT AREA WATER SUPPLIES

There are many areas of the world where rainfall is severely limited, but there are sources of saline water deep within the earth. One of the only viable methods of providing fresh, potable water in these areas is membrane treatment. Some examples of desert membrane treatment applications are given in Table 2.3. The largest potable water applications are located within the Middle East with the world's largest municipal brackish feedwater membrane treatment facilities located at Riyadh and Buwayb, Saudi Arabia and the largest seawater membrane treatment facility at Jeddah 4.

Table 2.3. **Examples of Membrane Treatment Facilities in Desert or Interior Areas**

Location	Water Type	Source	Size (mgd)
Yuma, AZ[a]	Brackish	Surface Water	72.0
City of Nevada, MO	Brackish	Groundwater	2.0
Unayzah, Saudi Arabia	Brackish	Groundwater	13.7
Riyadh, Saudi Arabia	Brackish	Groundwater	17.5
Buwayb, Saudi Arabia	Brackish	Groundwater	15.0

[a]Colorado River Project (Mexico Treaty).

Within the United States, there are relatively few interior applications of potable water membrane treatment on a large scale, although many small potable systems utilize the reverse osmosis treatment method. Various locations within the interior of the United States, not necessarily located in desert regions, do have problems with a lack of a freshwater supply source. One example is the city of Nevada, Missouri, which must utilize a brackish groundwater source and reverse osmosis water treatment. There are other examples, such as Brighton, Colorado; Granbury, Texas; and Buckeye, Arizona.

ORGANIC COMPOUNDS AND HARDNESS IN WATER SUPPLIES

Drinking water quality standards have become progressively more stringent over the last 20 years. One of the most costly and tiresome standards to meet by conventional methods is the control of a group of compounds known as trihalomethanes (THMs). These compounds commonly form from the reaction of natural organic compounds in the raw water source with chlorine during the disinfection process. The maximum concentration level (MCL) for total THMs is presently 100 parts per billion, but may be lowered in the United States by the Environmental Protection Agency (EPA) over the next 10 years to as low as 25 parts per billion. The uncertainty of this future standard has convinced many utilities to build new membrane treatment facilities to replace "conventional" water treatment facilities or to supplement existing facilities by diluting THM concentrations produced at conventional water treatment facilities and to add flexibility to the facilities systems (i.e., Fort Myers, Florida; Plantation, Florida; Collier County, Florida).

It has been found that membrane processes are extremely effective in the removal of organic precursors in both groundwater and surface water sources (Taylor, Thompson, and Carswell, 1987; Edwards, Watson, and McKenna, 1988; Lozier and Carlson, 1991; Tan and Sudek, 1992; Blau and others, 1992). Based on numerous pilot studies and economic evaluations, several major membrane treatment facilities are either under design or construction to treat freshwater with organic compound problems (Table 2.4). This application of membrane treatment technology will be greatly expanded over the next 10 years.

There are a class of membranes that can be used to selectively remove larger ions from raw water. The removal of hardness from water can be accomplished using the membrane softening process (Duranceau, Taylor, and Mulford, 1992; Conlon and McClellan, 1989). A number of other compounds can be selectively removed using either the membrane softening or the nanofiltration process (Cheryan, 1986; Blau and others, 1992). The mem-

Table 2.4. **Examples of Membrane Softening Applications for Removal of Organics from Freshwater Sources**

Location	Water Source	Size (mgd) (Initial)
City of Fort Myers, FL	Surface water (modified recharge)	12
Palm Beach County, FL[a]	Groundwater	6
City of Boynton Beach, FL[a]	Groundwater	4
City of Hollywood, FL[a,b]	Groundwater	20
City of Plantation, FL	Groundwater	12
Palm Coast Utilities, FL	Groundwater	2
Collier County, FL	Groundwater	12

[a]All facilities under construction.

[b]14 mgd softening, 6 mgd brackish RO.

brane softening process can be used to replace the conventional lime softening process providing a more cost-effective level of treatment when high organic compound concentrations are present in the water.

SPECIAL WATER TREATMENT APPLICATIONS

Water reuse is becoming a more accepted practice and in fact is absolutely necessary, particularly in areas where even brackish water is in short supply. Reverse osmosis is one of the processes being used to treat domestic wastewater to potable water quality for direct or indirect reuse. The city of Denver, Colorado is considered to be one of the leaders in the field of converting domestic wastewater to potable water (Lauer, Rogers, and Ray, 1985; Lauer, 1991). Many other cities in the western United States are considering the direct reuse of treated domestic wastewater for potable supply. Indirect reuse of treated wastewater, using the reverse osmosis process (along with others), has been a part of the water management plan for Orange County, California for many years (Argo and Sudak, 1981).

Membrane technology is also currently being utilized to treat substantial quantities of water to potable standards for multiple uses including human consumption. An example of this application involves the largest reverse osmosis desalination facility in the world at Yuma, Arizona (72 mgd). By treaty, the United States must deliver to Mexico specific quality water in the Colorado River. A combination of the natural salinity of the river at its source (saltwater springs) and the high salinity of return flow from various agricultural projects has caused the United Sates to construct a very large membrane treatment facility at Yuma, Arizona to desalinate the irrigation return flows. Upon completion, this 72-mgd facility will be the world's largest membrane treatment application to be used for a combination of both potential potable supply and irrigation requirements.

Reverse osmosis technology is also being used to help clean up contamination of groundwater that could be used for potable water supply (Baier et al., 1987). The removal of metals, pesticides, and other compounds from groundwater can be accomplished using membrane technology.

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