MEMORANDUM

Date: April 2013

To:	Heidi Luckenbach
From:	Jonathan Dietrich
Re:	Comparison of Desalination Technologies
Subject:	scwd[2] Regional Seawater Desalination Project

Each year, the water treatment research and development community continues to bring forward innovative ideas to provide competitive, innovative, and cost-conscious drinking water to the public. For example, reverse osmosis (RO) technology was first developed for commercial purposes in the late 1960's and has seen continuous improvements in performance, reliability, and water quality since that time. Lately, innovative technologies have made headlines as possible solutions to traditional seawater desalination methods such as reverse osmosis technology. Many of the technologies envisioned by these ideas may be very promising; however many are in the early stage of development. A few innovations have progressed beyond the initial bench-top research phase and proceeded (with varying degrees of success) to proof testing, pilot or demonstration testing, and commercial introduction for select applications.

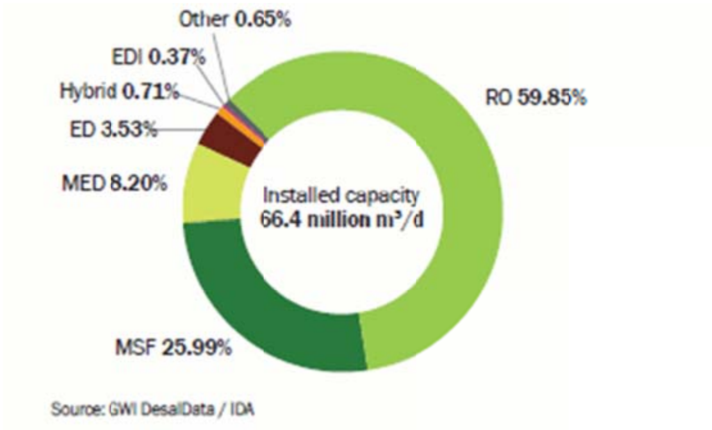
scwd[2]'s goal with this informational memorandum is to further describe why RO is the preferred technology for the proposed seawater desalination plant (Plant). This memorandum in intended to enhance meaningful discussion points regarding other desalination technologies that were considered, however have not progressed beyond the initial consideration point, as alternatives for the Plant.

Technologies Commercially Available – Keeping Things in "Perspective"

Around the globe, more than 99-percent of the technologies used to desalinate water can be divided into three main categories: reverse osmosis (using a semi-permeable membrane and manipulating the effects of osmotic pressure); thermal (by heating/evaporation/condensation); and electric current (by applying electricity across an ion exchange membrane). RO accounts for just under 60-percent of installed global desalination capacity by technology; followed by thermal, Multi Stage Flash (MSF) + Multi Effect Distillation (MED) + Vapor Compression (VC) with about 34 percent; followed by Electrodialysis (ED) with about 3.5%. A breakdown by technology is shown in Figure 1; with an accompanying list and brief definition of the technology contained in Table 1[1].

[1]Global Water Intelligence "IDA Desalination Yearbook", 2011-2012.

Figure 1
Total Worldwide Installed Capacity by Technology[2]



That's almost 20 *million* acre-feet per year[3] of RO membrane desalination technology installed around the globe to purify water. In addition, about 59-percent of desalination plants worldwide treat seawater (remaining sources treated include wastewater, rivers, brackish water, pure or "ultra" pure water, and brine).

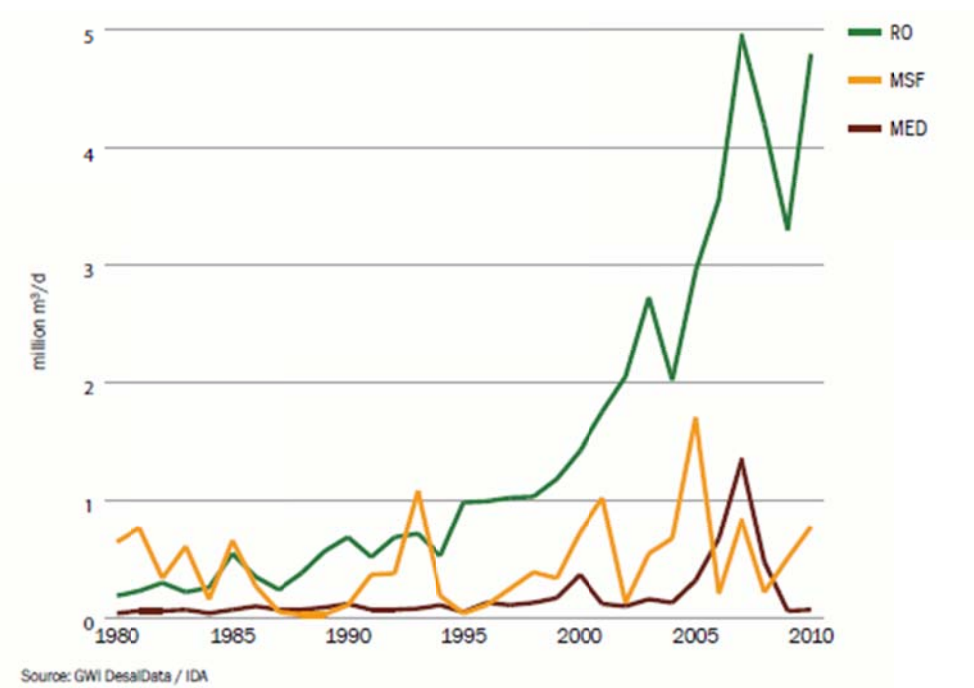
Table 1
Worldwide Desalination Capacity by Technology, 2011-2012

Technology	Percent of Market (%)	Brief Definition
Membrane Separation		A mechanical process where water is pushed through a semipermeable membrane in a direction opposite to that for natural osmosis
Reverse Osmosis (including Nanofiltration)	59.85	
Thermal		A thermodynamic process where water is subjected to heat and low atmospheric pressure to facilitate evaporation and condensation
Multi Stage Flash, MSF	25.99	
Multi-Effect Distillation, MED	8.20	
Electric Current		Electrochemical process for the removal of select dissolved salts across a membrane by applying electricity.
Electrodialysis (ED) (Category includes ED Reversal)	3.53	
Electrodeionization (EDI) including Continuous EDI	0.37	
Hybrid / Other		Various mechanical, thermal, and chemical processes applied in combination to achieve project-specific requirements (such as zero waste discharge).
RO/Thermal	0.71	
Freezing, ZLD Crystallization	0.65	

[2] Global Water Intelligence "IDA Desalination Yearbook", 2011-2012.
[3] 1 acre-foot = 325,854 gallons. $1 m^3$ = 264.17 gallons.

