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Progress with the desalination and water purification technologies US roadmap

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Abstract

The worldwide need for fresh sources of drinking water continues to outstrip supply while the resources necessary to develop new supply remain limited. The best solution to this dilemma is the coordination of research efforts on an international basis. The Desalination and Water Purification Roadmap presents a summary of the water supply challenges facing the United States, and suggests areas of research and development that may lead to technological solutions to these challenges. These solutions have international application at the same time that innovation is occurring internationally.

This Roadmap is a living document—updates to the Roadmap may be made on a regular basis to ensure that it remains current and relevant. The Roadmap is also complemented by a series of additional documents, created as a result of meetings to be held, focused on:

- Defining discrete research projects and priorities based on the information contained within this Roadmap;
- Identifying regulatory issues related to the implementation of desalination and water purification technologies, and developing potential solutions where conflicts are found;
- Identifying, evaluating, and quantifying the impaired water resources to better assess the impact that desalination and water purification technologies may have on water supplies;
- Generating plans to accelerate the commercialization of desalination and water purification technologies developed as a result of this Roadmap.

This Roadmap cannot exist in a vacuum—technology development must be undertaken with the context of the product's end-use in mind. The goal of this process is to:

- Develop a consensus and direction to guide investments for the creation of new water purification technologies;
- Identify the roles that various sectors of the economy (e.g., national government agencies, the private sector, educational and non-profit organizations) can play in the creation of new water purification technologies; and
- Develop an expert group to review alternative water purification technologies.

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Toward these ends, we are now joined by a number of national and international organizations, each of which is contributing its own resources to a common end. This end includes assistance in developing novel water treatment technologies as well as improving and sharpening the roadmap itself.

1. The roadmapping process

This Roadmap presents an argument for the need to engage in research and development activities that will:

- Accelerate the evolution of current-generation advanced desalination and water purification technologies so that they are better able to meet the short-term needs of the water providers; and
- Create the revolutionary, next-generation advanced desalination and water purification technologies that will be necessary to produce high-quality waters from increasingly-impaired sources in the mid/long-term.

These technologies, however, will have to meet some set of performance standards above and beyond what currently available technologies can meet—otherwise, why would industry or government invest in their development? Current-generation desalination and water purification technologies are not cost-competitive, and present significant concentrate management problems.

1.1. The Roadmap—Grounded in Reality

The Desalination and Water Purification Technology Roadmap is grounded in reality. Through the development of case studies, the Roadmap establishes a suite of 'Needs' that are representative of the emerging challenges facing the nation. Working from these needs, the roadmap lays the foundation for a science and technology research enterprise the results of which will provide the technologies that can meet these emerging needs. In essence, the Roadmap examines how good today's technologies are, maps this performance against how good technologies must be in the future, and details a suite of research projects that will result in technologies that can meet the nation's future needs.

The primary goal of the desalination and water purification roadmap is to identify research areas that will result in next-generation, revolutionary desalination and water supply purification technologies that are cheaper to build and more efficient to operate than current generation-technology based plants. The secondary goal of the roadmap is to identify evolutionary research that can address the shortcomings of current-generation technologies. Thus, this Roadmap **focuses on real-world concerns**—primarily, evaluating and mapping R&D activities that will:

- Drive down the capital and operating costs of next-generation technologies;
- Increase the efficiency of these technologies by reducing energy costs and treating more water than current-generation plants of the same size;
- Reduce the post-treatment waste disposal concerns that currently hinder widespread application of desalination and water supply purification technologies;
- Allow the 'upgrading' of more diverse sources of water, to include seawater, brackish water, reclaimed (post-consumer) water, and produced waters from oil and gas activities; and
- Improve the sustainability of desalination processes through reductions in the consumption of energy and chemicals.

1.2. The people behind the roadmap

To ensure the development of a comprehensive Roadmap, Sandia and the Bureau of Reclamation convened an Executive Committee and a Working Group (known collectively as the Roadmapping Team) of well-respected water researchers, technologists, and consultants from Federal and local government agencies, academia, research institutions, industry associations, and the private sector. The number of people and organizations is growing.

