Water Desalination:

A novel low-energy distillation method

Master of Engineering
(Civil Systems)
Capstone Project
Final Report

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PART I. TECHNICAL CONTRIBUTIONS (INDIVIDUAL)

(THIS SECTION WAS WRITTEN BY HARRISON DURBIN)

1 INTRODUCTION

During a 1962 news conference, President Kennedy took a moment to stray from the thrilling topic of human space exploration because he felt another technological topic was arguably more important: *"if we could ever competitively, <u>at a cheap rate</u>, get fresh water from salt water … it would really dwarf any other scientific accomplishment. And I am hopeful that we will intensify our efforts in that area.*" The need for a dependable water supply remains, yet we are living in a vastly different age with societal concerns shifted from economy toward carbon emissions. Roughly 50 years later, President Obama showed this shift in an interview: *"If there's one thing I would like to see, it'd be for us to be able to price the cost of carbon emissions".* Had Kennedy been elected in 2016, one could imagine the quote would have been: "*if we could ever competitively, <u>with low-carbon emissions</u>, get fresh water from salt water."*

The global population, exceeding 7 billion and growing, has resulted in unsustainable freshwater consumption while water supplies grow even scarcer due to droughts. The common response to water scarcity, seawater reverse osmosis (SWRO), simply trades a sustainable water problem to a sustainable energy and environment problem (i.e. not a sustainable solution). The following report first examines alternative water supply options (focused on California) and then explores technical and economic feasibility of a proposed novel desalination method that can desalinate will a small carbon-footprint. This section addresses individual technical research and contributions made.

1.1 PROJECT DESCRIPTION

We are investigating the viability of a novel water desalination method based on fundamental principles of thermodynamics. This novel method uses a naturally created vacuum to readily evaporate and then condense water molecules in a self-sustaining system that requires little to no energy input. It differentiates itself from similar concepts by using carbons tubes to enhance evaporation and condensation and assumes a much larger scale. Our aim is to create a disruptive technology to outperform seawater reverse osmosis (SWRO), economically, environmentally, and aesthetically.

1.2 Associated Tasks

Several steps are being taken to determine whether this novel method is feasible. A work breakdown including primary project team roles and deliverables is presented below. For additional information, see reports by Eric and Rahul that detail physics and thermodynamic equations that can be used to model the process and additional proposals for heat removal.

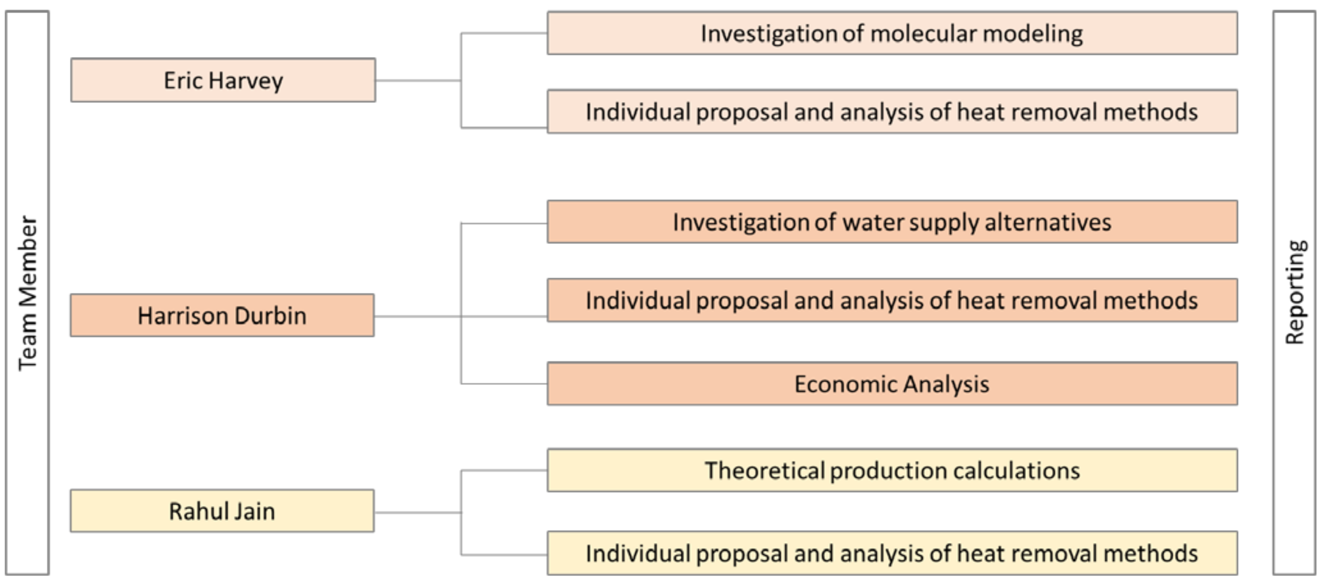

Figure 1: Work breakdown

2 EVALUATION OF ALTERNATIVES

Before delving into technical and economic feasibility of the proposed method, it is important to first determine whether this problem is already solved, or could be solved in another obvious way, and what are the financial and energy costs. The following section investigates alternative water sources assuming groundwater, locally imported water, and melted snowpack are no longer available in California.

2.1 SEAWATER REVERSE OSMOSIS (SWRO)

As SWRO has emerged as the dominant means of desalination across the world, SWRO is of particular interest. This sections investigates whether SWRO has reached respectable efficiency (i.e. whether the novel method is worth pursuing). Advancements in energy recovery devices (ERDs) such as the PX pressure exchanger by Energy Recovery Inc. (ERI), has allowed up to 50% energy savings for SWRO plants (Frenkel, 2011). Consequently, desalination has grown and estimated to increase an additional 10 to 20 percent by 2025 (Water Education Foundation, 2015). The figure shows this trend.

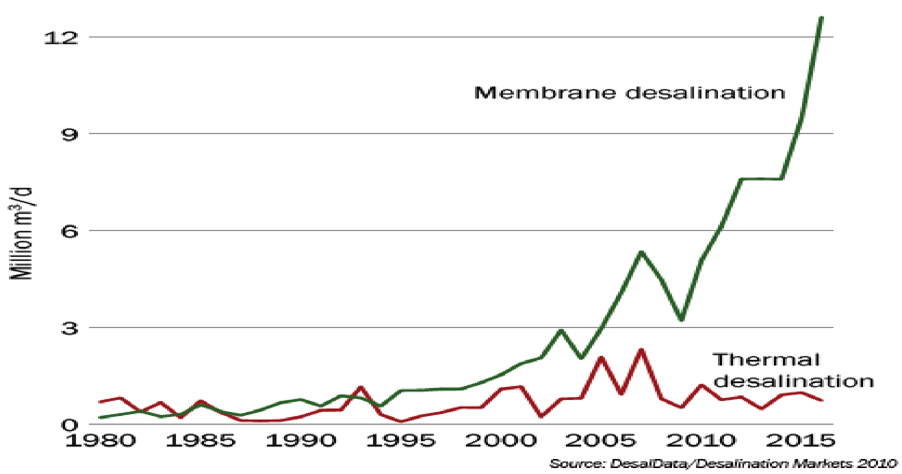

Figure 2: Growth in membrane desalination (Source: Desal Data)

Three components contribute to the financial cost of a SWRO plant and the associated cost of water production: ***capital investment***, ***energy***, and ***operation & maintenance (O&M)***. Cost data for a 16 MWD plant in Chile was collected by speaking with plant operation management, and a breakdown is presented below:

