AIL Research

Technology Introduction and Test Summary

As shown in the one-plate illustration in Figure 1, the key components of a brine concentrator that uses Brine-Zero Diffusion-Gap Distillation (DGD) are (i) the condenser—a plastic-plate heat exchanger within which the feed brine flows upward, (ii) the evaporator—a porous hydrophilic wick positioned in the gaps between condenser plates on which the hot brine flows downward, and (iii) the brine heater—an external source of thermal energy that further heats the preheated brine exiting the condenser to its maximum temperature before delivery to the wicks. During operation water vapor diffuses across the small gap (2 to 4 mm) between the wick and the condensing plate, condenses and forms a falling film on the exterior surface of the condenser. The latent heat released by the condensing vapor preheats the brine flowing upward within the plate. With most of the brine's temperature rise provided by condensing vapor, DGD achieves exceptionally high Gain Output Ratios (GOR)[1].

The Brine Zero installation at the Yuma Desalting Plant (YDP) is schematically represented in Figure 2. As shown in this figure, the DGD processor consists of three separate stacks, each with 70 plate/wick pairs. Fifteen gallons per minute of brine is pumped from the storage tank, through the plate stacks, and after being preheated in the plates, flows into the precipitation tank. An 18-kW steam generator directly supplies one-atmosphere pressure steam to the precipitation tank where the steam condenses, releasing thermal energy that heats the brine to its maximum temperature. From the precipitation tank, the heated brine is metered to the individual wicks of the stacks. The water vapor that evaporates from the hot brine condenses on the outer surfaces of the plates. The brine that does not evaporate is collected by gutters attached to the bottom of each wick from which the brine drains into a channel that returns the brine to the storage tank. The condensate that flows down the outer surfaces of the plates is collected separately from the brine that flows off the wicks and flows to the product tank (not shown in Figure 2). A separate evaporative cooler (which operates like a small cooling tower) dissipates the thermal energy conveyed by the warm, concentrated brine flowing off the wicks into the storage tank.

Operating the Brine Zero processor at the YDP proved challenging. The design for the 70-plate modules was based on prior laboratory experience with assemblies of up to ten full-sized plates. The demanding schedule for the competition did not allow for laboratory testing of a 70-plate module prior to the June 21 start of the evaluation period. Furthermore, the logistics of competing required that the 70-plate modules be assembled on site in Yuma from parts fabricated at our lab and shipped to the site.

The first problem our team encountered was the collapse of one of the three plate stacks during assembly. The collapsed stack was rebuilt, and all three stacks (coded Red, Green and Yellow) are shown assembled but before they were insulated in Figure 3. All three stacks operated at the start of the competition, but the Red stack, whose integrity had been compromised by its collapse during assembly, was taken out of operation on the second day of competition when the conductivity of its produced water exceeded 4,400 muS.

[1] For thermally driven separation processes, Gain Output Ratio is the mass of produced water divided by the mass of steam that drives the process.

The other two modules (Green and Yellow) also experienced a gradual buckling of the plates (shown in Figure 4 in a post-test photograph) that collapsed the gaps between the wicks and the condensing plates leading to ever increasing contamination of the product water and loss of condensate product.

Figure 5 compares the measured average GOR for the Green and Yellow modules after the Red module was removed from service (Hour 40). For this figure, the GOR is calculated as the YDP-monitored water delivered to the product tank divided by the YDP-monitored feedwater to the steam generator. Also shown in Figure 5 is the conductivity of the product water from the Green and Yellow modules as measured independently from YDP monitoring with an AILR hand instrument.

The conductivity data shows acceptable product produced during the first day of competition (i.e., conductivity between 500 and 3000 muS[2]). At the time that the Red module was taken off line (Hour 42) so that YDP-monitored data applied to only Green and Yellow module operation, the conductivity of the product for the Green and Yellow modules had increased to about 4000 muS.

From Hour 42 through Hour 77, the measured GOR mostly equaled or exceeded the GOR predicted by our computer model of the DGD process at the measured values for: 1) temperature of the brine in the sump, 2) temperature of the hot brine delivered to the wicks, and 3) brine flow rate. From Hour 100 through Hour 120, the measured GOR was significantly below the computer-predicted value reflecting the compromised performance caused by the steadily buckling plate stacks.

