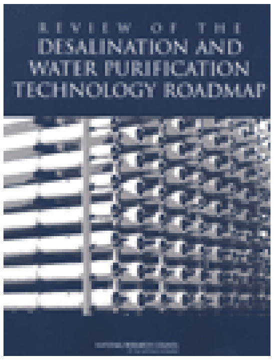

Review of the Desalination and Water Purification Technology Roadmap

Committee to Review the Desalination and Water Purification Technology Roadmap, National Research Council

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REVIEW OF THE DESALINATION AND WATER PURIFICATION TECHNOLOGY ROADMAP

Committee to Review the Desalination and Water Purification Technology Roadmap

Water Science and Technology Board

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
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[1] The activities of this committee were overseen and supported by the NRC's Water Science and Technology Board (see Appendix B).

Preface

Water is a nutrient vital to human life, just as it is a fundamental element in the economic vitality of any country. In arid regions across the globe, people have long depended upon desalination to supplement limited fresh water resources despite its historically high costs. Based on recent decreases in the costs of desalination, this technology is increasingly being considered to expand existing water supplies in the United States as local regions are facing water shortages.

The Desalination and Water Purification Technology Roadmap (Roadmap), developed by the Bureau of Reclamation and Sandia National Laboratories, has identified desalination and water purification technologies as one component of the solution to the nation's future water needs. The Roadmap was developed to present "broad research areas that are representative of the types of scientific and technical advances that will be necessary for desalination and water purification technologies to find wide acceptance" (USBR and SNL, 2003). The Roadmap will be used to guide desalination research and investments in the United States, in hopes of contributing to a water supply that is safe, sustainable, affordable, and adequate.

This report is a product of the Committee to Review the Desalination and Water Purification Technology Roadmap, which was organized by the National Research Council (NRC) upon request by the Bureau of Reclamation. The committee was charged to review the Roadmap and produce two reports. An interim letter report (see Appendix A) was produced in June 2003 that addresses whether or not the Roadmap represents an appropriate and effective course to help address future freshwater needs in the United States. In this final report, all remaining questions of the statement of task (see Chapter 1) are addressed. Broadly, the committee evaluated the research areas presented in the Roadmap and presented general priorities for investments. Issues of implementation are also discussed.

The NRC composed a committee representing a range of expertise in desalination technology, environmental engineering, water resources planning, and public health. The findings of the committee are based on their own expertise as well as discussions with some of the creators of the Desalination and Water Purification Technology Roadmap and experts in the desalination field during two information gathering meetings. The committee is grateful to the many individuals who provided information to assist in the completion of this study, including the following people who made presentations to the committee: James Birkett, Peter Fox, Michael Gritzuk, Shannon Cunniff, Drew Downing, Lisa Henthorne, Michael Hightower, Thomas Hinkebein, Thomas Jennings, Jack Jorgenson, James Lozier, Jerry Maxwell, Wade Miller, John Pellegrino, Kevin Price, and Robert Reiss. This report is also based on analysis of the Roadmap and is supplemented by review of pertinent peer-reviewed literature.

I would like to thank and express my appreciation to our committee members for recognizing the high priority of this effort and for dedicating their time and talents to produce this report on an accelerated schedule. We were guided in our efforts by the Water Science and Technology Board and its director Stephen Parker. Study directors Stephanie Johnson and Mark Gibson set the pace, focus, and agenda for our work, maintained contact with the study sponsor, and acted as liaison to ensure compliance with NRC policies. Stephanie and Mark worked tirelessly to assemble and edit the two reports, making sure that the final product represented our best thinking and advice. Jon Sanders, senior project assistant, provided project support including meeting logistics, research assistance, and help with editorial tasks.

This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with the procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report: Mr. Leon Awerbuch, Leading Edge Technologies, Ltd.; Mr. James Birkett, West Neck Strategies, Inc.; Dr. Menachem Elimelech, Yale University; Ms. Virginia Grebbian, Orange County Water District; Dr. Bruce Macler, U.S. Environmental Protection Agency; Mr. Thomas Seacord, Carollo Engineers; and Dr. Rhodes Trussell, Trussell Technologies, Inc. Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. Henry Vaux, Jr., University of California, Berkeley. Appointed by the National Research Council, he was responsible for making certain that an independent examination of the report was carefully carried out in accordance with the institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

David Marks
Chair

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APPENDIXES

Executive Summary

In order to maintain economic development and minimize future regional and international conflicts, the United States will need sustainable supplies of high-quality fresh water. Solutions to local water scarcity issues will likely require a combination of approaches, including demand management, improved water storage capacity, water quality protection, and advancements in supply-enhancing water treatment technologies. Desalination technologies can create new sources of freshwater from otherwise impaired waters such as seawater or brackish water. However, like nearly all new fresh water sources, desalinated water comes at substantially higher costs than today's existing water sources, keeping these technologies out of the reach of many communities.

The Bureau of Reclamation and Sandia National Laboratories jointly developed the *Desalination and Water Purification Technology Roadmap* (Roadmap) to serve as a strategic research pathway for desalination and water purification technologies to "contribute significantly to ensuring a safe, sustainable, affordable, and adequate water supply for the United States" (USBR and SNL, 2003). Critical objectives for desalination technology advancement were determined, and research topics were identified in the technology areas of membranes, thermal technology, alternative technologies, concentrate management, and reuse and recycling. The Roadmap will be used within the Bureau of Reclamation as a planning tool to facilitate science and technology investment decisions and as a management tool to help structure the selection of desalination research, development, and demonstration projects. The Bureau of Reclamation approached the National Research Council (NRC) in the fall of 2002 to request an independent assessment of the Roadmap (see Box ES-1 for the Statement of Task), and the study was carried out by a committee organized by the NRC's Water Science and Technology Board between January and December 2003. A summary of the committee's findings follows.

OVERARCHING REVIEW OF THE ROADMAP

Supply-enhancing technologies represent just one component in a multi-faceted strategy necessary to address future water needs. Nevertheless, a careful research and development strategy is necessary to facilitate technological advancements and nurture

BOX ES-1

Statement of Task for the Committee to Review the Desalination and Water Purification Technology Roadmap

An expert panel was organized by the National Research Council to address the following questions:

1. Does the Desalination and Water Purification Technology Roadmap present an appropriate and effective course to help address future freshwater needs in the United States?
2. Can further investments advance the implementation of desalination by significantly reducing its cost and otherwise addressing issues associated with its increased use?
3. Does the Roadmap correctly identify the key technical and scientific issues that must be resolved so that desalination can be made more cost-effective?
4. Are there any missing research areas from the Roadmap that should be included?
5. What should be the general priorities for investments?
6. What are the best roles for federal agencies, national laboratories, other research institutions, utilities, and the private sector to help implement the Desalination and Water Purification Technology Roadmap?

novel ideas that can enhance water supplies and reduce the costs of current technologies.

The Roadmap and its underlying process appear to present an appropriate framework for advancing research in several areas of desalination and water purification technology to help address future water needs across the United States, but the Roadmap document lacks an appropriate focus on desalination research and technology needs to meet the identified water supply objectives. Several recommendations are provided to support future planning efforts that develop from the Roadmapping process:

- The Roadmap should be developed to include clear, understandable logic and scientific basis for each of the critical objectives.
- The Roadmap should be developed to include analyses of recent technological advancements, descriptions of current limitations of desalination technologies, theoretical limits in ideal processes, and quantifications of baseline desalination values from which future advancements can be measured, which could provide the basis for developing a strategic research agenda for desalination.
- A subsequent research agenda should be developed that logically builds from the current state of desalination technology toward the critical objectives.

TECHNOLOGIES

The five technological areas highlighted in the Roadmap represent appropriate priorities for research and development in the field of desalination and membrane-based water purification, but these technological areas and associated research issues receive only limited attention in the Roadmap. Some important cross-cutting research areas were also not adequately addressed within the Roadmap, including energy use and air emissions from energy intensive desalination technologies. For each technology area, this report describes the cost issues and technical opportunities for contributing to desalination and reviews the related projects identified in the Roadmap. Suggested revisions to the research areas itemized in the Roadmap are provided for each of the technology areas, and these suggestions are summarized in Tables 3-1 through 3-6.

Membranes

The use of membrane processes for desalination has increased markedly in recent years, as desalination costs for reverse osmosis have declined. Considering the recent improvements in membrane-based desalination, substantial further cost savings could be more difficult to achieve, suggesting the need for a carefully developed research agenda targeted to areas that offer the most promise for cost reduction. Some of the objectives in the Roadmap will not be possible with advances in existing membrane technology alone.

The membrane research areas identified in the Roadmap cover a significant portion of the important research areas, but the committee has identified other key areas that are overlooked in the Roadmap. Research is needed to develop on-line sensors to determine the integrity of the membranes and to detect pathogens and other biological contaminants. The development of fouling resistant elements and systems, appropriate indicators of fouling, and improved cartridge filter design to reduce replacement rate could lead to reduced operational costs. Large cost savings are also possible through research to reduce the use of pre- and post-treatment chemicals. Further research should explore improved membrane process design configurations and materials to reduce costs, including dual membrane and hybrid membrane designs. The development of tailorable membrane selectivity would facilitate reliable removal of specific contaminants at an acceptable cost in terms of permeability.

Among the membrane technology areas identified in the Roadmap and those additional areas suggested by this committee, several have been designated as high priority research topics within this category:

- Improving membrane permeability.
- Improving or developing new methods for reducing energy use or recovering energy.
- Improving pretreatment and posttreatment methods to reduce consumption of chemicals.
- Developing less expensive materials to replace current corrosion-resistant alloys used for high pressure piping in seawater reverse osmosis systems.
- Developing new membranes that will enable controlled selective rejection of contaminants.
- Improving methods of integrity verification.
- Developing membranes with more fouling resistant surfaces.

Thermal

While thermal desalination is not expected to displace membrane-based desalination in the United States, thermal technologies have substantial potential and should be more seriously considered, especially when combined with other industrial applications, such as electric power generating facilities (termed cogeneration), to utilize waste heat and improve flexibility and economics. Overall, thermal desalination research intended to reduce desalination costs should focus on energy efficiency and on material or design research that could influence capital costs.

The thermal technology research topics identified in the Roadmap are generally appropriate but could be expanded and, in some cases, revised. The use of alternative energy sources, particularly waste heat sources, is a potential area for future research which could result in improved desalination economics and broader application of thermal desalination. The use of innovative cooling systems may reduce the water intake requirements and allow operation at higher concentration factors. Research to evaluate or refine nonmetallic or polymeric heat transfer materials could significantly reduce capital costs, and improvement in the efficiency of heat transfer surfaces could also reduce operating costs. Research that identifies corrosion mitigation techniques or develops innovative materials of construction that resist corrosion could improve plant economics for thermal desalination plants.

Because energy is expensive in the United States and comes with significant environmental impacts, the highest priority research topics focus on examining ways to harness wasted energy for the benefit of water production, including evaluating opportunities for cogeneration of water and power and developing alternative energy sources, including improved use of industrial waste heat.

Alternative Technologies

The Roadmap's long-term objectives for desalination cost reductions (50-80 percent by 2020) will not likely be achieved through incremental improvements in existing technologies. Such dramatic cost reductions will require novel technologies, perhaps based on entirely different desalination processes or powered by entirely new energy sources. Specific areas that could benefit from alternative technologies for cost reduction include energy, capital costs, and brine disposal. Because there are many ideas in varying states of development, it is impossible to list all the possibilities, let alone prioritize them. Although the list of alternative desalination research topics contained in the Roadmap is highly speculative in nature, it contains reasonable examples of the types of research that could be considered in a call for proposals. A research funding program to include alternative desalination technologies also would need to be open to consider new, unforeseen research areas, and all proposals should be subjected to a rigorous review process.

Reuse/Recycling

Aside from the desalination of seawater or brackish aquifers, one potential solution to the nation's water supply problem is to utilize increasingly impaired waters, such as municipal wastewaters, by applying desalination treatment technologies for contaminant removal. The starting source water qualities and the product water quality objectives for desalination are different from those of water purification by reuse/recycling, and these differences influence the research needs. The committee offers many suggestions to expand upon the research proposed for reuse and recycling in the Roadmap.

More complete identification of the contaminants present in treated wastewaters and lower analytical detection limits for contaminants are needed so that potential associations with observed health effects can be discerned. To inform the development of analytical surrogates, an improved understanding of structure-activity relationships between organic molecules and reverse osmosis membrane materials are needed. On-line contaminant monitoring tools, including tools to measure the integrity of membrane systems in real time, are also important research areas. With additional research and development to support cost reductions, membrane bioreactors could provide a higher level of treatment at comparable costs of traditional treatment, thus contributing to better public health protection in reuse applications. Several applied research efforts are proposed that could improve the applicability of water reuse and recycling. A feasibility study should be conducted on the topic of decentralization of water recycling facilities, examining regulatory monitoring and permitting issues. The water reuse industry should also review both successful and unsuccessful reuse projects and apply the lessons learned to future reuse efforts.

Among the reuse and recycling research topics identified in the Roadmap and those additional topics recommended by this committee, the following topics have been identified as high priorities:

- Developing improved techniques for identification and quantification of chemical contaminants.
- Examining the feasibility of decentralized treatment.
- Enhancing membrane bioreactor technology.
- Conducting a risk comparison between various water reuse schemes and potable water counterparts.
- Developing a set of chemical and microbiological surrogates for indirect potable reuse and developing a better understanding of the relationship between rejected solutes and the membrane.
- Developing more sensitive on-line membrane integrity monitoring systems.

Concentrate Management

Concentrate is a residual that needs to be handled in a manner that minimizes environmental impacts and protects human health. Coastal desalination plants are often able to safely dispose of saline concentrate into the ocean or estuaries at relatively modest costs. However, concentrate management can be a very large portion of the cost at inland desalination facilities, and this cost greatly reduces the economic feasibility of desalination technology at inland locations. Reducing the costs of concentrate handling would make many sources of water, especially brackish groundwater, available for use.

The committee recommends that several concentrate management research topics be added to those proposed in the Roadmap. Innovative methods are needed for dealing with silica and potentially toxic contaminants, such as arsenic and selenium. Research should explore the fate of these contaminants and the concentration at which deleterious impacts occur in concentrate management applications. Due to limits in salt concentration tolerated in the root zone and the possibility of leachate degrading ground or surface waters, crop irrigation may not be a viable option in most cases, although research is needed to further examine the limits of this disposal option. Research to evaluate methods of improving the efficiencies of near-zero liquid discharge (and possibly zero liquid discharge) could increase their areas of applicability. Cost reductions could also be gained if further research aimed to improve beneficial and sustainable reuse of desalination concentrate. For example, designs should be developed for the management of commercially valued salt solids. Additional geochemical and hydrologic research is needed for further advancement of subsurface concentrate storage.

The following high-priority research topics have been identified from those included in the Roadmap and the additional topics suggested by the committee:

- Reducing concentrate volume.
- Management/removal of toxic compounds such as arsenic.
- Improving systems for beneficial and sustainable concentrate reuse, including underground storage and management of concentrates with a total dissolved solids (TDS) level of less than 10,000 mg/L and management of commercially valued salts.

Cross-Cutting Technologies

One major research area—energy—emerged in this review of the Roadmap, which has the potential to contribute broadly to all aspects of desalination, regardless of the technology chosen. The Roadmap does not look at the broader context of energy costs, such as the contribution of fossil fuels to greenhouse gases or the effect of a large-scale desalination on the cost of energy, which could have a substantial influence on wider implementation of desalination. Research is needed to further examine these broad issues, including research on renewable energy sources, energy conservation, methods to reduce energy emissions, and life-cycle analyses for desalination and water reuse.

IMPLEMENTATION

The Roadmap does not provide an implementation strategy, and current funding levels within the federal government for non-military application of desalination are insufficient to fund research efforts that would trigger a step change in performance and cost reduction for desalination technologies. Much remains to be done to build on the efforts to date and turn these preliminary research ideas into a program for strategic research investments in the area of desalination technologies. In order to achieve the objectives of the Roadmap, the program will need adequate funding for research, involvement of talented researchers worldwide through a broadly distributed request for proposals, rigorous independent peer review of proposals, strategic awarding of research funding, and effective communication of the research findings to the desalination community. Several recommendations are provided with regard to a future implementation process:

- The Bureau of Reclamation should work collaboratively with desalination experts from different sectors to develop a strategic research agenda and to estimate the resources needed to place the nation in a likely position to reach the long-term objectives set forth in the Roadmap.
- Requests for proposals should be announced as widely as possible to scientists and engineers in government, academia, and private industry, and unsolicited proposals should also be considered in areas of innovative technologies. Proposals should be selected through a rigorous independent peer review process, utilizing a rotating panel of independent expert reviewers.
- The Bureau of Reclamation should encourage and lead the publication and communication of research activities and results through various media, including a central website on the activities and progress of the Roadmap.
- The general public should be informed about the benefits, affordability, and environmental considerations of desalination.

1

Introduction

Access to freshwater is an increasingly important national and international issue. In order to maintain economic development and minimize future regional and international conflicts, the United States will need to develop sustainable supplies of high-quality freshwater for drinking and other uses. This will require innovative water management, increased application of water conservation, and novel technologies that can "create" fresh water from nontraditional sources. Desalination technologies can create new sources of fresh water from otherwise impaired waters such as seawater or brackish water, but current financial and energy costs keep these technologies out of the reach of many communities. As a result, the U.S. Bureau of Reclamation and Sandia National Laboratories have developed a research plan to improve desalination technologies, which may lead to more cost effective water treatment so that desalination technologies can better contribute to the water supply needs in the United States.

This chapter presents an overview of current water supply needs both nationally and internationally and describes the potential contribution of desalination technologies in that context. Desalination technologies and the historic role of U.S. federal agencies and other public and private organizations in desalination research and development are discussed. The chapter also describes the origins and development of the Desalination and Water Purification Technology Roadmap (Roadmap) and summarizes the study charge and activities that led to this report reviewing the Roadmap.

WATER AVAILABILITY

Less than three percent of the world's water has a salinity content that can be considered safe for human consumption. According to the World Health Organization (WHO, 1984), total dissolved solids (TDS) should be less than 1,000 mg/L in drinking water based on taste considerations, and the EPA has set a secondary standard for TDS in drinking water of 500 mg/L (EPA, 2002). By comparison, seawater has an average TDS of about 35,000 mg/L (see Table 1-1). Thus, the vast majority of the earth's readily available water is too saline for potable use, and yet much of the world's fresh water is trapped in polar icecaps or is located far underground. It is estimated that less than one-

TABLE 1-1 Classification of source water, according to quantity of dissolved solids.

Water source	**Total dissolved solids (milligrams per liter)**
Potable water	<1,000
Mildly brackish waters	1,000 to 5,000
Moderately brackish waters	5,000 to 15,000
Heavily brackish waters	15,000 to 35,000
Average sea water	35,000

Note: Some seas and evaporative lakes can show wide variability in TDS; for example, the Arabian Gulf has an average TDS of 48,000 mg/L and Mono Lake, CA has a TDS of 100,000 mg/L. SOURCE: USBR, 2003a; Pankratz and Tonner, 2003; NRC, 1987.

half of one percent of the world's water is easily accessible and has acceptable salinity levels.

According to *Envisioning the Agenda for Water Resources Research in the Twenty-First Century* (NRC, 2001b), both in the United States and worldwide, "the principal water problem in the early twenty-first century will be one of inadequate and uncertain supplies…." Finite quantities of developed water supplies exist, and growing demand has outstripped supply in many regions of the world, including parts of the United States (see Figures 1-1 and 1-2). Traditional solutions to water scarcity have focused on developing additional supplies (e.g., drilling wells, building dams to store water that would otherwise become irretrievable). However, even when options are available for developing new supplies or transferring water from other areas where supplies are more plentiful, water development can be extremely expensive (AMTA, 2001a). Awareness has also grown over the past few decades about the negative environmental consequences of expanding water development, such as stream degradation and aquifer depletion (Gleick, 2003).