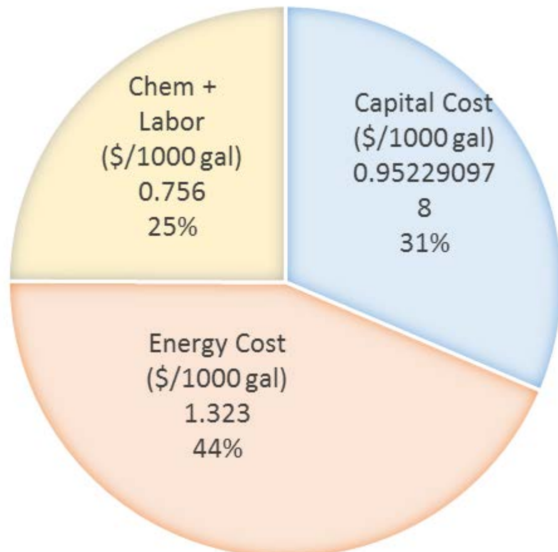

Figure 3: Cost Breakdown of the La Chimba SWRO Plant in Antofagasta, Chile (Source: AWT)

2.1.1 SWRO Energy Cost

Despite aforementioned energy improvements, total cost remains highly sensitive to energy prices as energy accounts for 44% of the cost. One can conclude SWRO remains extremely energy intensive with a large room for improvement. Average energy usage is 14 kWh per thousand gallons, for plants researched across the world, based on values in the compiled table:

Table 1. SWRO energy requirements

Plant	Plant Capacity (MGD)	Energy Use (kWh/1000gal)
La Chimba, Chile	16	13
Eilat, France	5	14
Tampa Bay, Florida	25	14
Ashkelon, Israel	44	14
Carlsbad, California	50	13
Perth, Australia	37	14
Hadera, Israel	72	17
China	9	16
Raleigh, Saudia Arabia	61	18
Rambla Morales, Spain	16	12
Valdelentisco, Spain	37	17
Khor Fakhan, UAE	6	15
Gold Coast, Australia	34	14
Alicante II, Spain	17	14
Fujairah 1, UAE	45	18
Caofeidian, China	13	15
Ashkelon, Israel	11	14

For comparison to actual energy consumption, theoretical energy for SWRO was roughly calculated by estimating the work required to lift water to the required pressure of the RO membranes:

$$W = \int_1^2 F\, ds$$

The pressure requirement for membranes is from 600 to 1000 psi to drive water through the membrane pores. The low-end 600 psi is equivalent to 1,384 feet of water head, resulting in 32 kWh per thousand gallons if no energy recovery device is used and 45% recovery. However, using an energy recovery device allows 99% of brine energy to be recovered. Theoretical demand for SWRO in this case would be *14 kWh* per thousand gallons. The calculated theoretical values are consistent with reported values but are surprisingly slightly higher, which brings into question accuracy of reported plant data.

2.1.2 SWRO Financial Cost

In addition to investigating opportunities to improve upon SWRO's energy costs, we should look at financial costs the same way. Results indicate the cost of production for SWRO varies from $2.62 to $6.10, with an average of $3.70 per thousand gallons. Cost data is compiled below:

Table 2. SWRO production costs

	Plant	Plant Capacity (MGD)	Total Capital Cost (millions)	Capital Cost ($/1000 gal)	Energy Cost ($/1000 gal)	Chem + Labor ($/1000 gal)	Total Water Cost ($/1000 gal)
1	La Chimba, Chile	16.3	$99	$0.95	$1.32	$0.76	$3.03
2	Eilat, France	5.3	$20	$1.02	$1.54	$0.79	$3.35
3	Tampa Bay, Florida	25	$110	$1.19	$1.54	$0.83	$3.56
4	Ashkelon, Israel	44	$213	$0.64	$1.54	$0.44	$2.62
5	Carlsbad	50	$1,000	$3.15	$2.02	$0.85	$6.02
6	LADWP	12.5	NA	NA	NA	NA	$4.50
7	Blue Hills	6	NA	NA	NA	NA	$4.95
8	Windsor	3	NA	NA	NA	NA	$6.10
9	Perth, Australia	37	$347	$1.48	NA	NA	$4.54
10	Hadera, Israel	72	$425	$0.93	NA	NA	$2.38
11	Skikda	26	$110	$0.66	NA	NA	$2.76
12	Hamma	53	$250	$0.75	NA	NA	$3.10
13	Palmachim	29	$110	$0.60	NA	NA	$2.95

Although the table presents definite values, in reality it can be difficult to determine the true cost as water providers may invest in these facilities as a contingency, rather than a primary source, and the average production over the life of the plant may be much lower than expected. Often, local fresh water may become available and cheaper to treat, so despite capital investments, infrastructure may rarely be used. Ignoring this complication, SWRO remains significantly more expensive, yet the cost is justified in cases where certainty is necessary (GIbson & etal, 2015) and when the only supply option.

2.2 Importing by Pipeline

Perhaps California should not invest in SWRO but rather construct a pipeline from a region with an abundant freshwater supply. If significantly cheaper, it may be a better alternative than SWRO or the proposed novel method, so it is important to consider and evaluate the costs. This section discusses theoretical pipelines from Alaskan rivers, and from the Great Lakes.

2.2.1 A Pipeline from an Alaskan River

While this idea may seem far-fetched, in a former plan from 1992, the US Government considered the construction of a subsea pipeline to carry water from Alaska to Northern California (Andelin & etal, 1992). The project was expected to provide 1.3 trillion gallons per year of water from an Alaskan River. In this plan, four pipelines each with 14-feet diameter run along the Pacific Ocean sea floor. One of the great benefits of this plan is that the energy use would be extremely low as the pipeline would simply siphon water from the Alaskan River to California, so there would only be a minimal amount of head. Additionally, with the large pipelines, there would be extremely low friction losses. If we roughly estimate 400 meters of head required for head losses throughout the system, the total energy can be calculated by multiplying the weight of 1,000 gallons of water by this head. The energy need was roughly calculated to be 4 kWh per thousand gallons.

While the plan sounds great in terms of energy, the capital cost would be enormous. Estimated to cost $450 million in 1991 dollars (Andelin & etal, 1992), today would be over $110 billion. In addition, the plan presents several issues in regards to maintenance (it would be extremely difficult to access in the ocean) and sub-sea leaks could go undetected. Moreover, there would be controversial environmental impacts to Alaskan wildlife.

2.2.2 A Pipeline from the Great Lakes

The idea of extracting from the Great Lakes to satisfy far away demand has been proposed in the past: in 1982 the Army Corps of Engineers investigated using the lakes to replenish the Ogallala Aquifer, located across several Great Plain states but mostly Nebraska, which has been overused for agriculture (IJC, 1999). Roughly the same time, in 1981, a proposal failed to pipe the lake water to Wyoming for a coal project. These projects in the early 1980's led to Governor's working together to ensure Great Lakes are protected (IJC, 1999). Ignoring this obstacle, a pipeline on land from the Great Lakes has another problem as it must pass the Rocky Mountains to reach California. The head requirement was roughly estimated to be 8000-feet (2438-meters), which results in energy need of 25 kWh per thousand gallons. Likely, some of this energy could be recovered, but it would create significant environmental damage and would be complicated to obtain a large easement across the country—assuming four 14-feet diameter pipelines, an easement of at least 50-feet wide would be needed. For the above reasons, importing from the Great Lakes is not recommended as it would be problematic, costly, and environmentally damaging.

2.3 Summary of Alternatives

As the demand and availability of water supplies is constantly changing over time, it is impossible to say broadly the best solution to water scarcity as it is space and time dependent and must be determined on a case-by-case basis. However, if we assume no local fresh or brackish water exists, SWRO is currently the most common option to provide a new potable supply along coastal areas. In spite of its popularity, SWRO remains extremely costly, inefficient, and environmentally damaging. As SWRO has improved, this process has matured and likely won't see more drastic improvements in efficiencies in the near future (Ghaffour & etal, 2013). Significant room for improvement exists for SWRO which warrants more research of alternatives, including the proposed method presented herein.