1.3. The structure of the roadmap

Science and technology roadmaps serve as pathways to the future. They call attention to future needs for development in technology, provide a structure for organizing technology forecasts and programs, and communicate technological needs and priorities and expectations among end-users and the research and development community.

The purpose of the desalination and water purification roadmap is to identify, evaluate, and prioritize research areas that will satisfy near-, mid-, and long-term water supply challenges. Development of the Roadmap followed this five-step process:

Step 1: Identify needs through construction of case studies and examination of state-of-the-practice technologies. These case studies examine the challenges facing geographically-diverse regions of the United States that are representative of the challenges facing much of the nation. Case study authors were tasked with examining and evaluating the future impacts of current patterns of use, economic growth, and population increases.

Step 2: Create critical objectives for each of these Needs. The Critical Objectives provide the overall framework for the roadmap and represent the high-level goals of the Roadmap. The Critical Objectives ensure that research addresses specific Needs, and that research projects stay on target.

Step 3: Identify metrics for each Objective. Metrics are quantitative values that define a Critical Objective. Metrics are comprised of near-term and long-term sub-targets. Metrics quantify the technological and scientific improvements necessary to meet future water needs. Critical Objectives may contain 'stretch' targets that serve to challenge researchers to expand the functionality and performance of technologies beyond what is currently thought possible.

Step 4: Identify technology areas that offer the best chances of meeting future Needs, Critical Objectives, and Metrics.

Step 5: Identify research areas within the Technology Areas and from which scientific understanding and technological advances could emerge to meet the 'Targets'. The Roadmap does not identify specific research projects, but rather areas of research that will provide the science and technology foundations for meeting our future water needs.

The Roadmap Executive Committee recognizes that there is no 'silver bullet' solution to our water-supply challenges. The complexity of the challenges will require a disciplined, focused, and interdisciplinary program to create a 'toolbox' of solutions.

Technological advances in how we purify our water are one important 'tool' that will help mitigate our future water supply challenges. Technologies originally designed to desalinate water are extremely effective in removing contaminants (ranging from naturally-occurring salts to man-made chemicals) from impaired waters. This unique ability allows these technologies to **'create' new water** from underutilized impaired sources (e.g., salty groundwater, impaired rivers, and post-consumer reclaimed waters) and to **produce safe water** by removing a wider range of contaminants than possible with conventional water treatment processes. By purifying impaired waters to create 'new' water for the nation's consumers and industries, desalination technologies will also help to **ensure the sustainability of conventional water supplies**—every gallon of 'new' water created using these technologies is one less gallon that must be drawn from rivers and aquifers, and one more gallon that can be used to maintain our nation's aquatic environments.

The Guiding Vision for the Desalination and Water Purification Technology Roadmap: By 2020, desalination and water purification technologies will contribute significantly to ensuring a safe, sustainable, affordable, and adequate water supply for the United States.

Technology areas for future R&D: A myriad of advanced desalination and water purification technologies exist—some only as curiosities in the laboratory, others in widespread commercial use. In order to effectively identify and evaluate potential research areas, the Roadmap divides the 'world' of advanced desalination and water purification technologies into the following five segments:

- Membrane technologies.
- Alternative technologies.
- Thermal technologies.
- Concentrate management technologies.
- Reuse/recycling technologies.

These five areas have defined the Bureau of Reclamation R&D programs for many years. Some of the research performed in these programs was considered 'unsuccessful' at the time of its completion. Scientific advances realized in the past several decades may enable the success of these projects—for example, materials that have failed in the past may no longer fail due to advances in materials science, or important (recently discovered) concepts may work to overcome fundamental flaws in past research projects. Because of these advances, a review of the historical body of work may open new and interesting avenues of investigation for today's researchers.

Critical objectives and targets: This Roadmap presents an agenda for a balanced basic science, applied research, and development research portfolio—that is, goal-oriented research to meet the needs of desalination/treatment development. Only focused, directed, prioritized, well-conceived and executed activities will result in the technological solutions that are an important component in ensuring our continuing ability to provide additional supplies of water to its people, industries, and environment.

