BRINE LAKE VTE-MED PILOT WITH GEOTHERMAL WASTE STEAM

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Abstract

Large areas of the Southwestern USA depend on the Colorado River as an essential water supply. The final diversion in the USA supplies about 230,000 hectares of farms and cities in the Imperial Valley in the southeastern corner of California. Return flows from farms, industries, and cities all drain to a large terminal brine lake called the Salton Sea.

The Colorado River is in a 16 year drought. Even if flows return to historic norms, demand for water is predicted to outstrip supply. The Imperial Valley relies almost solely on the Colorado River for water supply and predicts a shortfall of 123 million cubic meters annually. The region's water future is threatened by drought and agricultural to urban water transfers reducing current and future supply.

As a terminal brine lake with no outflow, and fed by brackish agricultural drain flow, the Salton Sea salinity has gradually risen to 6% salt by weight. In late 2001 a proposal was made to the Salton Sea Authority by Dr. Hugo Sephton and three colleagues to gradually dilute the Salton Sea to ocean salinity by employing a vertical tube evaporator multi-effect distillation (VTE-MED) design. The proposal at the Salton Sea was to use low pressure geothermal steam as a heat source. Eleven geothermal steam power plants operate near the southeast shore of the Salton Sea. Several plants vent a substantial amount of atmospheric flash steam continuously. This is essentially a 'waste' steam source released at close to 100°C, sufficient to support at least 15 MED effects at desert cooling water temperatures of 35°C.

A proposed demonstration was scaled back to a pilot and commenced in late 2004 with funding from the U.S. Bureau of Reclamation Two 5,000 GPD VTE units were installed at a geothermal power plant adjacent to the Salton Sea with a condenser and connections to the geothermal plant.

The pilot testing employs two VTE effects. Sand filtered, deaerated Salton Sea water is the feed source. Low pressure geothermal steam is the heat source. Up to five effect conditions are tested by matching temperatures, pressures, and Salton Sea brine concentration to that predicted for a commercial scale 15 effect VTE-MED system. Both forward and reverse feed configurations are tested. Steam side temperatures range from 100°C for effect 1 tests to 51°C for effect 15 tests. Mineral scaling is controlled by the Dispersed Seeded Slurry Evaporation (DSSE) method described in a 1992 patent.

Pilot testing showed that recovery of up to 86% of Salton Sea feed water as distillate was feasible. Extrapolation of data from the five effect conditions tested indicates that a 15 effect commercial system could achieve a performance ratio of 14 lbs. of distillate per 1,000 Btu. The preliminary estimated cost is $0.63 per cubic meter of distillate.

I. INTRODUCTION

This Pilot Project has been undertaken to investigate whether geothermal steam driven distillation is a viable, cost effective technology for control of salinity, mitigation of contaminants such as selenium, and production of potable quality water from the Salton Sea. The Pilot Project included assembling a Vertical Tube Evaporator (VTE) pilot plant and testing the efficacy of desalinating Salton Sea water with geothermal steam as an energy source. The VTE Pilot Plant has been configured to operate at the same temperatures, pressures, and brine chemistry conditions as a commercial VTE-MED plant using geothermal steam flashed at atmospheric pressure or 100°C. The process was operated with low pressure geothermal steam reduced to atmospheric pressure or lower for testing. Atmospheric pressure geothermal steam is a renewable energy resource available in the region, which is currently not being used for any commercial purpose.

1.1 General Background

Large areas of the Southwestern USA depend on the Colorado River as an essential water supply including major cities such as Las Vegas, Phoenix, Tucson, Los Angeles, and San Diego as well as industry and vast areas of farmland. After diversions to these and other cities and farms, with some of the return flow rejoining the Colorado River, about one third of the remaining flow goes to the Mexicali Valley in Mexico. The other two thirds of the remaining flow is diverted by canal to supply about 230,000 hectares of farms and cities in the Imperial Valley in the southeastern corner of California with a diversion north to the adjacent Coachella Valley. Return flows from farms, industries, and cities in both valleys all drain to a large terminal brine lake with a current surface elevation 76m below mean sea level called the Salton Sea.

Regional Water Stress 1.1.1

The Colorado River is in a 16 year drought. Even if flows return to historic norms, demand for water is predicted by the U.S. Federal Government to outstrip supply [1]. The entire State of California was in a four year drought until higher than normal rainfall this past winter. With an average of only 76 mm of rainfall annually, the Imperial Valley relies almost solely on the Colorado River for agricultural, municipal, and industrial water supply. Compounding the drought, growing water demand from coastal cities in California, reluctant to accept the high cost and regulatory hurdles of seawater desalination on the Pacific coast, led to demands to transfer agricultural water to urban areas. A 2003 agreement codifies a transfer of Imperial Valley water to urban water districts ramping up to 372 million cubic meters annually. This combined with gradual increases in local demand has led to a predicted shortfall in Imperial Valley water resources of 123 million cubic meters annually [2]. The Imperial Valley is also at high risk for earthquakes that have damaged canal infrastructure in the past. This seismicity benefits the Imperial Valley by providing one of the world's most productive geothermal resources. On the other hand, the region's water future is threatened by drought and water transfers reducing current and future supply and by earthquake damage to canals and dams that could cut off the sole substantial Imperial Valley water supply for an extended period of time.

Local Saline Water Source 1.1.2

As a terminal brine lake with no outflow, fed 90% by brackish agricultural drain flow for the last 100 years, the Salton Sea salinity has gradually risen to 6% salt by weight measured in 2016. The brine lake is mostly sodium chloride, but has high sulfate and elevated magnesium compared to ocean water. The major ions are chloride 37%, sodium 25%, sulfate 19.5%, magnesium 3%, and calcium 1.5% by weight with many other ions all well below 1%. With over 7 billion cubic meters of saltwater, the Salton Sea has been a very productive fishery over time and supports 430 species of birds, but rising salinity from rapid evaporation under a desert sun has long held that ecosystem under threat. This pilot project seeks to evaluate reclamation of the hypersaline water to preserve those benefits.

Local Geothermal Resource 1.1.3

Geothermal power is generated by using heat from aquifers heated by molten rock from the core of the earth. Three general processes are in use, dry steam, flash steam, and binary. The Geysers field in California is the only dry steam operation in the U.S. The Imperial Valley in Southern California has both flash steam and binary plants. Binary plants operate on low temperature resources typically less than 150°C. Flash steam plants use a higher temperature geothermal brine resource that spontaneously flashes into steam at atmospheric pressure.

The geothermal aquifer at the Salton Sea is a high temperature resource typically over 250°C two to three thousand meters underground. The Salton Sea resource is saturated brine that comes up a wellbore under natural high pressure. All of the power plants exploiting the Salton Sea geothermal resource are of the flash steam type. CalEnergy Operating Company is by far the largest geothermal plant operator at the Salton Sea with 327 MW of generation combined from ten plants. The geothermal aquifer under the southeast shore of the Salton Sea is saturated brine with many minerals heated by magma that rose close to the earth’s surface due to multiple local faults. About 20% of the brine is flashed to steam that drives turbines and generators. The remaining 80% or more of the brine is cleared of precipitated solids and pumped back down into the aquifer to be reheated and reused. As shown in Figure 1, only a fraction of the Salton Sea Known Geothermal Resource Area (KGRA) has been exploited to date.