Improvements in the efficiency of seawater RO membranes became more pronounced in the 1990's. During that time, seawater desalination using RO technology began to significantly outpace thermal technology. Figure 2 shows how RO capacity has continued an upward rise, for example, compared to thermal-based technologies. Addition of thermal desalination capacity is tied to the cyclical growth of the Middle Eastern desalination market. Largely due to very low fuel and associated power costs, three countries have greater than 1 million m^3/day (264 mgd; or about 300,000 ac-ft/yr) of installed thermal capacity: United Arab Emirates, Saudi Arabia, and Kuwait. Rounding out the top 5, the other two are Qatar and Libya.

Figure 2
Annual New Contracted Seawater Desalination Capacity by Technology; 1980-2010[4]



New and emerging desalination technologies typically follow a 10-step process to reach commercial maturity. These steps are described as:

1. Discovery – Discovery is when a new idea or concept is initially thought about.

2. Mathematical Modeling – Mathematical equations are developed to understand the physical, chemical, thermodynamic, structural, and safety capabilities and limitations of the concept. Usually mathematical modeling takes several months to less than a year.

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[4] Figure 2: Global Water Intelligence DesalData Database "IDA Desalination Yearbook 2010-2011"

3. Lab (Bench Scale) Testing – During this period, the concept is constructed in very-small scale simulation tests to provide first-level observations regarding the critical performance characteristics of the concept to compare it with mathematical models. Bench scale testing can take several years based on the development of a manufacturing method to test the mathematical models.

4. Proof of Concept – Typically, a "miniature", custom-constructed and purpose-built embodiment of the core concept is developed which works as modeled (and predicted) to establish preliminary direction for projected operating characteristics. This is done in order to further develop the business case with information about additional development costs and manufacturing costs, which helps to establish the concept's value to the industry. The proof of concept period can take several months to a year (or longer if setbacks occur).

5. Pilot Testing – A small-scale configuration of equipment, sometimes customized to meet the smaller scale equipment size and dimensions, is arranged to demonstrate the operating characteristics of the concept when placed into service. Pilots embody concept-to-execution in the form of either limited or fully functioning equipment, which is observed to record meaningful operational characteristics and performance data. This data can be analyzed to support the business case, and make plans for further testing at a larger scale. Pilot testing can last from several months to a year or longer based on the newness of the concept and its' ability to operate in a sustainable, repeatable, and reliable fashion. Performance results from the pilot test are integrated into the design of the concept for further refinement if necessary.

6. Demonstration Scale – The arrangement of demonstration equipment does not rely on smaller scale custom-manufactured equipment and is more adaptable to commercially available components for assembly. Usually scale-up and the potential mathematical and operational inaccuracies associated with pilot scale are eliminated at the demonstration scale. Results from a demonstration scale operation fully substantiate the business case (capital and operating costs versus alternatives) and validate key characteristics necessary for a commercially viable product including reliability and predictability of performance. Demonstration scale testing can take from a few months up to a year.

7. Deployment – Deployment is the period where the technology is considered available to "outside" parties. Deployment usually involves a scale similar to the demonstration testing to further demonstrate and reinforce performance projections, reliability requirements, and operating costs. Deployment is used as a measure to reduce exposure to risk.

8. Infancy - The pool of operating data is widened and the quantity of deployed installations adds to the pool of operating data. Different installations can, and do, present varying types of treatment challenges, enhancing the perception and operating capability of the technology, risks and associated costs in a market sector.

9. Establish Track Record – A technology in operation over a sufficient number of installations over a period of time has an established track record. The technology is considered reliable, and capital and operating costs are very well understood.

10. Commercial Maturity –A technology is considered commercially mature during the extension of the track record period – essentially, the pool of information associated with the technology is fully developed and cannot be further refined or modified without introduction of another concept to modify the characteristics of the fundamental technology.

Long ago, the RO, thermal, and electric/ion exchange technologies reached the "commercially mature" stage. The majority of most other desalination technologies, however, have not reached this point and none are operating as the primary treatment technology within a drinking water production facility in the United States. Because of the lack of installations, inapplicability of the technology for drinking water, and/or absence of approval by the California Department of Public Health, such alternatives do not practically present an acceptable risk for use by scwd².

Factors Considered

A number of factors are considered in making the determination as to whether a technology should be considered as a viable alternative to RO for drinking water production (and hence, for scwd²). These primary factors are:

1. Commercial maturity. Discussed in the previous section.

2. Where the technology is suitably applied. A cross-over technology from oilfield production, for example, might appear to qualify as a technology cross-over for drinking water production. However, the technology would be required to meet the codes and standards for drinking water facilities, and would also need to have a track record treating seawater effectively and in a reliable manner.

3. Energy and associated costs.scwd² is very conscientious about capital costs, power consumption, and the expense associated with operations. Compared to other water infrastructure projects, this point is even more poignant regarding the proposed seawater desalination plant. Capital costs come from a budget that is planned years in advance and reviewed and re-balanced annually. The budgeting process for capital costs is similar to how someone might budget household expenses, but on a larger scale, with a 4-5 year horizon (or more); and with many more factors. Capital costs associated with

alternative technologies will not be thoroughly understood or predictable unless the technology is already in-service at another, similar application.

Yearly operation and maintenance costs come from the operating budget, and cost forecasts must be as precise as possible to meet the expectations of the community. In the process of evaluating the energy cost of a technology, historical operating information is necessary to support accurate cost projections and for planning purposes. Therefore, if operations and maintenance costs simply are not available nor reliable because a technology has no operating history, it is not practical to consider it for treatment of a water supply for the region.

4. Capability to meet stringent drinking water quality goals. There are two parts to meeting drinking water quality regulations and requirements: the materials of construction used to build the facility; and the quality of the drinking water produced by it. Material and equipment used in the production of drinking water must meet vigorous public health and sanitation standards (for example, use of "NSF – National Sanitation Foundation[5]" certified material). With few exceptions, many concepts and alternative treatment configurations may not carry certification for use in drinking water treatment. Additionally, the equipment or process must have a track record of meeting strict drinking water quality criteria as established by the United States Environmental Protection Agency (USEPA), as well as State, Regional, and Local water quality standards. If a proposed alternative does not meet the criteria established by regulatory agencies, it is not considered in the immediate future to provide a public drinking water supply.