To this end, the Roadmap develops a set of 'Critical Objectives' and associated 'Targets' that quantify the future goals of research activities. These Critical Objectives were developed by Roadmapping Team members and are based on the principle of getting the most bang from each research buck. In those cases where there is no economic model of the interactions between components, reliance on the judgment of the roadmap team was required to set priorities. For more established technologies, an economic model can assist in making these priority judgments.

Fig. 1 illustrates the cost structure of producing potable water from seawater in a reverse-osmosis plant (a current-generation technology employed around the world). Examining this cost breakdown quickly leads to the conclusion that the greatest economic gains are to be found in reducing energy consumption and fixed charges (essentially the capital cost of the reverse-osmosis equipment). Once an economic model exists, this model allow for the setting of research priorities. Those areas that produce the greatest gain should have the highest priority. Consequently, researching technological innovations that lead to a 50% reduction in labor costs (for instance, developing extensive facility automation systems) hold the

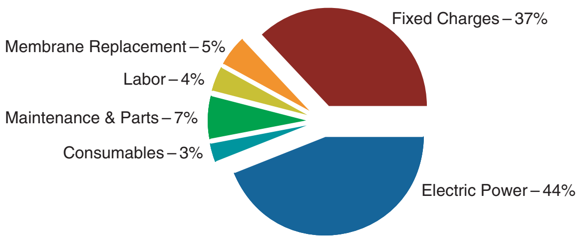

Fig. 1. Cost structure for reverse-osmosis desalination of seawater.

potential of providing only a 2% reduction in the overall cost structure. Spending the same amount of research dollars investigating ways to reduce energy consumption by 50% however, hold the potential of providing a 22% reduction in the overall cost structure—a much larger gain from the same research dollar. The Roadmapping Team used this principle to develop the Critical Objectives found in the Roadmap.

It is important to note that the Critical Objectives and Targets are not set in stone, and may be modified as technologies develop or as demand- and supply-scenarios change. They play an important role, however, in that they provide public and private sector researchers, managers, and organizations targets at which to aim—such targets are essential for research projects such as those proposed in this Roadmap.

Timeframes: The desalination and water purification technologies roadmap identifies research, development, and deployment needs through the year 2020. To facilitate discussion of these R&D needs, the Roadmapping Team considered two roadmap-specific timeframes: the near-term (out to 2008); and the mid/long-term (ranging from 2009 to 2020).

The near-term: Near-term research projects are defined as those projects that must be completed before or by the year 2008. Due to 'lags' between the time when research is completed to the time that it is available for real-world testing and evaluation, near-term research projects must be started immediately, or as soon as funding for them becomes available. Near-term research is generally defined in terms of current technological shortcomings—that is, fixing (as soon as possible) problems currently found in current-generation technologies—and in terms of laying the foundation for the development of revolutionary desalination and water purification technologies.

The mid/long-term: Mid-term research projects will provide the science and technology necessary to transition from current-generation technologies to next-generation technologies. Mid-term research projects will advance current-generation technologies to their logical limits—when applied, these research projects will result in the zenith of current-generation technologies. Mid-term research projects will also introduce the first generation of revolutionary technologies.

Long-term research projects will create the second generation of revolutionary desalination and water purification technologies. Many of these technologies are exploratory and are just entering laboratory studies. Due to the longer timeframe involved with these research projects, it is not necessary that these receive aggressive funding support in the next several years.

Mid- and long-term research areas have been combined due to the uncertainties inherent in predicting the future—the farther from the present that one looks, the blurrier the picture becomes. Thus, trying to separate projects into mid-term and long-term categories may result in artificial divisions.

Mid/long-term research projects are designed to meet the future water needs as opposed to merely evolving those technologies that are currently available. Mid/long-term research projects represent progress toward meeting our long-term water supply needs and the 'stretch' goals.

Supporting a variety of mid- and long-term research projects is important from a research project portfolio-management perspective. The blurriness of the future and the inherently-uncertain nature of research success dictates that all appropriate avenues of research be followed until such time as the research proves itself unwarranted. Such an approach effectively balances risk (the likelihood that any given research project will not reach a successful conclusion) and reward (the chances that any given research project will revolutionize desalination and water supply purification).

The most useful sort of roadmap is one that provides alternative routes to one's destination.