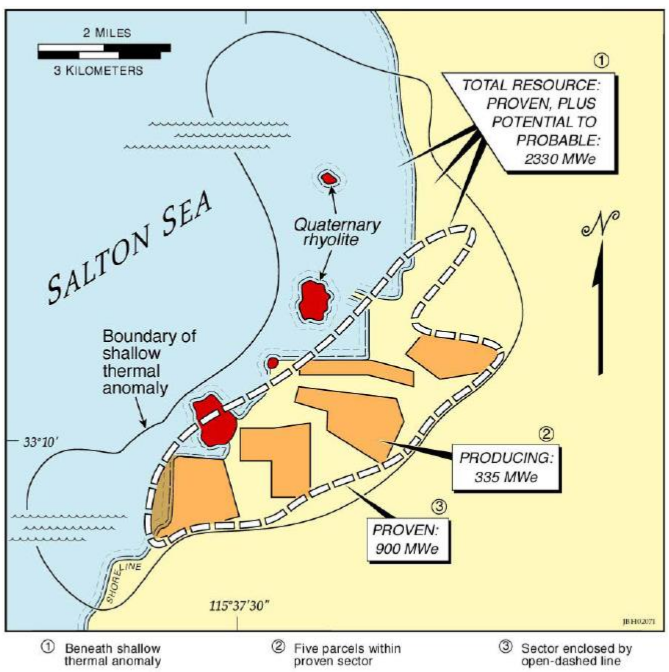

Figure 1. Salton Sea KGRA boundaries from CalEnergy and University of Utah Study

A diagram of the triple flash process employed by CalEnergy and other local geothermal operators is shown in Figure 2. Hot geothermal brine at up to 450 psig is piped from production wells to a High Pressure Separator where high pressure steam is flashed from the brine at about 330 psig. The high pressure steam goes through a regulating valve to a steam turbine. The geothermal brine, now a little cooler and more concentrated after releasing some steam, goes to the Standard Pressure Crystallizer where additional steam is flashed at about 50 psig and directed to a turbine. The brine is seeded with a mineral slurry to absorb precipitating salts as the brine concentrates and sent to the Low Pressure Crystallizer where a third flash takes steam at about 20 psig and directs it to a turbine. The brine then goes to an Atmospheric Flash Tank where a final flash near atmospheric pressure is vented to the atmosphere. This final flash is the source of non-commercial (waste) steam at about 100°C available for a thermal desalination process. The geothermal brine goes from the Atmospheric Flash Tank to a Primary and Secondary Clarifier where silica and precipitated solids are separated out before the remaining brine is injected back to the underground aquifer to be reheated.

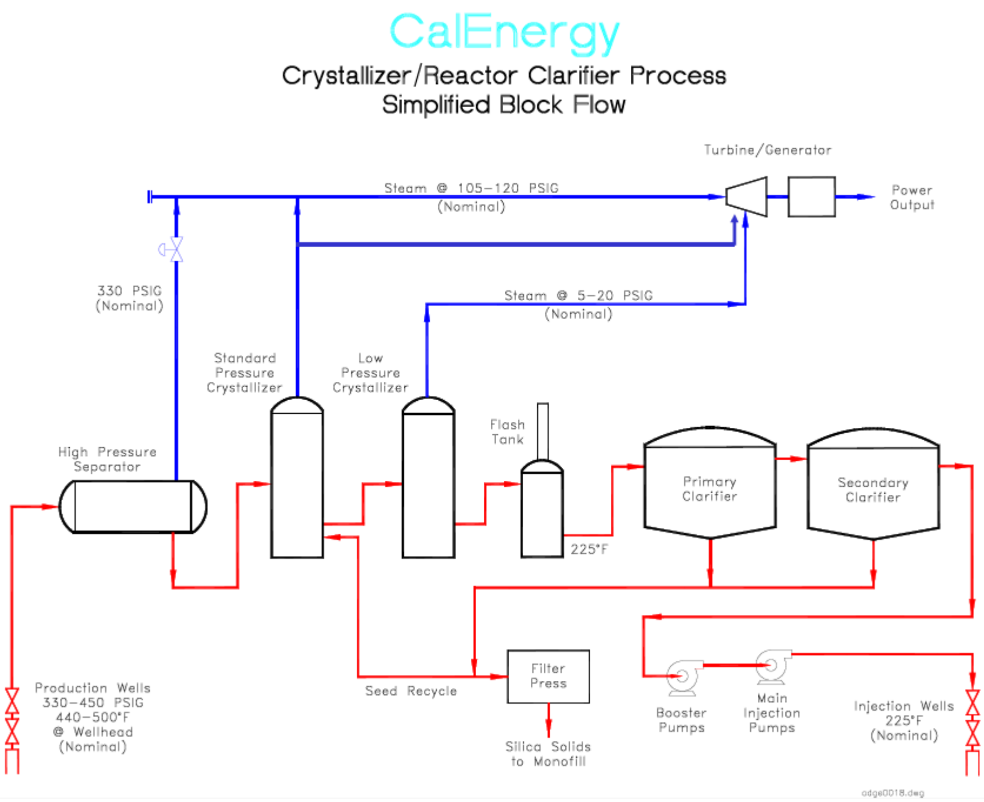

Figure 2. Triple flash brine and steam process as employed by CalEnergy (from CalEnergy public talk)

Eleven triple flash geothermal power plants use this process near the southeast shore of the Salton Sea. Several plants vent a substantial amount of atmospheric pressure steam to the air continuously as it's not economic for power production. This is essentially a 'waste' steam source released at close to 100°C, sufficient to support at least 15 MED effects at desert summer cooling water temperatures of 35°C.

Pilot Test Background 1.1.4

In late 2001 a proposal was made to the Salton Sea Authority (an agency of local governments) by Dr. Hugo Sephton and his colleagues Ferris Standiford, Phil Hammond, and Dieter Emmermann to gradually dilute the Salton Sea to ocean salinity by employing a modification of a 30 effect MED system composed of Vertical Tube Evaporator (VTE) tube bundles stacked in a tower similar to a 1993 design the same team created for the largest Southern California water utility [3]. That design concept was validated in pilot testing by the utility as reported in 1997 [4] and has several features in common with a low temperature VTE-MED design using a concrete shell, polypropylene components, and fluted aluminum evaporator tubes proposed by Bom in 1997 [5].

The proposal at the Salton Sea is to use lower temperature steam sources available at reduced cost near the Salton Sea. Salinity gradient solar ponds were proposed in 2001 and then low pressure geothermal steam was proposed in 2002. The 15 effect waste steam VTE-MED Salton Sea salinity management concept was evaluated by the United States Bureau of Reclamation in January 2003 for 110 MGD capacity operating over 30 years with a total cost of $1.2 billion [6], competitive at that time with other concepts being evaluated for Salton Sea salinity management, and published in 2005 [7]. A demonstration test with low pressure geothermal steam was planned using a single effect 40,000 GPD VTE unit previously demonstrated using waste steam at power plants in California [8]. This unit has 199 double fluted 76 mm evaporator tubes of 3,000 mm length.

An Imperial Valley agriculture to urban water transfer deal signed in 2003 made salinity management of the whole Salton impractical as agricultural return flows would be reduced substantially and the surface area of the lake would eventually decline by half, concentrating the salts. With less to gain, the demonstration test was scaled back to a pilot and commenced in late 2004 with funding from the U.S. Bureau of Reclamation by refurbishing two 5,000 GPD VTE effects and installing them at a geothermal power plant adjacent to the Salton Sea with a condenser and connections to the geothermal plant.

1.2 Research Objectives

This pilot project has been undertaken to investigate the adaptation of existing technology, multi-effect distillation with vertical tube evaporators (MED-VTE), to use non-commercial (waste) steam from a geothermal power plant as a heat source to distill water from a high salinity brine lake, the Salton Sea to potable quality. Located within an inland region and with an ecosystem already threatened by rising salinity in this terminal lake, discharging the high volume of brine typical from an RO or horizontal tube MED system into the lake or elsewhere into the local environment would not be acceptable. The VTE technology with dispersed seeded slurry evaporation (DSSE) for scale control offered an option that could achieve high recovery rates with limited brine discharge. The DSSE process was described in the 1992 U.S. patent number 5156706 and published in 1997 [10]. This pilot project was undertaken to test and adapt these technologies to achieve the following objectives:

1. Efficiently apply geothermal steam as a primary heat source for multi-effect distillation.
2. Distill high salinity brine lake water to potable quality with high recovery.
3. Develop a method to safely dispose of the residual brine without harm to the environment.

A single effect 40,000 GPD VTE unit [8] is under installation with additional funds from the U.S. Bureau of Reclamation and the California Department of Water Resources for demonstration scale testing and is also planned for use in conjunction with an ongoing brine concentrate reuse test project.

II. VTE PILOT PLANT PROCESS

The pilot scale testing employs two VTE effects, the first with smooth wall titanium tubes, the second with fluted copper-nickel tubes. The heat transfer performance benefit of fluted tubes was described by Genkin and Shechter in 1999 [9]. Sand filtered, deaerated Salton Sea water is the feed source. Low pressure geothermal steam is the heat source. Up to five effect conditions are tested by matching temperatures, pressures, and Salton Sea brine concentration to that predicted for a 15 effect VTE-MED system. Both forward feed and reverse feed configurations were tested. Steam side temperatures range from 100°C for effect 1 tests to 51°C for effect 15 tests. Mineral scaling is controlled by the Dispersed Seeded Slurry Evaporation (DSSE) method described in 1997 [10] and patented in 1992.