5. Permitting feasibility. The safety and general health and welfare of everyone drinking the water that comes out of the tap is of paramount importance – compliance is an ethical and legal obligation. When considering use of a technology in a water treatment plant, it is important to know that a project could be permitted and how long the process will take. If a technology has never been permitted by agencies responsible for regulating the quality of water served to the public, it is unlikely to be approved by a public entity such as $scwd^2$ for use as a treatment technology. One of the reasons for this is that regulatory agencies responsible for the safe supply of water to the public may require a year or more of exhaustive, expensive testing to validate the concept. $scwd^2$ does not consider it a practical, responsible course of action to pursue a technology that is unlikely to bring a reliable source of water to the community in a timely fashion.

6. Environmental Impact. We evaluate how an alternative technology would affect our environment. This category includes various environmental technical "inputs" for consideration, such as space and land

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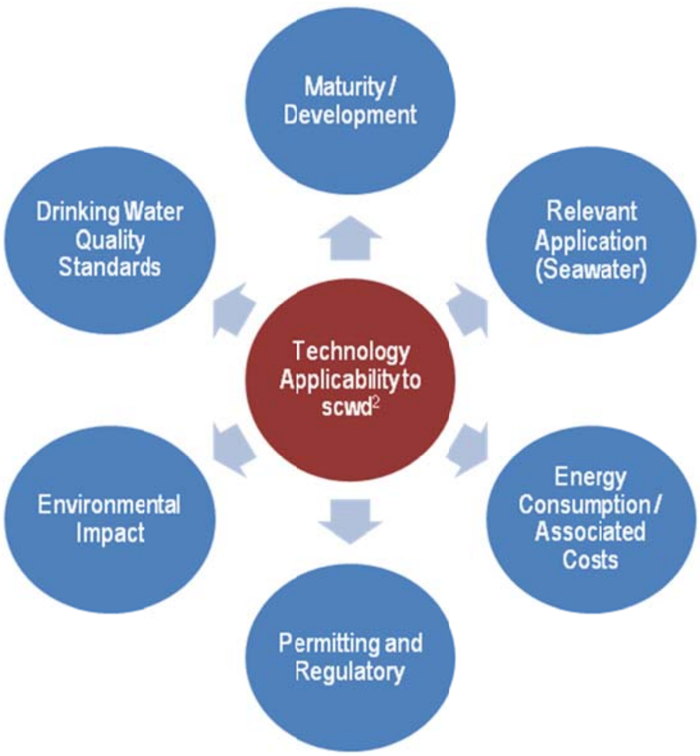
[5] http://www.nsf.org/business/about_NSF/
Other public health and material safety references are located at the American National Standards Institute: ANSI (http://www.ansi.org/about_ansi/overview/overview.aspx?menuid=1); and American Water Works Association: AWWA (http://www.awwa.org/).

allocation, materials used for the construction of the facility, materials required for operations and maintenance purposes, process, sanitary and solid waste byproducts, potential air emissions, and the general environment surrounding the proposed Plant. This can generally be a controversial topic because it frequently can transcend beyond "black and white numbers".

scwd[2]'s approach is to determine first, if the proposed technology has merit as based on the results of the first five primary determination factors above. If these merits have ground, then "environmentally friendliness" is compared with other competing technologies.

Figure 3 shows the various factors in decision-making and their relationship to the applicability of desalination technologies for scwd[2].

Figure 3
Desalination Technology Decision-Making Factors



These factors are not inter-dependent and carry various degrees of significance when considered for drinking water service. For example, if a technology is suitable for drinking water production, but it is still in the early stages of development, it is not a practical alternative until commercial maturity is reached. Another example would be energy requirements and associated facility costs which can influence environmental aspects of the project, such as the associated production of greenhouse gases with a facility that requires energy to produce drinking water.

Based on thoughtful consideration of a number of factors (including a preliminary technical and environmental assessment of available technologies), scwd[2] has moved forward with membrane seawater desalination as a preferred technology. A fundamental change from seawater membrane desalination to an alternative technology would require its successful passage through the multitude of qualifying factors previously discussed.

A number of questions have been raised regarding alternative seawater desalination technologies. The questions are typically voiced, on occasion, in regularly scheduled public meetings about the project. This informational memorandum provides a more thorough discussion of emerging technologies and the decision-making factors considered by scwd^2 when an appropriate treatment technology was selected for the proposed Project. This memorandum may therefore be a helpful reference for those seeking additional justification or resources regarding desalination technologies. All available technical information about the Project is available on the Regional Seawater Desalination Program Website (http://www.scwd2desal.org/).

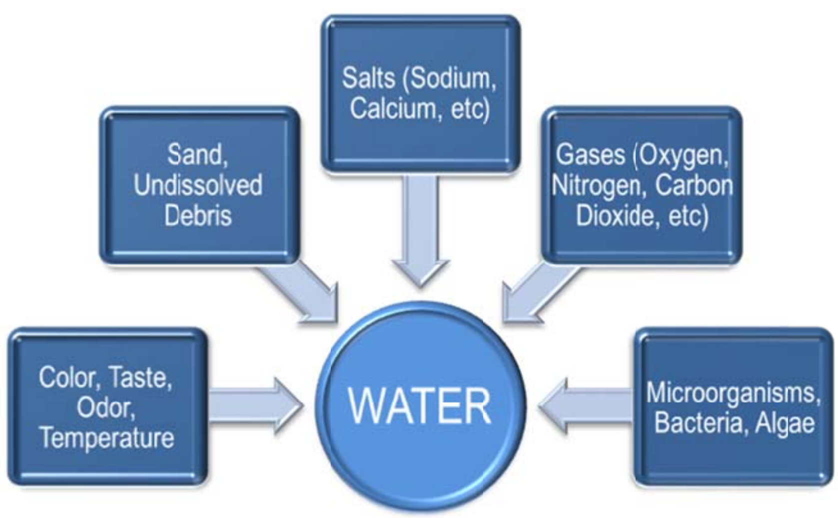
After applying the "Factors Considered" criterion in numbers 1-6 above, there are a few situations where a concept or technology is proven and/or has seen limited commercial service. Since most of the technologies considered rely on the principles of osmosis, it is worthwhile to explain the underlying principles of osmosis.

<u>Water Sources</u>

Water is a universal solvent and will have characteristics, or contaminants, imparted to it based on its source. These characteristics are physical, chemical and biological. All water sources share the same characteristics; though to varying degrees, based on where it comes from – for example, the primary difference between seawater and brackish or fresh water is the salt content; where seawater is the saltiest.

Physical characteristics include color, taste, odor, temperature, debris such as sticks, leaves, silt, sand, and suspended solids. Chemical characteristics describe any material that can be dissolved in water (and invisible to the naked eye) such as soluble salts and gases; and biological content could include bacteria, microorganisms, viruses, and pathogens. Figure 4 shows this association.