Water availability includes issues of both water quantity and quality. After all, just as drought conditions can reduce the amount of water available, reductions in water quality can diminish the available water supply for its intended use. Properly designed water treatment can transform otherwise non-usable water to usable water, thereby increasing the amount of available water. Nevertheless, as increasingly degraded waters are utilized as drinking water sources, caution is required to ensure that the treated water is safe for the general public and sensitive subpopulations to drink, considering the large number of potential contaminants that are not subject to detection by routine water quality monitoring (NRC, 1998; NRC, 2001a).

Although water supply issues in the United States are primarily local or regional in nature, the wide distribution of anticipated water shortages has elevated concern to a national level. Water management needs to be considered in a broader context since some approaches that will improve local water availability may impact the quality or quantity of water for downstream users and for the environment. For example, water transfers can increase availability on a local level by decreasing availability elsewhere where water may presently be more plentiful and of a lower economic value. Solutions to local water scarcity issues will likely require a combination of approaches, including demand management (e.g., water trading, conservation), improved water storage capacity such as aquifer storage and recovery (NRC, 2001c; NRC, 2002a), water quality protection, and

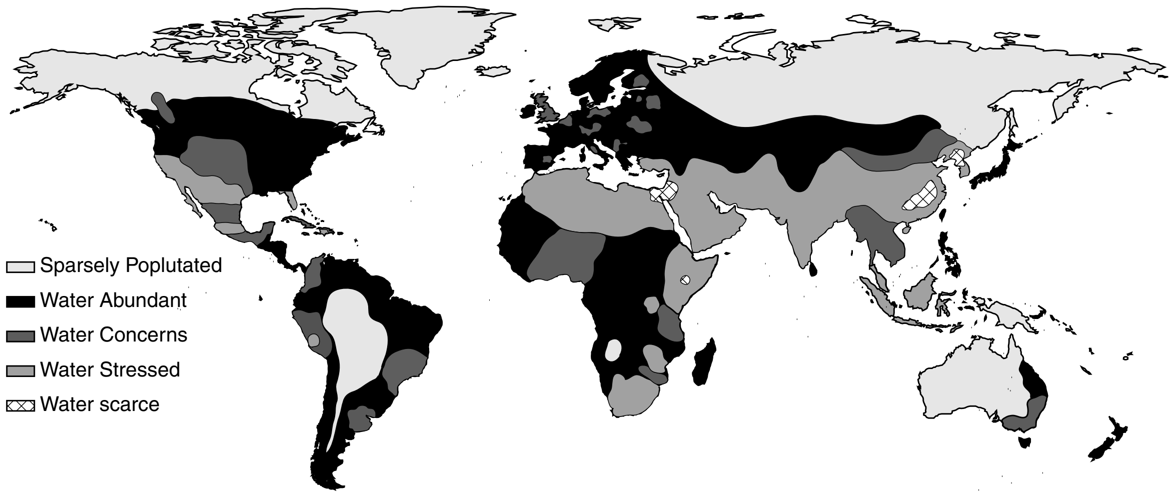

FIGURE 1-1 Estimated water availability worldwide. SOURCE: Adapted from United States Filter Corporation, 1998 (with permission).

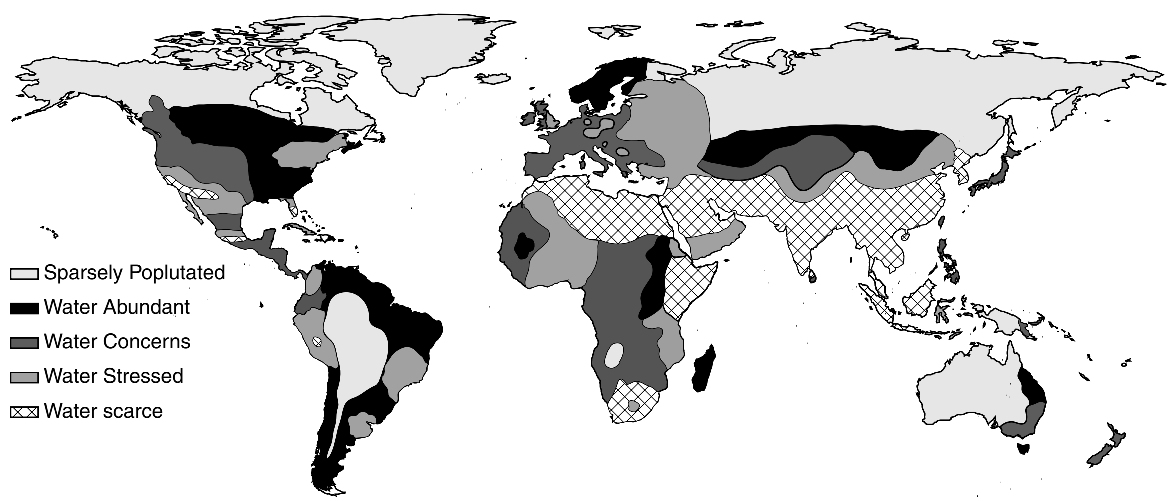

FIGURE 1-2 Projected worldwide water scarcity through 2020. SOURCE: Adapted from United States Filter Corporation, 1998 (with permission).

advancements in supply-enhancing water treatment technologies (e.g., membrane filtration for desalination or water purification). Desalination technologies offer the potential to add significantly to freshwater supplies although these supplies currently are associated with substantial energy and financial costs.

DESALINATION

In simple terms, desalination is the process of removing dissolved solids—primarily dissolved salts and other inorganic species—from water (see Box 1-1). Desalination occurs naturally in the hydrologic cycle as water evaporates from oceans and lakes to form clouds and precipitation, leaving dissolved solids behind. Historical records, including descriptions by Aristotle and Hippocrates who described its use in the fourth century B.C., show that humankind has long used basic desalination processes to create drinking water (Koelzer, 1972).

Desalination technologies and their application have grown substantially over the last fifty years. As of 1953, there were approximately 225 land-based desalination plants worldwide, with a total capacity of about 27 million gallons per day (mgd) (Evans, 1969). Advances in desalination technologies during the 1960s, including the development of reverse osmosis, led to significant reductions in the cost of desalination processes,

BOX 1-1

Desalination and Water Purification Terminology

The term *desalination* means different things to different people. By definition, desalination refers to the process of removing dissolved solids—primarily dissolved salts and other minerals—from water. The terms *desalting* and *desalinization* are frequently used interchangeably with *desalination*, although these terms have additional, alternate meanings. *Desalting* is used in food, pharmaceutical, and oil industries to describe the removal of salts from a product containing other valuable materials. The term *desalinization* also describes the removal of salts from soil, typically by leaching. For clarity, the term *desalination* is used throughout this report.

Many persons associate the term specifically with the treatment of seawater or brackish groundwater and are unfamiliar with the application of desalination technology to treat effluent in wastewater reclamation and reuse projects. Wastewater *reclamation* refers to the treatment of wastewater to water quality conditions that will allow its beneficial reuse. Modern wastewater treatment plants typically reclaim biologically treated wastewater through a final sand filtration step. These reclaimed wastewaters can then be *reused* for agricultural and landscape irrigation, or for industrial cooling purposes. *Water recycling* describes the reclamation of wastewater for on-site reuse by the same user. In contrast, the final sand filtration step may be replaced with a desalination technology such as reverse osmosis (preceded by a pretreatment step such as microfiltration or ultrafiltration) to produce much higher quality product water. Sufficient removal of dissolved solids through such a desalination process can result in *repurified* water that usually exceeds drinking water quality standards (also called *potable reuse*). *Direct potable water reuse* involves the immediate addition of repurified wastewater into the water distribution system. With *indirect potable reuse*, treated water is added to a source water storage area so that it receives additional treatment prior to consumption and provides added protection through mixing, dilution, and time for biological process to further purify the water (NRC, 1998).

enabling its broader use. By 2002, there were more than 15,000 desalination plants that had a capacity of 0.026 mgd (100 m^3/d) or larger (Wangnick, 2002). Worldwide, the combined capacity of these plants has been estimated to be 8,560 mgd, although the actual production may be less since some of these plants do not operate at full capacity. Desalination plants operate in approximately 125 countries, with seawater desalination plants contributing 59 percent of the total worldwide desalination capacity (Figure 1-3) (Wangnick, 2002). Although some arid regions depend heavily on desalination for their water supply, as of 1999, desalination plants contributed less than 0.2 percent to the world's water use (Gleick, 2000). More than 1,200 desalination plants operate in the United States, which has 16 percent of the world's total desalination capacity (Figure 1-4). These U.S. plants primarily desalinate brackish groundwater or purify water for industrial use (AMTA, 2001b).

Many different desalination technologies exist to separate dissolved salts from water, and the choice of technology used depends on a number of site-specific factors, including source water quality, the intended use of the water produced, plant size, capital costs, energy costs, and the potential for energy reuse. Thermal technologies heat seawater or brackish water to form water vapor, which is then condensed into fresh water. Membranes can be used to selectively allow or prohibit the passage of ions, enabling the desalination of water (see Chapter 3 for more detail on common desalination technologies). Although thermal technologies dominated from the 1950s until only recently, membrane processes now approximately equal thermal processes in global desalination capacity (Figure 1-5).

The U.S. government contributed significantly to the advances in desalination technology and implementation through considerable desalination research funding, beginning with the Saline Water Conversion Act (66 Stat. No. 328) of 1952. The Office of Saline Water was established in 1955, followed by the Office of Water Research and Technology (OWRT) in 1974. Over their history, these offices spent more than $1.4 billion (in 2003 dollars) for desalination research (USBR, 2003b), supporting work that

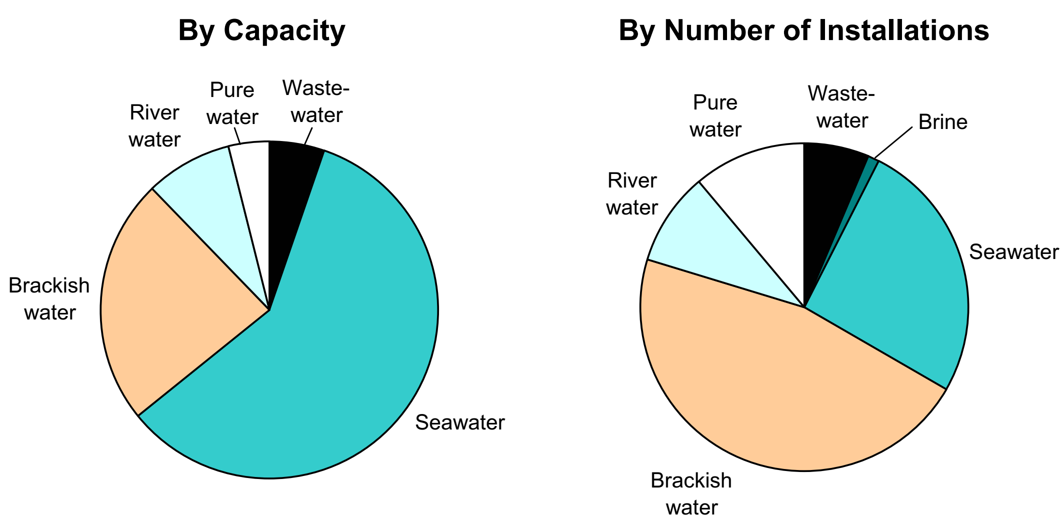

FIGURE 1-3 Charts showing portions of total desalination capacity and total number of desalination plant installations worldwide by source water. SOURCE: Wangnick, 2002.

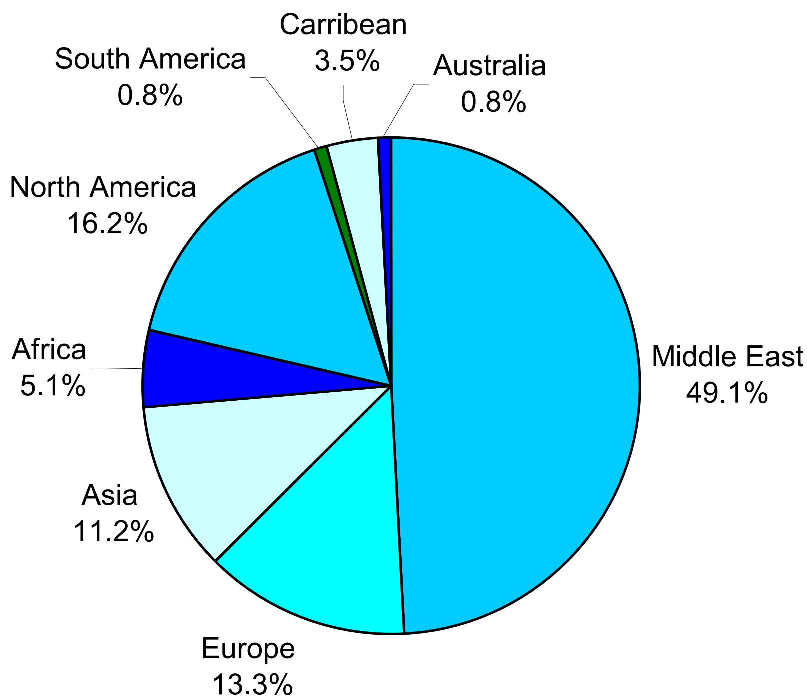

FIGURE 1-4 Chart showing fraction of the worldwide capacity of desalination plants by region. SOURCE: Wangnick, 2002.

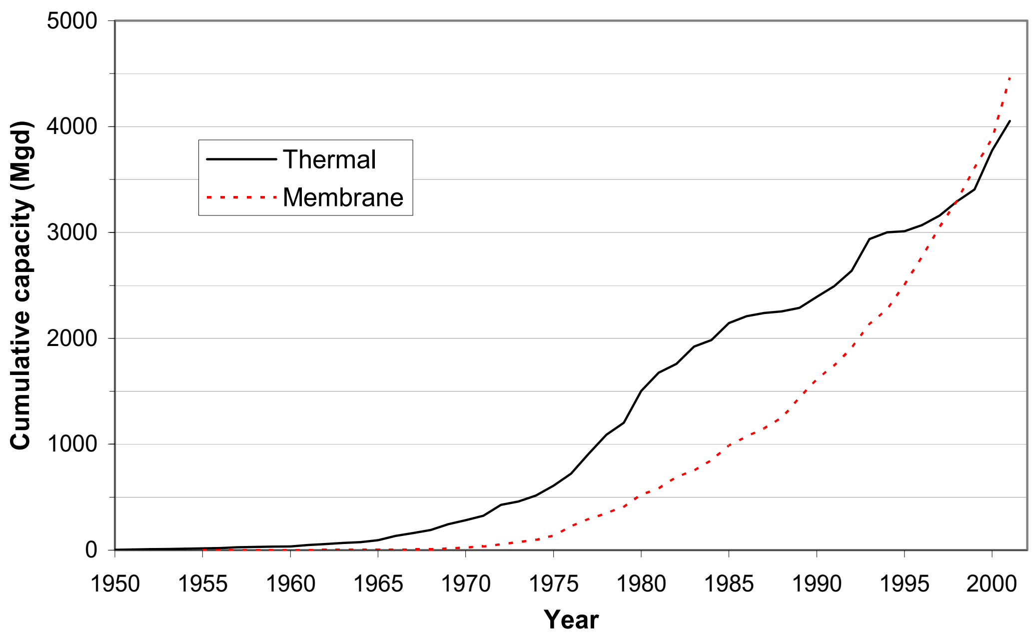

FIGURE 1-5 Chart showing total capacity of desalination plants worldwide by type of technology used. SOURCE: Wangnick, 2002.

comprises the foundation of much of today's desalination technology, including the development of reverse osmosis. In 1982, the OWRT was abolished, and the funding for water resources research was cut sharply. Although approximately $1 million per year was appropriated for the Bureau of Reclamation's Advanced Water Treatment Program, little federal support existed for desalination research for the next fourteen years until the passage of the Water Desalination Act of 1996 (Public Law Number 104-298). The Water Desalination Act authorized $5 million/year over six years for desalination research funding and an additional $25 million over six years for demonstration and development projects (Mielke, 1999). From 1996 until fiscal year 2003, a total of $14.15 million has been appropriated under the Water Desalination Act (Kevin Price, written communication, USBR, 2003). The Bureau of Reclamation developed the Desalination and Water Purification Research & Development Program to provide funding grants and cost-sharing agreements to support desalination research and development.

With modest investments in research and development from both government and industry, the costs of desalinating seawater with reverse osmosis technology have been coming down, although in most regions desalinated water remains more expensive than water from existing freshwater sources (Figure 1-6; Table 1-2). This decline in costs is attributable to the economies of scale being realized with most new plants and other technological advances. It is, however, very difficult to generalize about costs since they depend so importantly on variables that are peculiar to each site. Desalination costs include capital costs and operation costs, which can vary significantly across various locations and according to source water type (e.g., seawater, brackish water), desired

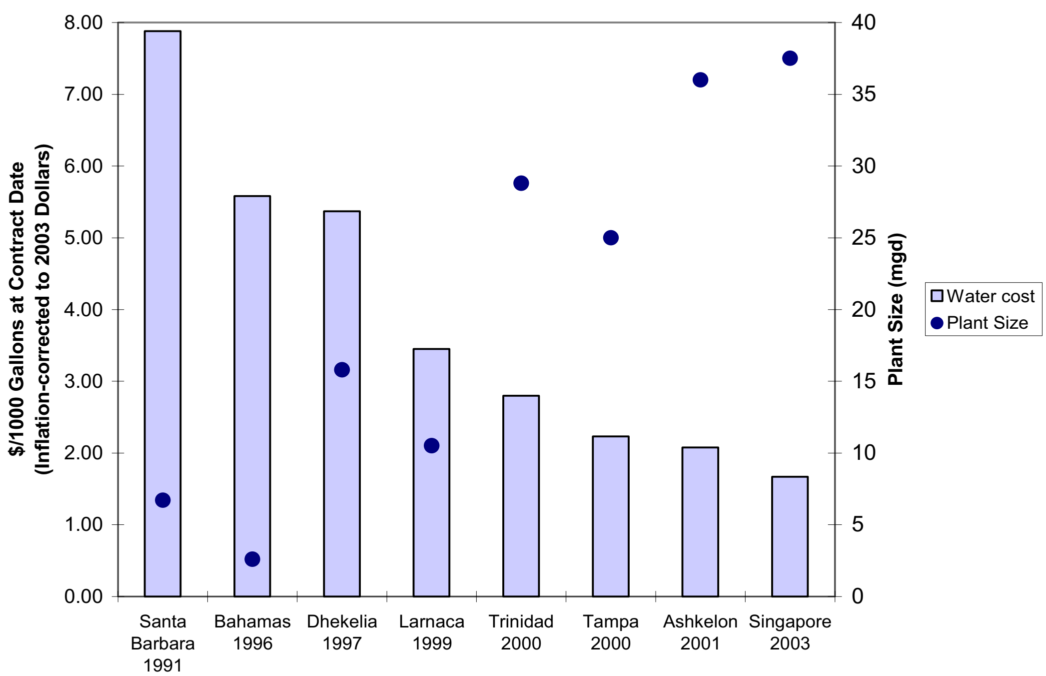

FIGURE 1-6 Recent cost reductions for seawater reverse osmosis production. The price represents the cost per 1000 gallons of water produced, and does not account for additional costs to the consumer, such as distribution (see Table 1-2). The water costs have been corrected for inflation. SOURCE: Lisa Henthorne, Aqua Resources International, personal communication, 2003.