2.1 VTE Pilot Plant Configuration

The VTE Pilot Plant installed at the CalEnergy Units 1&2 geothermal plant near the shore of the Salton Sea (Photo in Figure 3) has two small vertical tube evaporators configured to recreate, or physically simulate, the temperature, pressure, and brine chemistry conditions in one or two effects in a conceptual 15-effect commercial VTE-MED plant.

Figure 3. Two Effect VTE Pilot Plant Installed at CalEnergy Geothermal Plant by the Salton Sea

The VTE Pilot Plant can use up to 450 kg/hr of low-pressure (20 psig) steam from the Cal Energy geothermal plant to distill Salton Sea water. The condensed geothermal steam is returned to the Cal Energy geothermal plant condensate pond and the non-condensable gasses are returned to the geothermal plant vacuum system as shown in the VTE Pilot Plant schematic in Figure 4.

Low pressure geothermal steam (GS in Figure 4) from the Cal Energy Unit 1&2 plant is reduced to atmospheric pressure for high temperature effect 1 simulations or reduced further for lower pressure/temperature simulations. Geothermal steam from the power plant is typically saturated, but after reducing pressure, is de-superheated by the injection of a spray of geothermal condensate (GC) into 10 meter long, straight pipes at two stages. Excess water droplets are removed in a cyclone separator and recycled. Droplet free geothermal steam goes to the VTE 1 steam-side. Geothermal steam flow is controlled by two pneumatic valves in series at each depressurization stage, which are adjusted automatically to maintain a set pressure (and temperature) in the steam shell of the evaporator (VTE 1).

Geothermal steam condenses on the outer surface of the 18 smooth titanium evaporator tubes of 5 cm diameter in VTE 1 and drains by gravity into the Condensate Tank in Figure 4. Geothermal steam at these power plants contains about 2% carbon dioxide and small amounts of other gasses including about 6 ppb hydrogen sulfide. The carbon dioxide and other non-condensable gases must be vented continuously to maintain flow of steam through the tube bundle. In VTE 1 this is done with a perforated central vent tube connected through a control valve to the geothermal power plant's vacuum system for non-condensable gasses. The titanium evaporator tube material of VTE 1 prevents corrosion by the low, but damaging hydrogen sulfide and ammonia content in the geothermal steam.

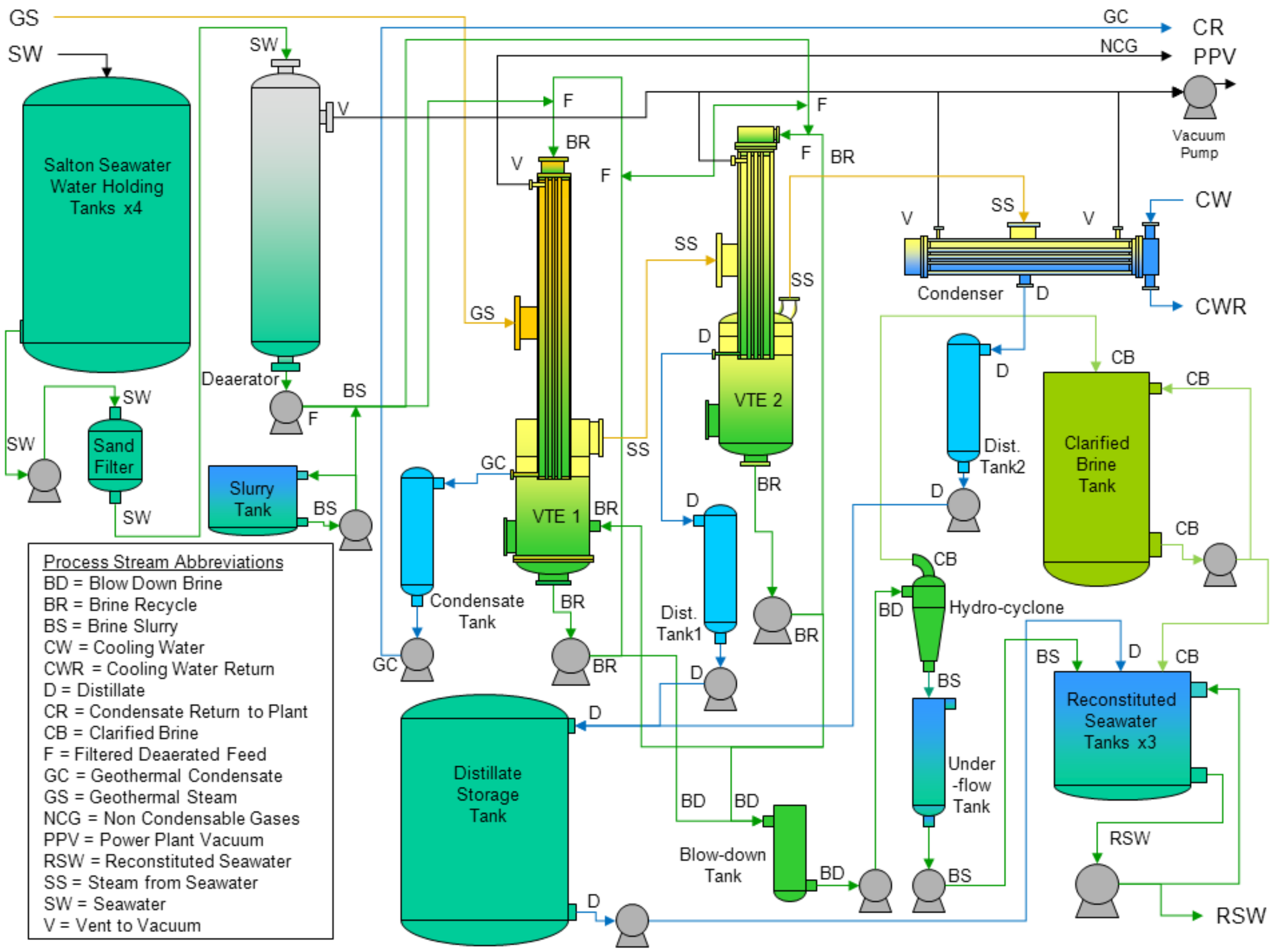

Figure 4. Process Flow Diagram of Two Effect VTE Pilot Plant

Evaporator feed water from the Salton Sea is brought in by tank truck and held in one of two 10,000 gallon sealed Holding Tanks for several days until substantially all of the Salton Sea barnacle larvae in it are inactive. The seawater is then transferred to one of two working seawater tanks from where it's pumped through a sand filter at the rate of flow needed. Air and other gasses are next removed from the seawater by spraying it into the Deaerator where it flows over packing material while under vacuum. Gypsum brine slurry (BS) and DSSE dispersant can be dosed into the deaerated feed stream as it is pumped out of vacuum.

The deaerated feed is then pumped into the recycle loop of brine concentrate being circulated from the brine sump to the top of the VTE 1 tube bundle. Recycled brine and new feed is distributed through an orifice plate into the 18 evaporator tubes.

Water vapor is produced in VTE 1 from the evaporation of seawater brine as it flows as an annular falling film down the inside of the 18 vertical evaporator tubes. The vapor is separated from the brine as it cascades down out of the evaporator tubes into the lower chamber of VTE 1 and is drawn into the steam side of VTE 2 by vacuum. The vapor is stripped of brine droplets by passing through a stainless steel wire mesh demister screen installed inside the VTE 1 around and above the lower tube bundle exit. The demister screen is periodically washed with a distilled water spray.

Vapor, or seawater steam (SS in figure 4) condenses on the outer surface of the 49 double fluted copper nickel evaporator tubes of 2 cm diameter in VTE 2 and drains by gravity into Distillate Tank 1 in Figure 4. The VTE 2 steam side is vented from the side of the cylindrical steam jacket at the apex of a V shaped tube bundle arrangement through a liquid ring vacuum pump.

Water vapor is produced in VTE 2, similarly to VTE 1, from the evaporation of seawater brine as it flows as an annular film down the inside of the 49 vertical evaporator tubes. The vapor is separated from the brine in the lower chamber of VTE 2 and drawn into the Condenser by vacuum through a stainless steel demister screen inside VTE 2. This demister screen is also periodically washed with a distilled water spray.