Figure 4
Characteristics and Content of Water Supplies



Many treatment technologies have been tested, developed and commercialized in order to effectively treat and/or remove contaminants that are harmful in drinking water. Multiple technologies targeting several types of contaminants are usually combined “under one roof” in one treatment plant to sufficiently protect the quality, safety, and reliability of drinking water. This memorandum focuses on the capabilities of a treatment technology to remove soluble salts from the ocean.

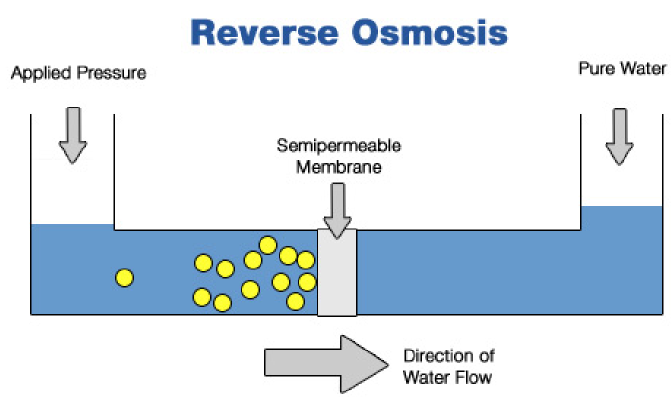
Seawater Reverse Osmosis (SWRO)

SWRO Technology

Osmosis is a naturally occurring phenomenon. When two liquids of different concentration (for example, salt water, and drinking water) are separated by a semi permeable membrane, thermodynamics tells us the fresh water will move through the membrane to dilute the salt water until both sides are equal in concentration; or “equilibrium”. This is called osmosis; and the tendency of the fresh water to want to move through the membrane creates a pressure gradient called “osmotic pressure”. Reverse osmosis, therefore, involves pushing water (a solvent) on the side of the high solute concentration (seawater) through a semi-permeable membrane to a region of low solute concentration (drinking water) by applying pressure in excess of the osmotic pressure. Figure 5 shows this effect.

According to the Center for Disease Control (CDC), (http://www.cdc.gov/), reverse osmosis is “A filtration process that removes dissolved salts and metallic ions from water by “forcing” it through a semi-permeable membrane”.

FIGURE 5
Producing Drinking Water by Applying Pressure



The force that the CDC describes is one that is necessary to overcome a naturally-occurring osmotic pressure gradient across the semi-permeable membrane. Seawater is pushed through the membrane, leaving behind more concentrated seawater and pure water containing a small quantity of dissolved salts on the other side exiting the membrane.

The force needed to reverse the osmotic process varies with the dissolved salt content of the feed water; because as dissolved salt content increases, so does the osmotic pressure (and hence the pressure to reverse the flow of water to produce pure water). For example, SWRO treating ocean water off the coast of Santa Cruz would require more than 900 pounds per square inch (psi) of pressure to push water through the RO membrane. Conversely, RO membranes desalinating brackish water throughout California and elsewhere around the United States requires a much lower pressure of 150-200 psi because of the lower salt concentration.

Whenever salt levels are undesirable or exceed drinking water quality regulations, and where concerns exist based on potential microbial contamination, membrane treatment is typically the preferred and most effective treatment technology to meet drinking water regulations. Not surprisingly, the EPA designated reverse osmosis as a best available technology (BAT) for removal of numerous inorganic contaminants, including antimony, arsenic, barium, fluoride, nitrate, nitrite, boron, selenium, radionuclides, and emerging contaminants, including endocrine disrupting compounds (synthetic and natural hormones), and several pharmaceutical compounds.

One recent innovation to SWRO technology is the introduction of encapsulated, benign nanostructured material into the reverse osmosis membrane[6]. NanoH2O is one company who has refined this process, ultimately leading to commercial introduction in 2011. The "enhanced" SWRO membrane offers the potential to reduce the energy required for the membrane desalination process by about 10-percent (based on feed water quality).

SWRO Costs

Any project's attributes affect cost and are primarily based on project complexity. Most SWRO project costs are spread across a wide range of $2.00/kgal ($650/ac-ft) to $12.00/kgal ($3,900/ac-ft); based on the complexity of the intake system, distance to distribution, and site location[7]. In 2010, the scwd² Seawater Reverse Osmosis Desalination Pilot Program Report presented projected construction costs and operations and maintenance costs for the proposed seawater desalination plant which are consistent with the range of costs for other similar plants worldwide[8].

SWRO Limitations

Compared to other desalination technologies, there are relatively few technical limitations to the implementation of SWRO. Seawater desalination is known for relatively high power consumption compared to other conventional non-desalinating water treatment methods; however the other conventional methods are not designed to reduce or remove dissolved salts from water. The energy consumption for scwd²'s proposed SWRO desalination process ranges from 14.5 – 15 kWh/kgal[9](4,725 to 4,888 kWh/ac-ft) compared to 1.23 – 2.85 kWh/kgal for other local surface water and groundwater treatment sources[10].

SWRO Commercialization

SWRO technology was commercialized in the late 1960's; and by the early 1970's, a multitude of configurations and membrane materials were commercially available to purify seawater. In fact, dozens of

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[6] http://www.nanoh2o.com/

[7] WateReuse Association, "Seawater Desalination Costs", December 2011, website: http://www.watereuse.org/information-resources/desalination/resources

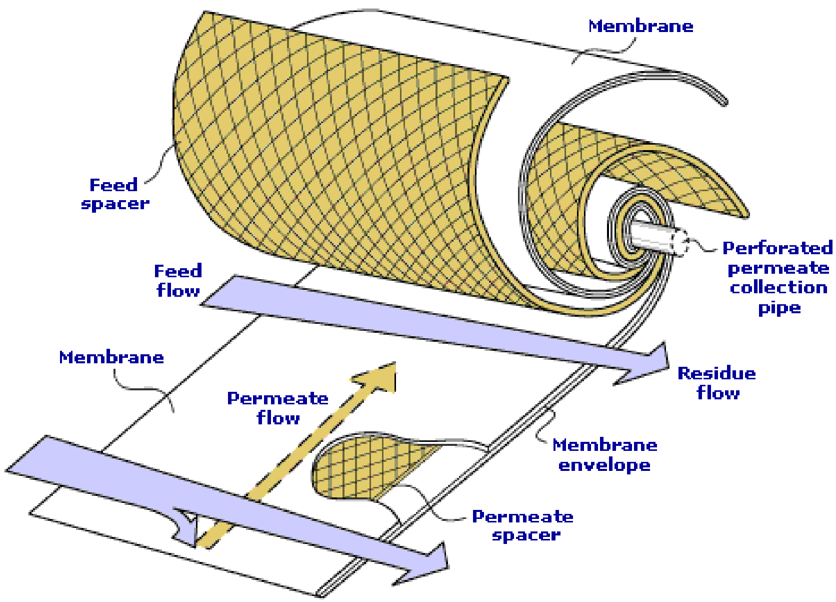
[8] Range of costs worldwide as reported by the Water Desalination Report; Texas Innovative Water Workshop, San Antonio, Texas, October 11, 2010.