Both the relatively low conductivity of the product water from the Yellow and Green modules during the first 24 hours of operation and the good GOR (mostly between 6 and 10) measured through the first three days of the competition were positive test results that confirm the DGD process' potential to operate as a high efficiency brine concentrator.

However, this potential will not be realized until a stable mechanical design for the plate stacks is proven. Although the requirement to design within an acceptable budget for material presents challenges, our understanding of the source for plate buckling does provide a possible solution.

Based on past experience we've designed plate stacks to stand vertically on a base with each plate in compression. (Although buckling of plates can be prevented by hanging each plate, the tension in the plates, which will be highest at the hot, upper sections of the plates, causes creep that distorts the plates.) To prevent buckling of the plates our design tightly compresses the stack of plates at both the top and bottom so that inter-plate rubber gaskets seal the fluid connections in and out of the plates, and lightly compress the stack along its central section using discrete ribs and tie rods (which are shown in both Figures 3 and 4). In principle, the compressed stack should act like a wide beam that can support compressive loads without buckling.

Unfortunately, the compressed stack was not a rigid structure. When the stack is compressed, solid silicone spacers press against the edges of the condensing plates. However, the condensing plates are not solid, but rather have internal passages across their entire width. If local compressive loads become too great, the condensing plates will collapse. Post-test inspection of the plate stacks showed many

[2] To be eligible to win the competition, the TDS if product water averaged over the week must be less than 2,200 mg/L, which is approximately equivalent to a conductivity of 3,000 muS.

locations where local compressive load had collapsed the condensing plate, which then allowed the entire plate stack to buckle.

Although now obvious in retrospect, the plate stack should be modified so that all compressive loads are born by solid elements.

Technology Feasibility at Full Scale

Our Brine Zero entry in the competition was designed to recover at least 90% of the water in a 1 gpm stream of RO concentrate in three modules each composed of 70 plates. Although we were not able to operate at the maximum design temperature of 95°C, monitored operation during the first three days of testing did confirm the performance projections of our design software at peak operating temperatures up to 82°C. With the assumption that Future Work will produce a design that operates reliably at 95°C and meets or exceeds the performance projections of our design software, we have scaled up our 1-gpm design to a full-scale plant that has a water recovery of 95% when processing 100,000 gpd of RO concentrate. Salient features of the full-scale plant the uses the Brine Zero technology are:

- RO concentrate is concentrated from 8,000 ppm TDS to approximately 200,000 ppm TDS in seven stages.
- The basic element of the processing unit—the condensing plate and wick pair—duplicates that used in the competition. Modifications are made to the plate-to-plate spacing elements used in the "competition" modules to stabilize the assembly.
- A "unit" processing module is an insulated stack of approximately 320 plates (which is a modest scale-up of the 70-plate stacks used in the competition).
- As shown in Table 1, the first stage processes the highest volume of brine (69.4 gpm) in 41 modules, increasing brine TDS from 8,000 to 19,300 ppm; the first-stage discharge is the second-stage feed, the second-stage discharge is the third-stage feed, etc.; the final seventh stage concentrates 3.4 gpm of brine from 162,000 ppm up to 193,000 ppm in a single module.
- The seven-stage processor has 70 modules arranged in a 7 x 10 array. With 40-inch aisles between strings of modules, the building for the processor has a footprint of 51' x 92' (4,700 ft2).
- Projected installed cost for the 100,000 gpd brine concentrator is $511,000. This is based on: 1) the material, labor and tooling costs to produce 70 modules is $256,000 (where actual material costs for the 1-gpm pilot for the competition have been discounted by about 25% to allow for high volume purchases), and 2) a 2.0 multiplier has been applied to the cost for the modules to estimate the installed cost for the fully functional installation.

Similar to the operation of our entry in the competition, the full-scale Brine Zero brine concentrator would process concentrate that was received directly from the RO facility (i.e., no pretreatment would be required other than that required by the RO facility.)

As described in the Technology Introduction, the Brine Zero process is designed to operate with the continuous precipitation of reverse soluble salts (e.g. $CaSO_4$) in a hot, seeded precipitation tank that is immediately upstream of the processor's wicks. With hot brine in phase-equilibrium before flowing onto the wicks, reverse-soluble salts stay in solution as the brine flows down the wicks and cools by evaporation.