TABLE 1-2 Water costs to consumer, including treatment and delivery, for existing traditional supplies and desalinated water.

Supply Type	Water cost to consumer $ per 1000 gallons
Existing traditional supply	$0.90-2.50
New Desalted Water:	
Brackish	$1.50-3.00
Seawater	$3.00-8.00
Combined supply:	
50% traditional supply and 50% brackish water	$1.20-$2.75
90% traditional supply and 10% seawater	$1.10-$3.05

NOTE: Cost is typical for urban coastal community in the United States, but inland desalination costs may be higher. Note that these costs will be higher than contract water costs shown in Figure 1-6, since consumer costs include fees for distribution to the customer and administrative expenses. SOURCE: AMTA, 2001a.

product water quality, and plant capacity. Regulatory issues, concentrate disposal options, and local energy costs also contribute to the overall price of desalinated water. Increased application of desalination technologies will depend upon advancements in concentrate disposal and energy efficiency (see Chapter 3), which contribute substantially to the cost-effectiveness and environmental impacts of desalination. Future penalties on emissions that adversely affect the environment could eventually add to desalination costs.

It should also be recognized that new fresh water sources come at substantially higher costs than today's existing sources, since much of the easily developed fresh surface and groundwater sources in the United States are already being utilized. When these waters are returned to their normal water courses, their water quality is less than that of the original source, as contaminants have been added through normal human activities. Water quality and economics have always been inseparable variables in water supply development. In the past, high quality source waters required minimal treatment and minimal cost to deliver as sources of domestic supply, but as these high quality source waters become scarcer, additional resources will be needed to maintain or restore water quality. While setting an objective to reduce the cost of water in future desalination and water purification projects is admirable, the true cost of water needs to be ascertained for each situation.

DESALINATION TECHNOLOGY ROADMAP

Since its creation in 1902, the Bureau of Reclamation has been a leader in water resources management and the provision of fresh water, including irrigation water, throughout the arid western states. In 2001, Congress directed the Bureau of Reclamation, in cooperation with Sandia National Laboratories, to evaluate the potential for developing an inland desalination research center in the Tularosa Basin of New Mexico (U.S. Congress Committee on Appropriations, 2001). Because irrigation of agricultural lands can contribute to increased salinity in ground and surface waters, the advancement of inland desalination research is consistent with the agency's traditional role. The central role of the proposed Tularosa Basin facility would be to evaluate and improve the design and application of desalination technologies for inland brackish waters and would include research initiatives on concentrate management and renewable energy for inland applications (SNL, 2002).

In the 2002 Energy and Water Development Appropriation Bill, Congress also suggested that a "technology progress plan" be prepared that could be used to develop the desalination research and development program at the Tularosa Basin facility. Thus, a technology roadmapping activity (the Desalination and Water Purification Technology Roadmap)[2] was initiated by the Bureau of Reclamation and Sandia National Laboratories in January 2002. An Executive Committee and a Working Group (collectively known as the Roadmapping Team) comprised of representatives from government, industry, academia, and private and non-profit sectors, including water utilities, were formed to help develop a desalination technology progress plan with a national scope beyond the inland desalination focus of the Tularosa Basin facility. A large number of researchers and managers participated in the roadmapping activity during 2002 through a series of collaborative workshops organized and conducted by Sandia National Laboratories to identify future programmatic and technical objectives for desalination. The Roadmap report (USBR and SNL, 2003) was released in February 2003 and is a product of the Executive Committee.

A technology roadmap identifies future needs for technology development, provides a structure for organizing technology programs and technology needs forecasting, and attempts to improve communication between the research and development community and end users. The Desalination and Water Purification Technology Roadmap considers itself a "critical technology roadmap" that is intended to serve as a strategic pathway for future desalination and water purification research. As described in the Roadmap, "Critical Technology Roadmaps must be responsive to the needs of the nation; must clearly indicate how science and technology can improve the nation's ability to meet its needs; and must describe an aggressive vision for the future of the technology itself" (USBR and SNL, 2003).

The Desalination and Water Purification Technology Roadmap report is structured around several national-level water needs that comprise a vision statement for the activity. These needs are to:

- provide safe water,
- ensure the sustainability of the nation's water supply,
- keep water affordable, and
- ensure adequate supplies.

From these needs (USBR and SNL, 2003), critical objectives were identified that provide metrics that can be used to gauge progress and success in both near- and long-term time horizons (Table 1-3). For example, one long-term critical objective for the national need to "keep water affordable" is to reduce desalination operating costs by 50-80 percent between 2003 and 2020. Near-term objectives were developed based on feasible improvements to current technologies, but reaching the mid- or long-term objectives will

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[2] The Desalination and Water Purification Technology Roadmap was also called the Desalination Technology Progress Plan and the Desalination Research Roadmap in previous versions of the document and related correspondence.

TABLE 1-3 Near-term and long-term critical objectives, as presented in the Roadmap.

NATIONAL NEED	Near-term Critical Objectives (2008)	Mid/long-term Critical Objectives (2010/2020)
Provide safe water	• Develop on-demand removal technologies • Remove 60% of synthetics • Microbial removal at 4-6 orders of magnitude (today's removal is 2-3 orders) • Remove endocrine disruptors, MTBE, nitrosamines, perchlorate • Develop true indicators (not just SDI and turbidity) • Surface water and land disposal: Develop science-related concentrate specific regulations related to dispersion modeling of mixing zones and ion imbalance • Subsurface injection: Large scale regional characterization of US subsurface injection capability	• Add all other concentrate specific regulations, refined geographically and addressing cumulative issues. • Demonstrate isolation with hydrologic model of receiving formation and formation scale model of subsurface injection capability of US
Ensure adequate supplies/ensure sustainability	• Decrease cost of reclaimed waters by 20% • Beneficial use: 5% of concentrate • Reduce reject to 15% for non-surface water applications • Maintain stability of reclaimed waters over time	• Decrease cost of reclaimed waters by 50% (Stretch target – 80%) • Beneficial use: 15% of concentrate • Reduce reject to 5% for non-surface water applications
Keep water affordable	• Reduce capital cost by 20% • Increase energy efficiency by 20% • Reduce operating costs by 20% • Reduce cost of ZLD by 20%	• Reduce capital cost by 50% (Stretch target – 80%) • Increase energy efficiency by 50% (Stretch target – 80%) • Reduce operating costs by 50% (Stretch target – 80%) • Reduce cost of ZLD by 50% (Stretch target – 80%)

Source: USBR and SNL, 2003.

require revolutionary technological advancements. After developing a series of critical objectives relevant to each of the needs, relevant technological areas and research projects were identified. The five technological areas considered in the Roadmap include membranes, thermal technology, alternative desalination technologies, concentrate management, and reuse and recycling. Case studies are developed to describe how future desalination technologies can help address water supply needs across the nation in coastal cities, inland urban and rural areas, the Mid-Atlantic States, and oil, gas, and coal basin communities. The Roadmap also explores two scenarios of investment in research and development for desalination and the effects on the advancement of desalination technologies. Lastly, the Roadmap identifies several broad strategic actions that will be necessary to enhance water supplies through technological advancements in desalination.

The Roadmap will be used within the Bureau of Reclamation as a planning tool to facilitate science and technology investment decisions and as a management tool to help structure the selection of desalination research, development, and demonstration projects. Proponents hope that the Roadmap also will be used by other organizations funding or conducting desalination research (including government, educational and non-profit organizations, and the private sector) to help ensure that research is coordinated and complementary.

CHARGE TO THE COMMITTEE

The Bureau of Reclamation approached the National Academies[3] in the fall of 2002 to request an independent assessment of the Roadmap. To carry out this study, a committee was formed in early 2003, overseen by the National Research Council's (NRC) Water Science and Technology Board. This report summarizes the findings of the Committee to Review the Desalination and Water Purification Technology Roadmap and addresses the following questions, which comprise the committee's Statement of Task:

1. Does the Desalination and Water Purification Technology Roadmap present an appropriate and effective course to help address future freshwater needs in the United States?
2. Can further investments advance the implementation of desalination by significantly reducing its cost and otherwise addressing issues associated with its increased use?
3. Does the Roadmap correctly identify the key technical and scientific issues that must be resolved so that desalination can be made more cost-effective?
4. Are there any missing research areas from the Roadmap that should be included?
5. What should be the general priorities for investments?
6. What are the best roles for federal agencies, national laboratories, other research institutions, utilities, and the private sector to help implement the Desalination and Water Purification Technology Roadmap?

An interim letter report released in June 2003 (NRC, 2003; see Appendix A) provided an initial assessment of the Roadmap, addressing question #1 of the Statement of Task. This report provides a summary of the findings in NRC (2003) and addresses the remaining questions of the Statement of Task. The committee's conclusions and recommendations are based on a review of the Desalination and Water Purification Technology Roadmap and relevant technical literature, information gathered at two committee meetings, and the collective expertise of the committee members. The committee's first meeting included presentations from the Bureau of Reclamation, Sandia National Laboratories, members of the Roadmapping Team, and other experts in desalination research. These presentations were intended to brief the committee on the Roadmap's development, expected uses, and follow-up activities; help frame the issues; and inform the committee of activities of other federal, state, and local entities engaged in desalination and water purification research and development.

Following this introduction, Chapter 2 provides a general assessment of the Roadmap and summarizes the findings in NRC (2003). The major technology areas for desalination are described in Chapter 3 along with the opportunities for cost reductions by further research in these areas. An additional cross-cutting technology area is also presented. The research topics proposed in the Roadmap are evaluated and general priorities are presented for each technology area. Chapter 4 presents suggestions for implementing the Roadmap.

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[3] The National Academies consists of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The National Research Council is the advisory arm of the National Academies.

Chapter 2

Overall Assessment of the Roadmap

This chapter provides a broad review of the Desalination and Water Purification Technology Roadmap (Roadmap; USBR and SNL, 2003) and summarizes the findings presented in the committee's letter report (NRC, 2003; see Appendix A), which addresses whether the Roadmap presents an appropriate and effective course to help address future fresh water needs in the United States. In this review, it is important to distinguish between the Roadmap document and the underlying process to develop, refine, and implement the Roadmap, which continues to evolve. Although the committee was specifically tasked to review the Roadmap document, several observations and suggestions are provided about the roadmapping process, since continued desalination research planning should benefit from lessons learned. This chapter also describes general recommendations to improve the effectiveness of the Roadmap. The chapter highlights concerns in the following areas: the vision statement, targets for critical research objectives, desalination technology needs, and implementation. A more detailed review of the desalination and water purification technologies presented in the Roadmap and implementation needs are provided in Chapters 3 and 4, respectively.

Desalination technologies have the potential to serve as significant components of future water supply management, and a national research plan for desalination and water purification technology is important to help meet the nation's future water needs (NRC, 2001b; NRC, 2003). As noted in Chapter 1, supply-enhancing technologies represent just one component in a multi-faceted strategy necessary to address future water needs. Nevertheless, a careful research and development strategy is necessary to facilitate technological advancements and nurture novel ideas that can enhance water supplies and reduce the costs of current technologies. The committee commends the Bureau of Reclamation and Sandia National Laboratories for leading this important research planning initiative.

An initial assessment of the Roadmap was presented in the committee's interim letter report (NRC, 2003). Because the Roadmap represents an evolving document that engages desalination experts in a process to guide desalination research investments, NRC (2003) noted "…this Roadmap and its underlying process appear to present an appropriate framework for advancing research in several areas of desalination and water purification technology to help address future water needs in all regions of the United States." Several suggestions, however, were presented to strengthen the process and focus future efforts. NRC (2003) recommended that the Roadmap emphasize *research* to support advances in technology. Much of the Roadmap is dedicated to explaining the national need for safe, adequate, sustainable, and affordable water supplies, which could be enhanced by desalination technologies. However, little attention is devoted to the actual technologies and the associated research needed to meet the identified water supply objectives.

Overall, a sharper focus on desalination research and technology and related treatment would improve the Roadmap, which loses clarity in its breadth. While water reuse and recycling utilize some of the same technologies as desalination, the field of reuse has research needs that are generally distinct from desalination technologies, especially when considering the issue of potable reuse. For lower-order reuse applications, such as landscape irrigation, desalination technologies may not be necessary. The Roadmap would be strengthened if research to support water reuse was considered separately in an initiative parallel to the development of a desalination research agenda, with each serving as a component to meet the nation's freshwater needs. Concerns were raised in NRC (2003) about the use of the term "water purification" in the Roadmap title, which includes a wide array of treatment technologies and processes that are more often related to conventional water treatment plants than to desalination or desalination pre- and post-treatment.

The committee was also tasked to evaluate whether the Roadmap presents an effective course for meeting the nation's freshwater needs. Ultimately, the effectiveness of the Roadmap and its underlying process will depend upon its future implementation, and plans for implementing the Roadmap have not yet been resolved.

VISION

The Roadmap presents a vision statement that is intended to provide motivation to the entire effort (USBR and SNL, 2003):

> By 2020, the desalination and water purification technologies will contribute significantly to ensuring a safe, sustainable, affordable, and adequate water supply for the United States.
>
> - Provide safe water. A safe water supply is one that meets all drinking water standards, meets all standards for use by agricultural and industrial interests, and that strives to move toward greater water security during drought, natural disasters, transport, and terrorist attacks.
> - Ensure the sustainability of the nation's water supply. A sustainable water supply is one that meets today's needs without jeopardizing the ability to meet the needs of future generations.
> - Keep water affordable. An affordable water supply is one that provides water to the nation's future citizenry at rates comparable to that of today.
> - Ensure adequate supplies. An adequate water supply is one that guarantees local and regional availability of water and that maintains reserves of water sufficient to endure episodic shortages such as drought.

The first sentence of the vision statement accurately reflects the contents and discussion contained in the body of the report, stating that desalination and water purification technologies will provide an important contribution to the development of water supplies that are safe, sustainable, affordable, and in adequate supply. However, inconsistent with the overall tone and direction of the remainder of the report, the expansion of the vision statement strays into water policy. For example, the text associated with "keep water affordable" suggests that research should strive to keep future water prices "at rates comparable to that of today." While there are opportunities for research to determine the true cost of water in various regions across the United States, asserting what cost is appropriate steps beyond the stated mission of the Roadmap. The text associated with "provide safe water" attempts to define safe water as that which meets drinking water standards; the text does not consider the quality of the original water sources, which could include impaired waters such as municipal wastewater, or potential adverse health effects associated with emerging contaminants, which may not be included in existing drinking water standards. Although the current vision statement provides a means to structure the Roadmap, the vision should remain focused on the research and technology efforts that could contribute to future water needs.

CRITICAL OBJECTIVES

A series of critical objectives for desalination and related water purification technologies are presented in the Roadmap. These critical objectives represent quantifications of the United States' needs in areas associated with the vision statement (see also Table 1-2). The objectives are broken down into near-term (by 2008) and mid/long-term (by 2010/2020) time frames and set metrics (or targets) for technological advancements in order to meet the nation's anticipated water needs related to providing safe water, keeping water affordable, and ensuring adequate supplies and sustainability. Additional "stretch targets" were also provided. It can be useful to connect critical objectives to such, admittedly arbitrary, time frames, but the baseline values for these critical objectives should be provided (e.g., 2003 values for desalination cost and energy efficiency for various technologies) as a point of reference to gauge future progress. It should also be noted that research initiated today is not likely to be translated into technological improvements by 2008.

The Roadmap would be substantially strengthened if the critical objectives had a logic and origin that could be readily understood. As noted in NRC (2003), "some of the targets identified do not appear well founded in science and may be unachievable." The rationale for the critical objectives in the Roadmap should be clarified and referenced to historical improvements and current and theoretical limitations for the technologies. For example, the Roadmap presents an explanation of the cost structure for reverse-osmosis desalination of seawater (see Figure 3-2) that highlights the potential for reducing the costs through various technological improvements. Similar examples should be developed and referenced to justify the critical objectives identified, thereby increasing the plausibility of the Roadmap and fostering a more strategic approach to accomplish the goals of the Roadmap. Additional comments on the critical objectives for specific technology areas are provided in Chapter 3.

TECHNOLOGIES

In the Roadmap, research and technological improvements are presented as the mechanism for reaching the critical objectives. The five technological areas highlighted—membrane, alternative, thermal, concentrate management, reuse/recycling—represent appropriate priorities for research and development in the field of desalination and membrane-based water purification. Nevertheless, these technological areas and their associated research issues receive limited discussion. Analyses of recent technological advancements, current limitations of desalination technologies, and opportunities for reaching the objectives identified are essential to strategic research planning, yet these are not developed in the Roadmap. A convincing justification of future research needs can only be developed based on a solid understanding of the current state of desalination technology relative to the technology objectives. As noted in NRC (2003), "the report would be improved by more thorough descriptions of the technologies and associated research opportunities, along with a list of technical references supporting the technologies identified in the report." Increased involvement of representatives from the desalination industry (including thermal desalination technologies), the U.S. Environmental Protection Agency, and the energy/power industry in the desalination research planning process would be necessary to strengthen the technical discussions. The recommendations presented in the Roadmap for each of these technological areas are evaluated in detail in Chapter 3.

Several important cross-cutting research areas are not adequately addressed within the five technology areas in the Roadmap, including energy use and air emissions from energy intensive desalination technologies. Energy efficiency and emissions (e.g., carbon dioxide and nitrogen oxides) could influence the potential and sustained contribution of desalination technologies to meet future water supply needs and merit additional attention in desalination research planning. Therefore, a sixth technology area entitled "cross-cutting desalination technology-related research" is proposed and described in further detail in Chapter 3.

IMPLEMENTATION

As stated previously, the effectiveness of the Roadmap and its underlying process will ultimately depend upon its future implementation. Although implementation issues have been discussed within the Bureau of Reclamation and by the Roadmap's Executive Committee, an implementation strategy has not been determined and a detailed implementation plan is absent in the Roadmap. Thus, the interim report (NRC, 2003) stated that the Roadmap would be improved if it included a general implementation plan for this research initiative. Such an implementation strategy for the Roadmap should include a comprehensive peer-review process for selecting and funding research proposals, involving the widest range of scientists and engineers available. Mechanisms for setting research priorities, information sharing, and technology transfer should be developed. These implementation issues are discussed in more detail in Chapter 4.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion: The Roadmap does not explain how the critical objectives were derived.

***Recommendation**:* The Roadmap should be developed to include clear, understandable logic and scientific basis for each of the critical objectives.

Conclusion: The five technical areas highlighted—membrane, alternative, thermal, concentrate management, reuse/recycling—represent appropriate priorities for research and development in the field of desalination and membrane-based water purification, but these technological areas and associated research issues received only limited attention in the Roadmap.

***Recommendation**:* The Roadmap should be developed to include analyses of recent technological advancements, descriptions of current limitations of desalination technologies, theoretical limits in ideal processes, and quantifications of baseline desalination values from which future advancements can be measured, which could provide the basis for developing a strategic research agenda for desalination.

Conclusion: The Roadmap and its underlying process appear to represent an appropriate framework for advancing research in several areas of desalination, but the Roadmap document lacks an appropriate focus on desalination research and technology needs to meet the identified water supply objectives.

***Recommendation**:* A subsequent research agenda should be developed that logically builds from the current state of desalination technology toward the critical objectives.