[9] The membrane treatment process consumes 8 to 9 kWh/kgal of the total treatment power consumption

[10] scwd² Technical Memorandum, "Summary of scwd² Energy and GHG Approach" July 9, 2012.

membrane desalination plants dot the California landscape11 and several hundred large-scale plants are in operation worldwide. Today the most common configuration and material for drinking water applications is called "spiral wound" which is an element made of a highly specialized thermoplastic membrane. Figure 6 shows how a spiral wound element produces fresh water from seawater.

FIGURE 6
Spiral Wound Reverse Osmosis Module[12]



THERMAL (DISTILLATION)

Technology

When salty water is boiled, the steam vapor that is created contains pure water, leaving salts which were initially dissolved in the water, behind. Oil or gas is needed as a fuel source to heat the water. As the steam vapor cools and condenses, pure water droplets form, which is called "distilled water". This process was first knowingly discussed during the days of Aristotle[13] (320 B.C.). Figure 7 shows the basic distillation process[14].

Basic distillation technology has matured significantly over the ages; although, still, the growth and progression of thermal-based distillation through today focuses primarily on locations where clean water is an absolute necessity for life and fuel is not prohibitively expensive. For example, 1,000 British Thermal Units ("BTU's") of energy are necessary to vaporize one pound of water into steam[15]; or 8.55 *million* BTU's

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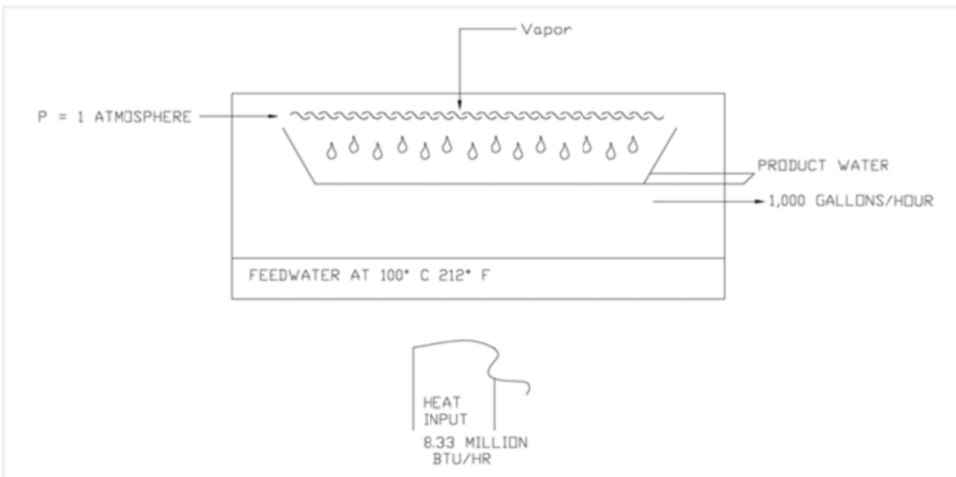
[11] Johns, J, California Department of Water Resources: "The Role of Desalination in Meeting California's Water Needs", June 15, 2006, http://documents.coastal.ca.gov/reports/2006/6/Th3a-6-2006-presentation.pdf. Also American Membrane Technology Association website Desalination Facility interactive map: http://www.amtaorg.com/map.html.
[12] http://www.mtrinc.com/faq.html
[13] Meteorologica (II.3, 358b16)
[14] Desalting Handbook for Planners, 3rd Ed., July 2003. US Department of the Interior, Bureau of Reclamation, Desalination and Water Purification Research and Development Program Report No. 72.
[15] For a number of historical reasons many different terms and symbols are used for power and energy

per kgal. This would equate to over 6 megawatts of power necessary to boil enough water to match the capacity of the proposed seawater desalination plant.

For these primarily fuel-related economic reasons, the distillation process has been optimized to increase the efficiency of the basic distillation process. These are[16]:

- Multiple Effect Distillation (MED),
- Multi-Stage Flash Distillation (MSF), and
- Vapor Compression Distillation (VC)

FIGURE 7
Basic Distillation Process



Water boils at successively lower temperatures as atmospheric pressure drops (familiar with "baking at high elevations" instructions?). This effect helps the modern flash/distillation system become more efficient by applying a vacuum. Although MSF and MED processes rely on the presence of heat (steam) to boil water under a slight vacuum to extract the vapor to condense into pure water, both accomplish the task in a slightly different way. In the conventional MSF process, heated seawater flows through the bottom of a multi-chambered rectangular vessel. Each chamber – also called "stage" - operates at a successively lower pressure, causing the hot seawater to begin boiling immediately as it enters each new stage. The portion of the seawater that instantly vaporizes, or flashes into steam, is then condensed into pure water. Figure 8 shows this process. The main difference between MSF and MED is in the method of evaporation and heat transfer; resulting in lower costs for the MED process because there is no need to recirculate large quantities of brine. MED efficiencies can also be improved with "thermal vapor compression"(TVC) whereby part of the vapor formed in a low-temperature effect is recompressed and reintroduced to the first effect[17].

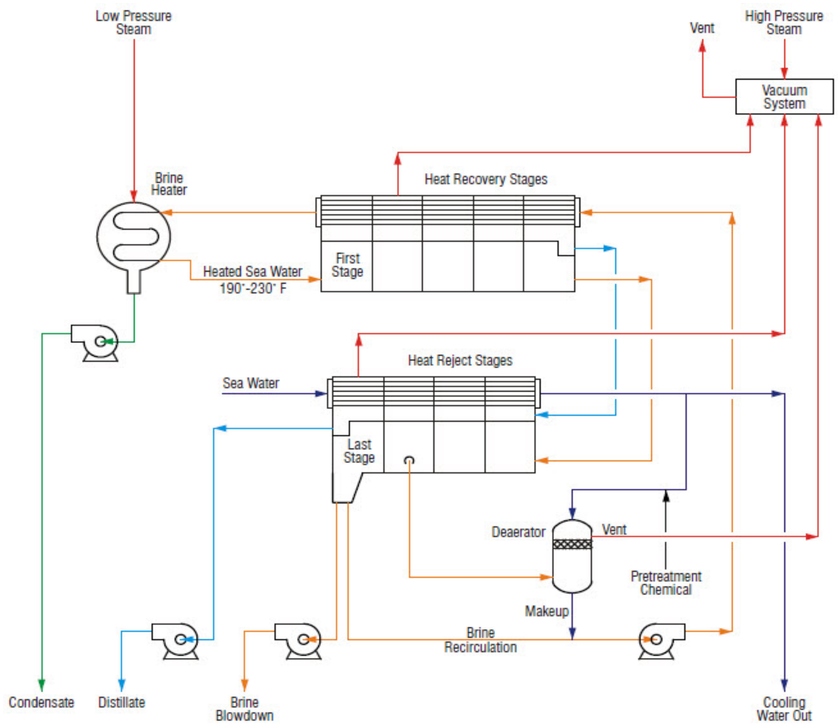
Due to the costs associated with power generation and the exotic materials needed to coexist in the harsh saline water temperatures, most thermal desalination plants are cogeneration facilities. In a