2. Developing technologies to meet future needs

Water planners know that the supply of water must be increased over time to meet the ever-increasing demand. They also know that traditional water supplies are largely tapped out; this will force water suppliers to turn to overlooked and underutilized non-conventional or impaired sources while at the same time employing innovative water management options. The question then becomes: what technology or technologies will meet the needs?

Roadmapping participants identified five broad technology areas. Some of these technologies are currently in use, while others exist only in the laboratory. Ensuring that these technologies develop to help meet our future needs will require investments to both evolve current-generation technologies and develop revolutionary, next-generation technologies.

2.1. Evolution of current-generation technologies

Current-generation desalination and water purification technologies can produce the volumes of water that will demand in the future—at a price. Advanced desalination and water purification plants are currently expensive to build and operate, resulting in water prices that are unpalatable in all but the most extreme situations and for all but the wealthiest consumers (generally those in large, urban areas that have no alternative means of meeting their water demand and industries that require high-quality water). Thus, the application of these current-generation advanced desalination and water purification technologies to provide water for residential users has been limited.

Treatment cost for water from current-generation advanced desalination and water purification facilities is between \$1 and \$3 per thousand gallons (or up to 5–6 times more than 'conventionally treated' fresh water).[1] The cost of producing water from these advanced desalination and water purification technologies has declined over time, albeit at a rate of only approximately 4% per year (Fig. 2).

This improvement may be viewed in terms of the thermodynamic minimum of salt removal from seawater. For a solution of 3.5% sodium chloride, the minimum energy use due to osmotic pressure is 3 kJ/kg of water. This may be expressed in terms of electrical energy as 3.1 kWh per 1000 gal or approximately \$0.30 per 1000 gal. This energy use will never be achieved but is presented to illustrate that substantial improvement is possible.

[1] It must be noted here that the cost of water produced using current-generation desalination and water purification technologies varies widely depending upon location, ownership of the facility, the financing used to construct the facility, operating contracts, distribution infrastructure costs, conveyance to the customer, and a myriad other issues.

2.2. The impact of revolutionary, next-generation technologies

Maintaining the status quo in R&D investments will result in more than the cost of water increasing (in terms relative to the percentage of income spent on water and wastewater services) over the next two decades.[2] For some, municipalities, it will result in buying unimpaired waters from nearby agriculture, with the possible result that local agriculture economies may suffer.

Establishing a desalination and water purification technology research program that is 'planned and prioritized in a coordinated and systematic way'[3] can reduce the absolute and relative cost of water in the next two decades. Fig. 3 illustrates the impact of developing and applying revolutionary, next-generation advanced desalination and water purification technologies – an accelerated reduction in the cost of water.

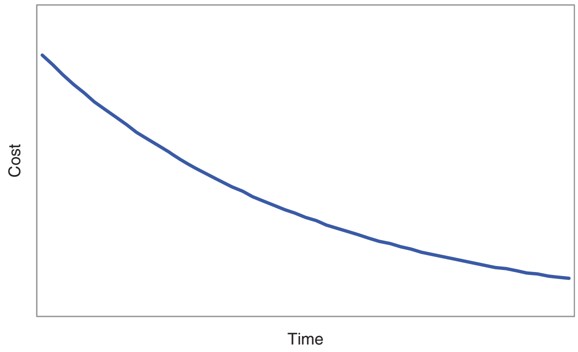

Fig. 2. Historical and projected reduction in cost for water produced by current-generation desalination facilities.

[2]This is largely due to the increasingly salinity of many water sources. As salinity increases, so too do the costs when using conventional water treatment plants and current-generation desalination and water purification facilities. The large volumes of concentrate that these technologies generate will require costly treatment or disposal, thus increasing the per unit cost of water.

Development and application of these revolutionary technologies will play an important role in meeting water needs in the coming decades. We cannot realistically (that is to say, economically) increase the volume of water available in the future relying solely on conventional water treatment plants and the evolution of current-generation desalination and water purification technologies. It is the revolutionary technologies outlined in this Roadmap that will act to fundamentally shift the cost curve for desalination and water purification technologies, making the cost of the plants accessible to a greater number of communities and the cost of the water they produce more affordable for a greater percentage of the world's population.