3

Key Technological and Scientific Issues for Desalination

In order to meet the long-term objectives for cost reduction and wider applicability of desalination identified in the Roadmap, innovative ideas will need to be developed and nurtured. The Roadmap and recommendations made in this report should not restrict investment in emerging ideas and technologies but should instead serve to stimulate creative thinkers to apply their expertise and knowledge to achieve the goal of improving desalination and water purification processes and considerably lowering their costs.

Five technology areas are identified in the Roadmap: membranes, thermal technology, alternative technologies, concentrate management, and reuse and recycling. These areas clearly point in the right direction, although the environmental, economic, and social costs of energy for desalination should be included within an additional cross-cutting research area. According to one example provided in the Roadmap, electrical power accounts for 44 percent of the costs of reverse osmosis of seawater (USBR and SNL, 2003), although the exact costs will vary with plant size or the cost of electricity. The impacts of energy use will need to be examined for desalination plants to become more widely used.

While research and technological developments continue to reduce the costs of desalinated water by optimizing performance, additional cost reductions may be more difficult to achieve, especially as many current systems are already operating at high efficiencies. This chapter discusses the technological and scientific issues for desalination, according to the five technological areas in the Roadmap. For each technology area, the cost issues and technical opportunities for contributing to desalination are described, and the projects identified in the Roadmap are reviewed. Missing topics that deserve further study are presented, and some research areas are suggested to be deleted. Research topics proposed in the Roadmap that were considered appropriate are not discussed at length; thus, the amount of discussion on individual projects should not be viewed as a reflection of the panel's priorities. These suggested revisions to the research areas itemized in the Roadmap for each of the technology areas are summarized in Tables 3-1 through 3-6.

MEMBRANE TECHNOLOGIES

Semi-permeable membranes can be used to selectively allow or prohibit the passage of ions, enabling the desalination of water. Over the last 40 years, tremendous advancements have been made in the field of membrane technologies. In fact, reverse osmosis (RO) represents the fastest growing segment of the desalination market, and as of 2002, RO represented 43.5 percent of the capacity of all desalination plants greater than 0.026 mgd, approximately equal to the thermal desalination capacity (Wangnick, 2002). As noted in the Roadmap, "membranes are expected to play critical roles in formulating future water supply solutions." Membrane technologies can be used for desalination of both seawater and brackish water, but they are more commonly used to desalinate brackish water because energy consumption is proportional to the salt content in the source water. Membrane technologies have the potential to contribute to water supplies through their use in treating degraded waters in reuse or recycling applications since membrane technology can remove microorganisms and many organic contaminants from feed water. Compared to thermal distillation processes, membrane technologies generally have lower capital costs and require less energy, contributing to lower operating costs. However, the product water salinity tends to be higher for membrane desalination (<500 ppm TDS) than that produced by thermal technologies (≤25 ppm TDS) (USBR, 2003a).

Membrane technologies for desalination and water purification typically operate under one of two driving forces: pressure or electrical potential. The following pressure-driven membrane technologies are commercially available for treating impaired waters in a range of applications (Lee and Koros, 2002) (Figure 3-1). In addition to understanding the removal capabilities of the membrane process, it is important to note the typical pressure driving force ranges and separation mechanisms, because it can affect their power consumption.

- **Reverse osmosis** (RO) membranes are used for salt removal in brackish and seawater applications. RO membranes have also been shown to remove substantial quantities of some molecular organic contaminants from water (Sedlak and Pinkston, 2001; Heberer et al., 2001). RO removes contaminants by solution diffusion[4] and operates under a trans-membrane pressure difference in the range of ~ 5 – 8 MPa.
- **Nanofiltration** (NF) membranes are used for water softening (removing primarily divalent cations), organics and sulfate removal, and some removal of viruses. NF membranes operate under a trans-membrane pressure difference in the range of 0.5 – 1.5 MPa. Removal is by combined sieving and solution diffusion.
- **Ultrafiltration** (UF) membranes are used for removal of color, higher weight dissolved organic compounds, bacteria, and some viruses. UF membranes also operate via a sieving mechanism under a trans-membrane pressure difference in the range of ~50 – 500 kPa.

[4] The solution diffusion theory presumes that both the solutes and water molecules dissolve in the RO membrane material and diffuse through. Water passes based on pressure, but solute separation occurs because of a difference in diffusion rates through the RO membrane.

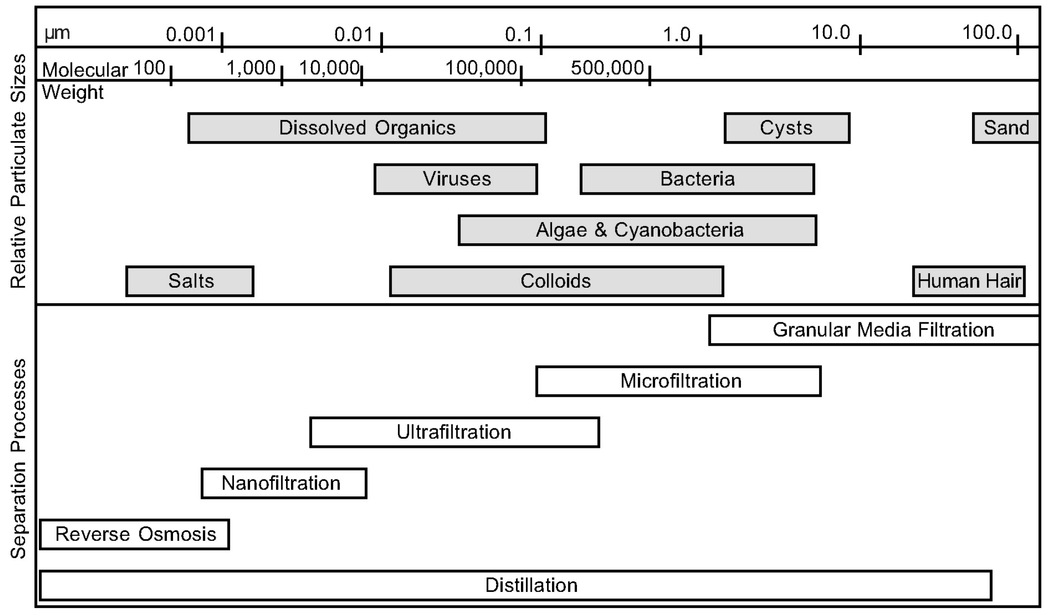

FIGURE 3-1 Size ranges removed by various membrane types along the filtration spectrum. SOURCE: Pankratz and Tonner, 2003.

- **Microfiltration** (MF) membranes are used for turbidity reduction and removal of suspended solids and bacteria. MF membranes operate via a sieving mechanism under a trans-membrane pressure difference in the range of ~50 – 500 kPa.

Electrodialysis is another membrane-based process that is important to desalination, which operates under a different driving force, applying an electrical potential to motivate ions in opposite directions to produce an ion-depleted and ion-enriched stream in each cell pair.

- **Electrodialysis** (ED) is the separation of the ionic constituents in water through the use of electrical potential and cation- and anion-specific membranes. In ED applications, hundreds of positively and negatively charged cell pairs are assembled in a stack to achieve a practical module (Lee and Koros, 2002; Strathmann, 1992).

Electrodialysis reversal (EDR) operates according to the same principles, but periodically reverses the polarity of the system to reduce scaling[5] and membrane clogging. Electrodialysis represents approximately three percent of worldwide desalination capacity (Wangnick, 2002).

Summary of Cost Issues

Desalination costs associated with the reverse osmosis process have markedly declined in recent years (Figure 1-6). These cost reductions have occurred through economies of scale and improvements in membrane technology (e.g., increased salt-

[5] Scaling is the deposition of mineral deposits on the interior surfaces of process equipment or water lines as a result of heating or other physical or chemical changes.

rejection, flux rate, and longevity), energy recovery devices, and reduced material costs. Considering the recent improvements in membrane-based desalination, substantial further cost savings could be more difficult to achieve, suggesting the need for a carefully developed research agenda targeted to areas that offer the most promise for cost reduction. The Roadmap provides an example of the cost breakdown for seawater desalination by RO that suggests that the largest cost reduction potential lies in capital costs (fixed charges) and energy (Figure 3-2). Continued improvements in membrane materials, permeability, and energy recovery devices could generate additional cost reductions. Substantial savings could also arise from improvements or simplifications to pretreatment systems for membrane desalination, since capital and operating costs for reverse osmosis pretreatment can represent more than 50 percent of the overall cost of a reverse osmosis system (Pankratz and Tonner, 2003).

The Roadmap proposes long-term critical objectives of 50–80 percent reduction in capital and operating costs and an increase in energy efficiency of 50–80 percent. For membrane-based desalination facilities, these energy goals will not be possible with advances in existing membrane technology alone. A simplified but fundamental example can illustrate the hard limits that the technology, as it is currently practiced, is encountering. Production of a purified stream of permeate water typically involves a permeate recovery ratio (the fraction of feedwater passing through the membrane) much less than 100 percent. The salt concentration increases in the water that does not pass through the membrane (the concentrate) and requires even more driving force to produce the next increment of product water as higher permeate recovery ratios are achieved. Given the mechanical limits of membranes and the desire to avoid excessive pressure, the permeate recovery ratio is typically limited to 50 percent or less for seawater feeds (Wilf and Klinko, 1997). As an example, in a RO seawater system operating at 50 percent feedwater recovery, flux rate of 8.5 gallons per square foot per day (gfd), with a 34,000 ppm TDS seawater feed at 22ºC, the required feed pressure will be about 65 bar (940 psi). If the system would utilize a 100 percent efficient pumping and energy recovery

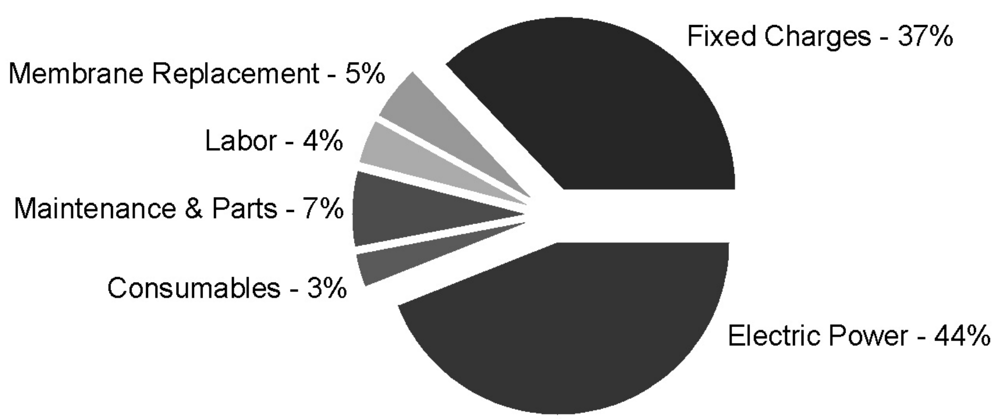

FIGURE 3-2 Cost structure for a reverse osmosis desalination of seawater. SOURCE: USBR and SNL, 2003.

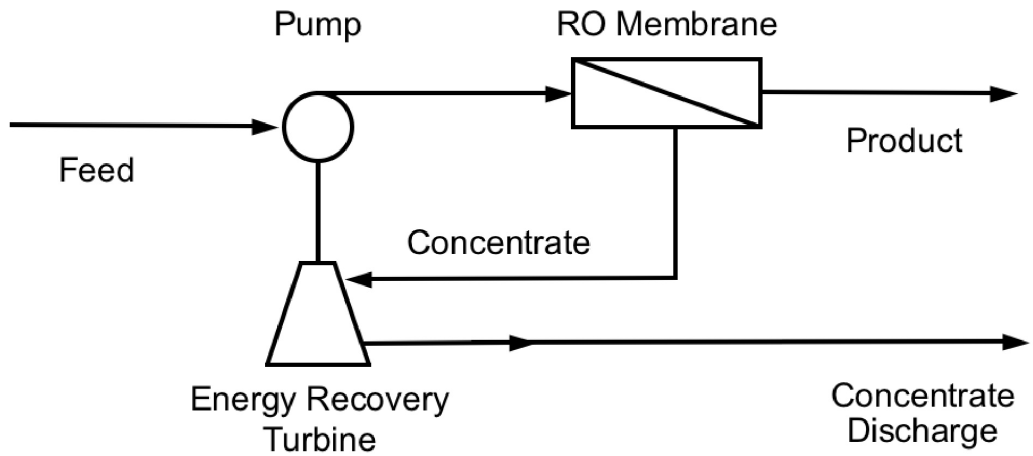

FIGURE 3-3 Typical reverse osmosis membrane desalination system with energy recovery.

unit, the minimum energy consumption would be 6.7 kWh/1000 gal (1.77 kWh/m^3).[6] A typical RO system with energy recovery is illustrated in Figure 3-3. Current state-of-the-art seawater RO systems under similar conditions can operate at 8.4 kWh/1000 gal (Andrews et al., 2001); an 80 percent reduction would result in 1.7 kWh/1000 gal, which is not a realistic goal for standard RO technology. Such energy recovery approaches provide, at best, the ability to operate at the thermodynamic efficiency limit. Based on the above 6.7 kWh/1000 gal limit, this would represent a maximum optimistic reduction of 20 percent.[7] To obtain further reductions in energy, a different desalination approach is required, such as the targeted ability to remove only impurities from the water, rather than passage of all of the purified water across the membrane.

The Roadmap correctly states that, as noted above, technology breakthroughs could result in more efficient membrane technologies that would remove only the specific target contaminants from the water stream. This targeted removal has attractive aspects in many cases with a well-defined feed stream containing known impurities. The lower

[6] This value—the energy required for high pressure pumps for reverse osmosis of seawater, E_{ro}—was calculated as $E_{ro} = K*P_f/(Eff_{hyd}*Eff_{mot}*R) - E_{rec}$, where K is a unit conversion factor, P_f is the calculated feed pressure, Eff_{hyd} is the pump hydraulic efficiency, Eff_{mot} is the pump motor efficiency, R is the system recovery ratio (assumed here to equal 0.5), and E_{rec} is the energy recovered through an energy recovery turbine. The required feed pressure was calculated with the above stated parameters for a multi-element membrane unit using the software package IMS by Hydranautics, which assumes the performance of commercial seawater membranes. The value for $E_{rec} = K*P_c*Eff_t*(1-R)/(Eff_{mot}*R)$, where P_c is the pressure of the concentrate stream, and Eff_t is the energy recovery turbine efficiency. Assuming 100 percent efficiencies and no frictional losses in the system (so that $P_f = P_c$), the equations can be combined into $E_{ro}=K*P_f$. Actual RO operations would require additional energy to power the necessary pretreatment and auxiliary equipment.

[7] Similar estimates are also derived by consideration of fundamental thermodynamic calculations based on free energies for typical feed, permeate and concentrate streams.

operating pressures possible with such an approach would also result in lower operating costs.[8] Selective contaminant removal would reduce the amount of mass of chemicals in the concentrate that then must be properly disposed. However, this approach runs the risk of not producing as pure a water product, since unrecognized contaminants that are not targeted for removal may remain in the treated water. This aspect is a significant public health concern when dealing with degraded waters from diverse sources.

Review of Research Directions

The membrane research areas and projects identified in the Roadmap for improving the efficiency and cost of desalination are appropriate but incomplete. The Roadmap identifies a significant portion of the research areas critical to improving membrane technologies in desalination. However, there are some areas that are not included in the Roadmap, and some of the existing topics should be expanded. The table of research topics included in the Roadmap has been modified (Table 3-1) to highlight these missing topics and summarize the suggested revisions.

Sensor Development/Membrane Integrity

To address the "national need" of providing safe water, the project to develop an on-line viral analyzer should be expanded to include pathogens as a broader definition of potentially harmful biological contaminants in water. The integrity of the membranes and membrane system is also a critical research area that should be included. Even a tiny area of defects in the membrane surface of an otherwise perfect barrier to pathogens can allow a number of organisms to pass across the barrier into the product water. In cases involving long storage time, some non-parasitic organisms could multiply to an unsafe level of pathogens in the product water. Integrity verification of RO/NF membranes is expected to become an important issue in the future as potential sources of water for desalination (including seawater) are facing contamination by municipal and agricultural discharge.

Tailorable Membrane Selectivity

In order to ensure sustainability and adequate water supplies, it is important to develop the ability to design in selectivity as well as permeability. Tailorable membrane selectivity would facilitate reliable removal of specific contaminants if and when they are identified in a given source water. This technology would enable undesirable components to be removed at some acceptable cost in terms of permeability and contribute to water supply and reuse options.

Membrane Fouling

Efforts to mitigate membrane fouling should be expanded to include the development of fouling-resistant elements and systems and appropriate indicators of fouling.

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[8] Since RO/NF operation is based on applying pressure higher than the osmotic pressure difference between the feed and the permeate, if only selective ions are rejected, the osmotic pressure of the permeate is closer to the osmotic pressure of the feed; thus, lower feed pressures would be required for the same permeate flux rate.

Membranes can be fouled by any number of organic or inorganic materials, including microbial biomass, such as algae or bacteria. Harsh cleaning agents decrease the life of a membrane element and contribute significantly to membrane system operating costs. Therefore, the development of fouling-resistant membrane surfaces and elements would be beneficial, leading to longer membrane life spans and reduced operating costs from both cleaning and pretreatment to reduce fouling. Given widely different feed water qualities and membrane configurations, it would be difficult to develop a membrane surface that is completely resistant to all types of fouling; thus, module restoration will also be necessary. Therefore, improved methods of cleaning and restoring fouled membrane modules rather than disposing of them is an important priority for research.

Membrane Operating Costs

Reduction of operating and maintenance costs is imperative to the goal of reducing the costs of desalination. Specifically, reducing the use of pre- and posttreatment chemicals and improving cartridge filter design in order to reduce replacement rate are two areas for potential cost savings related to membrane processes. The selection of pretreatment methods is based on the feedwater quality, membrane material, module configuration, recovery, and desired effluent quality (Taylor and Jacobs, 1996). It would be advantageous to reduce the need for pretreatment by improving the membrane materials or configuration, including the use of backwashable MF or UF as prefilters. For example, advances in membrane configurations could improve the hydrodynamics of the system by increasing the cross-flow velocity or introducing dean vortices in the module to minimize concentration polarization and thus the need for removal of particulates upstream of the module (Belfort et al., 1994). Posttreatment is an important cost component and should also be addressed. RO- and NF-treated permeate tends to be corrosive because of reduced pH, calcium, and alkalinity. The corrosive tendency of desalted water can be reduced by the addition of lime or soda ash and/or by the addition or removal of CO_2. The amount of chemicals added for posttreatment can be reduced by developing membranes with selective ion rejection (e.g., to specifically reduce boron, which can be hazardous in agricultural applications) or through application of integrated processes to optimize the overall treatment scheme.

Membrane Process Design

Further reductions in manufacturing costs of membrane desalination facilities should be explored, such as designing equipment to utilize less expensive materials and improving configurations to reduce element costs. Membrane process design should specifically include integrated membrane (Glueckstern et al., 2002) and hybrid membrane/non-membrane components. Integrated membrane systems utilize two membrane technologies, either including membrane pretreatment or using two different membrane types for salinity reduction, thereby improving the efficiency of the plant. Strategically designed hybrid membrane systems, such as membrane-thermal systems, may decrease energy consumption and/or control water quality, depending on the quality of the feedwater (Ludwig, 2003). These membrane/thermal desalination hybrid plants may offer greater flexibility when determining the final salt content and overall energy consumption of the system. Opportunities remain for process optimization in integrated membrane and hybrid desalination systems.

TABLE 3-1 A summary of the committee's recommendations for research topics for membrane technologies.