[16] Desalting Handbook for Planners, 3rd Ed., July 2003. US Department of the Interior, Bureau of Reclamation, Desalination and Water Purification Research and Development Program Report No. 72.
[17]Wade, N., "Distillation plant development and cost update", Desalination 136 (2001) 3-12.

developing region where additional sources of power are needed, a thermal-based desalinated water facility can utilize waste heat generated by the power plant to produce desalinated water.

In the late 1950's-early 1960's, the United States Bureau of Reclamation heavily investigated distillation as a method to desalinate seawater for drinking purposes. In fact, President John F. Kennedy "started up" a drinking water distillation plant in 1961 at Dow's Freeport, TX petrochemical complex[18]. The water cost from the 1 mgd (3,800 m3/d or 811 ac-ft/d) plant (in 1961 dollars) was 8-10 times the cost of alternative water supplies in the area at $1-$1.25 per 1,000 gallons ($325 to $407/ac-ft).

FIGURE 8
Multistage Flash Distillation Diagram[19]



MSF/MED/TVC Costs

Thermal desalination plants have higher capital and operating and maintenance costs compared to virtually all other desalting processes[20].The latest (2010) published economic analysis comparing thermal desalination to membrane desalination is at Saudi Arabia's Shoaibah III power/water plant and the Shuqaiq power and water project in Kuwait. At Shoaibah III, the 232 mgd (713 ac-ft/d) MSF plant required around 95 kWh/kgal of power compared to about 17 kWh/kgal for the adjacent 40 mgd (122 ac-ft/day) SWRO

[18] The "start" button was pressed in the White House at the President's desk
[19] http://www.aquatech.com/
[20] Desalting Handbook for Planners, 3rd Ed., July 2003. US Department of the Interior, Bureau of Reclamation, Desalination and Water Purification Research and Development Program Report No. 72.

plant. At another location, Shuqaiq, the 56 mgd (172 acre-ft/d) SWRO project was awarded with a cost of water 24-percent lower than the next competing thermal bids (at an oil price of $4 per barrel nonetheless)[21].

Preliminary power consumption estimates for the proposed scwd² seawater desalination plant show greater than 90-percent less energy consumption compared to thermal desalination.

MSF/MED/TVC Limitations

The glaring, significant limitations that thermal desalination processes have compared to traditional membrane desalination processes include:

- The availability of a power generation facility to produce waste steam (and power for nearby geographic regions);
- The absolute necessity of the cost of fuel to be as a minimum, equivalent to the production cost of oil available in select middle eastern countries;
- The need for brine cooling (via cooling towers or significantly larger intake) to cool brine produced as a byproduct of the distillation process.

If scwd²were to pursue thermal desalination, a new power plant would have to be constructed in Santa Cruz for steam; or the project would have to be located at a significant distance from scwd² water service areas if the power plant in Moss Landing were utilized to boil water for the thermal desalination process. A new power plant in Santa Cruz would actually be larger than the power needs of the thermal desalination process alone – due to the process requirements to remove supplemental steam needed for the desalination process. Also, due to the lower total recovery of seawater using thermal distillation compared to SWRO, the currently proposed intake capacity would have to be about 2.5-times larger to accommodate the need for additional cooling water (for dilution of brine and inefficiencies in the process). Lastly, cooling towers would need to be installed to decrease the temperature of the brine before it is returned to the ocean. In sum, scwd² does not consider thermal desalination a practical and environmentally sensitive option because of the requirements discussed above.

MSF/MED/TVC Commercialization

Thermal distillation is one of the most commercialized, mature seawater desalination processes in the world, having been around for centuries.

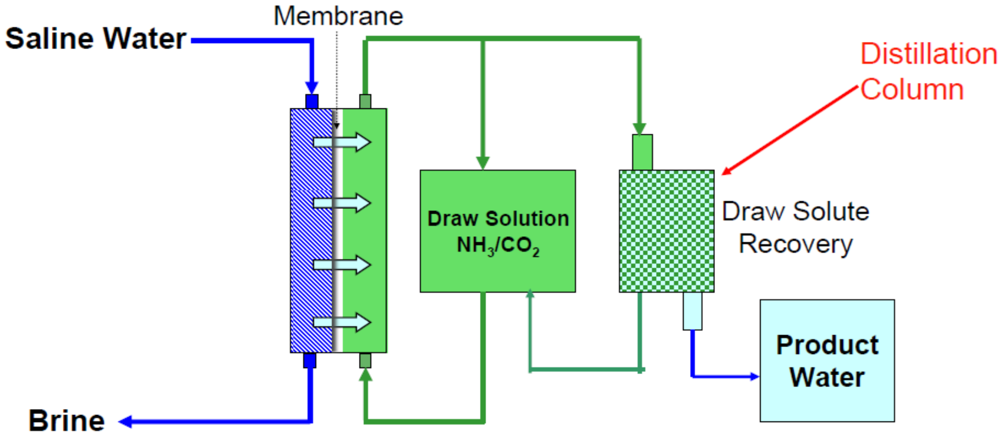
<u>FORWARD OSMOSIS (FO)</u>

Technology

This is sometimes termed “forward osmosis“, or (FO); the opposite of reverse osmosis. In FO, osmotic pressure from a concentrated solution, also known as the “osmotic agent”, draws seawater (without the majority of the accompanying dissolved salts) or other sources of water containing impurities, through a semi-permeable membrane. The water dilutes the osmotic agent, leaving concentrated impurities and salt behind in the seawater and a diluted osmotic agent + water mixture. The osmotic agent is needed because without it, there would be no naturally-occurring osmotic pressure gradient to draw the water across the membrane (leaving behind concentrated seawater). The osmotic agent then would either need to be separated out from the water or can be ingested, depending on the agent. Figure 9 shows one companies’ depiction of the FO process.