The actual and theoretical costs in dollars and kilowatt-hours to supply California with new potable water is presented in below:

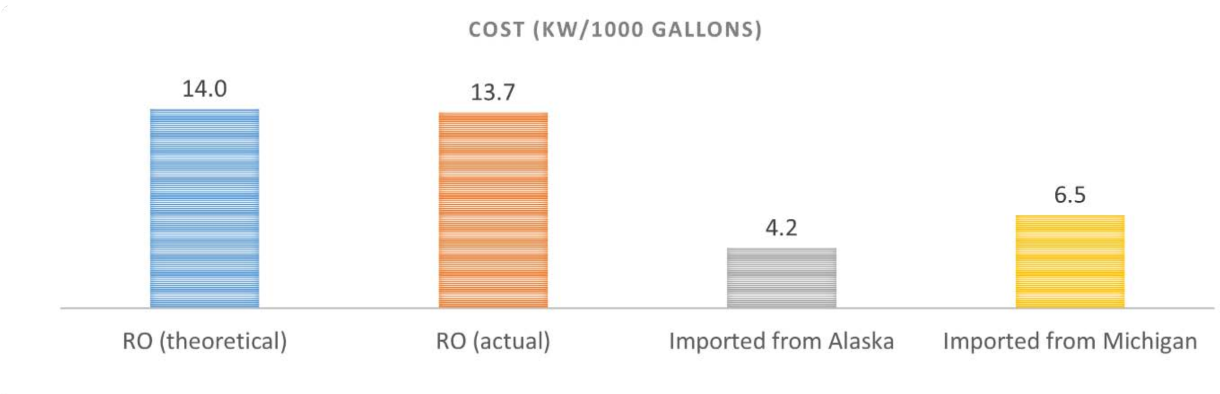

Figure 4: Water energy cost (kW per 1,000 gallons)

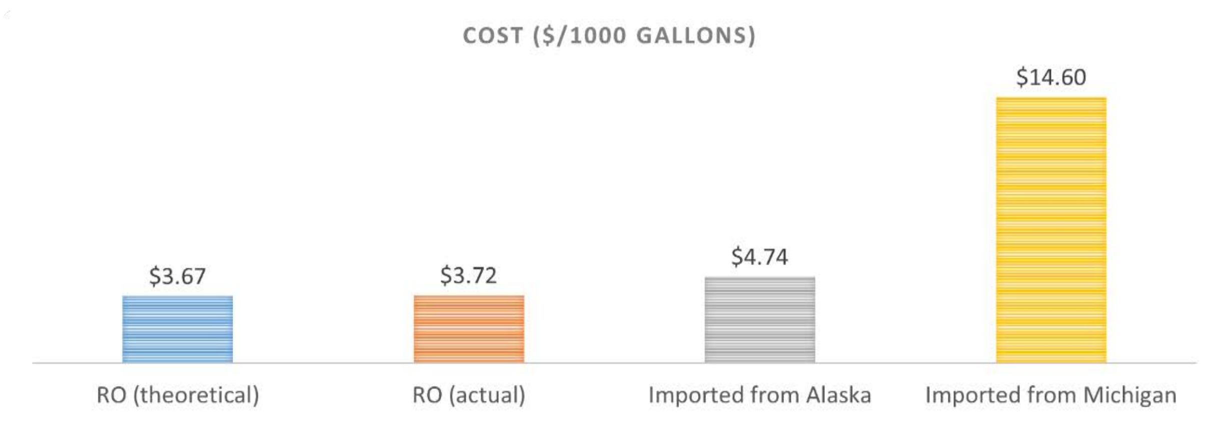

Figure 5: Water financial cost (dollars per 1,000 gallons))

3 Overview of Proposed Novel Desalination Method

A thorough knowledge of various domains is critical in this project as it weaves together various technologies. This section discusses the key system components and relevant research findings.

3.1 System Description

The proposed system is a type of distillation process that uses an elevated water column to induce a vacuum. This vacuum allows seawater to boil at ambient temperatures in accordance with the pressure-temperature curve for water. Saturated vapor, via natural or forced convection, flows to a condensation area where a layer of hydrophilic carbon tubes are used to alter the pressure-temperature curve such that water condense quicker, and at a warmer temperature. As water molecules move from evaporation to condensation, they carry heat energy that accumulates if not removed by a heat sink. The hydrophilic carbon tubes provide the key benefit of permitting warmer distillate temperatures, which allows easier transfer to the outside environment. A figure showing various variables and parameters is shown below:

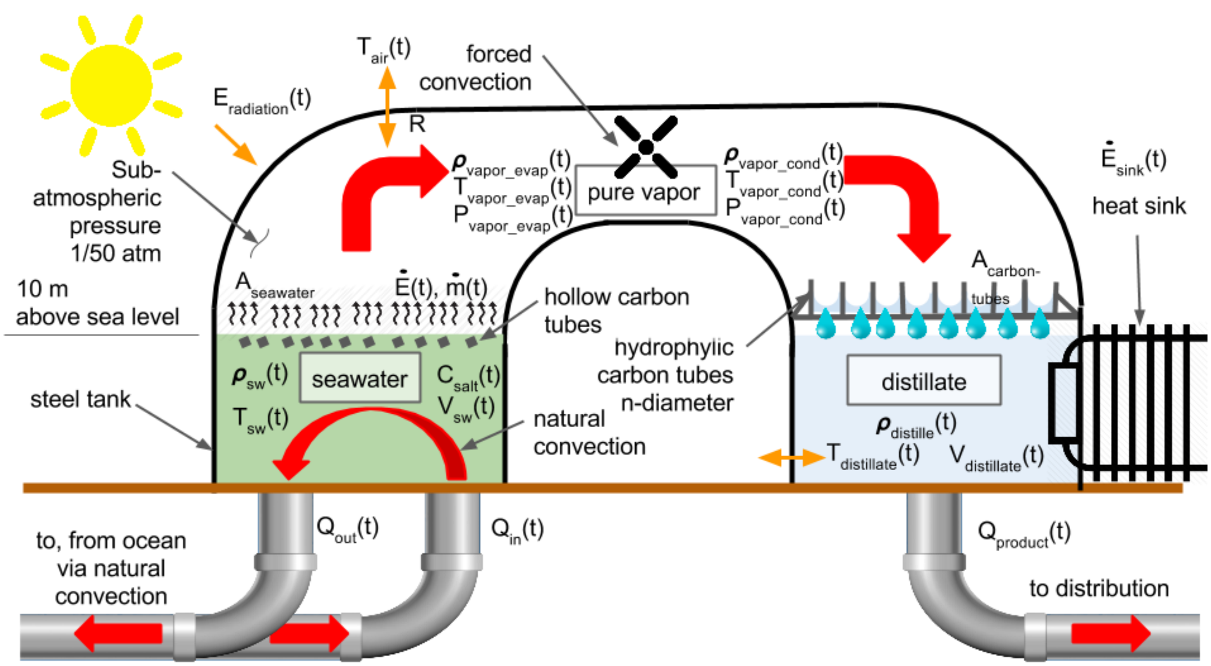

Figure 6: System Schematic

3.2 Sub-Atmospheric Distillation

The vacuum in the proposed process s created by means of gravity with the water surface at an elevation of 10.33 meters, which is the maximum water height a tube can maintain (Moore, 2008). This precise height can be calculated with Bernoulli's equation (Midilli, NVD technique--Part I, 2004). To establish this vacuum, a sealed system can be filled at the top with water, and afterward subsea valves on the inlets/outlets can be opened. Similar ideas involving this gravity induced vacuum have been patented, with some research conducted by others, however it remains out of commercial use. Results of other studies are useful to learn from and improve upon the work of others. Findings are summarized below.

3.2.1 Existing Intellectual Property (IP)

Knowing existing patents helps identify potential conflicts of IP if implemented in practice. While reviewing hundreds of patents related to desalination, two were discovered with a similar concept. In 1995, a system using a siphoning conduit above salt water was patented, US 5552022 A (Wilson, 1995), but had a fee lapse. Roughly 15 years later, a vacuum system with internal sprayers (which is not used in our method) was patented as US 7597785 B2 (Levine, 2009). The system also includes a sealed chambers at an elevation of 10-meters above sea level. While these are fundamentally similar, there are many possible variations to the concept.