National Need → Technology Area ↓	Provide Safe Water	Ensure Sustainability/ Ensure Adequate Supplies	Keep Water Affordable
Membrane Technologies	• Smart membranes o Contain embedded sensors o Disinfection treatment o 2020: sense contaminant differential across the membrane, automatically change performance and selectivity • Sensor development o Model compounds for organics o On-line viral/*pathogen/pyrogen* analyzer o Micro/in-situ/built-in EPS sensor to detect biofilms; particulate fouling sensor o *Integrity verification* • Membrane research o Completely oxidant resistant o Operate over a range of pH's (*enable either* mechanical/chemical cleaning) o Adjust removal capability based on feed water quality and removal needs (2014—pharmaceuticals removal based on molecular weight, hydrophilicity) o Biofilm-resistant surfaces • *Develop high integrity membranes & systems*	• Mechanistic/fundamental approach to membrane design o CFD of feed channel o Conduct research to gain understanding of molecular-level effects o Design-in permeability*/selectivity* • Develop understanding of whole system (based on current knowledge) o Develop model of optimization o Research sensitivity of parameters for model • Develop fundamental understanding of fouling mechanisms o Understand how to mitigate fouling - Understand biofouling - Optimize operational controls - *Develop fouling resistant elements/systems* o *Develop indicators for fouling* • *Develop performance restoration of fouled membrane*	• Basic research to improve permeability o Minimize resistance o Model/test non spiral configurations • *Improve methods or* develop new methods of reducing/recovering energy • Integrate membrane and membrane system designs • *Reduce membrane operating/maintenance costs* o *Reduce consumption of pretreatment and posttreatment chemicals* o *Improve cartridge filter design to reduce replacement rate* • *Reduce manufacturing costs through design* o *Identify or develop less expensive materials for membranes and filtration systems, including corrosion resistant materials* o *Improve configuration to reduce elements cost*

NOTE: These recommendations are presented as revisions to the "research areas with the greatest potential" as identified in the Roadmap. The table has been reproduced in the same format that appears in the Roadmap, and italicized topics indicate additional promising research areas suggested in this report. SOURCE: Modified from USBR and SNL, 2003.

Membrane Bioreactors

An important opportunity for membrane processes in water reuse applications is in membrane bioreactors (MBRs). MBRs have grown in use and applicability in recent years, and are now used for municipal and industrial wastewater treatment applications. Water treated by MBRs routinely meets reuse standards for certain feedwaters (Manem and Sanderson, 1996; Rittman, 1998); however, further research could increase the applicability of MBRs to a wider range of feedwater qualities. The long-term operation of a MBR is a function of the performance of the membranes, which depends on the membrane material, operational parameters, flux characteristics and module configuration. This important membrane application is further discussed in the reuse section of this chapter.

Priorities

Among the membrane technology areas identified in the Roadmap and those additional areas suggested by this committee (see Table 3-1), several have been identified as the highest priority research topics within this category. These topics were identified as those most likely to contribute substantially to the objectives set by the Roadmapping Team, with regard to improved energy efficiency, reduced operating costs, and high quality water. The priority topics are:

- Improving membrane permeability (in order to operate at a lower feed pressure for a given module cost) while improving on or maintaining current salt rejections.
- Improving or developing new methods for reducing energy use or recovering energy (e.g., improving the efficiency of high pressure pumps).
- Improving pretreatment and posttreatment methods to reduce consumption of chemicals.
- Developing less expensive materials to replace current corrosion resistant alloys used for high pressure piping in seawater RO systems.
- Developing new membranes that will enable controlled selective rejection of contaminants.
- Improving methods of integrity verification.
- Developing membranes with improved fouling-resistant surfaces.

THERMAL TECHNOLOGIES

Approximately one-half of the world's installed desalination capacity uses a thermal distillation process to produce fresh water from seawater. Thermal processes are the primary desalination technologies used throughout the Middle East because these technologies can produce high purity (low TDS) water from seawater and because of the lower fuel costs in the region. Three thermal processes represent the majority of the thermal desalination technologies in use today.

- **Multi-Stage Flash Distillation** (MSF) uses a series of chambers, each with successively lower temperature and pressure, to rapidly vaporize (or "flash") water from bulk liquid brine. The vapor is then condensed by tubes of the inflowing feed water, thereby recovering energy from the heat of condensation. Despite its large energy requirements, MSF is among the most commonly employed desalination technologies. MSF is a reliable technology capable of very large production capacities per unit.
- **Multi-Effect Distillation** (MED) is a thin-film evaporation approach, where the vapor produced by one chamber (or "effect") subsequently condenses in the next chamber, which exists at a lower temperature and pressure, providing additional heat for vaporization. MED technology is being used with increasing frequency when thermal evaporation is preferred or required, due to its lower power consumption compared to MSF.
- **Vapor Compression** (VC) is an evaporative process where vapor from the evaporator is mechanically compressed and its heat used for subsequent evaporation of feed water. VC units tend to be used where cooling water and low-cost steam are not readily available. (Pankratz and Tonner, 2003)

Three other thermal techniques—solar distillation, membrane distillation, and freezing—have been developed for desalination, although they have not been commercially successful to date (Buros, 2000). In brief, solar distillation uses the sun's energy to evaporate water from a shallow basin, which then condenses along a sloping glass roof. In membrane distillation, salt water is warmed to enhance vapor production, and the vapor is exposed to a membrane that can pass water vapor but not liquid water. Freezing technologies use ice formation under controlled conditions in the source water, initially eliminating salt from the ice crystals and allowing the brine to be rinsed away.

As noted in the Roadmap, thermal seawater distillation processes employed in the Middle East are mature technologies that may not have broad application in the United States. While thermal desalination is not expected to displace membrane-based desalination as the predominate desalination technology in the United States, thermal technologies have substantial potential and should be considered more seriously than they have been to date. For example, thermal technologies can be built in conjunction with other industrial applications, such as electric power generating facilities, to utilize waste heat and lower overall costs while providing other significant process advantages, such as high-quality distillate even in seawater applications.

Summary of Cost Issues

Wangnick (2002) notes that energy use represents 59 percent of the typical water costs from a very large thermal seawater desalination plant (Figure 3-4). The other major expense comes from capital costs. Thus, cost reduction efforts would be most effective if they were focused on these areas. For example, research efforts to develop less-costly corrosion-resistant heat-transfer surfaces could reduce both capital and energy costs. The most significant cost reduction opportunities for thermal desalination may be found in the area of energy management by utilizing "new" sources of heat or energy to accomplish evaporation or through the use of existing energy sources during off-peak periods for thermal desalination purposes.

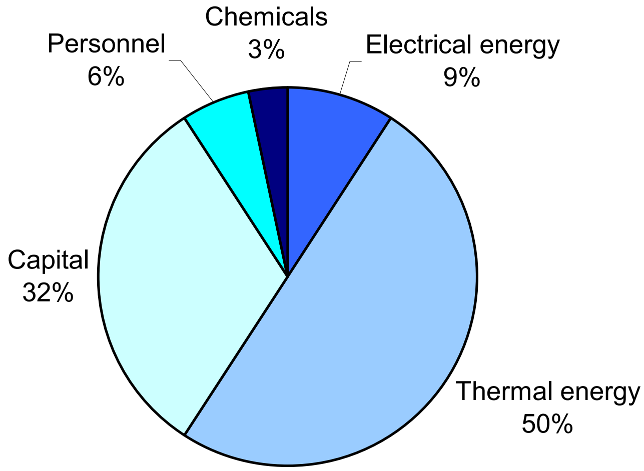

FIGURE 3-4 Breakdown of typical costs for a very large seawater thermal desalination plant. SOURCE: Wangnick, 2002.

As acknowledged in the Roadmap, the lack of centralized water and power planning in the United States contributes to the high cost of thermal desalination. Yet the Roadmap seems to dismiss cogeneration plants (combined water and power production), despite their notably reduced energy consumption, because they are "expensive to build and operate." Wider application of cogeneration should be explored further, particularly as older power plants are replaced or repowered.

Review of Proposed Research Directions

The Roadmap does not develop a research path based on opportunities for improving thermal technologies, nor does it adequately identify areas of research in thermal technologies which might help meet the report's objectives. Overall, the Roadmap's Working Group appears to have lacked thermal desalination expertise, and several misleading statements are made in the Roadmap about thermal desalination. For example, the report misinforms readers by neglecting to state that the energy requirement of thermal technologies ("260 kw-hr/1000 gallons – or one quarter of the electricity consumed by the average house in a month") can be met by "waste" heat and other low-grade energy sources. The Roadmap also states that thermal plants produce "more dilute concentrate waste." In the case of vapor compression, this is incorrect. In the case of MSF and MED processes, the concentration factor for thermal and membrane seawater desalination is very similar, but the overall thermal desalination plant discharge may be diluted because a significant amount of cooling water may also be discharged with the concentrate.

The thermal technology research areas and projects identified in the Roadmap are generally appropriate but could be expanded and in some cases revised. Additional research on the topic of hybrid technologies is proposed in the Roadmap, although the rationale is not well described. The Roadmap should emphasize that integrating membrane and thermal processes with an electric generating station to meet fluctuating water/power demands improves flexibility and economics. Instead the Roadmap incorrectly states that hybrid plants "reduce waste streams."

The discussion below describes some missing research topics that could provide improvements to thermal desalination technologies. These suggestions are also summarized in Table 3-2. While the table includes some topics that are more speculative than others, all of the topics listed in Table 3-2 are deemed to have potential to contribute to the advancement of thermal technologies.

Evaluate the Benefits of Cogeneration

Virtually all large, non-U.S. seawater desalination plants combine water production with the generation of electric power using the same fuel source. These "dual purpose plants" reduce overall costs, since thermal energy from power production can be used effectively in the desalination process. Efficient cogeneration depends upon an appropriate ratio of power-to-water production that matches regional demand, considering seasonal fluctuations and the types of power and desalination technologies used. Hybrid (thermal and membrane) may offer additional flexibility to reach the optimal power-water production ratio. Research to evaluate the benefits of integrating power and water production at power plant sites should be conducted (including case studies of select existing and future power facilities).

Membrane Pretreatment for Thermal Desalination

Water production in thermal plants is often limited by scaling considerations. Membrane pretreatment (e.g., nanofiltration to remove scaling constituents such as calcium and sulfate ions) may allow operation at higher temperature and production rates, potentially reducing overall costs. Research into cost-effective pretreatment methods could also be valuable to the overall thermal plant design.

Alternative Energy Sources for Desalination

Most thermal desalination processes have the ability to use low-grade energy or "waste" heat rather than a primary energy source. The use of alternative energy sources, which is discussed later in this chapter under "Cross-Cutting Technology-Related Research," is a potential area for future research which could result in improved desalination economics and broader application of desalination.

Cooling Water Alternative

Most thermal seawater desalination processes require large amounts of cooling water and have significantly greater seawater intake flow rates than comparably sized membrane systems. The use of innovative cooling systems may reduce the water intake requirements and allow operation at higher concentration factors, thereby reducing the pumping costs, reducing the environmental impacts of the water intake process, and creating a smaller volume of concentrate for disposal.

Heat Transfer Materials

Current heat-transfer surfaces use expensive corrosion-resistant materials (e.g., titanium, high-grade stainless steel); thus, research to evaluate or refine nonmetallic or

TABLE 3-2 A summary of the committee's recommendations for research topics for thermal technologies.

National Need → **Technology Area ↓**	**Provide Safe Water**	**Ensure Sustainability/** **Ensure Adequate Supplies**	**Keep Water Affordable**
Thermal Technologies	• Hybrid - Membrane and thermal ~~to reduce waste stream~~ ~~• Develop solar ponds for energy and concentrate management~~ • Enhanced evaporation	~~• Renewable energy (in small communities)~~ ~~o Geothermal~~ ~~o Solar~~ ~~o Wind~~ ~~o Biomass~~ • *Alternative energy sources (e.g., waste heat)* • Water harvesting from air • Membrane distillation • *Membrane pretreatment*	• Hybrid – membrane and thermal • Clatharate sequestration ~~• Forward osmosis~~ • *Evaluate the benefits and limitations of cogeneration* • *Investigate cooling water alternatives* • *Evaluate and refine nonmetallic or polymeric heat transfer materials* • *Corrosion mitigation*

NOTE: These recommendations are presented as revisions to the "research areas with the greatest potential" as identified in the Roadmap. The table has been reproduced in the same format that appears in the Roadmap, and italicized topics indicate additional promising research areas suggested in this report. Words shown in strike-out represent suggested deletions. SOURCE: Modified from USBR and SNL, 2003.

polymeric heat-transfer materials could significantly reduce capital costs. Improvement in the design of heat-transfer surfaces to improve their efficiency could also reduce operating costs.

Corrosion Mitigation

Corrosion increases with increasing operating temperatures. Research that identifies corrosion mitigation techniques or develops innovative materials of construction that resists corrosion could improve plant economics for thermal desalination plants, which operate under high temperature conditions or in the presence of corrosive noncondensible gases.

Research Topics to be Deleted

Three of the research topics proposed in the Roadmap—renewable energy sources, solar ponds and forward osmosis—should be deleted from the section on thermal technologies (see Table 3-2). These research areas are more appropriate to other technology areas (e.g., see Tables 3-3, 3-5, and 3-6).

Priorities

Among the thermal technology areas identified in the Roadmap and additional topics suggested by this committee (see Table 3-2), two have been identified as the highest priority research topics within this category for application of desalination in the United States. Because energy is expensive in the United States and comes with significant environmental impacts, the highest priority research topics focus on examining ways to harness otherwise wasted energy for the benefit of water production, either through cogeneration of water and power or by utilizing alternative energy sources, such as industrial waste heat. Nevertheless, much thermal technology research is being conducted in Middle Eastern countries where thermal desalination has been the dominate technology, and care should be taken to utilize the existing knowledge.

ALTERNATIVE TECHNOLOGIES

Alternative (or novel) technologies are far-reaching in nature, and the Roadmap correctly identifies that investment in these novel technologies will be required to see a significant shift in the desalination cost curve. According to the Roadmap, "alternative technologies can be categorized as either nascent and emerging technologies or radical combinations/advances to existing technologies." By definition, these technologies are currently in an early stage of development or exist only as promising ideas. It is impossible to predict at this time what these novel advancements will be. Thus, in order for the Roadmap to adequately nurture novel technologies, there must be flexibility in the desalination research agenda to incorporate emerging research ideas that show significant promise. In order to develop novel technologies, funding will need to be invested in higher risk research that has the potential for significant payoffs.

TABLE 3-3 Suggestions for an edited listing of the research topics in the area of novel technologies.

National Need → Technology Area ↓	Provide Safe Water	Ensure Sustainability/ Ensure Adequate Supplies	Keep Water Affordable
Novel Technologies	*Potential examples include:* • Ultrasonic o Supersonic • Membrane and Membrane Combinations • Biomimetic o Active membranes o Biological sensors o Signaling capabilities o Mangroves	*Potential examples include:* • Ion Sorption o Zeolite crystallization • Sodium pump/biomimetic • Advanced membranes/separation o Porcelain o Thin-film o Biologic o Bioreactors	*Potential examples include:* • Magnetics • Nanotechnology (active/smart membranes) • Capacitive desal o Nanotubes or large surface areas o Current swing sorption • *Forward osmosis*

NOTE: These recommendations are presented as revisions to the "research areas with the greatest potential" as identified in the Roadmap. This list is not intended to be exhaustive. SOURCE: Modified from USBR and SNL, 2003.

Summary of Cost Issues

The Roadmap's mid/long-term objectives for 50 percent desalination cost reductions (80 percent cost reductions as stretch targets) by 2020 will not likely be achieved through incremental improvements in existing technologies. Such dramatic cost reductions will require novel, alternative technologies, perhaps based on entirely different desalination processes or powered by entirely new energy sources. Specific areas that could benefit from novel technologies for cost reduction include energy and capital cost reduction and brine disposal.

Review of Research Directions

Because there are many ideas in varying states of development related to desalination and membrane-based water treatment, it is impossible to list all the possibilities, let alone prioritize them. Although the list of alternative desalination research topics provided in the Roadmap is highly speculative in nature, it contains reasonable examples of the type of research that could be considered in a call for proposals. Thus, the committee did not attempt to add to the list of research topics in the Roadmap, but Table 3-3 was simply edited to reflect that the research areas currently presented are in no way intended to be exhaustive. A research funding program to include alternative desalination technologies would need to be flexible and open to consider new, unforeseen research areas. However, any proposed research (including those topics listed as examples in Table 3-3) would need to be more systematically justified in the proposal submission process, with thorough explanations of the technical background supporting the potential success of the proposed research (see also Chapter 4). Because of the far-reaching nature of these research topics, an appropriate amount of due diligence will need to be undertaken prior to funding research in novel technologies, and proposals should be subjected to careful review and prioritization by qualified technical experts.

WATER RECYCLING AND REUSE

It is widely recognized that when high quality water supplies are limited, alternative sources should be considered as long as prudent public health practices are implemented (NRC, 1998). Aside from the desalination of seawater or water from brackish aquifers, one potential solution to the nation's water supply problem is to utilize increasingly impaired waters, such as municipal wastewaters,[9] by applying desalination treatment technologies for contaminant removal (water purification). The Roadmap suggests that membrane-based water purification technologies could be applied to reuse and recycling applications and thereby create additional water supplies for nonpotable uses (e.g., industry, irrigation, recreation, the environment) and indirect potable reuse applications. Thus, this section on water recycling and reuse is not focused on the purification technologies themselves, since improvements to membrane technologies are addressed in a previous section of this report. Instead, this section addresses specific concerns and

[9] While these waters are highly treated, the term reclaimed "municipal wastewater" better suits the nature and origin of the water being discussed as opposed to the term "post-consumer reclaimed waters."

research needs regarding the safety, reliability, and cost effectiveness of producing recycled water using a technology originally developed to desalinate seawater.

It is important to note that the starting source-water qualities and the product-water quality objectives for desalination are different from those of water purification by reuse/recycling, and these distinctions should receive greater emphasis in the Roadmap. Reclamation and reuse of municipal wastewater must handle a more complex mixture of chemicals (Daughton, 2003) and pathogens, including protozoans, bacteria, and viruses, since inadequately treated wastewaters can lead to waterborne disease outbreaks. Source water quality and the degree of human exposure to the product water should dictate the extent of treatment required. Although reuse/recycled water is widely used for nonpotable applications today, the National Research Council (1998) only endorsed indirect potable reuse under certain conditions, since a number of questions remain regarding the risks. The decision to adopt indirect potable water reuse cannot be made by researchers but must be made locally, influenced by public and political support and informed by risk management and water management considerations, including a full assessment of the community's alternative water resources.

Membrane technologies appear promising for use in many water purification applications. However, the Roadmap's presentation of reuse and recycling technology needs would be improved if membrane performance was discussed in the context of various impaired source-water and product-water qualities. Although desalination technologies can reduce levels of total dissolved solids by several orders of magnitude, it is not clear that membranes developed for desalination will remove all contaminants and pathogens to the same degree as salts (Olivieri et al., 1998; Faust and Aly, 1998; AWWA, 1999). For example, an American Water Works Association Research Foundation (1999) report showed variable synthetic organic compound removal by reverse osmosis membranes ranging from 0 to 99 percent. RO membranes have been shown to be effective for removing many pharmaceuticals from wastewater to below detectable levels (Drewes et al., 2001; Heberer et al., 2001). Desalination technologies for reuse applications will most likely be used in conjunction with other treatment technologies in a multiple barrier approach that results in the reliable production of water that is protective of public health (Sakaji et al., 1998). Nevertheless, membranes offer a significant improvement over conventional-unit water-treatment processes, and the reduction of dissolved solids and removal of a range of contaminants will markedly improve water quality for human consumption.