[21] Water Desalination Report, Vol 11, Issue 10, Oct 2010

FIGURE 9
Forward Osmosis (FO) Process[22]



A number of companies are heavily invested in FO research and development; however few are candidates for commercial applications.

One company, HTI[23], is relatively established and has developed commercial versions of FO technology for specific uses in the oil and gas and wastewater market segments, and also for limited use for the general public and the military. For the products manufactured for human consumption, syrup packs containing an enriched electrolyte is used as the osmotic agent. The packs produce small quantities of water for short-term emergency use when no other suitable source is nearby. This is a commercial product already in use for the general public; however, because of the high concentration of sugar (dextrose and fructose), the taste is similar to drinking the juice of pressed wine grapes. The mixture meets or surpasses 6-log bacteria (99.9999%), 4-log virus (99.99%) and 3-log parasites and cyst (99.9%) reductions as specified by the EPA for "water purifiers". It also removes 97% of salt from seawater or a concentration of about 1,000 mg/L of salts in the solution, not including the sugar. It should be noted that the EPA secondary water drinking water quality standard is less than 500 mg/L TDS; therefore the mixture does not meet this secondary standard. The scwd[2] Seawater Reverse Osmosis Desalination Pilot Study demonstrated that the proposed seawater desalination plant will produce drinking water with salinities meeting the secondary standard or less.

Modern Water Company has developed and commercialized another FO technology which is in use at two small-scale pilot plants in the Middle East. Their technology involves a two-step process where

[22] http://www.oasyswater.com/index.php
[23] http://www.htiwater.com/

(1) an osmotic agent is recirculated through an osmotic membrane and then (2) water is separated from the osmotic agent. According to the company that owns the rights to the technology, they have eleven key patent families at various stages of the patent process (including FO); and "Protection and exploitation of our intellectual property is fundamental to our success"[24].

Oasys Water[25] is the third FO process that appears promising; however has significant challenges because of the type of osmotic agent they use (ammonia) for desalinating water. Their osmotic agent solution relies on a more porous membrane that has water on one of its sides and a solution made from ammonia and carbon dioxide on the other side. The ammonia + carbon dioxide + water mixture is heated to draw off the ammonia and carbon dioxide (which are reused), leaving the water behind.

FO Costs

HTI's FO purifier costs approximately $30 to produce 1 gallon of syrup-enriched water (equivalent to $9.8MM/ac-ft); and the solution must be consumed within 24 hours[26]. The ocean water desalination process proposed by **scwd**[2] will produce water costing less than a penny per gallon[27].

The most recent published data for Modern Water's largest planned (52,000 gpd; 0.8 ac-ft/d) desalination plant is about $700,000 for the equipment only; which is more than two times the cost of conventional SWRO processes. In the future, the competitive nature of the free market may bring the costs of FO technology down to a point of greater cost compatibility with larger-scale SWRO projects.

Regarding Oasys, FO costs and water quality performance criterion are not available. According to Oasys, "the availability of heat determines the best desalination method. If heat is available for cogeneration, FO is likely preferable to RO in energy cost. If only electricity or fuel is available, RO is best." [28] Note that the comparison is with brackish water RO; which consumes 4-5 times less energy compared to SWRO.

FO Limitations

A significant, known limitation of FO technology today is the low membrane flux due to the time it takes for water to permeate across the semi-permeable barrier into the osmotic agent. Compared to the seawater desalination plant currently considered by **scwd**[2]; a FO plant would require greater than 10 times the surface area (or greater) and associated land mass needed to produce the equivalent capacity of water. Companies specializing in this technology continue to research and improve this flux limitation.

A second limitation is the ability of the FO membrane to reject the osmotic agent. Since osmotic agents are largely toxic (with the exception of HTI's syrup, which can be ingested), back-transport of the agent into the discharge/concentrate could significantly affect the environment. Additionally, it must also be separated from the purified water. Consistent with the acknowledgement of this limitation, Sandia National Laboratories[29] summarized work performed at their lab in the area of FO. They review the status of the technology for desalination applications; and according to them, "At its current state of development, FO

[24] http://www.modernwater.co.uk/about-us/what-we-do
[25] http://www.oasyswater.com/index.php
[26] http://www.htiwater.com
[27] Based on $8.00/kgal estimated cost of delivered water. $8.00/1,000 gallons = $0.008/gal.
[28] Yale University: North American Membrane Society Conference, 2007, Orlando FL. Presentation located at: http://www.yale.edu/env/elimelech/Research_Page/desalination/desalination_presentation3.pdf
[29] Miller, J; *Forward Osmosis: A New Approach to Water Purification and Desalination*; Report SAND2006-4634, July 2006

will not replace reverse osmosis (RO) as the most favored desalination technology, particularly for routine waters. However, a future role for FO is not out of the question"…"The identification of optimal osmotic agents for different applications is also suggested as it is clear that the space of potential agents and recovery processes has not been fully explored."

FO Commercialization

The more challenging aspects of commercializing the FO process for drinking water desalination are related to elimination of toxicity risk from both drinking water and concentrated brine; to obtain applicable NSF testing credentials that the process is safe to use for drinking water purposes; and for commensurate testing of the technology.

Promising Future Technologies

scwd^2 will consider allowing limited amount of testing of alternatives at the proposed full scale Plant. Limited space will be considered as a set-aside for testing a promising technology for possible future implementation in drinking water service. However, it is important to note that a tested technology must have met the following criteria: it should have progressed beyond proof of-concept, been approved for use in drinking water systems, and have in-field service reliability and reliable performance data.

Carbon nanotubes (CNT), ED-CEDI, solar evaporation, and clathrate formation (freezing) are in a group of alternative technologies that offer a promising future for desalination technology. None are prevalent or commercialized in seawater desalination, and do not bear consideration as a full-scale desalination process by scwd^{2}at this time. However, although these technologies would not be placed into full-scale service at the proposed Plant in the near future; they could be candidates to consider for testing at it. A brief discussion regarding the status of these technologies is merited.