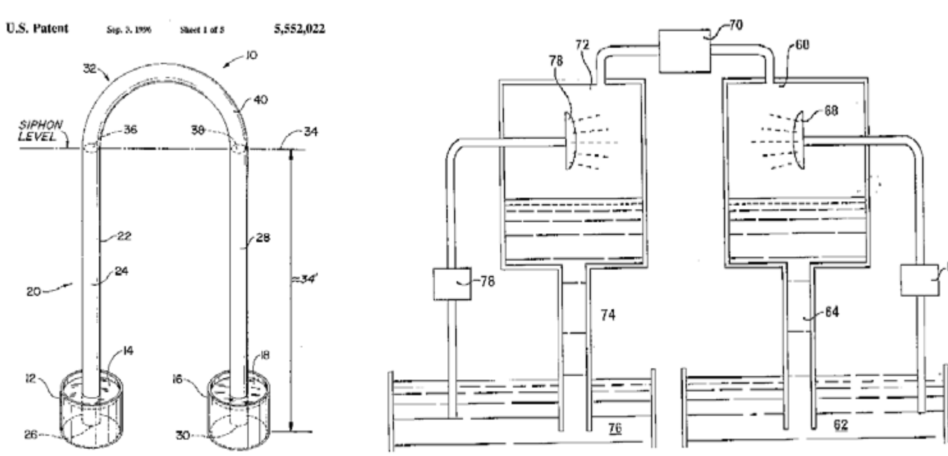

Figure 7: Wilson Patent (left), Levine Patent (Levine, 2009) (right)

Low-energy water distillation is the concept name given by patentee Levine, who supported a university study of it in 2008 (discussed below). While a promising technology, the government may be unwilling to fund research on an idea patented by others, which may explain why further academic research has not been conducted.

3.2.2 Low-energy water distillation

Under the support of patentee (Levine), Moore & etal at Florida Atlantic University set-up and conducted experiments for the low-energy distillation method. Results were presented in "*waste to water: a low energy water distillation method*." One insight from experiments was distillation slows until stopping when the two chambers reach a thermal equilibrium (see figure below) (Moore, 2008). The experiment was prolonged by adding hot salt water and cold freshwater (to the evaporator and condenser), but this is not practical in real life. This is a serious flaw that led Prof. Marcus to request our team to focus on solving and is discussed later.

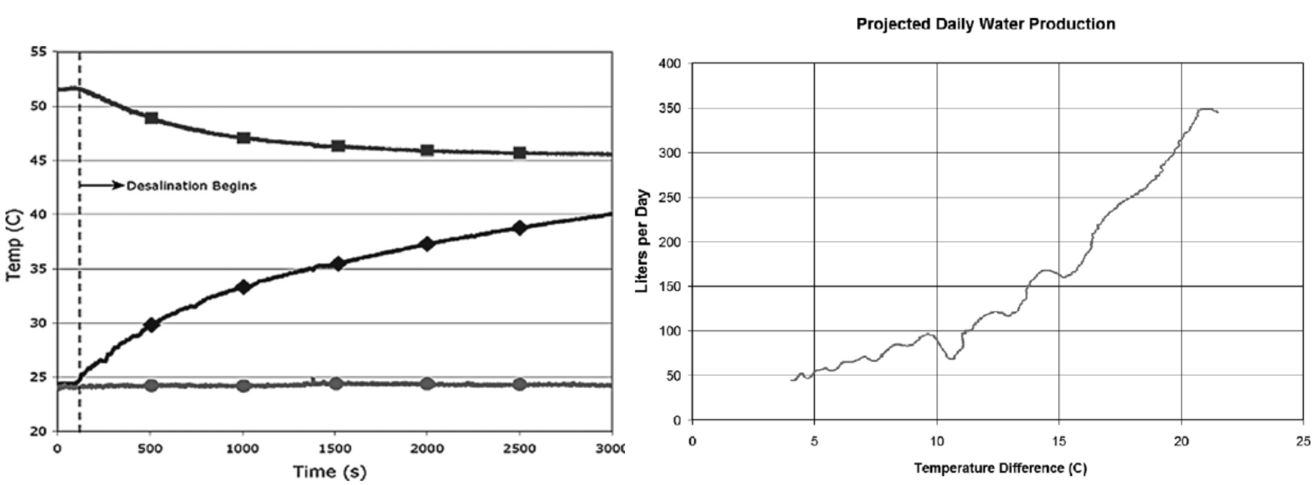

Figure 8: Low-energy water distillation experimental results (Moore, 2008)

3.2.3 Natural Vacuum Distillation

Natural Vacuum Distillation (NVD) is a name given to a concept by Midili and Ayhan who have written several articles on it. Journals articles include:

- *Natural vacuum distillation technique—Part I: Theory and basics (2004),* Midilli & Ayhan
- *Natural vacuum distillation technique—Part II: Experimental investigation(2004),* Midilli & Ayhan
- *Feasibility study of renewable energy powered seawater desalination technology using natural vacuum technique (2010),* Ayhan & Madani

The NVD method appears identical to the low-energy distillation method, but Midilli and Ayhan have developed variations involving heating and cooling. Ayhan developed an off-shore concept that uses renewable energy sources (Ayhan, 2010):

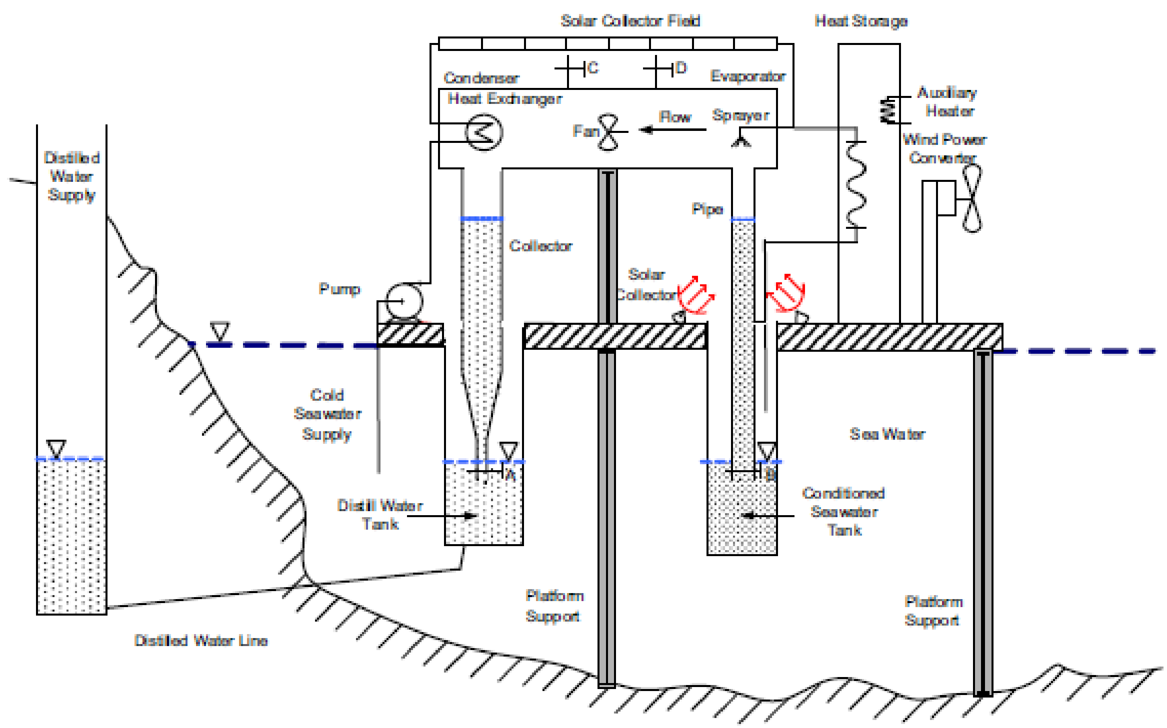

Figure 9: Off-shore NVD Concept (Ayhan, 2010)

One of the key conclusions from experiments was heat and pressure losses due to evaporation must be prevented in order to maximize vapor to seawater mass ratio (Midilli, NVD technique--Part II, 2004). The floating carbon tubes in our concept may solve this problem by speeding up the rate of continual seawater boiling (evaporation leaves a thin cooler layer on the surface, which must be heated again to boil the next layer).