Summary of Cost Issues

While the Roadmap emphasizes advancing desalination technology to promote safe, sustainable, cost-effective water in sufficient supplies, reuse and recycling is an additional application of desalination technologies to different impaired water sources, and therefore the issues limiting its wider use are much broader than cost. The primary issues for reuse and recycling include public health, membrane effectiveness, and safe distribution of the product water. Current approaches to transport the product water from the reuse treatment plant to the end user create substantial costs for reuse applications, but this is only one factor of concern.

Review of Research Directions

Within the Roadmap, public health is mentioned several times as an objective, but additional research is needed to address the range of public health issues associated with water reuse. Recommendations are provided below to expand some research areas identified in the Roadmap while others are recommended to be deleted. Several additional research topics are also suggested below, and Table 3-4 provides a summary of the recommended changes.

Identification and Quantification of Contaminants

More complete identification of the contaminants present in treated wastewaters is needed so that the risks of indirect potable reuse can be more clearly understood. For example, there is no mention in the Roadmap of microbiological concerns, such as prion diseases (e.g., "mad cow disease") caused by proteins as the primary agents of the disease. These agents are known to be present in the urine of infected individuals (Borman, 2001), and their response to membrane treatment is not known.

While well-functioning membranes can be a robust barrier that can result in significant contaminant reduction, one should not presume complete removal. Sensitive detection technologies are important for contaminants that may cause acute or chronic adverse health effects at low concentrations. Additional research and development are needed to lower analytical detection limits for contaminants so that potential associations with observed health effects can be discerned. Similar concerns exist for analysis of viruses and protozoa in drinking water. The sensitivity of current log removal calculation methods is a function of both the volume of sample collected and the concentration of pathogens. Studies conducted to date have measured recovery using relatively high virus or protozoan concentrations (Nieminski et al., 1995; De Leon et al., 2002); however, ongoing studies have shown that recovery can decrease at lower pathogen concentrations (S. Thompson, Sanitation Districts of Los Angeles County, personal communication, 2003). Concentration techniques and quality assurance procedures should be improved to enable risk managers to analyze the impact of pathogens at low concentrations (Crohn and Yates, 1997), since only a few pathogens may be required to cause deleterious health effects.

Chemical and Microbiological Surrogates

Surrogates are compounds or organisms that are innocuous and can be rather easily detected, and they serve as indicators for the presence of other more harmful contaminants, which may be more difficult to detect through standard analytical technologies. The need for surrogates is not limited to organic chemicals (as suggested in Table 2 of the Roadmap), but extends to microbiological and other chemical contaminants found in municipal wastewater. More than 3,000 chemical products and pharmaceuticals are manufactured each year, and water managers cannot possibly analyze for all of the ever widening range of contaminants that could occur. Therefore, analytical surrogates are needed. At present, total organic carbon (TOC) is used as a surrogate to evaluate the efficacy of organics removal as a treatment performance standard—not a health-effects-based standard. TOC is not a good surrogate for specific compounds (Langlois et al., 1984) because not all organics are amenable to oxidation and because it cannot detect pollutants that might be present in the part per trillion range, given its high detection limit (about 0.1 mg/L). To support the identification of appropriate chemical surrogates, an improved understanding is needed of structure-activity relationships between organic molecules and RO membrane materials (AwwaRF, 2000; NWRI, 2003).

Real-Time Sensing/Monitoring/Controls

Given the wide range of contaminants and uncertainties associated with the reuse of municipal wastewater, better process-control tools would improve the consistency and reliability of the quality of the product water. For example, monitoring wastewater particulates based on size and shape should be explored, because newer technology that classifies particulates based on pattern recognition promises to provide early pathogen warning through on-line/real-time applications. Further research is needed that develops on-line tools to measure the integrity of membrane systems in real time, because providing a consistent barrier and being ensured that such a barrier is intact is essential to evaluating the reliability of a membrane treatment system for reuse applications.

Comparative Risk Assessment

Toxicologists and epidemiologists have difficulties extrapolating and estimating the impacts of trace organics on human health at extremely low concentrations. Although the Roadmap addresses chemical contaminants, further research should also specifically explore the uncertainties associated with exposure to low levels of pharmaceuticals, personal care products, and endocrine disruptors (NRC, 1999). There is also sizeable uncertainty associated with negative findings in epidemiological studies since observing positive health outcomes requires a high incident rate or an extremely large sample population (Sloss et al., 1999). Certain subpopulations (e.g., pregnant women, children) might be more susceptible or vulnerable and therefore might be at greater risk from contaminant exposure.

Although no documented cases of illnesses from exposure to reclaimed municipal wastewater are known, only a few epidemiological studies have been conducted to date, and these have focused on chronic endpoints or pregnancy outcomes (Sloss et. al., 1999). The impact of short-term exposure following cross-connection events has not been carefully examined and is warranted. The Roadmap recommends that a risk assessment be done to compare various reuse schemes with potable water counterparts. This research topic is important, but this study should also quantify the uncertainties in such an analysis and evaluate the data quality on which the assessment is based.

Membrane Bioreactors

The submersible membrane bioreactor (MBR) is an emerging membrane technology that has the potential to revolutionize industrial and wastewater treatment. Application of MBRs to municipal wastewater treatment results in replacing a number of conventional treatment steps with a single membrane device with higher output per unit volume than the conventional technology. Application of MBRs for municipal wastewater treatment can produce consistently high environmental quality effluent (Manem and Sanderson, 1996) that is suitable to be treated directly by RO or NF membrane systems, without additional pretreatment. In wastewater plants equipped with a MBR, the subsequent membrane treatment step for salinity or pathogen concentration reduction will be much less expensive than the current approach of treating secondary effluent in a multi-barrier membrane system. With additional research and development to support cost reductions in membrane technologies, MBRs could provide a higher level of treatment at comparable costs of traditional treatment, thus contributing to better public health protection in reuse applications.

Examine Feasibility of Decentralized Treatment of Recycled Water

Recent papers suggest that decentralized wastewater treatment using membrane-based technologies could serve to produce recycled water closer to reuse sites, reducing the need for costly distribution system infrastructure (Tchobanoglous, 2003; Gagliardo and Mallia, 2003). A feasibility study should be conducted on the topic of decentralization of water recycling facilities and also examine regulatory monitoring and permitting issues.

Lessons Learned from Successes and Failures in Reuse Projects

The Roadmap cites the lack of public and regulatory acceptance for indirect potable reuse projects as a key factor limiting the ability to expand water reclamation and reuse, stating that recycling and reuse suffers from an "unfair stigma." However, the Roadmap does not appear to address this controversial issue. Several states have demonstrated regulatory acceptance of recycled water for a variety of applications from landscape irrigation to indirect potable reuse, and Arizona, California, and Florida have identified indirect potable reuse projects. The water reuse industry should examine both successful (Mills et al., 1998; Seah, 2003) and unsuccessful (Lauer and Rogers, 1998; Olivieri et al., 1998) projects using the lessons learned from those projects for future reuse efforts.

Lessons can also be learned from successful and unsuccessful water reuse treatment train design. Wastewater treatment process trains are becoming more complex as additional unit processes are being added to them to meet increased water quality objectives for some reuse applications. The sequencing, placement, and integration of unit treatment processes within a wastewater treatment process train can impact process performance and economics, often determining the success or failure of a reuse application. Efforts should be made to publish both successes and failures in reuse design, so that the technical community can learn from the experiences of others and better understand the complex variables and processes involved.

Research Topics to be Deleted

While salinity management in agricultural watersheds is important, the project seems well beyond the scope of the original legislative mandate to focus on desalination technologies. If such a task were included in the Roadmap, other management-based strategies should be considered such as water transfers, conservation, and demand management. Therefore, for consistency with the objectives of the Roadmap, this task should be addressed elsewhere by the Bureau of Reclamation. Because constructed wetlands do not fit into a desalination- or membrane-technology-based purification strategy to ensure sustainable water supply, this item should also be deleted because it appears to be beyond the scope of the Roadmapping effort.

The subject of life-cycle economics of water reuse, while valuable, contains significant overlap with the many other sections and has been moved to the section on cross-cutting technologies. Pretreatment is primarily a membrane technology issue, and for consistency these topics should be deleted from the section on reuse technologies.

TABLE 3-4 A summary of the committee's recommendations for research topics for reuse and recycling technologies.

National Need → **Technology Area ↓**	**Provide Safe Water**	**Ensure Sustainability/ Ensure Adequate Supplies**	**Keep Water Affordable**

Reuse/Recycling Technologies	• *Develop improved techniques for identification and quantification of chemical contaminants*
	• Develop a set of chemical *and microbiological* surrogates acceptable to the public for *indirect* potable reuse
	  o *Develop an understanding of structure activity relationship between selective organic molecules and RO membrane materials*
	• Risk comparison between various water reuse schemes and potable water counterparts *with potential uncertainty described*
	  • *Develop tools for risk assessments, including consideration of data needed and the potential uncertainty of the analysis*
	• Real-time sensing/monitoring/controls
	  o *Monitoring wastewater particulates based upon physical characteristics*
	  o *Molecular based biological markers for integrity monitoring*
	• *Research and development for membrane bioreactors*
		• *Examine feasibility of decentralized treatment based local use of recycled water*
		• *Lessons learned from successes and failures in water reuse*
		• ~~Watershed-based salinity management strategy~~
		• ~~Constructed wetlands~~
		• Develop large-scale regional characterization of subsurface injection capability of US
			• Enhance membrane bioreactor technology *for cost reduction*
			• ~~Document the lifecycle economics of water reuse for various applications~~
			• ~~Pretreatment~~
			  ~~o Filtration~~
			  ~~o Biological coating (disinfectant)~~
			  ~~o Research to enable prediction of migration and recovery through aquifers~~

NOTE: These recommendations are presented as revisions to the "research areas with the greatest potential" as identified in the Roadmap. The table has been reproduced in the same format that appears in the Roadmap, and italicized topics indicate additional promising research areas suggested in this report. Words shown in strike-out represent suggested deletions. SOURCE: Modified from USBR and SNL, 2003.

Priorities

Among the reuse and recycling research topics identified in the Roadmap and those suggested by this committee (see Table 3-4), several have been identified as those most likely to contribute substantially to the objectives set by the Roadmapping Team. The priority topics are:

- Developing improved techniques for identification and quantification of chemical contaminants.
- Examining the feasibility of decentralized treatment in order to reduce the transport and distribution system costs.
- Enhancing membrane bioreactor technology for cost reduction.
- Conducting a risk comparison between various water reuse schemes and potable water counterparts.
- Developing a set of chemical and microbiological surrogates for indirect potable reuse and developing a better understanding of the relationship between rejected solutes and the membrane.
- Developing more sensitive on-line membrane integrity monitoring systems.

CONCENTRATE DISPOSAL

Desalination and membrane-based water purification technologies do not eliminate the water constituents of concern. Rather, these constituents are concentrated in a fraction of the water, thus improving the water quality of the other fraction. Designing a desalination plant to minimize production of salt solids is not technologically feasible. However, the volume of water containing concentrated salts can be reduced through various technologies.

The concentrate is a residual that then must be handled in a manner that minimizes environmental impacts. The Roadmap acknowledges the need for concentrate disposal by stating "finding environmentally-sensitive disposal options for this concentrate that do not jeopardize the sustainability of water sources is difficult, and, thus, next-generation desalination plants will have to be designed to minimize the production of these concentrates, or find useful applications for them." (USBR and SNL, 2003) The concentrate from seawater desalination is generally returned to the sea where the process of dilution is used to minimize potential negative impacts. Concentrate from the desalination of brackish inland water supplies generally cannot be returned to sea because of geographical location. Various options are available for inland desalination concentrate management, including: deep well injection, pond evaporation, near zero liquid discharge (n-ZLD) and ZLD, solar energy ponds, shallow aquifer storage for future use, or return to a saline water body via pipeline.

The best option for concentrate disposal must be selected on a site-specific basis based on economic and environmental considerations. The options may be constrained by trace metal contaminants such as selenium and arsenic that have ecologically toxic effects. Under these conditions, the concentrate must be handled in a manner to protect wildlife and human health. As recognized in the Roadmap (see Table 3-5), in some cases additional research will be necessary to determine the nature of the hazard posed by various concentrate disposal options in order to ultimately develop appropriate science-based concentrate disposal regulations. Consideration should be given to disposing concentrate from inland desalination plants in a manner that the concentrate will not degrade surface or ground waters; thus, discharge into surface streams should be avoided.

Several current or future concentrate management alternatives are summarized below.

- **Disposal in a Saline Water Body** is a reasonable option when the desalination plant is located close to a very salty water body such as the ocean. In this case the main constraint is to meet environmental concerns. In most cases, appropriate dilution of the concentrate can be achieved to reduce or eliminate its impact on the environment, but saline disposal could become an issue if the concentrate contains elements with toxic effects on aquatic organisms or on wildlife that feed on aquatic organisms.

- **Deep Well Injection** is often the most viable option for concentrate management at inland desalination facilities when suitable geologic formations are available. Generally, suitable formations must be confined and/or isolated to prevent contamination of adjacent aquifers. Suitable formations for injection often contain water with TDS concentrations in excess of 10,000 mg/L and are located at great depths. Injection wells are expensive to develop and operate.

- **Evaporation Ponds** offer a means to reduce the concentrate volume by confining the concentrate water in a pond designed for the sole purpose of evaporating the water. This option can be expensive due to the large surface area required and the associated land and impermeable liner costs. Land costs are a function of location but the cost of liners could be reduced through technological improvements.

- **Zero Liquid Discharge (ZLD) or near-ZLD** employs evaporative/crystallization systems to remove as much water as possible to reduce the cost of concentrate disposal and to improve the options for beneficial use of the salt products. Gypsum is mined at many locations, and sodium chloride can be extracted from high salt content water bodies.

- **Crop Irrigation** is suggested in the Roadmap as a means for disposing of lower concentration desalination waste by application to salt-tolerant plants (halophytes).

- **Solar Energy Ponds** utilize concentrate from desalination plants to capture solar radiation and convert it into useable energy. In a sense, a solar energy pond is simply an evaporation pond with the opportunity to produce energy under the appropriate conditions. Solar radiation penetrating the water heats the lower dense layers of water which remain heavier than the layers above in spite of their rise in temperature. With no convection currents to disburse the heat due to the dense saline water layer topped by a less concentrated layer, the bottom layer’s temperature rises to very high levels. The stored heat from this bottom layer of hot brine is then extracted using a heat exchanger.

Summary of Cost Issues

Coastal desalination plants are often able to dispose of saline concentrate into the ocean or estuaries at relatively modest costs. However, costs associated with concentrate management can constitute a very large portion of the total costs of desalination at inland facilities, and this cost greatly reduces the economic feasibility of desalination technology at inland locations. Reducing the costs of concentrate handling would make available many sources of water, especially brackish groundwater, by making desalination a more amenable option for inland sites.

Near-term options for reducing the costs of inland concentrate disposal include research on concentrate volume reduction, development of engineering design tools for concentrate storage for future use, deep-well concentrate injection technology, lower-cost evaporation pond liners, and concentrate salt mineral storage for future utilization as part of a sustainable-use strategy. Long-term options may include extraction of minerals for commercial use rather than disposal at landfills or through burial. Commercialization of these minerals at large inland desalination facilities may prove feasible if life-cycle analysis is used during the design phase. Currently very little information is available for use by engineering design firms conducting feasibility analysis of the commercial use options.

Review of Research Directions

The Roadmap contains a rather disjointed list of items related to concentrate management technologies that are limited to chemicals associated with desalination plants and do not include research on disposal techniques for waste from reuse/recycling facilities. Recommendations are provided based on the research areas proposed in the Roadmap. Several additional research topics are proposed, while others are recommended to be deleted. Table 3-5 provides a summary of the recommended changes.

Silica Control/Removal for Concentrate Minimization

Concentrate volume reduction during the desalination process is an important initial component of concentrate management, and concentrate chemistry must be optimized during this process. For example, silica must be removed from the concentrate stream to achieve high recovery rates and reduce concentrate volume because silica greatly limits the application of membrane technology when present in feed water at concentrations greater than 25 mg/L. Anti-scalants are ineffective at high silica concentrations. The standard technology for silica removal is precipitation with lime, but lime precipitation of silica produces large volumes of lime sludge and adds another process to the treatment train thereby increasing cost. Research is needed to find innovative methods for dealing with silica.

Control Contaminant Concentrations in Evaporation Ponds

Evaporation ponds hold the potential of providing wildlife habitat; however, it is important that the concentrate not contain elements which could be detrimental to wildlife. For example, the opportunity to dispose of saline agricultural drainage waters in evaporation ponds in the western San Joaquin Valley of California has been greatly impacted by the presence of selenium in the drainage water, which moves up the food chain with negative impacts on the birds utilizing the pond. Technologies are being developed to address this problem, but more work remains (Green et al., 2003).

Arsenic is a common constituent in groundwater in the western United States; thus, arsenic and, to a lesser extent, selenium will likely occur in the concentrate from the desalination of brackish groundwater in the West. Research is needed to identify concentrate constituents from various water sources and determine the concentration at which deleterious impacts occur. Also, an improved understanding of the fate of these contaminants in concentrate management processes will be needed along with models for contaminant management and control. Technologies to remove these contaminants from the concentrate are also needed.

Pond Liners

Degradation of aquifers by water percolating from evaporation and solar energy ponds must be prevented. This can be accomplished by appropriately locating ponds where the percolate will not reach fresh water bodies or restricting water percolation using a geomembrane or chemical sealing method for controlling percolation rates. To improve the costs of evaporation ponds, research on low-cost liners and on chemical sealing of the soil is needed to reduce costs associated with this concentrate management method. There may also be opportunities for using existing dry lakebeds that have subsurface groundwater with very high TDS concentrations.

Solar Energy Ponds

The salt concentration in the storage zone for solar energy ponds must be 20 percent or higher. Reject water from a reverse osmosis desalination plant is not sufficiently concentrated and must be further concentrated—most likely in an evaporation pond—before it can be utilized in a solar power pond. Wider use of solar energy ponds may depend on research to improve salt concentration technologies and studies to evaluate using life-cycle economics.

Concentrate as a Resource

Current thinking views concentrates as an undesirable residual of desalination and water purification that requires disposal. If concentrate can be managed as a future resource, the feasibility of desalination can be greatly improved for inland sites. Evaporation ponds hold the potential for recovery of the chemical components of the concentrate that have commercial value. Gypsum, sodium chloride, and magnesium sulfate are three minerals that have commercial value. The potential of designing and operating evaporation ponds for long-term recovery of these minerals would certainly contribute to the sustainable aspects of desalination and should be explored. Solar ponds also offer the potential of using the stored heat energy for separation of useful minerals based on solubility differences. Additional work is needed to examine concentrate management designs and consider the use of ion-selective membranes for improved management and marketability of commercially valued desalination-derived salt solids.

Concentrate containing 10,000 mg/L of dissolved solids is still 99 percent water. Treating it solely as a waste ignores its potential as a water resource. Concentrate could be stored underground using managed injection well systems for future recovery. Taking this approach would eliminate the very expensive concentrate processing systems. For example, desalination of slightly saline water with a TDS of 2,000 mg/L at a 75 percent recovery creates concentrate with approximately 8,000 mg/L TDS. Texas defines all groundwater with a TDS of between 3,000 and 10,000 mg/L as a “moderately saline” resource that has potential usefulness (TGPC, 2003). Currently, the injection of treated wastewater is used in California and Florida to control saline water movement into freshwater aquifers (Mills et al., 1998). Injection of concentrate for storage underground in either confined or unconfined aquifers as a future resource could greatly reduce the cost of handling this product and make it available for recovery in the future.