Carbon Nanotubes (CNT)

Integration of carbon nanotubes into a new reverse osmosis membrane manufacturing platform is a relatively new concept; having been initially conceived and developed at the lab-scale in the mid to-late 2000's. One startup company (NanOasis) technology was initially developed at the Lawrence Livermore National Laboratory several years ago based on the observation of extremely high water molecule passage through carbon nanotubes. To make the membranes, according to the company[30]:

> *"The researchers started with a silicon wafer about the size of a quarter, coated with a metal nanoparticle catalyst for growing carbon nanotubes. …the small particles allow the nanotubes to grow "like blades of grass -- vertically aligned and closely packed. Once grown, the gaps between the nanotubes are filled with a ceramic material, silicon nitride, which provides stability and helps the membrane adhere to the underlying silicon wafer. The field of nanotubes functions as an array of pores, allowing water and certain gases through, while keeping larger molecules and clusters of molecules at bay".*

CNT Status

A high level of interest and investment money has poured into the development of CNT technology; which is primarily in the pilot testing and early demonstration stages of development. Only one company

[30] Massachusetts Institute of Technology (MIT) "Technology Review" newsletter, June 2006: http://www.technologyreview.com/Nanotech/16977/.

has commercialized CNT based on the premise that the CNT membrane improves production flow rates and reduces required pressures by 10 to 20-percent compared to traditional SWRO processes. Time will tell if any of the competing nanotube-based processes are successful in gaining a foothold in the industry. It remains to be seen if nanotube-based process would substantially improve the SWRO process through the reduction of power consumption.

CNT Cost

The actual cost-benefit of CNT technology is not highly published nor is readily available based on the infancy of the technology and the limited number of bench and small-scale installations that are in operation. Preliminary estimates place the cost of the technology equal to or greater than SWRO technology.

CNT Commercialization

Carbon nanotube membranes are not widely commercially available at this time.

ED-CEDI (Electrodialysis + Continuous Electrodeionization)

Although the Siemens ED-CEDI system has been applied commercially on brackish and ultrapure water applications, the system underwent testing (beginning in 2008) to gauge performance on seawater in Singapore. In 2012, Siemens issued a press release[31] stating that the tested energy consumption was 1.8 kWh/m^3 (6.8 kWh/kgal, 2,220 kWh/ac-ft). This is slightly less than half of the energy consumption proposed for the scwd² seawater desalination plant. However, a very low water recovery rate of 30-percent was necessary to facilitate low energy consumption (compared to 42-50% for scwd²). The impact of lower recovery rates translates to significantly larger feed and concentrate discharge streams (on the order of 50% larger) which increase capital, infrastructure costs, and power consumption to move the additional volumes needed. Additionally, permeate produced by the ED-CEDI process needs additional RO membrane treatment for polishing to meet water quality goals. Overall, the energy savings "gap" closes substantially after these additional factors are considered. The technology is very promising and is likely to be tested on various seawaters in the coming years.

Solar Evaporation and Clathrate Formation (freezing)

These technologies have undergone various stages of conceptual testing in the laboratory and very small-scale testing since the 1970's. Solar technologies are potentially useful to explore in regions where sunlight is prolific and space is abundant. Conceptual and tested technologies include salinity gradient ponds, heat exchanger collectors, solar stills, humidification/dehumidification, and greenhouses.

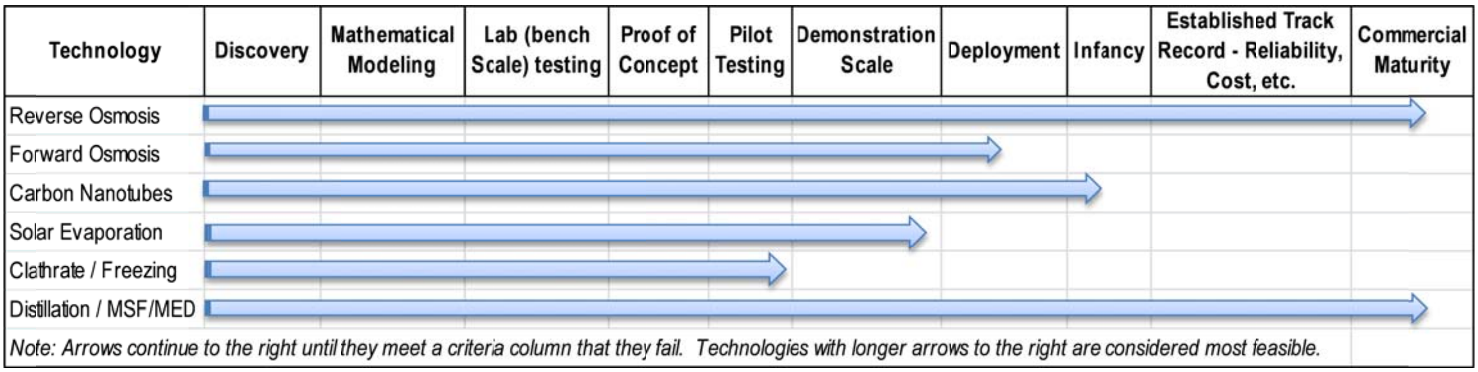
Clathrate formation, as well as a number of other similar concepts and ideas, have been researched and tested in laboratory, bench-top and demonstration scale. Research continues to attempt to balance the economics of producing desalinated water with solar evaporation and clathrate formation that would be competitive with the commercialized SWRO systems around the globe today.

[31] http://www.desalination.biz/news/news_story.asp?id=6008&channel=0

Summary Stages of Development

The various stages of development for each of the discussed technologies, for use as a drinking water supply, are shown in Figure 10.

FIGURE 10
Technology – Stages of Development



Conclusion

Many promising, innovative technologies require more testing, analysis, industry validation, and progression through the commercialization process to gain wide acceptance as an alternative to existing, mature desalination technologies. Table 2 contains a qualitative assessment for each desalination technology, based on practical metrics such as development of the technology for commercialization and costs.

TABLE 2
Technology – Qualitative Assessment

Technology	Infancy	Permitted for Public Supply	Cost (Capital, Operating)	Recommended
Seawater Reverse Osmosis	NO	YES	MED	YES
- SWRO Subset: NanoH2O	NO	YES	MED	YES
Forward Osmosis (FO)	YES	NO	HIGH	NO
Carbon Nanotubes (CNT)	YES	NO	UNKNOWN	NO
Solar Evaporation	NO	NO	UNKNOWN	NO
Clathrate / Freezing	YES	NO	UNKNOWN	NO
Distillation / MSF/MED	NO	YES	HIGH	NO

Based on a thorough review of worldwide desalination practices and technologies, SWRO membrane desalination is the most appropriate and suitable to use in Santa Cruz. SWRO membrane desalination is commercially mature, and is being used to produce fresh water of high quality for municipal and private water agencies. SWRO was successfully pilot tested in Santa Cruz from 2008 to 2009. SWRO is the desalination technology planned for the proposed seawater desalination plant because it has an established track record, will meet the codes and standards for drinking water facilities, its capital and operation and maintenance costs are well understood, it represents the lowest environmental “footprint” of the commercially mature technologies, and it has been permitted in the United States to treat public water supplies. For these reasons, none of the alternative technologies are considered further for the proposed full-scale municipal facility in Santa Cruz.