The studies by Midilli and Ayhan were referenced by Jitsuno in a study on a vacuum distillation system using solar heat and vacuum pump to initially create 1/100 atm before sealing (Jitsuno, 2012).

3.2.4 Summary of Prior Work

As we do not have experimental data of our own, despite having varying system configurations, it is helpful to compare results of similar system studies. These results may give a general sense of what our system may produce. Results of varied widely and it is not clear why—Junitso and Moore results may be much higher than the Ayhan system because they were adding heat to the raw water and cooling the distillate and the Ayhan noted that his pilot system was primitive, with conservative results.

Table 3. Experimental production results

Research Study	Production [kg/m^2/day]	Notes
Moore, 2008	1,542	Based on an approximate 8-inch tube with distillate temperature 5 deg C less than raw water temperature.
Ayhan, 2009	108	Based on a primitive pilot system with 14-inch diameter tube.
Junitso, 2012	1,645	This uses a vacuum of 1/100 atm and a ~ 6-inch diameter tube and solar heater and cooling fans.

3.3 CARBON TUBES

A technology currently being researched for water treatment applications but not yet commercialized is nanotubes or graphene membranes for RO desalination. The benefit of carbon-based membranes is they would require less energy and could have anti-fouling and self-cleaning capabilities that current membranes cannot offer (Das & etal, 2014). One may ask, why isn't everyone already using graphe or carbon nanotubes (CNTs) for desalination? One of the major obstacles is the difficultly in synthesizing CNTs with a consistent pore size (Das & etal, 2014), which is critical for health. Consequently, they are currently too expensive to use commercially as membranes, but could eventually improve efficiency of SWRO. While not commercially feasible for SWRO now, carbon tubes are now ready to improve evaporation and condensation, where pore size is not critical.

While carbon tubes were initially proposed for condensation in our novel method, research indicates they may be equally useful for evaporation. In a study on the use of carbon beads to enhance evaporation, they discovered hollow carbon beads, which float on the water surface, can increase evaporation rate by 2.37 times compared to without carbon beads (Zeng & etal, 2014). The increased rate of evaporation occurs because the millimeter-sized carbon beads absorb light and increase the water surface temperature. (Zeng & etal, 2014). These carbon beads may be useful to maximize evaporation rates, resolving the issue of heat losses during evaporation mentioned above. A figure showing the beads and test results are shown below:

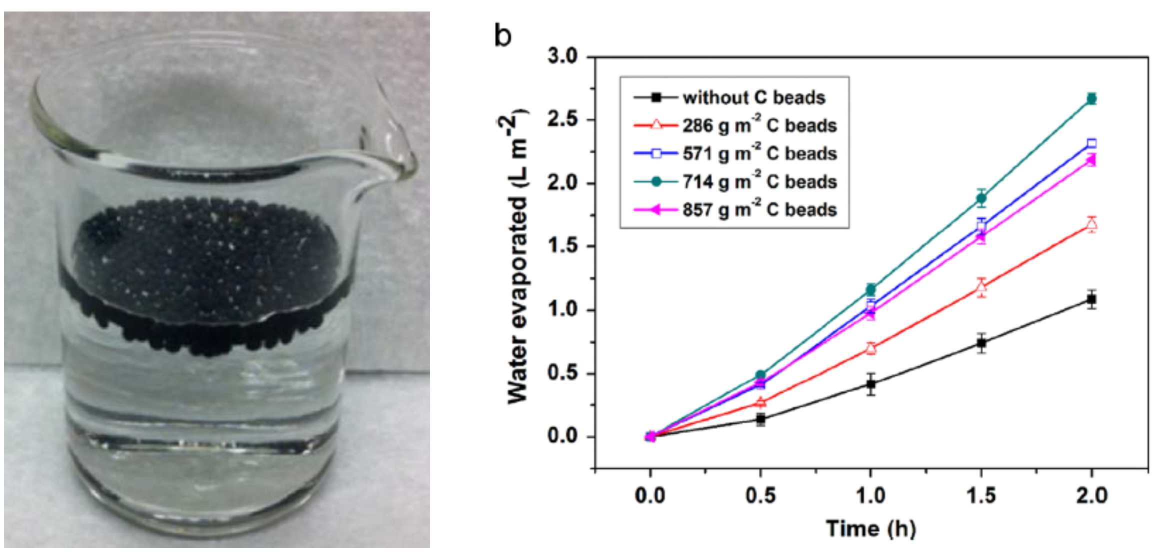

Figure 10: Floating hollow carbon beads image ((left), experiment results (right) (Zeng & etal, 2014)

4 Conceptual Design

To assess the technical and economic feasibility of the proposed method, a conceptual design must first be developed. This section will discuss the conceptual design first in terms of site location, and then the crucial design options for heat removal.

4.1 Off-shore vs On-Shore

It is important to initially determine whether the system is better suited on- or off-shore, which allows design issues to be anticipated and costs to be roughly estimated. There are tradeoffs between off- and on-shore:

Table 4. Off-shore vs. on-shore comparison

Location	Advantages	Disadvantages
Off-shore	• No cost for land • Minimal risk of a pipe breaking causing a loss of sub-atmospheric pressure in the system	• Potential for damage from waves • Potential damage from ships • Difficult to perform maintenance if the system is 10-meters high • May be difficult for maintenance workers to be on site
On-shore	• Easier maintenance as the system does not need to be as tall if it is on higher land elevation • Maintenance workers can be on-site • Safe from waves and ships	• Coastal land is expensive and those who can afford it do not want their view destroyed • Long sections of siphoning pipe could break and cause a loss of sub-atmospheric pressure in the system

A significant concern with the off-shore based concept is that destructive forces from large waves may cause costly damage. Similarly, an earthquake would cause sloshing within the tank, while triggering large ocean waves outside, creating structural stresses. Consequently, the structural and foundational stability of a heavy, off-shore structure is concerning, but may be made possible by retrofitting an off-shore oil rig.

Still, it is unclear how much tank weight an off-shore rig could safely hold; therefore, this report will assume an on-shore design. The figure shows two inlet/outlet structures and associated siphoning piping that lead to the on-shore evaporation/condensation unit.

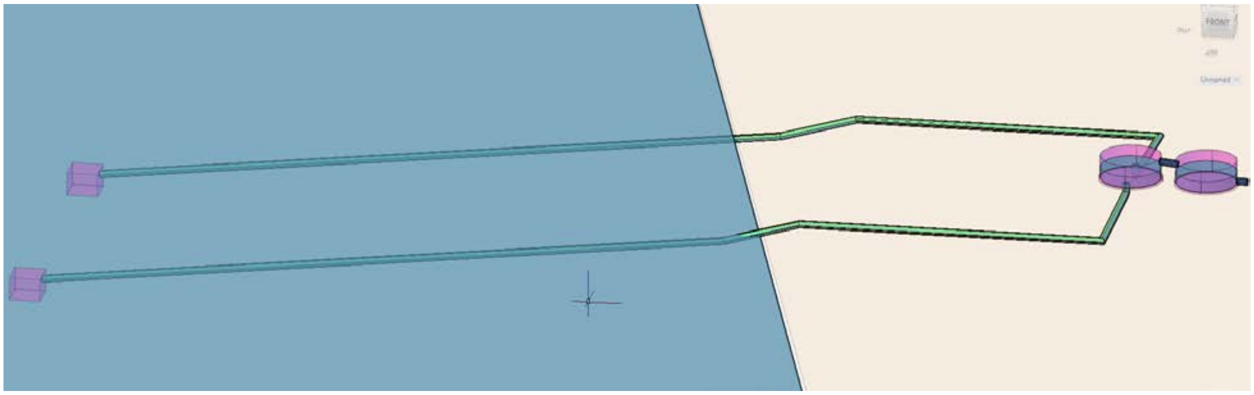

Figure 11: On-shore conceptual layout

A more detailed view of the desalination process units is shown below—it differs from studies discussed above because it is assumes much larger surface areas, and as mentioned will be enhanced with carbon beads and carbon tubes. Water vapor can flow either by free or forced convection (forced convection uses a fan to pull vapor from the evaporator to condenser, increasing production but requiring more energy) (Midilli, NVD technique--Part I, 2004).