Vapor drawn into the condenser by vacuum flows across the outside surface of tubes circulating cooling water. The condensate drains by gravity to Distillate Tank 2. Cooling water is provided by the Cal Energy Unit 1&2 power plant at flow rates controlled to provide a selected ΔT for the process conditions to be tested. Cooling water at up to 190 gpm is drawn from and returned to the geothermal plant. The condenser steam side is vented from the sides of the vessel through a liquid ring vacuum pump

The flow of deaerated feed into the recycled brine is regulated to maintain the brine level in the bottom chamber of VTE 1 and VTE 2. In the case of a forward feed test configuration, deaerated seawater feed supplies VTE 1, while heated brine from VTE 1 supplies the feed inlet of VTE 2 above the orifice plates that distributes feed to create an annular falling film flow within the 49 evaporator tubes. In the case of reverse feed configuration, deaerated seawater feed can supply VTE 2, while heated brine from VTE2 can supply the feed inlet of VTE 1. The salinity or concentration of the recycled brine in each evaporator is regulated by opening a brine blow-down valve down-stream of the brine recycle pump which allows flow to either the feed inlet of the other VTE unit or to the Blow-down Tank.

This blow-down includes brine concentrate, process precipitates, gypsum seed slurry, and the DSSE dispersant (LAS-99 surfactant) incorporated into the precipitates as micelles and in solution. Solids in the blow-down are partially separated by centrifugal force in a Hydrocyclone. The solids in the blowdown consist mostly of gypsum particles. These are recycled for reuse as DSSE feed slurry (BS in Figure 4) after separation from the clarified brine (CB). All soluble products (less lab samples) are ultimately combined in one of three Seawater Remix Tanks for eventual return to the Salton Sea.

2.2 Key VTE Pilot Plant Process Parameters

In addition to the above-mentioned process controls, continuous measurements and recording are provided for the following:

1. The geothermal steam pressure and temperature at the supply point and at each of two stages of pressure reduction along the length of steam supply and de-superheating pipe.

2. The VTE1 tube bundle steam-side pressure and temperature at inlet and at three elevations.
3. The VTE2 tube bundle steam-side pressure and temperature at inlet and at two elevations.
4. The Condenser inlet pressure and temperature.
5. The coolant inflow and outflow temperature from the Condenser.
6. The recycled brine temperature in VTE 1 and VTE 2 in the sump before addition of feed.
7. The recycled brine temperature in VTE 1 and VTE 2 at the top after addition of feed.
8. The VTE 1 vapor pressure and temperature above the de-mister.
9. The de-aerated feed temperature and feed or brine flow rate into VTE 1 and VTE 2.
10. The recycled brine flow rate and conductivity in VTE 1 and VTE 2.
11. The blowdown flow rate into and out of the blowdown tank to the hydrocyclone.
12. The flow rate of brine reinjected from VTE2 to VTE 1 to maintain target salinity in VTE 1.
13. The VTE 1 geothermal steam condensate instantaneous flow rate by Coriolis flow meter and averaged flow rate by cylindrical tank fill time between measured points.
14. The VTE2 seawater steam condensate instantaneous flow rate by Coriolis flow meter plus averaged flow rate by cylindrical tank fill time between measured points.
15. The Condenser seawater steam condensate averaged flow rate by cylindrical tank fill time between measured points.
16. The outflow rates of the Condensate Tank and of Distillate Tanks 1 & 2.
17. The Condenser coolant flow rate applied to adjust the ΔT imposed on the two effect system and coolant temperatures in and out of the condenser.

III. TEST METHODS AND MATERIALS

3.1 Performance Measurement

The flow of geothermal steam condensed on the outside of the evaporator tubes in VTE 1, or distilled seawater condensed on the outside of the VTE 2 evaporator tubes, and the temperature difference across the tube walls in each unit are critical values in determining the overall heat transfer coefficient (U in equation 1) computed as heat flux (Q) per tube surface area (A) divided by (ΔT), difference between the steam-side temperature and the brine evaporation temperature, which is the driving force.

$$U = Q / A / \Delta T \tag{1}$$

Heat flux in this case can be measured by the mass flow of condensate, or volumetric flow (V) times density (ρ), multiplied by the heat of vaporization (H_{vap}). This overall heat transfer coefficient measures the efficiency of the evaporation process across the tube walls. Any change during an otherwise steady state would be an indication of scaling or some other process performance problem.

$$U = \rho\ V\ H_{vap}\ /\ A\ /\ \Delta T \tag{2}$$

The performance ratio (PR) is traditionally defined as mass of distillate (M_d) produced over heat flux (per 1,000 BTU in English units), or as gained output ratio (GOR) defined as mass of distillate produced per mass of steam (M_s) consumed.

$$PR = M_d\ /\ (Q\ /\ 1000) = \rho\ V_d\ /\ (\rho\ V_s\ H_{vap}\ /\ 1{,}000) \tag{3}$$

3.2 VTE Pilot Plant Sampling

Water samples are taken from the seawater feed, slurry tank, VTE 1 and VTE 2 recycled brine and the Condensate Tank and distillate Tanks 1 & 2 outflow. These samples are analyzed in a small on site lab for pH, conductivity, total dissolved solids (TDS), and total suspended solids (TSS). Additional water samples from those sample points are shipped out to an analytical lab for chemical analysis.

Geothermal steam samples are taken from two inserts in the steam supply pipe through water vapor separators and sent to an analytical lab for hydrogen sulfide and ammonia analysis.

3.3 VTE Pilot Plant Test Materials

Salton Sea water is brought in by tank truck, transferred to holding tanks, separated into distilled water, solids, and concentrated seawater brine by the VTE process. The water samples are tested for chemical and physical properties. Distilled and concentrated seawater fractions are then recombined, mixed, and tested before return to the Sea.

The dispersant used is linear alkylbenzene sulfonic acid, available from Pilot chemical as Calsoft LAS-99. It is biodegradable and approved in the USA for use as a commercial detergent in laundry soap and other products. In addition to the anti-scaling DSSE effect and the evaporation performance enhancing vertical tube foam evaporation (VTFE) effect, it also facilitates the rapid re-dispersion of precipitates, if needed, by washing the evaporator with a freshwater recycle for about a day.

3.3 Multi-Effect Test Plan

The original 2006 grant proposal test plan included the set of reverse feed multi-effect simulation tests shown in Table 1. These were to be executed with VTE 1 and VTE 2 in series with feed flowing from VTE 2 to VTE 1 for a reverse feed simulation. The salinity of Salton Sea water had risen from 45,000 ppm to about 50,000 ppm in 2009 when a 1.5 year contracting process was completed and the VTE Pilot Plant system was fully built and ready for tests, so the brine salinity targets were no longer appropriate.

A four day baseline heat transfer test series was run with VTE 1 and VTE 2 in two-effect operation with parallel freshwater feed using LAS additive at 0, 20, and 2 mg/liter. Effects 14, 7, and 1 were simulated with VTE 1 steam side temperatures and effects 15, 8, and 2 with VTE 2 steam side temperatures. Due to a large difference in heat transfer performance between VTE 1 with smooth titanium tubes and VTE 2 with fluted copper nickel tubes, it was not possible to simultaneously match both the steam side and brine side temperatures of both evaporators to the multi-effect simulation targets in Table 1.

Table 1: Original Multi Effect Test Plan for 2 Effect VTE Pilot Plant

Test	Effect	Evaporator Unit	Feed Rate (gpm)	Distillate Rate (gpm)	Geothermal Steam Rate (lb/hr)	Steam Temp. (°F)	Tube ΔT (°F)	Brine Salinity (ppm)
1	1	VTE-1	N/A	0.19	382	212.0	2.85	220,000
1	2	VTE-2	0.95	N/A	N/A	199.9	3.04	189,802
2	7	VTE-1	N/A	0.37	374	164.3	3.21	81,866
2	8	VTE-2	1.85	NA	N/A	158.9	3.25	73,767
3	14	VTE-1	N/A	24.77	546	129.3	3.51	48,076
3	15	VTE-2	27.07	N/A	N/A	124.6	4.55	45,591

Since the planned two-effect, 3 point simulation would not be possible, a good alternative was to use the one-effect, 5 point simulation intended for a larger demonstration scale VTE unit and shown in Table 2 as target conditions for VTE 2, but at lower steam, feed, and distillate flow rates.

Copper alloy evaporator tube material samples were rapidly corroded by hydrogen sulfide in the geothermal steam. Since the copper nickel tubes in VTE 2 would be degraded by exposure to hydrogen sulfide and ammonia in geothermal steam, VTE 1 would still be used as a clean steam source and feed preheater for VTE 2.