2.3. Parallel track—developing evolutionary and revolutionary technologies simultaneously

Solving the problems of today's technologies while developing the revolutionary, next-generation advanced desalination and water purification technologies of tomorrow will require a comprehensive parallel track R&D

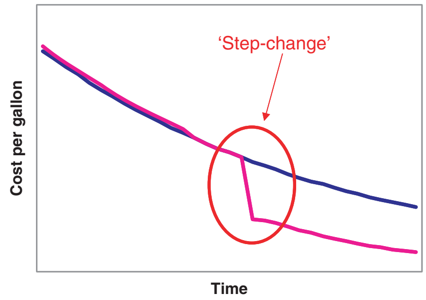

Fig. 3. Supporting revolutionary R&D: Anticipated reductions in cost for next-generation, revolutionary water purification technologies. Building on science and technology advances made over the past 10 years, revolutionary technologies offer the promise of a 'step-change' in the price of producing potable water from impaired waters. — Evolutionary Technology; — Revolutionary Technology.

program. Only through such an R&D program will we be positioned to increase its water supply through use of overlooked and under-utilized sources.

3. Next steps

Water—where it is found, who owns it, how and for what it is used—is a web of complex issues. The Desalination and Water Purification Technology Roadmap, in detailing a suite of research areas and critical objectives that hold the potential of producing technological solutions to our water supply challenges, addresses one small piece of a much larger puzzle.

Technological development must be conducted in context—technologists must consider where their technology will be used, under what conditions, with what constraints, and by whom. A conceptualization of the broader context in which the Roadmap operates is seen in Fig. 4.

The components presented here define the context for future technology developments—identifying where newly-developed technologies might find application (map saline water resources), under what conditions those technologies might have to operate (characterize chemical conditions), the constraints on their operation (address environmental/regulatory issues), and who will operate them (educate water-use communities, support early implementation).

The Desalination and Water Purification Technology Roadmap exists at the very upper-left of this continuum—it presents 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. The roadmapping