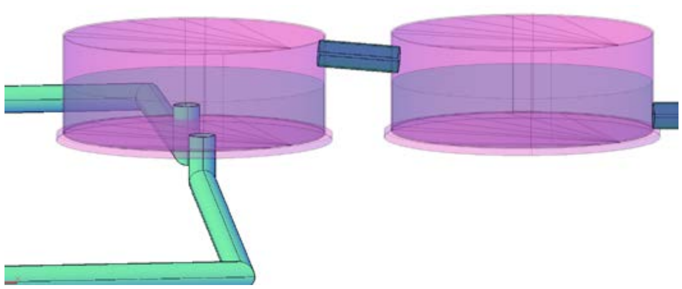

Figure 12: Two-tank concept

4.2 HEAT REMOVAL

Effective heat removal is critical because as water evaporates the energy leaves the water surface resulting in a lower temperature at the surface as new molecules replace those that boiled off. On the other hand, as condensation occurs, water vapor creates a higher temperature on the distillate surface. To optimize rate of evaporation and condensation, the distillate water temperature should be cooled as much as possible (assuming the carbon tubes rest on top of the water surface, or are occasionally dips to provide immersive cooling). For this reason, the most vital concern with this novel method is in the domain of heat transfer (as established by Moore). The heat transfer rate, Q, may be calculated with the following formula:

$$\dot{Q} = \dot{m}L$$

where:

- $\dot{Q}$ = heat transfer rate [J/sec]
- $\dot{m}$ = mass transfer rate [m3] → *treat as a variable*
- L = latent heat of vaporization [kJ/Kg] → *2460 kJ/Kg (at 0.02 atm)*

As heat accumulation is the primary concern, Professor Marcus has requested each team member to individually develop and propose options for removing heat. The amount of heat transferred is dynamically linked to the mass evaporating and condensing. Assuming various production rates, the corresponding heat transferring from the seawater evaporation surface to the distillate condensation surface (which must be removed to keep the process going), is shown in the table below. Based on the calculated amount of heat, cooling cost is calculated by dividing the power by the Seasonal Energy Efficiency Ratio (SEER) of the cooling system. Removing heat this way would be impractical due to the cost:

$$Avg\ Power = \frac{\frac{Btu}{h}}{SEER}\ ; where\ SEER\ is\ 21\ (Carrier\ Infinite\ Series)$$

$$Cooling\ Cost = (kWh)\ * (\frac{\$0.12}{kWh}) * (24hrs)$$

Table 5. Heat removal requirement and cooling cost per water production rate

Water Production (MGD)	Heat Removal Requirement [kJ/day]	Cooling Cost [$/day]
5	4.65×10^{10}	$64,672
10	9.31×10^{10}	$129,345
15	1.40×10^{11}	$194,017
20	1.86×10^{11}	$258,690
25	2.33×10^{11}	$323,362
30	2.79×10^{11}	$388,034
35	3.26×10^{11}	$452,707
40	3.73×10^{11}	$517,379
45	4.66×10^{11}	$582,052
50	5.12×10^{11}	$646,724

4.2.1 Conductive Retransfer to Seawater Process

One idea to remove heat is to combine seawater and distillate in the same tank, divided by a conductive wall. A portion of the heat transferred to the condensation water will be retransferred back to the cooler temperature seawater. As seawater reabsorbs the heat, it will slow the convective forces in the seawater, but because only a fraction of heat is added back, strong convective forces remain and seawater acts as in infinite reservoir.

Providing thin, conductive walls with a large surface area maximizes the rate of heat transfer between the seawater and distillate. One option is to spiral the wall to increase wall area, while a more simplified option is to have an inner, concentric circle. One possible issue is that it may make it difficult to force convection of the water vapor from the seawater chambers to the distillate chambers and has greater risk of already condensed distillate re-evaporating in the wrong direction or creating a thermal equilibrium in vapor that slows production. Additional research is recommended.

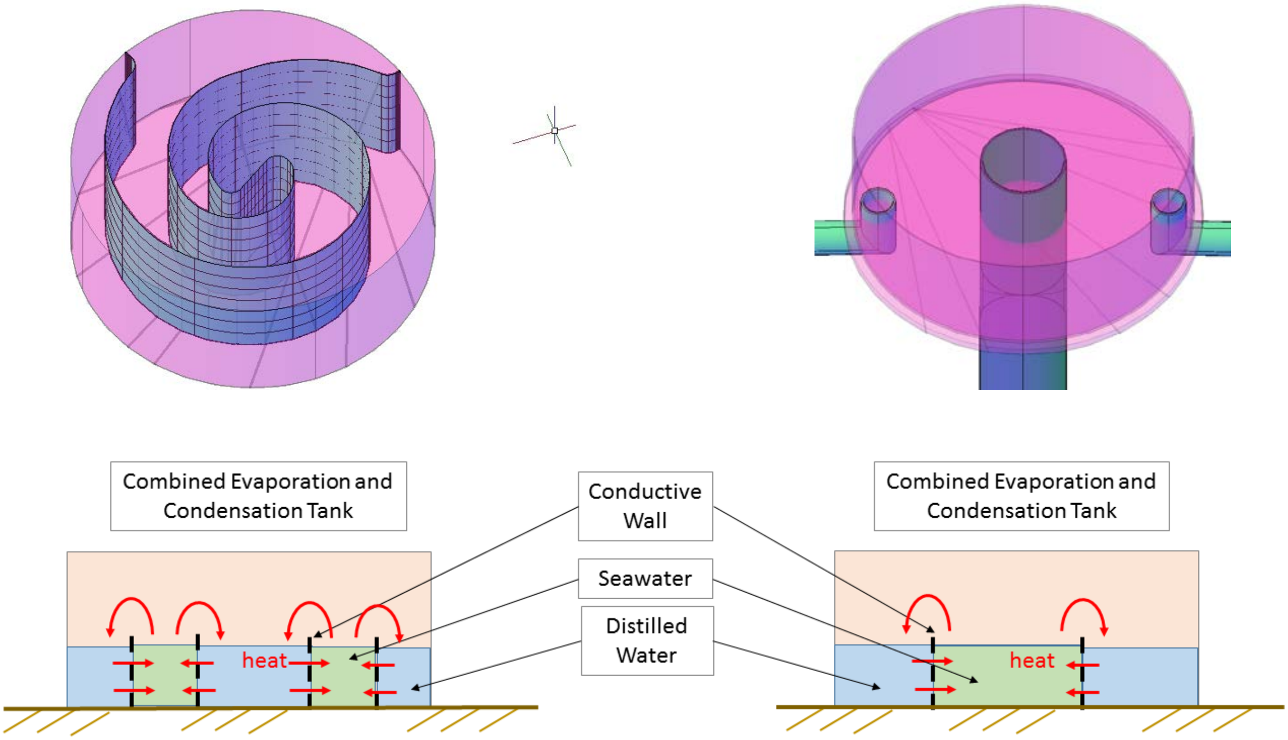

Figure 13: Heat Retransfer Wall, spiral (left), circular-not to scale (right)

The amount of heat transferred in this system by conduction can be calculated with Fourier's law (Wong, 2000), assuming the temperature gradient is constant:

$$Q = k * A * \frac{\Delta T}{\Delta x} = k * l * h * \frac{T_d - T_{sw}}{s}$$

where:

- Q = heat transfer
- A = heat transfer area [m2] (assume contained in a 135'-diam tank)
  - l = 530 feet, h = 15 feet (spiral wall)
  - l = 280 feet, h = 15 feet (circular wall, 40' diameter)
- k = thermal conductivity of the wall material → *205 W/mK, aluminum*
- T_d = temperature distillate → *assume 27 deg C*
- T_{sw} = temperature seawater → *17 deg C*
- s = wall thickness → *2" thick*

Per tank, heat removed is <u>2,575 million kJ</u> with spiral-wall, and <u>1,361 million kJ</u> with circular-wall.