Chemical and Hydrological Conditions for Subsurface Storage

Modeling of the geochemical and hydrologic behavior of injected concentrate coupled with monitoring would be necessary for further advancement of subsurface concentrate storage. The chemistry of the concentrate must be suitable for injection into the formation. Research is needed on the potential for chemical interactions between concentrates, the formation, and resident fluids and gases. Currently, the potential for plugging both the formation and injection wells is difficult to assess, and the technologies and methods to coordinate concentrate chemistry at the surface with geologic formation chemistry are not well understood.

Zero Liquid Discharge

Although the Roadmap correctly identifies the often prohibitively high cost of zero liquid discharge (ZLD), it does not address the evaporative/crystallization systems that are employed or recommend specific areas where research might be undertaken. Brine concentrators (e.g., vertical tube falling film evaporators) and forced circulation evaporators may be used individually or in series to concentrate dissolved solids to very high levels. These mechanical devices have extremely high energy requirements that often eliminate them from consideration. Research to evaluate methods of improving their efficiencies and test the benefits of alternative configurations, innovative use of chemical anti-scalants/sequestrants, and alternate materials of construction could reduce their cost and increase their areas of applicability.

The Roadmap should also acknowledge the incrementally high cost to move from “near-ZLD” to “ZLD.” Projects may be abandoned as economically or environmentally unfeasible because of the high cost to achieve ZLD, whereas near-ZLD (i.e., 90 percent concentrate volume reduction) is often acceptable.

Crop Irrigation

The salt concentration in the desalination concentrate can vary over a wide range depending upon the initial salinity of the water and the percent recovery of the process, and agricultural crops have a wide range of tolerance to soil water salinity. For example, cotton and sugar beets are examples of salt-tolerant crops whereas lettuce, strawberries, and green beans are examples of salt-sensitive crops. However, the water from the desalination plants producing the lowest concentration will usually exceed the salinity that can be used to irrigate the most salt-tolerant agricultural crops. An additional constraint to using desalination concentrate to irrigate crops is that even halophytes have an upper limit to the salt concentration tolerated in the root zone. Therefore, the excess salts must be leached from the root zone and the leachate has the possibility of degrading

TABLE 3-5 A summary of the committee's recommendations for research topics for concentrate management technologies.

National Need → **Technology Area ↓**	**Provide Safe Water**	**Ensure Sustainability/ Ensure Adequate Supplies**	**Keep Water Affordable**
Concentrate Management Technologies	• *Develop chemical and hydrological modeling for subsurface storage and control of concentrates with TDS of <10,000 mg/L* • *Develop technology and models for management and control of problem constituents like arsenic and selenium* • *Develop technology for control/removal of silica* • *Research to improve materials/methods for lining evaporation and solar energy ponds* • Develop science related concentrate specific regulations for dispersion modeling of mixing zones and ion imbalance for surface water discharge. • Research into engineered ecology/bioengineering to discover: o How to engineer disposal so that ~~at least~~ it does not harm ecosystems, and if possible benefits them o Natural analogs to current treatment • The biology of salty water, including understanding env. impacts, using bacteria for beneficial treatment, etc.	• Create "super concentrate" technolog*ies* – complete solidification of residuals and 100% recapture of water *for ZLG and > 90% capture of water for near-ZLG* • Explore beneficial uses of concentrate including recreation, solar pond; cooling water; manufacturing; irrigation; ~~farming~~ agriculture; repair of dead-end stagnant canals; energy recovery; artificial wetlands, halophilic irrigation; aquaculture • *Explore storage and management of desalination salt solids for recovery and future beneficial/sustainable commercial use* • Decentralized (Point of Use) Treatment and recycling as a way of managing concentrate	• Create a "super concentrate" technology –near-complete or complete solidification of residuals (*> 90% capture of water for near-ZLD* or 100% recapture of water *for ZLD)* • *Evaluate the life-cycle economics of solar energy ponds for inland desalination* • Cross-cutting: Develop methods of immobilizing/sequestering the concentrate stream • Cross-cutting: Develop beneficial uses for the concentrate stream to improve the economics of disposal for ZLD processes.

NOTE: These recommendations are presented as revisions to the "research areas with the greatest potential" as identified in the Roadmap. The table has been reproduced in the same format that appears in the Roadmap, and italicized topics indicate additional promising research areas suggested in this report. Words shown in strike-out represent suggested deletions. SOURCE: Modified from USBR and SNL, 2003.

groundwater or surface waters. Crop irrigation, therefore, is not a viable option under most cases, although research is needed to further examine the limits of this disposal option.

Priorities

Among the concentrate management research topics identified in the Roadmap and those additional topics suggested by this committee, several have been included among the highest priority. These topics were identified as those most likely of contributing substantially to the objectives set by the Roadmapping Team. The priority topics are:

- Reducing concentrate volume.
- Management/removal of toxic compounds such as arsenic.
- Utilization or storage of concentrate mineral at landlocked locations for sustainable system development; i.e., treat concentrate as resource for future mineral extraction rather than a waste for disposal.
- Underground storage and management of concentrates with a TDS of less than 10,000 mg/L as a water resource for future desalination.

PROPOSED CROSS-CUTTING TECHNOLOGY-RELATED RESEARCH

One major research area—energy—emerged in this review of the Roadmap, which has the potential to contribute broadly to all aspects of desalination, regardless of the technology chosen. Issues of energy appear throughout the previous discussions but are addressed collectively in this section and are summarized in Table 3-6.

Summary of Cost Issues

Energy is a main consideration of each of the technologies areas discussed previously, and finding ways to reduce the energy intensity per unit of water output is essential. The cost of energy is presented as relatively stable in the Roadmap, which assumes that moving to a large-scale desalination program will not alter the cost of energy significantly. This assumption may not be correct and deserves further exploration. The Roadmap also does not look at the larger environmental and social costs of energy, such as the contribution of fossil fuels to greenhouse gases and the concerns for energy security, which could have a substantial influence on wider implementation of desalination. In seeking sustainable water supplies through energy-intensive technologies, are concerns about water resources being replaced by concerns about the security of energy resources? A careful reexamination of our water policies will be needed to understand how much desalination is needed when traded off against other concerns about energy use, environmental impacts, and resource sustainability issues.

Review of Research Directions

Several energy research topics are proposed for various desalination technologies in the Roadmap, and these are compiled in Table 3-6 under the topic of cross-cutting technologies, along with additional research topics. Fossil fuels will likely be around for a long time as non-fossil alternatives presently lag in cost and in potential for large production. Therefore, research is needed to develop ways to lessen the impacts of fossil fuel. Examples include “downhole” energy production that can leave potential emissions underground at the source of the fossil fuel, carbon sequestration, and a much greater emphasis on conservation and energy recovery in end uses. Application of nuclear energy and renewable energy sources, such as biomass, solar, wind, and geothermal energy, for desalination also deserve additional research and development. Yet even with promising research advancements, renewable energy sources will need time to develop larger production capabilities in order to handle desalination energy needs. For this reason, a more careful look should be taken at the life-cycle aspects of desalination.

While the Roadmap looks at the energy costs of some current desalination technologies and the environmental impacts of the by-products of the process such as brine disposal, several important life-cycle elements are missing, including the impact of a much larger proportion of water coming from energy intensive technologies. In the next few decades fossil fuels will be the most likely source of energy for desalination, and more consideration should been given to the greenhouse gas emissions (e.g., CO_2) contributed by a greater reliance on desalination technologies. Complete life-cycle analyses for proposed desalination and water reuse facilities are needed to understand the future costs of increased use of desalination (compared to other new fresh water sources), including costs of water treatment, transportation, storage, and security, and all associated energy costs, including social and environmental costs. Life-cycle analyses may highlight other needed research, perhaps including research on using small decentralized solar energy facilities at the point of use regardless of the desalination technology choice.

TABLE 3-6 A summary of the committee's recommendations for research topics for cross-cutting technologies.

National Need → **Technology Area ↓**	**Provide Safe Water**	**Ensure Sustainability/ Ensure Adequate Supplies**	**Keep Water Affordable**
Cross-cutting Technologies		• *Energy conservation and energy recovery* • *Carbon sequestration* • *"Downhole" energy production* • *Renewable energy sources* o *Geothermal* o *Solar* o *Wind* o *Biomass* • *Alternative energy sources (e.g., fuel cells, nuclear)*	• *Life-cycle economics analyses for desalination and water reuse*

NOTE: This category does not exist in the Roadmap.

4

Implementation

The Roadmap notes that it is a "living document," that will continue to evolve and improve with time. The Roadmap's focus is to present "broad research areas that are representative of the types of scientific and technical advances that will be necessary for desalination and water purification technologies to find wide acceptance" (USBR and SNL, 2003). Section 5.0 of the Roadmap, entitled "Next Steps," positions the Roadmap at the upper end of a continuum of parallel activities to build additional water supplies through desalination and membrane-based water purification (Figure 4-1). While the Roadmap recognizes the broader steps necessary for wider application of desalination, including characterizing the resources, addressing regulatory issues, improving global collaboration, and addressing issues of commercialization and facility siting, the Roadmap does not provide an implementation strategy for its own research agenda.

IMPLEMENTATION STEPS

Much remains to be done to build on the efforts to date and turn these preliminary research ideas into a program for strategic research investments in the area of desalination technologies. In order to achieve the objectives of the Roadmap, the program will need adequate funding for research, involvement of talented scientific researchers worldwide, strategic awarding of research funding, and effective communication of the research findings to the desalination community. These necessary implementation steps and the roles of various agencies in these steps are described below.

Funding Implementation of the Roadmap

As noted in Chapter 1, past federal investments (pre-1982) in desalination research were substantial and resulted in large improvements in efficiency and the development of reverse osmosis technology. Current funding levels within the federal government for non-military application of desalination, however, are insufficient, if one key objective of the Roadmap is to fund research efforts that would trigger a step change in performance and cost reduction for desalination technologies. Research investments in desalination by the private sector, supplemented by modest current federal support, gradually continue to

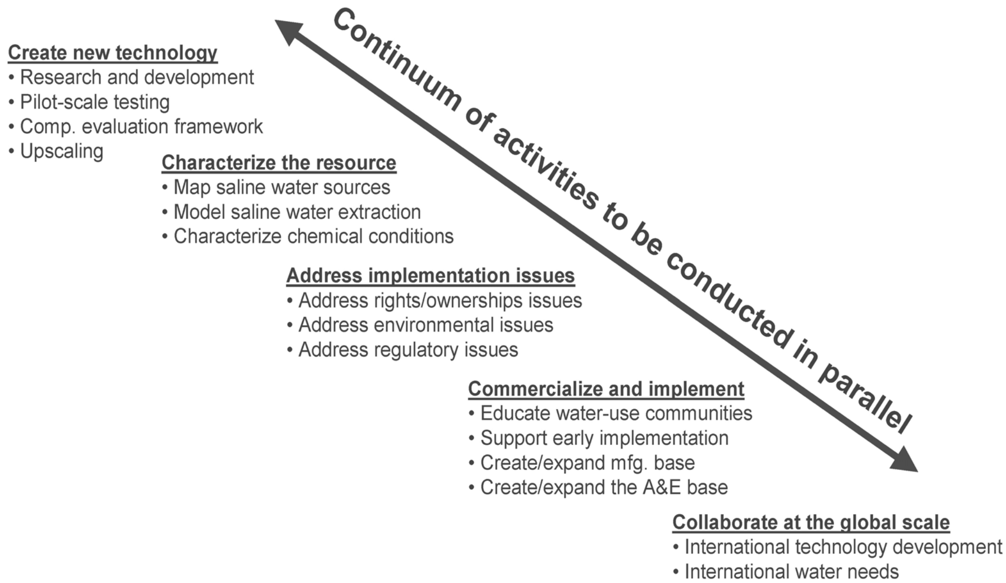

FIGURE 4-1 The steps identified in the Roadmap to advance the wider use of desalination. SOURCE: USBR and SNL, 2003.

improve the efficiency of desalination technologies and reduce overall costs; however, in order to achieve the far-reaching objectives presented in the Roadmap, adequate funding must be applied and distributed. Advancements in critical areas without strong commercial interests, such as concentrate disposal, will likely depend upon public financing.

This committee was not tasked to determine how much additional funding would be needed to significantly reduce the costs of desalination, and the Roadmap also did not address this issue. More thorough analysis is needed to estimate the research funding needed, beyond current industry investments in research and development, to place the nation in a likely position to reach the long-term objectives set forth in the Roadmap. As currently structured, the Roadmap does not contain sufficient justification for the research areas identified, and it contains no prioritization of the research presented. As noted in Chapter 2, a subsequent strategic desalination research agenda should be developed, which is founded upon a baseline assessment of the state of today's desalination technologies and identifies research areas most likely to reach the Roadmap's specific critical objectives (perhaps expanding on the ideas presented in Chapter 3). An analysis to provide estimated cost ranges—irrespective of funding source—to achieve each objective should be a natural outgrowth of the development of a strategic desalination research agenda. This analysis should include an assessment of current research activities in desalination, and it should also provide guidance on opportunities for shared funding responsibilities between federal agencies, research foundations or institutions, and the public sector, since cost-sharing can be an effective means to leverage limited research dollars. The Bureau of Reclamation, based on its long history of research funding in this area, should work collaboratively with desalination experts from these different sectors and industry (perhaps including key participants from the Roadmapping Team) to develop this subsequent research agenda and conduct the research cost analysis.

Step changes in technology are difficult to predict—let alone implement—and will require substantial investments in areas of great promise but sizeable uncertainty. Because this funding must be applied wisely, a strategic investment approach is needed that selects research topics and projects based on their potential for improving current technologies or developing revolutionary new technologies. A decision will need to be made on whether the Roadmap research agenda can include feasibility studies and pilot and demonstration plants or whether it should be used mainly to support research.

Broad Request for Proposals

Based on available funding, the opportunity to announce requests for proposals exists for federal agencies, such as the Bureau of Reclamation or the National Science Foundation, or other research institutions that explicitly target one or more Roadmap objectives. The principal funding agency should announce a request for proposals as widely as possible to scientists and engineers in municipal and federal government, academia and private industry. These requests for proposals could also be disseminated in a central website on desalination research, described below. At present, the desalination community is relatively small, but collectively there is a great deal of expertise across the world. International desalination experts and others from related areas of research should be encouraged and given the opportunity to offer innovative research ideas that have the potential to significantly advance the field. Thus, the request for proposals should extend to federal agencies, national laboratories, other research institutions, utilities, and the private sector. Since innovation cannot be pre-assigned, there should also be room for unsolicited proposals.

Selection

To achieve the objectives of the Roadmap, proposals should be selected through a rigorous independent peer review process (NRC, 2002b) irrespective of the agency issuing the request for proposals. A rotating panel of independent reviewers should be appointed based on their relevant expertise in the focal areas of the Roadmap and in the basic science of desalination. The process should allow for the consideration and review of unsolicited proposals, as long as their research goals meet the objectives of the Roadmap. Proposal funding should be based on the quality of the proposed work, the potential contribution toward meeting the Roadmap's critical objectives, prior evidence of successful research, and the potential for effective publication or dissemination of the research findings. The status of each request for proposal process could be monitored through the proposed website suggested below.

Communicating the Activities and Results of Research and Development

Scientific and technical breakthroughs and improvements will need to be transferred effectively to the desalination industry before they can be broadly adopted. The Bureau of Reclamation should encourage and lead the publication and communication of research activities and results, through various media. The following components should be considered:

- **A central website on the activities and progress of the Roadmap** could enhance coordination and collaboration while disseminating both research opportunities and research findings to the broader desalination community. This website could also provide a means to communicate with the general public and help interested parties understand what level of advancement exists for a particular desalination technology. Examples of information that should be incorporated into the website include:
  - Requests for proposals issued,
  - Proposals received,
  - Descriptions of projects awarded,
  - Interim and final project reports,
  - Resulting publications,
  - Synthesized information on resulting advances in the technology,
  - Progress reports on the Roadmap, including what progress has been achieved in meeting the performance targets,
  - Periodic updates to the desalination technology strategic research agenda at specific intervals (e.g., every five years), and
  - Recent data on water demands and supply around the nation, and details on the role of desalination to meet water demands.

  Based on its long history in desalination research, the Bureau of Reclamation should help coordinate this website (perhaps with assistance from other research institutions).

- **Effective research communication** requires clear dissemination of the research results to both the scientific community and those practitioners who will ultimately utilize the findings. Scientific communication includes publication in peer-reviewed journals, books, and presentations at scientific meetings. Clear communication of the scalability of research findings is important because this can facilitate rapid adoption of technological improvements at the appropriate step in their development (e.g., those that are scalable to full production). The Bureau of Reclamation should consider holding periodic meetings among Roadmap-funded researchers to enhance cross-fertilization of knowledge and improve communication.

- **Public Perception.** Without public acceptance, there will be no mandate to fund research in the areas identified. Therefore, it is important to inform the general public about the benefits, affordability, and environmental considerations of desalination. Desalination's place in the supply of water for drinking, industrial, and agricultural use should be demonstrated. Steps should be taken to provide this information to both the general public and policy makers through various media.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion: Current funding levels within the federal government for non-military application of desalination are insufficient to fund research efforts that would trigger a step change in performance and cost reduction for desalination technologies.

Recommendation: In order to achieve the far-reaching objectives presented in the Roadmap, adequate research funding should be applied and distributed.

Conclusion: The Roadmap does not provide an implementation strategy, and much remains to be done to turn these preliminary research ideas into a program for strategic research investments in the area of desalination technologies.

Recommendations:

- The Bureau of Reclamation should work collaboratively with desalination experts from different sectors to develop a strategic research agenda and to estimate the resources needed to place the nation in a likely position to reach the long-term objectives set forth in the Roadmap.
- Requests for proposals should be announced as widely as possible to scientists and engineers in government, academia, and private industry, and unsolicited proposals should also be considered in areas of innovative technologies.
- Proposals should be selected through a rigorous independent peer review process, utilizing a rotating panel of independent expert reviewers.
- The Bureau of Reclamation should encourage and lead the publication and communication of research activities and results through various media, including a central website on the activities and progress of the Roadmap.
- The general public should be informed about the benefits, affordability, and environmental considerations of desalination.

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Abbreviations and Acronyms

AMTA	American Membrane Technology Association
AWWA	American Water Works Association
AwwaRF	American Water Works Association Research Foundation
BC	before the Christian era
CO_2	Carbon dioxide
ED	electrodialysis
EDR	electrodialysis reversal
EPA	United States Environmental Protection Agency
gal	gallon
gfd	gallons per square foot per day
kPa	kilopascals
kWh	kilowatt hours
L	liter
mg	milligrams
mgd	million gallons per day
m^3	cubic meters
MED	multi-effect distillation
MBR	membrane bioreactor
MF	microfiltration
Mgd	million gallons per day
MPa	megapascals
MSF	multi-stage flash distillation
NaCl	sodium chloride
NF	nanofiltration
NRC	National Research Council
NWRI	National Water Research Institute
n-ZLD	near-zero liquid discharge
OWRT	Office of Water Research and Technology
OSW	Office of Saline Water
ppi	pounds per square inch
ppm	parts per million
RO	reverse osmosis
SNL	Sandia National Laboratories

TGPC	Texas Groundwater Protection Committee
TOC	total organic carbon
TDS	total dissolved solids
UF	ultrafiltration
U.S.	United States
USBR	United States Bureau of Reclamation
WHO	World Health Organization
VC	vapor compression
ZLD	zero liquid discharge

Appendixes

Appendix A

Letter Report dated June 12, 2003 to John W. Keys, Commissioner, Bureau of Reclamation[10]

[10] Attachments A and B of the June 12, 2003 letter report are not included in Appendix A because the statement of task can be found in the Executive Summary and the biographical information for the committee members is available in Appendix C.