Table 2: Multi Effect Test Plan for Larger VTE Demonstration Unit

Test	Effect	Feed Rate (gpm)	Distillate Rate (gpm)	Geothermal Steam Rate (lb/hr)	Steam Temp. (°F)	Tube ΔT (°F)	Steam Press. (psia)	Brine Salinity (ppm)
1	1	14.49	11.59	5,803	212.0	2.65	14.69	220,000
2	4	18.87	11.80	5,910	182.9	2.45	8.00	117,389
3	7	25.42	11.64	5,830	164.3	3.14	5.25	81,068
4	11	47.76	11.55	5,782	143.7	3.44	3.17	57,970
5	15	176.0	14.92	7,470	124.6	4.55	1.92	48,076

IV. RESEARCH RESULTS

4.1 Salton Sea Brine Concentration in the VTE Pilot Plant

In order to characterize the salt content of Salton Sea brine over a range of concentrations, a single effect Salton Sea brine concentration test to over 6 fold concentration factor was run in VTE 1 in January 2009 with monitoring of heat transfer data and sampling of brine slurry, distillate, and geothermal condensate. Adapting the method of the DSSE patent, gypsum slurry at 3% suspended solids was made up in Salton Sea water by mixing 5% $NaSO_4$ and 3% $CaCl_2$ salts by weight to form a precipitate. The VTE 1 was dosed with 20 ppm of LAS as deaerated seawater feed was added to VTE 1 to sustain a constant level. The TDS rose steadily during several hours of brine concentration in VTE 1 approaching saturation with a slight increase in the slurry total suspended solids (TSS in Figure 5a). The calculated heat transfer coefficient plotted in Figure 5b reduced slightly as the brine concentration rose near saturation.

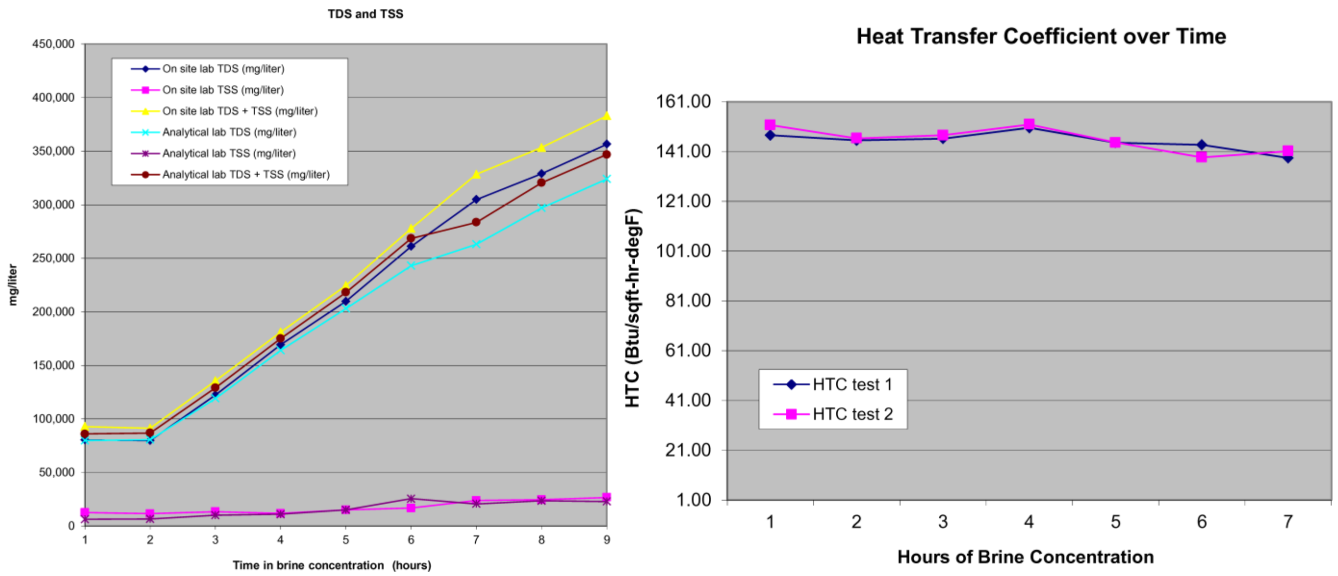

Figure 5a. TDS & TSS with 5b. Heat Transfer Coefficient during Salton Sea brine concentration in VTE 1 Jan 12-13, 2009

The major ion brine chemistry in Figure 6a shows the expected steady rise of sodium and chloride with concentration. Sulfate in solution clearly goes down after a concentration threshold is reached. This is consistent with gypsum precipitation as the Salton Sea brine is concentrated.

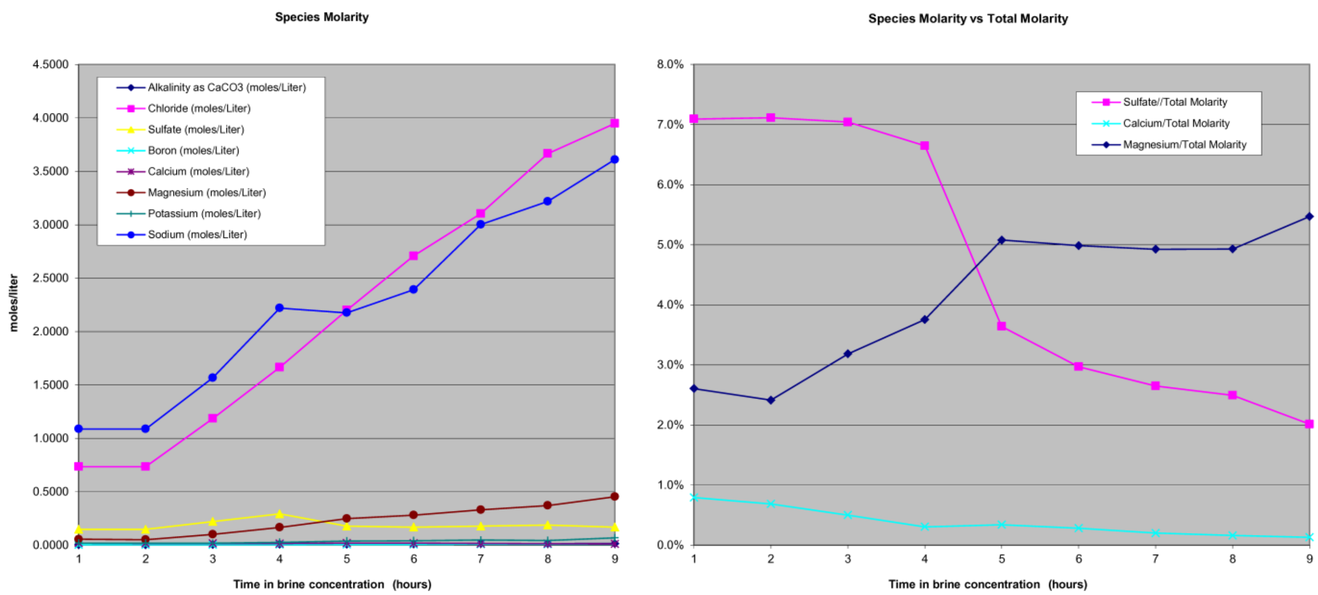

Figure 6a. Molarity of Major Ions, and 6b.Minor Ions during Salton Sea brine concentration Jan 12-13, 2009

Plotting the minor ions magnesium, sulfate, and calcium against total molarity of all ions, in Figure 6b, shows a coordinated reduction in calcium and sulfate consistent with expected gypsum precipitation. Gypsum is the most significant mineral scaling challenge when distilling Salton Sea water.

4.2 Reverse Feed Multi-Effect Simulation with Salton Sea Water in VTE Pilot Plant

A reverse feed 15 effect configuration was tested by first mixing fully settled mostly gypsum slurry recovered from earlier tests with filtered seawater. Both evaporators were charged with a mix of Salton Sea water, 3% slurry, plus 5 mg/liter LAS dispersant. A multi-effect simulation test of VTE 1&2 was run with reverse feed temperature and brine concentration conditions starting at Effect 15 with a low temperature and a low brine concentration, then increasing temperature and brine concentration through effects 11, 7, 4, and 1. Hot brine feed from VTE 1 to VTE 2, and brine re-injection from VTE 2 back to VTE 1 was used to maintain target temperatures and brine concentrations in VTE 2 matching the reverse feed effect conditions. Slurry was recovered from blowdown through the hydro-cyclone underflow while holding brine concentration steady to record data at each effect condition. Slurry was then fed back to the system during the brine concentration step between each effect simulation condition. Heat transfer performance was substantially reduced in VTE 2 at the high temperature and high brine concentration test conditions seen in Figure 7, but not in VTE 1.