Temperature losses due to heat energy losses can be calculated:

$$\Delta T = \frac{Q}{Cp * m}$$

where:

- Cp = specific heat of water [kJ/(kg K)] → *4.18* kJ/(kg K)
- Q = heat transfer → 2,575 million kJ (calculated above)
- m = mass of water in tank [kg] → 2,832 kg
- ΔT= change of temperature of distillate [deg C]

This heat energy loss equates to a loss of temperature of only about 0.4 degrees Celsius.

4.2.2 Geothermal Cooling

Another heat sink that can be used is the soil, which acts as a more stable thermal reservoir than the air, which has large temperature fluctuations throughout each day. The mean annual temperature is about 62 F in Carlsbad (USDA GK-RCH-LAB). Ground temperature still fluctuates, but to a smaller extent. For simplified calculations, assume soil temperature is constant and equal to the annual mean temperature.

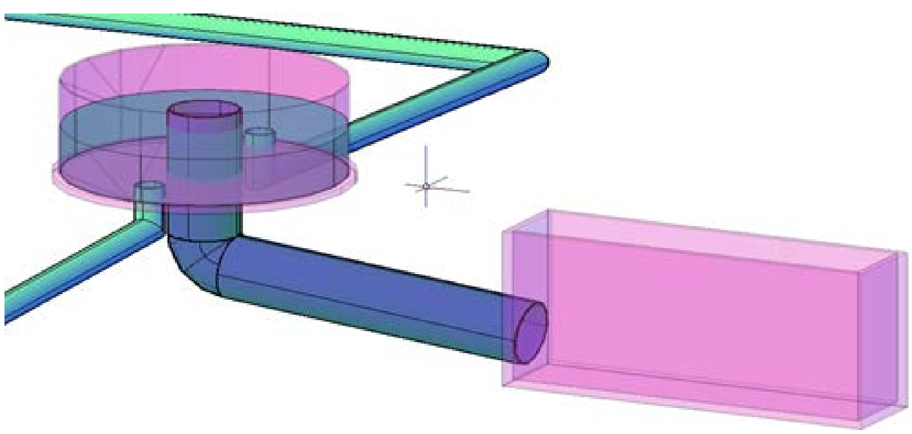

Figure 14: Geothermal cooling

$$Q = k * A * \frac{\Delta T}{\Delta x} = k * [(2l + 2w) * h + (l * w)] * \frac{T_d - T_{soil}}{s}$$

where:

- q = heat transfer [J/sec]
- A = heat transfer area [m2]
    - l = 100 feet, w = 50 feet, h = 10 feet
- k = thermal conductivity of the wall material → → *205 W/mK, aluminum*
- T_d = temperature distillate → *26.6 deg C*
- T_{soil} = temperature seawater → *16.6 deg C*
- s = wall thickness → *2" thick*

Per tank, heat removed is 2,585 million kJ but has little effect on reducing temperature in the large volume of water stored in the underground reservoir.

4.2.3 Cooling Tower

Sump pumps in the underground reservoir can be used to pump water up to cooling towers surrounding the reservoir to dissipate energy into the atmosphere as sprayed water evaporates and loses heat. Slotted walls along the perimeter may help induce dry air current to enhance the process (Subbarao). Assume nozzles are placed 1-foot on-center around the 300-foot reservoir perimeter (i.e. 300 nozzles per tank unit).

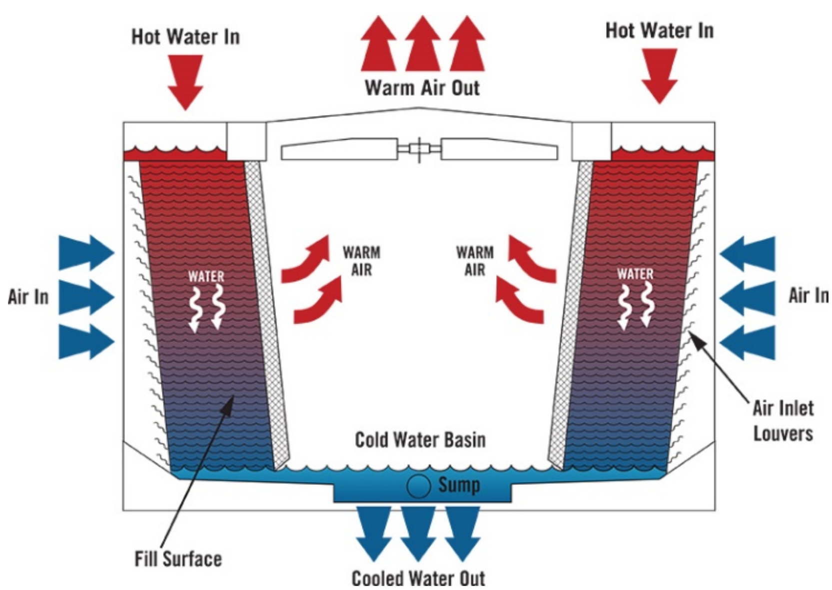

Figure 15: Cooling tower (Pitcher, 2015)

The cooling tower heat load can be calculated with the equation (Pitcher, 2015) :

$$Heat\ Load\ = V * Cp * (T_{hw} - T_{cw})$$

where:

- V = flow rate → assume 300 spray nozzles each with flow of 50 GPM
- T_{hw} = temperature distillate hot [deg C] → 26.6 deg C
- T_{cw} = temperature distillate cold [deg C] → 17 deg C (same as seawater)
- Cp = specific heat of water [kJ/(kg K)] → *4.18* kJ/(kg K)

4.2.4 Heat Removal Summary

The following table presents a breakdown of the proposed heat removal processes described above:

Table 6. Heat removal breakdown

Heat Sink Method	Heat Energy Removal [kJ/tank unit/day]
Conductive retransfer to seawater	2.575×10^{9}
Geothermal cooling	2.585×10^{9}
Cooling towers	6.540×10^{9}
Total	**1.049×10^{10}**

Calculations indicate that cooling towers offer the largest amount of heat removal, followed by the seawater flow, and the soil. Heat removal results align with results of a study on heat sinks for cooling in tropical climates, which had found cooling towers to have the highest cooling performance as an anergy sink, followed by rivers and the ground (Bruelisauer, 2013).

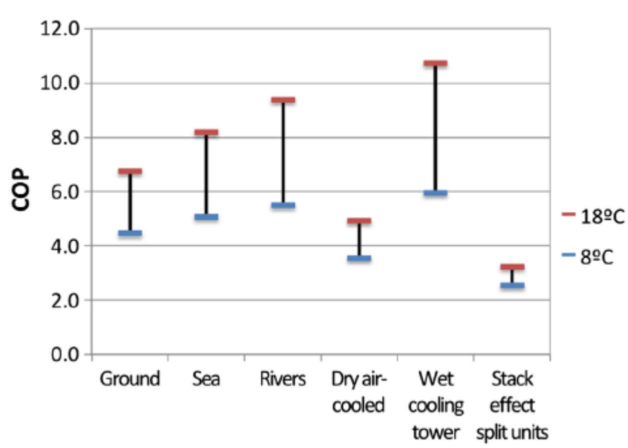

Figure 16: Cooling Performance in heat sink study (Bruelisauer, 2013)

5 Economic Comparison to Carlsbad Desalination Plant

To provide a direct comparison, this novel method is compared to the Carlsbad Desalination Plant, which is a controversially expensive RO Plant recently commissioned in December 2015. This direct comparison is useful to evaluate potential for financial and energy savings—perhaps this novel method would have been a better option.