THE NATIONAL ACADEMIES

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June 12, 2003

The Honorable John W. Keys, III
Commissioner
Bureau of Reclamation
U.S. Department of the Interior
1849 C Street, N.W.
Washington, D.C. 20240

Dear Mr. Keys:

The National Research Council (NRC) is pleased to provide this "letter report" on the *Desalination and Water Purification Technology Roadmap*[1] (Roadmap) developed by the Bureau of Reclamation with support from the Sandia National Laboratories as suggested by Congress in the 2002 Energy and Water Development Appropriation Bill. Your letter dated October 29, 2002 to the Water Science and Technology Board (WSTB) asked for a critical evaluation of the desalination Roadmap, which is intended to serve as a guide for federal agencies and other public and private organizations in their desalination research and technology investment decisions.[2] In response, the NRC's WSTB created the Committee to Review the Desalination and Water Purification Technology Roadmap to conduct the review. Committee members and NRC staff are listed in Attachment A. The committee's Statement of Task is provided in Attachment B. The results of the NRC review are intended to aid your ongoing efforts to develop a national, broadly supported plan for desalination research investments.

This letter report, as explicitly requested by the Bureau of Reclamation, provides an initial assessment of whether the Roadmap presents "an appropriate and effective course to help address future freshwater needs in the United States" (addressing task #1 of the Statement of Task; see Attachment B). Our assessment is focused on the *Desalination and Water Purification*

[1] For the purpose of this report, the term "Roadmap" is used to describe the Desalination and Water Purification Technology Roadmap, which was also called the Desalination Technology Progress Plan and the Desalination Research Roadmap in previous versions of the document and related correspondence.

[2] According to the Roadmap report, the Roadmap is a "critical technology roadmap" that is intended to serve as a high-level strategic pathway for future desalination and water purification research. As such, the Roadmap calls attention to future needs for development in technology, provides a structure for organizing technology forecasts and programs, and attempts to improve the communication between the research and development community and end users.

Technology Roadmap[3] that was published in January 2003 and augmented by presentations to the committee at its first meeting on May 12-13, 2003.[4] The committee has yet to complete its analysis based on the remaining review questions listed in the Statement of Task (#2-6, Attachment B), but these will be addressed in a final report, planned to be released in the fall of 2003.

Initial Assessment

Based on a careful review and discussion of the Roadmap report and related presentations and the initial deliberations of the committee at its first meeting, we conclude that a national research plan for desalination and water purification technology is important and necessary to help meet the nation's future water needs.[5,6] The potential for desalination technologies to become major components of future water supply management throughout the United States justifies a careful research and development strategy to nurture novel ideas and facilitate technological advancements. We strongly recommend the continuation of these activities and commend the Bureau of Reclamation and Sandia National Laboratories for providing the leadership in this important national initiative.

Nevertheless, we present some recommendations that we hope will strengthen the Roadmap document and better reflect the underlying "roadmapping process" that the report attempts to summarize. For example, based on the contents of the published Roadmap, we suggest that a more accurate title for the effort would have been the "Desalination and Membrane-Based Water Purification Technology Research Roadmap." The committee believes that emphasis of this effort should be on research to support advances in technology; therefore, the title of the initiative should again include *research* (see also Footnote 1). Furthermore, the term "water purification" includes a wide range of water treatment technologies and processes that are more often related to conventional water treatment plants than to desalination or desalination pre- and post-treatment. These technologies, such as granular media filtration and chlorination, were never the focus of the research planning effort. With these important

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[3] U.S. Bureau of Reclamation and Sandia National Laboratories. 2003. Desalination and Water Purification Technology Roadmap: A Report of the Executive Committee. Desalination & Water Purification Research & Development Report #95. Bureau of Reclamation, Water Treatment and Engineering Group, Denver, CO. The Bureau of Reclamation and Sandia National Laboratories formed an Executive Committee and a Working Group (collectively known as the Roadmapping Team) comprised of representatives from government, industry, academia, and private and non-profit sectors, including water utilities, to help develop a desalination technology progress plan. This large number of researchers and managers participated in the roadmapping activity through a series of collaborative workshops organized and conducted by Sandia National Laboratories during 2002 to help identify and rank future desalination and water purification research goals and objectives. The Roadmap report is a product of the Executive Committee.

[4] The committee's first meeting included presentations from the Bureau of Reclamation (the study sponsors), Sandia National Laboratories, and other members of the Roadmapping Team on May 12, 2003 and during a stakeholder workshop held on May 13, 2003. These presentations were intended to brief the committee on the Roadmap's development, expected uses, and follow-up activities; help frame the issues; and inform the committee of activities of other federal, state, and local entities engaged in desalination and water purification research and development.

[5] A previous NRC report, *Envisioning the Agenda for Water Resources Research in the Twenty-First Century*, published in 2001, notes that the development and implementation of increasingly cost-competitive desalination technologies deserves increased consideration on the nation's water resources research agenda.

[6] "Water 2025: Preventing Crises and Conflict in the West," a recently launched initiative by the U.S. Department of the Interior, includes among its six guiding principles, "Improve water treatment technology, such as desalination, to help increase water supply" to address future water needs (see http://www.doi.gov/water2025/).

clarifications, the committee concludes that this Roadmap and its underlying process appear to present an appropriate framework for advancing research in several areas of desalination and water purification technology to help address future water needs in all regions of the United States. The effectiveness of the Roadmap will ultimately depend on its future implementation, and, as described below, plans for implementing the Roadmap are not yet resolved.

This letter report details several other recommended changes to improve the effectiveness of the Roadmap. One primary concern was the overarching vision for the effort, which appears to stray into formulation of national water policy rather than remaining focused on a research plan to address desalination and water purification technologies and associated economic and public health issues related to future national water supply needs. The Roadmap would also be improved with explanations of targets for critical research objectives, a more comprehensive and detailed presentation of desalination technology needs, and a process for research prioritization, selection, and funding. These concerns are described below, and the committee's final report may consider these issues in greater depth.

Vision

As noted previously, the present vision statement, while intended to provide the motivation for the overall Roadmap, strays into the realm of national water policy in a manner that is inconsistent with the overall tone and direction of the remainder of the report. For example, the vision statement associated with "keep water affordable" indicates that future water supplies should strive to keep water prices "at rates comparable to that of today" (as actually stated in the report). Instead, the vision statement should remain focused on the roadmapping of research and technology efforts that could contribute to future water supply needs and thereby more accurately reflect the contents and discussion contained in the body of the report. The committee believes that a more suitable vision statement would confer to the reader that desalination and water purification technologies will provide an important contribution to the development of water supplies for the United States that are safe, sustainable, affordable, and adequate. In addition, the vision statement associated with the bullet "provide safe water" (p. 4) could be improved if revised in a manner that reflects public health concerns related to all applications of desalination and water purification. For example, as impaired waters are increasingly employed in the future—such as municipal and industrial wastewater streams containing complex mixtures of chemical and microbiological contaminants—the committee questions whether membrane desalination technologies alone will be appropriate or adequate for producing safe drinking water.

Critical Objectives

The Roadmap establishes a series of critical objectives for desalination and (largely membrane-based) water purification technology advancements. According to the Roadmap report, critical objectives are quantifications of the United States' national-scale needs that set metrics (also called technology targets) that must be met by a technology if it is to play a role in meeting the nation's water needs. However, in order for these targets to be useful, they need to have a logic and origin that are readily understandable. The theoretical basis for the technology targets listed in the Roadmap (e.g., 50 percent or 80 percent cost and power reductions needed by 2020; see Table 1, p. 11) should be clarified and referenced to the current state-of-the-art for each of these targets. For example, the committee found the example of the cost structure for reverse-osmosis desalination of seawater (Figure B1, p. 51) to be very informative in explaining the cost reduction potential of various technological improvements. Some of the targets identified do not appear well founded in science and may be unachievable. The provision of a rationale for the targets identified would advance the plausibility of the Roadmap.

Desalination and water purification national needs are separated into near-term (by 2008) and mid/long term critical objectives (by 2020). The committee generally supports connecting critical objectives to such (somewhat arbitrary) timeframes. However, we believe that while the 2008 timeframe is reasonable to obtain research results to support desalination research needs, it will not provide enough time to implement these research findings into desalination development efforts that are currently underway.

Technologies

The committee concludes that the five broad areas of desalination and water purification technologies (i.e., membrane, alternative, thermal, concentrate management, reuse/recycling) identified in the Roadmap report represent top priority areas for research and development. An issue of concern relevant to all of them, not discussed in the report, is corresponding energy use and air emissions (e.g., carbon dioxide and nitrogen oxides) resulting from these energy intensive technologies. These issues represent critical research areas that could influence the potential and sustained contribution of desalination technologies to meet future water supply needs.

The Roadmap could be strengthened as a whole by more thorough descriptions of the technologies and associated research opportunities, along with a list of technical references supporting the technologies identified in the report. In part, the Roadmap may lack adequate depth in some areas due to the notable absence of any U. S. Environmental Protection Agency personnel on the Roadmapping Team, the limited number of desalination industry participants, and the absence of workgroup members with expertise in energy/power issues or in thermal desalination technologies.

Implementation

The Roadmap would be improved by including a general plan of implementation for the research initiative. Based on the presentations and discussions with the Roadmapping Team members at the May 13 workshop, we understand that many of these issues have been discussed, but an implementation strategy for the Roadmap is not settled. The committee recommends that an implementation strategy for the Roadmap should include mechanisms for setting priorities for research and not provide legitimization for unknown technologies without a documented peer-review process. This proposed research initiative should utilize the widest range of scientists and engineers available, and a thorough peer-review/evaluation process should be developed to select and fund research proposals to ensure that the best research minds are engaged in these important issues. Because the ultimate advances in the efficiency and cost effectiveness of desalination will depend on information transfer to the water industry, a framework should be outlined for development of new desalination technologies. The committee further recommends that information should be provided to the general public and decision makers in order to maintain support for the program.

This letter report reflects the consensus of the NRC committee and has been reviewed in accordance with the procedures of the NRC. The list of reviewers is given in Attachment C. We hope our report is useful as you move forward and appreciate the opportunity to advise you with this important and challenging endeavor.

Sincerely yours,

David Marks, Chair
Committee to Review the
Desalination and Water Purification
Technology Roadmap

Attachment A: Biographical Information
Attachment B: Statement of Task
Attachment C: List of Reviewers

Appendix B

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Appendix C

Committee to Review the Desalination and Water Purification Technology Roadmap

David H. Marks is the Morton and Claire Goulder Family Professor of Engineering Systems and Civil and Environmental Engineering at the Massachusetts Institute of Technology. He is also the director for the Laboratory for Energy and the Environment and coordinator for the Alliance for Global Sustainability at MIT. Dr. Marks' research interests include the organization and management of large-scale infrastructure systems with concern for the anticipation and mitigation of larger-scale environmental and economic impacts. He has served on numerous NRC committees, chaired the Steering Committee on Cooperation in Urban Water Management, and was a member of the Board on Radioactive Waste Management. Dr. Marks also served as chair of the U.S. Office of Technology Assessment's Oversight Committee on Superfund Study. He is the recipient of the ASCE Huber Research Prize. Dr. Marks received his B.S.C.E. and M.S. in environmental engineering from Cornell University and his Ph.D. in environmental engineering from Johns Hopkins University.

Miriam Balaban is the founder and editor-in-chief of *Desalination,* the international journal on the science and technology of water desalting and purification and has served in this position for over thirty-seven years. She founded and edits the *Desalination Directory*, an on-line database of literature in the areas of water purification and desalination and of individuals and organizations active in the field. She is the secretary general of the European Desalination Society and has served on the Board of Directors of the International Desalination Association. Ms. Balaban received her B.S. in chemistry from the University of Pennsylvania, is now professor and program coordinator of the L'Aquila University Master's course in desalination. She is president of the International Federation of Science Editors, has served as professor and dean of the School for Scientific Communication, Mario Negri Sud Institute for Biomedical and Pharmacological Research, Italy and is a research associate at the Center for Philosophy and History of Science, Boston University.

B. Anatole Falagan is an assistant manager for the Water Resources Management Group at the Metropolitan Water District of Southern California. The Group oversees long-range water resources planning and program development for Metropolitan's service area as well as the Colorado River and State Water Project supplies. Mr. Falagan has over twenty years of experience in civil engineering planning and design in water resources. He also leads Metropolitan's Seawater Desalination Program, focusing on both research and development of seawater desalination plants. He received his B.S. and M.S. in civil engineering from Stanford University, and he has an M.B.A. from the University of California, Irvine.

Joseph G. Jacangelo is the manager of Municipal Technology for Montgomery Watson Harza (MWH), an international firm specializing in energy, infrastructure, water and wastewater issues. He also serves as the manager of the MWH Global Water Knowledge Center, and in this position he is responsible for water technology, application, and transfer. Dr. Jacangelo is an adjunct associate professor at the Johns Hopkins University Bloomberg School of Public Health and director of the Center for Water and Health. He is the vice chair of the Membrane Processes Committee of the American Water Works Association and chairs the International Water Association Disinfection Committee. Dr. Jacangelo received his B.A. from Rutgers University and his Ph.D. in environmental health engineering from Johns Hopkins University.

Kimberly L. Jones is an associate professor of civil engineering at Howard University. Her research interests include physical-chemical treatment processes, membrane processes, adsorption, mass transport, interfacial phenomenon, water and wastewater treatment plant design, and water quality. Dr. Jones is a member of the American Water Works Association, the American Society of Civil Engineers, the Association of Environmental Engineering and Science Professors, the International Water Association, and the Water Environment Federation. She was recently named one of the "Top Women in Science" by the National Technical Association. Dr. Jones received her B.S. and M.S. in civil engineering from Howard University and University of Illinois, respectively, and received her Ph.D. in environmental engineering from Johns Hopkins University.

William J. Koros is the Roberto C. Goizueta Chair for Excellence in Chemical Engineering at the Georgia Institute of Technology. His research interests include gas and liquid separations using membrane and barrier materials; formation and application of polymeric, ceramic, and carbon membranes; and structure-permeability relationships. Dr. Koros is editor-in-chief of the Journal of Membrane Science, board member of the North American Membrane Society, and managing editor for their newsletter, Membrane Quarterly. He received the National Science Foundation Presidential Young Investigator Award and the American Institute of Chemical Engineers' Clarence G. Gerhold Award and is a member of the National Academy of Engineering. Dr. Koros received all of his degrees (B.S., M.S., and Ph.D.) in chemical engineering from the University of Texas.

John Letey, Jr. is a Distinguished Professor in the department of soil and environmental sciences at the University of California, Riverside. He is the director of the University of California's Center for Water Resources, which supports water-related research and seeks to develop ecologically-sound and economically efficient water management policies and programs in California. His research interests include agriculture management under saline conditions, soil structure and infiltration, chemical transport through soil, and cooperative studies with resource economists to establish economically optimal management strategies. Dr. Letey is a fellow of the Soil Science Society of America, American Society of Agronomy, and the American Association for Advancement of Science. He is a current member of the Water Science and Technology Board. He received his B.S. in agronomy from Colorado State University and his Ph.D. in soil physics from the University of Illinois.

Thomas M. Pankratz is vice president for CH2M Hill's Global Water Group, with a focus on business development in international desalination and water reuse projects. He has over twenty-five years of experience in the fields of water, desalination, and reuse and has participated in the development of some of the world's largest and most technically advanced desalination projects. Previously, he was the corporate projects director for Vivendi/US Filter, also concentrating on desalination and water-reuse projects. From 1991-1997, Mr. Pankratz served as the Middle East regional manager for Aqua-Chem Inc. He serves on the board of directors for the International Desalination Association and is a member of the European Desalination Association. He received his B.A. degree in business administration from Landford University.

Richard H. Sakaji is a senior sanitary engineer at the California State Department of Health Services, Division of Drinking Water and Environmental Management. In this position, he reviews testing protocols for new water and wastewater treatment processes to ensure the technology meets accepted treatment standards, and he develops policy for water-treatment processes and indirect potable reuse applications. In previous roles at DHS, Dr. Sakaji designed water-quality studies and helped develop water-quality regulations. He has also worked as an engineer for the East Bay Municipal Utility District and Alameda County Water District. Dr. Sakaji is a member of the American Chemical Society, the American Water Works Association, and the American Institute for Chemical Engineers. He received his A.B. in biological sciences, M.S. in sanitary engineering, and Ph.D. in civil engineering all from the University of California, Berkeley.

Charles D. Turner is a professor of civil engineering at the University of Texas, El Paso. His primary research interests include membrane processing of brackish groundwater and surface water, desalting concentrate utilization, and membrane processes for reduction of disinfection by-products. He has also conducted research in water and wastewater treatment, water economics, and water reuse. Dr. Turner is a member of numerous professional societies, including the American Society of Civil Engineers, the American Society of Engineering Education, and the Association of Environmental Engineering and Science Professors. He received his B.S. and M.S. degrees in civil engineering from the University of Nebraska at Lincoln, and his Ph.D. in environmental engineering from Colorado State University.

Mark Wilf is vice president of corporate technology at Hydranautics, a firm specializing in membrane separations. In this position, he oversees development of membrane products and designs and evaluates commercial reverse osmosis plants. He has more than 25 years of experience in the membrane technology and desalination field. Before joining Hydranautics, he served as head of membrane products at Mekorot Water Co. Ltd., in Tel Aviv, Israel. Dr. Wilf was a member of the Research Advisory Council, which advised the Middle East Desalination Research Center on its research priorities. He is also a member of the International Desalination Association and the American Water Works Association. He received his Ph.D. in chemistry at Technior - Israel Institute of Technology in Haifa.

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Stephanie E. Johnson is a program officer with the Water Science and Technology Board. Since joining the NRC in 2002, she has served as study director for three committees, including the Panel to Review the Critical Ecosystem Studies Initiative and the Panel on Water System Security Research. She received her B.A. from Vanderbilt University in chemistry and geology, and her M.S. and Ph.D. in environmental sciences from the University of Virginia on the subject of pesticide transport and microbial bioavailability in soils. Her research interests include contaminant transport, aqueous geochemistry, and hydrogeology.

Mark C. Gibson is a program officer at the NRC's Water Science and Technology Board (WSTB). After joining the NRC in 1998, he directed the Committee on Drinking Water Contaminants that released three reports, culminating with *Classifying Drinking Water Contaminants for Regulatory Consideration* in 2001. He is directing the Committee on Indicators for Waterborne Pathogens for the Board on Life Sciences and the WSTB, and the Committee on Water Quality Improvement for the Pittsburgh Region and Committee on Assessing and Valuing the Services of Aquatic and Related Terrestrial Ecosystems for the WSTB. Mr. Gibson received his B.S. in biology from Virginia Polytechnic Institute and State University and his M.S. in environmental science and policy in biology from George Mason University.

Jon Q. Sanders is a senior program assistant with the Water Science and Technology Board. He holds a B.A. in anthropology from Trinity University. He is a member of the Society for Applied Anthropology and the American Indian Science and Engineering Society. Mr. Sanders has worked on a variety of projects at the WSTB ranging from assessment of the Corps of Engineers' methods of analysis and peer review for water resources project planning to Everglades restoration. He is coauthor of "Sitting Down at the Table: Mediation and Resolution of Water Conflicts" (2001). Jon's research interests include political ecology, Texas water issues, and environmental decision making.