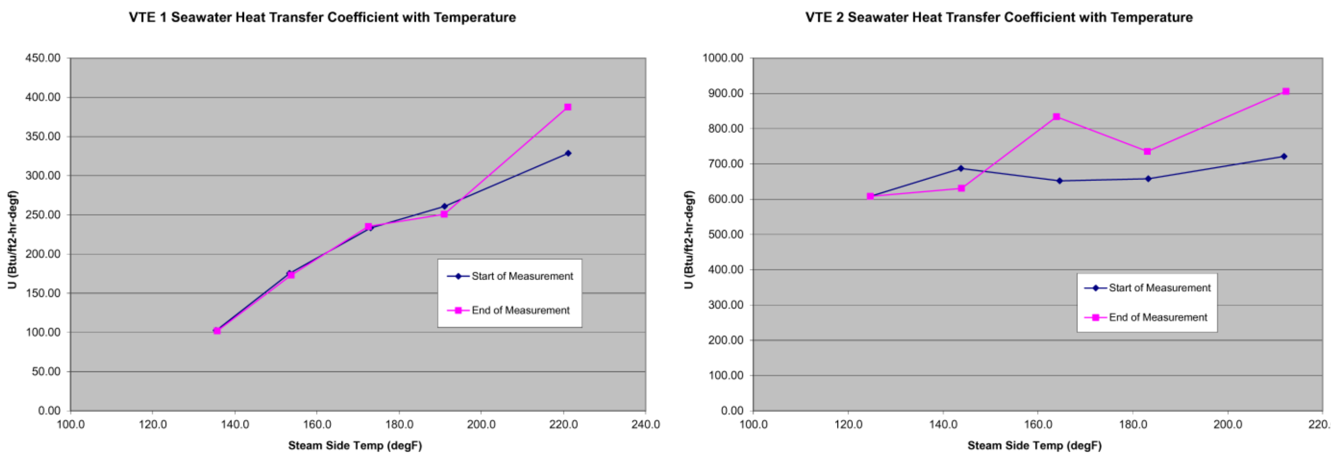

Figure 7. VTE 1&2 Heat Transfer Coefficient with Effect Temperature, Seawater July 2-5, 2011

Reduced VTE 2 performance in Figure 7 was apparently due to boiling point elevation. Per Figures 8, freshwater baseline tests before and after the seawater test did not show significant scaling in either unit.

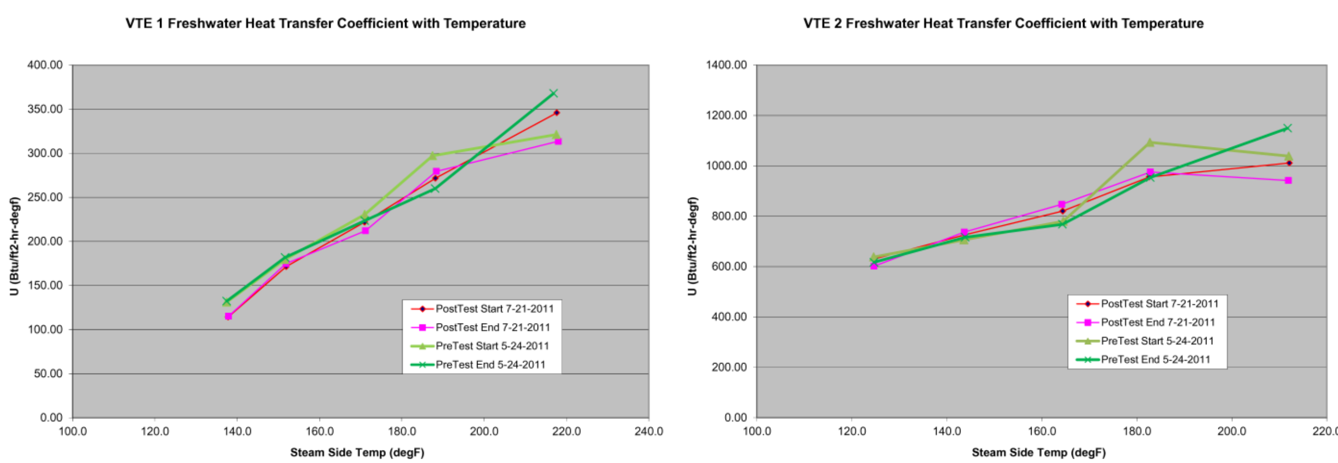

Figure 8. VTE 1&2 Freshwater Heat Transfer Coefficient, Pre and Post Seawater Test, May 24 & July 21, 2011

VTE 2 foamed over and lost level at the Effect 1 test condition. The loss of level was caused by failure of the high alarm switch when it became occluded with slurry during the foaming over. The Effect 1 test condition was repeated two days later, delayed by a utility power outage, with LAS dosing reduced to 2 mg/lit and after cleaning slurry from the high and low level alarm switches in VTE 2.

The Effect 1 retest did not have any foaming over problems. Samples were taken at each effect simulation for chemical analysis. Calcium concentration declined steadily as the brine concentration rose. Sulfate concentration rose at a lower rate than other constituents indicating precipitation of calcium sulfate. Bicarbonate was higher compared to carbonate as the brine concentration rose. Distillate samples taken from two days during the reverse feed multi-effect simulation test showed low levels of salt carryover from the Salton Seawater feed source and injected scale control slurry (Figure 9) indicating good distillate quality.

Sample ID	A-Slurry	B-Seawater	I1-Dist. VTE1 E 15	I2-Dist. VTE2 E 15	J1-Dist. VTE1 E 7	J2-Dist. VTE2 E 7
McCampbell Lab ID	1107530-001	1107530-002	1107530-015	1107530-016	1107530-017	1107530-018
Sample Date	07/02/11	07/04/11	7/2/2011	7/2/2011	7/3/2011	7/3/2011
Sample Time	17:00	23:58	22:10	22:10	3:55	3:55
Sample Source	Slurry Tank	Feed Tank A	Distillate Tank 2	Distillate Tank 1	Distillate Tank 2	Distillate Tank 1
Effect	0	0	15	15	7	7
On site lab Conductivity (mS/cm @ 25C)	72.8	60.2				
On site lab pH (at 25C)	8.02	7.92				
Analytical lab TSS (mg/liter)	10,900	2.1				
Analytical lab TDS (mg/liter)	62,700	49,300	<10	<10	37	<10
Sodium (mg/Liter)	14,000	14,000	<0.5	<0.5	<0.5	0.690
Potassium (mg/Liter)	400	300	<0.5	<0.5	<0.5	<0.5
Calcium (mg/Liter)	770.0	820.0	<0.5	<0.5	<0.5	<0.5
Magnesium (mg/Liter)	2,100	1,600	<0.05	<0.05	0	0
Lithium (mg/Liter)	6.60	4.90	<0.05	<0.05	<0.05	<0.05
Strontium (mg/Liter)	30.0	24.0	<0.05	<0.05	<0.05	<0.05
Arsenic (mg/Liter)	0.031	0.025	<0.0005	<0.0005	<0.0005	<0.0005
Boron (mg/Liter)	18.0	14.0	0.002	<0.0016	0.021	0.015
Barium (mg/Liter)	<0.1	0.11	<0.005	<0.005	<0.005	<0.005
Silica (mg/Liter)	19.0	18.0	<0.11	<0.11	<0.11	<0.11
Chloride (mg/Liter)	29,000	20,000	0.32	0.18	0.51	0.33
Fluoride (mg/Liter)						
Bromide (mg/Liter)	24.0	19.0	<0.1	<0.1	<0.1	<0.1
Sulfate (mg/Liter)	15,000	11,000	0.22	0.39	0.30	0.95
Phosphate (mg/Liter)						
Total Alkalinity (mg/Liter)	338.0	262.0	<1.0	<1.0	<1.0	<1.0
Carbonate (mg/Liter)	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Bicarbonate (mg/Liter)	338.0	262.0	<1.0	<1.0	<1.0	<1.0

Figure 9. Chemical Analysis of Distillate Samples versus Salton Seawater and Slurry Tank from July 2-5, 2011

4.3 Forward Feed Multi-Effect Simulation with Salton Sea Water in VTE Pilot Plant

A multi-effect simulation test of VTE 1&2 was run with forward feed temperature and brine concentration conditions for effects 1,4,7,11, and 15. Both evaporators were charged with Salton Sea water, 3% gypsum slurry recovered from prior test runs, and 5 mg/liter LAS dispersant. Feed preheating by heat exchange with geothermal condensate and brine re-injection from VTE 2 back to VTE 1 was used. The steam supply was at or near maximum to maintain the high temperature condition at a high feed and blowdown rate. A switch to feed preheating by blowdown showed some improvement in the steam demand. As shown in Figure 10, the heat transfer performance was slightly reduced in VTE 2 across the range of test conditions, but VTE 1 does not show any reduction.