5.1 Site Layout

A conceptual layout is useful to estimate construction costs and how much water may cost to produce with this system, assuming various production rates. The site appears to accommodate approximately fourteen 135-foot diameter steel tank process units coupled with distillate reservoirs and cooling towers. Additional space is needed for an operations building, disinfection, clear-wells, pumping, storage yard, and parking.

Figure 17: Conceptual overlay of novel plant atop Carlsbad Plant (inset: 135-ft diam. tank photo)

5.2 Production Rate Estimate

Assuming production rates determined in experiments by others [$kg/m^2/day$], theoretical production for this novel plant would be:

Table 7. Theoretical plant production (assuming experimental results by others)

Experimental Production Results	Theoretical Plant Production [MGD]
Moore, 2008	41
Ayhan, 2009	3
Junitso, 2012	44

If we assume production rate is constrained by how much heat can be removed, we can establish our own production estimate. As previously calculated, 1.049×10^{10} kJ/tank unit/day is the max amount of heat that can be removed from the system. Assuming 14 tank units, this equates to 1.469×10^{11} kJ/day, which corresponds to the heat generated for 15 MGD production. This value appears conservative when comparing to experimental results (except for the Ayhan study, which used a primitive pilot system). Consequently, the theoretical novel plant at Carlsbad is conservatively assumed to produce 15 MGD, but could likely be increased with further improvements to the heat sink system.

5.3 Cost Estimate

Total costs were estimated for the theoretical plant to compare with the actual Carlsbad costs. Capital costs were based on best guesses using professional experience on past water infrastructure projects. At the conceptual level, it is difficult to provide accurate costs as there are a large number of design unknowns, however, but can provide a reasonable estimate to assess the economics. O&M and electrical costs were assumed to be 25% percent of the actual Carlsbad plant as there will be no moving parts to maintain and energy costs will be mainly for distribution pumping and cooling towers. The theoretical plant with the proposed heat removal design is estimated to have a cheaper cost than the actual Carlsbad SWRO, in addition to being much more environmentally friendly:

Table 8. Total cost to produce water

Description	Actual Carlsbad Plant	Theoretical Novel Plant
Capital Cost	$484,000,000	217,000,000
O&M Cost (annual)	$28,000,000	4,000,000
Electricity Cost (annual)	$24,000,000	6,000,000
TOTAL - PRODUCTION COST	**$ 4.18** / 1,000 gallons	**$ 3.81**/ 1,000 gallons

It is important to look at sensitivity of production rate on cost as we are uncertain of the 15 MGD assumption. If the plant performed significantly better, say to 40 MGD in accordance with the studies (Junitso and Moore), the cost of water could be brought to under $2 per thousand gallons. On the other hand, if the plant underperformed to only 3 MGD (per Ayhan), the cost would be $12 per thousand gallons.

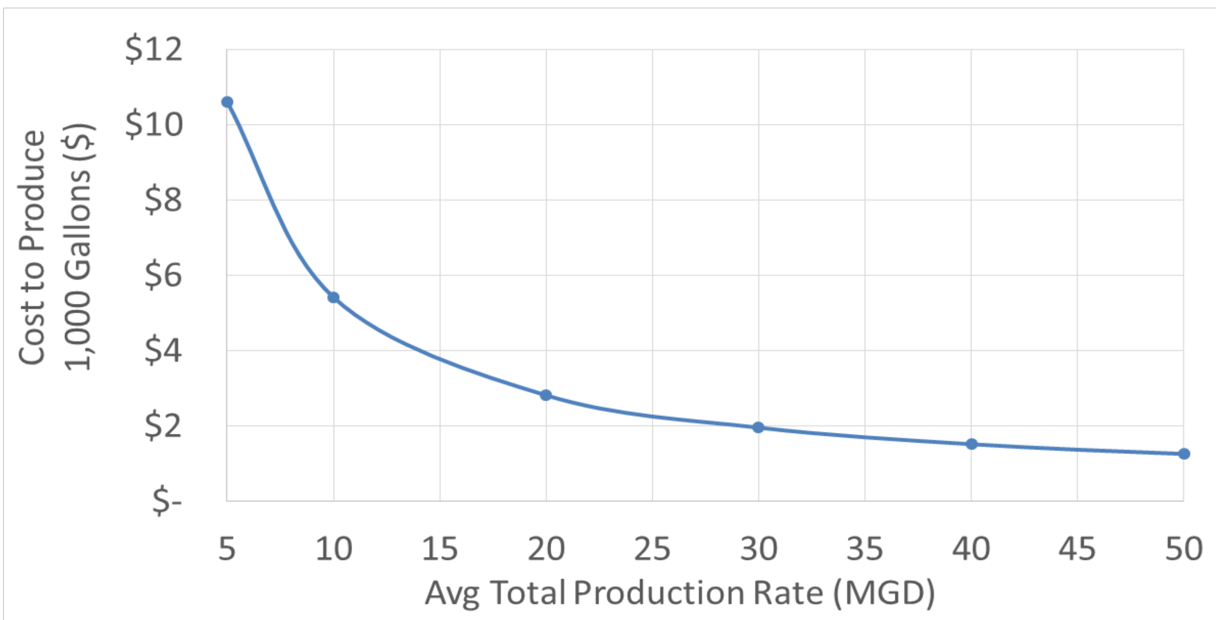

Figure 18: Sensitivity analysis for cost vs production

The greatest potential savings may be in reducing O&M and electrical costs, which are much higher for SWRO due to membranes and high pressure pump equipment, which have high annual costs throughout the life of the plant:

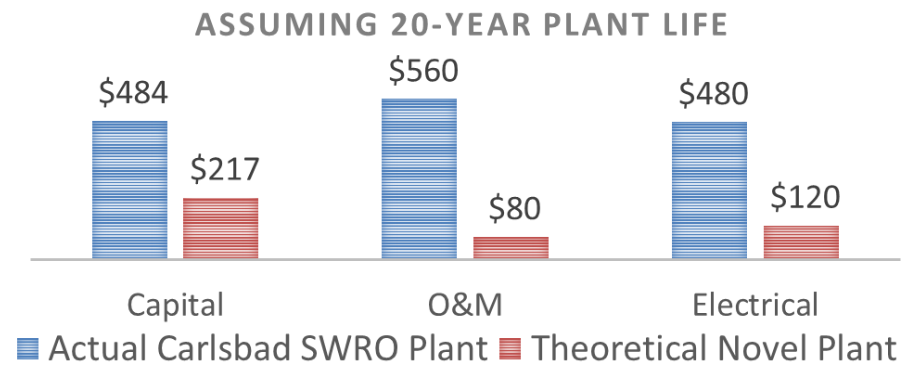

Figure 19: Life-time Cost Breakdown

6 CONCLUSION

The cost of water and determining whether desalination is the best solution is difficult to determine because water supplies are not always reliable, and there is a premium cost for supplies that are more reliable (e.g. SWRO). Although water demand and supplies are in flux, there exists a great need for a reliable water supply in places located throughout the world and an opportunity to fulfill this need as existing options are expensive and energy intensive.

Initially, the project team anticipated performing experiments and analyzing data results, however, the project shifted toward other areas to investigate feasibility. An attempt was made to solve the problem of heat accumulation during condensation, which determined cooling towers offer the best cooling performance. Some possible concerns are it requires a larger footprint than SWRO and real-world implementation may unveil unforeseen obstacles (e.g. there could be difficulties in operations in maintaining the vacuum system, or thermal equilibriums could slow the production to unacceptably low rates). Nonetheless, cost analysis (assuming production rates per other studies or based on a heat removal constraint) revealed this novel method has great theoretical potential in producing large quantities of water, with minimum energy and maintenance costs.

Future work is recommended to perform experiments on system with carbon tubes, and an advanced molecular model developed in a software than can estimate heat and mass transfer that occurs at a molecular level.