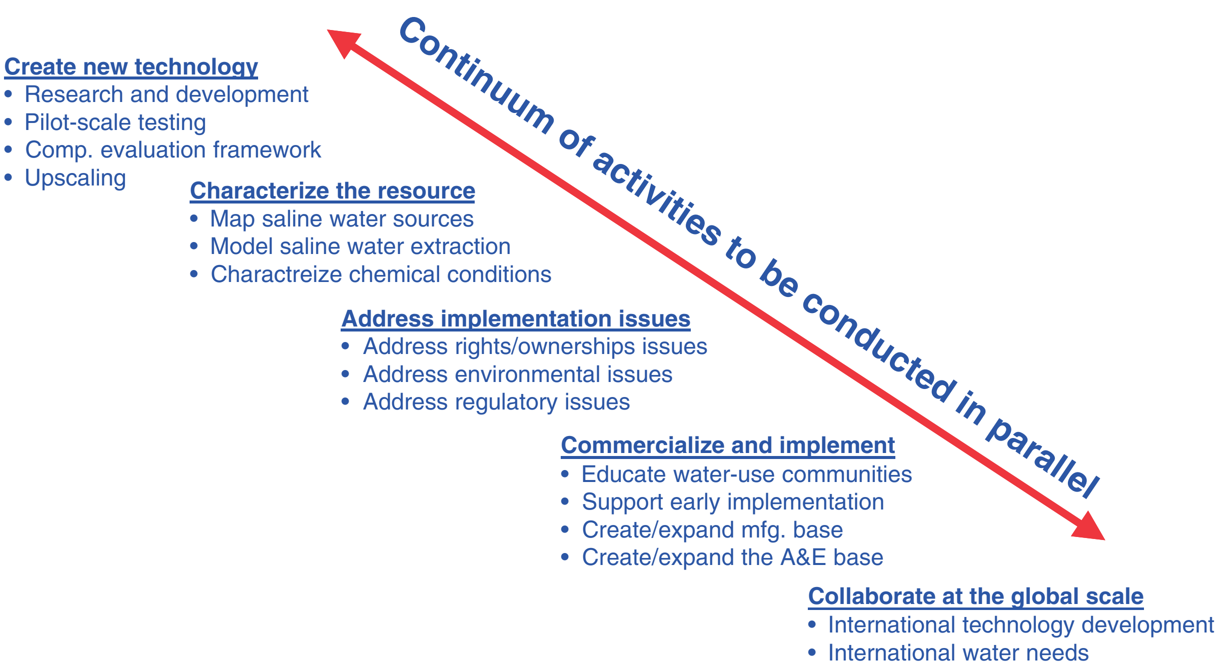

Fig. 4. A conceptualization of the roadmapping and implementation process.

process has revealed the need for complementary activities as shown along this continuum:

- **Create new technology.** Deciding which research proposals to fund when many are presented is a daunting task. Historically, much of the decision has been qualitative – a reviewer's opinion of the principal investigator or the 'interestingness' of the proposal. Such qualitative analyses are inappropriate when judging focused, targeted research projects. Thus, a comprehensive framework must be developed so that research projects are selected based on their ability to meet (or contribute to meeting) the metrics of the roadmap.
- **Characterize the resource.** Mapping and characterizing saline aquifers is an important part of the process to improve water availability. It is essential to know the size, delineation, and quality of our water resources. Another part of this same program is characterizing reservoirs that might receive concentrate produced by desalination technologies.
- **Address implementation issues.** Greater attention should be paid to issues found in areas where the need for desalination is acute. The complexity of these issues (environmental, ecological, economic, regulatory, ownership, etc.) demands a focused approach to identifying the core issues and developing a framework within which interested parties can work to resolve the issues. Systematically identifying the core issues related to the deployment of desalination and water purification technologies, identifying the key actors and interested parties, and establishing a framework within which issues can be constructively discussed may reduce the ad hoc nature of past discussions.
- **Commercialize and implement.** Freeing the road of deployment and implementation issues will not alone cause the widespread adoption of desalination technologies. The barriers found within the industry itself and within the public will have to be mitigated or removed. Educating the public regarding the safety of desalinated water and the benefits that it provides will be important to smoothing the path for deployment. Working with the industry to develop incentives for early adoption of new technologies will speed their introduction to the marketplace. Developing independent testing facilities and creating comprehensive cost modeling software tools will also serve to mitigate barriers to commercialization.
- **Collaborate at the global scale.** The worldwide deployment of desalination technologies can be an important component in enhancing national as well as international security. The United States should continue and expand its interactions with nations around the world where water supply issues may threaten regional stability.

4. Conventional water treatment vs Desalination and water purification

Conventional water treatment plants typically utilize a hundred-years-old, five-step process: coagulation to improve water clarity; sedimentation to remove suspended solids; filtration; disinfection; and direct delivery and/or storage. Sometimes all of these five steps are not needed, and sometimes additional steps (treatment using chemical additions, soda ash or weak acids, or by filtration with granular activated carbon or calcite filters) are required to meet water quality standards. Conventional water treatments plants do not remove total dissolved solids from the source water, and their ability to remove emerging water-borne threats to human health is unknown at this time.

Advanced desalination and water supply purification plants utilize a host of methods to remove salts and water-borne threats to human health. These processes include running water through a series of membranes, distilling water and then condensing the purified water steam, freezing water, and several other approaches. All of these technologies are effective at removing salts from water and in removing water-borne threats to human health. In addition, these advanced technologies are flexible in design and application, thus offering great potential in removing emerging human health threats from our water supply.

Biography

Thomas Hinkebein (*Albuquerque, NM*), *Sandia National Laboratories*

Tom Hinkebein manages the Geochemistry Department, which is responsible for a number of fundamental science studies as well as the development of novel water treatment processes. Tom received his Ph. D. in Chemical Engineering from the University of Washington, Seattle and has worked at Sandia for 25 years In the water treatment program, Tom is responsible for novel arsenic removal and perchlorate removal technologies. He is also currently managing several lab directed research and development programs which explore novel concepts in water supply enhancement and desalination. Additionally, Tom is responsible for coordinating the development of a technology roadmap for future research in desalination technology.