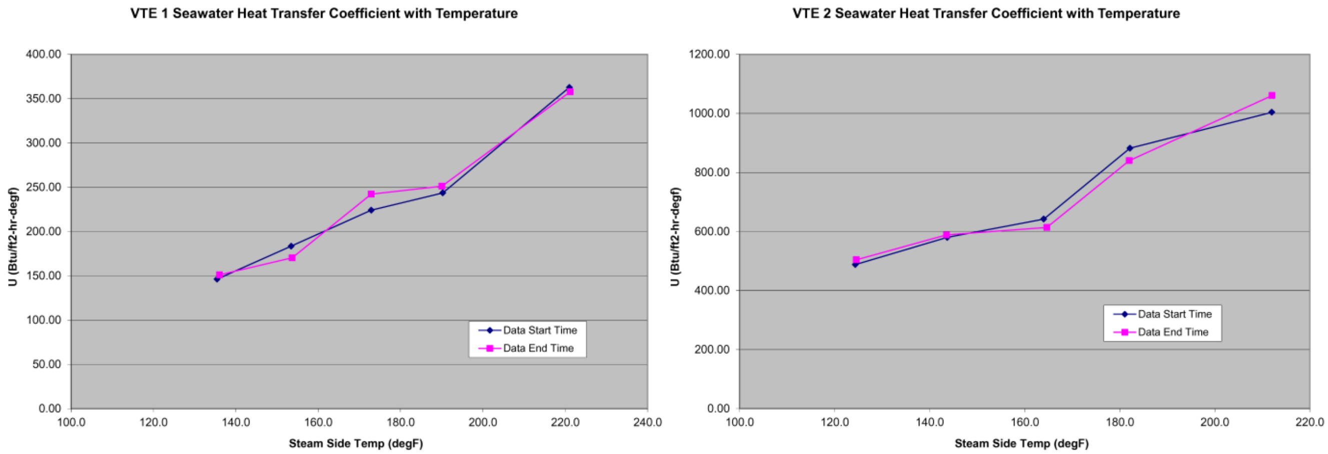

Figure 10. VTE 1&2 Heat Transfer Coefficient with Effect Temperature, Seawater March 17-18, 2011

The per effect performance ratio (PR) is shown in Figure 11 against the effect brine concentration over a five-fold overall concentration factor. The PR was measured for each evaporator as pounds of distillate evaporated per 1,000 BTU. These values are very close to the gained output ratio (GOR) in kg of distillate per kg of steam consumed. VTE 2 performs better when fed by brine pre-heated in VTE 1 to the appropriate effect feed temperature for a 15 effect forward feed system.

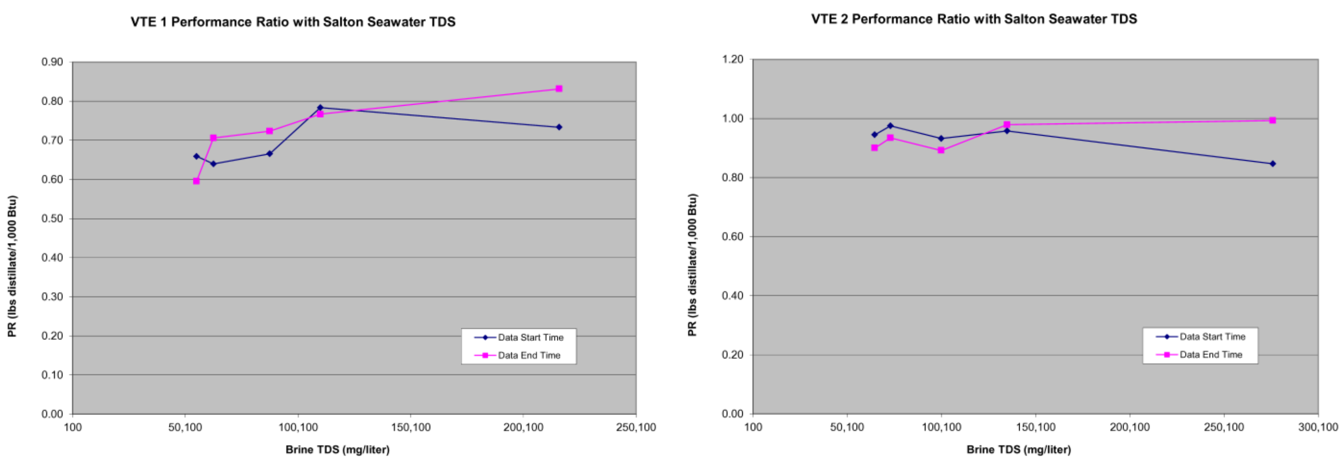

Figure 11. VTE 1&2 Performance Ratio versus Brine TDS per Effect Condition, Seawater March 17-18, 2011

Dilution of slurry at the high temperature, low brine concentration condition occurred due to the high blowdown rate. Slurry was recovered and fed back into VTE 1 to compensate for the loss. The system held the low concentration condition in VTE 2 with higher feed and blowdown rates allowed by installing larger bore flowmeters. Samples were taken at each effect simulation for chemical analysis. Major ions are charted in Figure 12, with minor ions in Figure 13.

Unlike prior data, sulfate in solution declined at two fold and further at four fold increase in overall solute concentration. Calcium in solution declined steadily with the rise in overall solute concentration as seen in prior tests. Sodium in solution rose, but the rise was up to 1 mole per liter less than trend at four fold overall solute concentration at effect 15. This indicates a substantial precipitation of sulfate as both calcium sulfate and sodium sulfate at high concentration, moderate temperature Effect 11 and Effect 15 conditions.

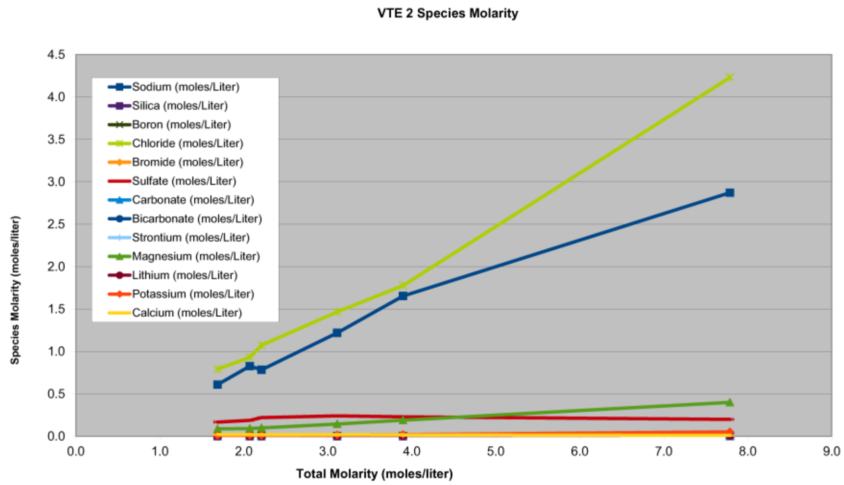

Figure 12. Molarity of Major Ions during Forward Feed Simulation, March 17-18, 2011

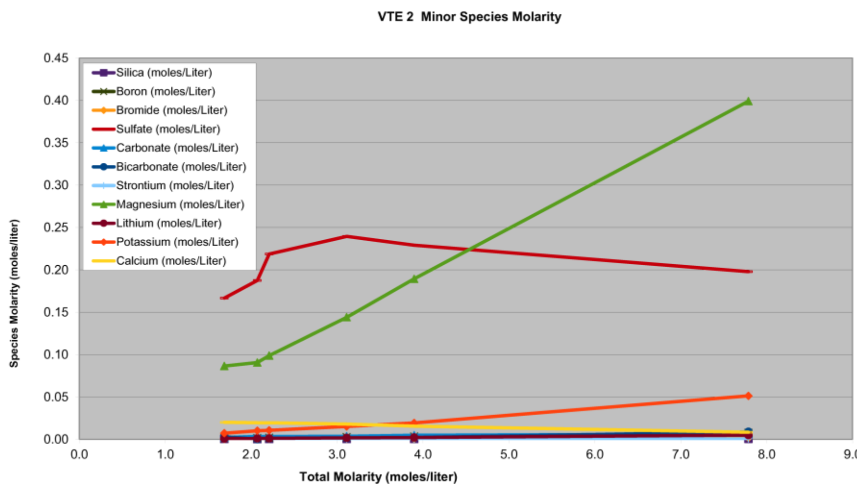

Figure 13. Molarity of Minor Ions during Forward Feed Simulation, March 17-18, 2011

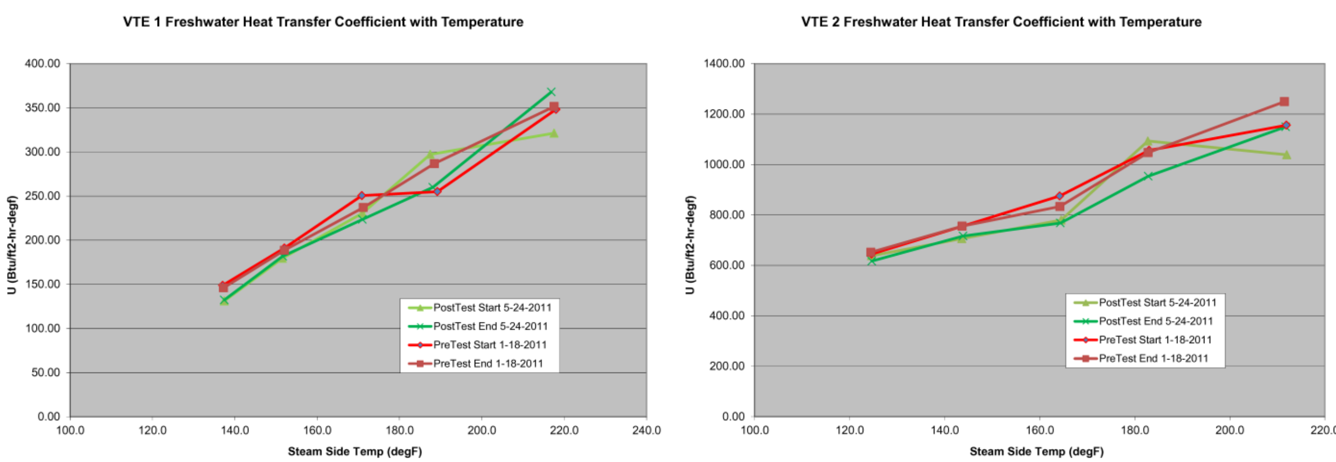

Figure 14. VTE 1&2 Heat Transfer Coefficient, Pre and Post Seawater Test, Jan 18 & May 24, 2011

A baseline multi-effect simulation test of VTE 1&2 in two-effect operation with freshwater feed and 2 mg/liter LAS was run to detect scaling by measuring performance after the seawater forward feed test. Feed preheating by heat exchange with geothermal condensate, hot brine delivery from

VTE 1 to VTE 2, and brine re-injection from VTE 2 back to VTE 1 was used. No change in performance was seen in VTE 1 compared to the pre-test baseline (Figure 14), but a slight reduction was seen in VTE 2.

V. CONCLUSIONS

Pilot testing showed recovery of up to 86% of Salton Sea feed water as distillate in a 6 fold brine concentration or 80% for 5 fold concentration. The VTE 1 unit with titanium tubes was not degraded by extended contact with geothermal steam in the temperature ranges tested but the heat transfer coefficient of smooth titanium tubes was four times lower than for the double fluted copper-nickel tubes in VTE 2 requiring more effect 1 surface area than for subsequent effects if smooth titanium tubes are used.

Table 3: Extrapolation of 15 Effect VTE-MED Performance from VTE 2 Test Data

Interpolated Effect	Steam Enthalpy	Condensate Rate	Distillate Rate	Heat Rate	Performance Ratio	Gained Output Ratio
	(Btu/lb)	(lb/hr)	(lb/hr)	(Btu/hr)	(lb/1000Btu)	(kg/kg)
VTE 2						
1	970.2	395.910	308.431	384,093	0.80	0.78
2	976.3	348.075	283.455	339,234	0.85	0.83
3	982.4	300.240	258.479	294,374	0.89	0.88
4	988.6	252.404	233.503	249,515	0.94	0.93
5	992.1	248.439	230.999	246,456	0.94	0.93
6	995.7	244.475	228.495	243,398	0.94	0.94
7	999.3	240.510	225.990	240,340	0.94	0.94
8	1,002.4	238.627	226.355	239,169	0.95	0.95
9	1,005.4	236.744	226.720	237,998	0.95	0.96
10	1,008.5	234.861	227.085	236,828	0.96	0.97
11	1,011.5	232.978	227.450	235,657	0.97	0.98
12	1,014.3	215.036	210.267	217,958	0.96	0.98
13	1,017.1	197.094	193.083	200,259	0.96	0.98
14	1,019.9	179.151	175.899	182,559	0.96	0.98
15	1,022.7	161.209	158.715	164,860	0.96	0.98
15 Effect Sum		248.4	3,414.9	384,093	14.0	14.0
Distillate Output	Steam Rate	120,000	1,680,917	116,418,000	4,841,236	4.8 MGD
Brine Output					968,247	1.0 MGD

Extrapolation of data in Table 3 from the five effect conditions tested indicates that a 15 effect commercial system could achieve a performance ratio of 14 lbs. of distillate per 1,000 Btu or 14 kg of distillate per kg steam consumed. A 5 MGD plant based on this technology is estimated to cost $25.4 million to construct in California. At 8% interest and an O&M cost of $1.9 million annually including electricity for pumping but assuming no substantial cost for waste steam, the preliminary estimated water cost for a 5 MGD plant based on this approach is $0.63 per cubic meter of distillate containing typically less than 10 mg/liter TDS.

VI. REFERENCES

1. U.S. Department of the Interior, Bureau of Reclamation. "Colorado River Basin Water Supply & Demand Study", (December 2012). http://www.usbr.gov/lc/region/programs/crbstudy.html
2. Imperial Irrigation District, "Integrated Water Resources Management Plan", (2012) http://www.iid.com/water/water-supply/water-plans/imperial-integrated-regional-water-management-plan
3. Metropolitan Water District of Southern California. "Seawater Desalination Plant for Southern California, Preliminary Design Report No. 1084". (October 1993).
4. Bednarski, John and Dean, David W. "Metropolitan Water District of Southern California's Enhanced Seawater Distillation Test Program", IDA Madrid Proceedings Vol. I, (1997) pages 227-241.
5. Bom, Robert P. "New Concept Multi-Effect VTE, with Falling Film", IDA Madrid Proceedings Vol. IV (1997) pages 113-126.
6. U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region "Salton Sea Study, Status Report". January 2003. http://www.usbr.gov/lc/region/saltnsea/pdf_files/statusrpt.pdf
7. Sephton T. and Tiffenbach A. 2005. "VTE Desalination using Geothermal Energy at the Salton Sea". Proceedings of the 2005 Solar World Congress, Orlando Florida.
8. Sephton, Hugo H. "Turbine Exhaust Steam Driven Desalination", IDA San Diego Proceedings Vol. IV, (1999) pages 161-170.
9. Genkin, Gregory G. and Shechter, Ronen I., "The Effect of Wetting Flow Rate on Vertical Fluted Tubes - Mathematical Model and Pilot Test Results", IDA San Diego Proceedings Vol. IV, (1999) pages 183-189.
10. Sephton, Hugo H. and Solomon, Robert R. "Use of Power Plant Turbine Reject Steam to Drive Desalination with Enhanced Heat Transfer Performance", IDA Madrid Proceedings Vol. IV (1997) pages 299-308.

VII. ACKNOWLEDGEMENTS

The author wishes to acknowledge the United States Bureau of Reclamation and the California Department of Water Resources for grant funding support and the invaluable assistance of CalEnergy Operations in hosting and supporting this series of tests over several years. The early technical advice of Kurt Frank, John Featherstone, Dr. Huanmin Lu, Shahid Chaudhry, and Fawzi Karajeh was highly beneficial, as was the expert mechanical engineering advice of John Matthew. Several current and former U.S. Bureau of Reclamation employees made this project possible including Andrew Tiffenbach, Becky Blasius, Mike Walker, Harry Remmers, Michelle Maher, Shaun Wilken, Randale Jackson, Janeen Koza, and Kevin Price. The author would especially like to thank Herb Hein and Luis Garcia for their expertise and excellent work in constructing and testing the VTE Pilot Plant and Dieter K. Emmermann in memoriam for his expert advice throughout.