Although much longer operating times at operating temperature closer to 95°C are required to prove the effectiveness of the hot, seeded precipitation tanks used by a Brine Zero processor, experience during the competition and the post-test inspection of the wicks tended to support the design goal of preventing salt/scale accumulation on the wicks by collecting reverse-soluble salts in a serviceable, hot, seeded precipitation tank located immediately upstream of the wicks.

A Brine Zero facility that processes 100,000 gpd of RO concentrate will produce on the order of one ton of solid salt per day. This solid salt must be periodically removed from the hot, seeded precipitation tank. The design of a subsystem that handles either a dense slurry or solid waste produced by a Brine Zero facility remains a major task to be completed as part of Future Work.

Energy Consumption

The primary energy input to the Brine Zero process is steam at slightly above one-atmosphere pressure. A first-generation processor would use a steam boiler fired by natural gas. The gain output ratio (GOR) for each stage appears in Table 1. With the earlier stages producing most of the product condensate, the average gain output ratio (GOR) for the processor is projected to be 16.4 (i.e., 16.4 pounds of product condensate per pound of input steam). The steam generator for the 100,000 gpd processor must then supply steam at 2,000 lb/h (i.e., 2.5 mmBtu [750 kW] firing rate). An automated, closed-loop controller would modulate the firing rate of the steam generator to maintain the hot-brine feed to the Brine Zero modules at a prescribed setpoint (i.e., 95 C). The steam generator would operate on mineral-free condensate produced by the Brine Zero processor and have minimal O&M requirements.

Projected Cost of Water

Assuming that steam is provided to the Brine Zero facility by an 80% efficient boiler fired by natural gas priced at $0.0188 per kWh-thermal (i.e., the average price paid by industrial customers in Arizona in 2021), the cost of water recovered from RO concentration breaks down as follows,

Energy Cost	$0.928 per m3
Capital Cost	$0.357 per m3
O&M Cost	$0.260 per m3
Total Cost	$1.545 per m3

(where Capital Cost has been projected using the preceding $511,000 installed cost for a 100,000 gpd plant that is amortized over 12 years operating at a capacity factor of 0.9; and the O&M costs are a rough estimate that match reported O&M costs for a brackish water RO facility operating without brine concentration[3].)

As reported in Reference 3, the average cost of water supplied by seven brackish water RO plants in Texas in 2011 was $0.487 per cubic meter (in 2021 dollars). Assuming that the initial processing in the RO plant recovers water at 70% efficiency, and the Brine Zero process recovers 95% of the water from the RO concentrate, the blended cost of water from plant is $0.801 per cubic meter.

[3] Arroyo and Shirazi, "Cost of Brackish Groundwater Desalination in Texas," www.twdb.texas.gov, September, 2012.

Although a 95% water recovery from RO concentrate at a cost of $1.545 per cubic meter is low compared to the cost for conventional brine-concentration means, the impact on the blended cost of water is significant (i.e., 64% increase from $0.487 to $0.801). We do note that the largest component in the COW for the Brine Zero process is for energy. In this analysis, the industrial cost of natural gas was relatively high--$0.0188 per kWh-thermal in 2021 versus $0.0134 per kWh-thermal in 2019 (the last full year not affected by the pandemic). With natural gas at 2019 prices, the blended cost of water would decrease from $0.801 to $0.722 per cubic meter.

We also note that the Brine Zero process can be directly driven by steam produced by solar thermal collectors. AIL Research (AILR) is now competing for the Solar Desalination Prize. All entries in this second competition must operating on thermal energy provided by solar collectors. AILR's entry will be driven by steam produced within an array of evacuated-tube collectors. The proof-of-concept array of AILR's steam generating solar collectors shown in Figure 6 is now operating in Freestone, CA. In a sunny, Southwest location, AILR's solar collectors are projected to supply thermal energy at less than $0.015 per kWh-thermal. A Brine Zero facility operating in Arizona, driven by AILR's steam-generation collectors and backed-up with natural gas would provide a low-cost means of desalting brackish water that had a very low carbon footprint.

Innovation

With a GOR projected to exceed 16, the DGD process far exceeds the efficiency of alternative thermal separation processes (e.g., MSF and MED) in a design composed mostly of low-cost plastic heat-transfer components. Furthermore, the potential to operate with the continuous precipitation of reverse-soluble salts up to TDS levels of 200,000 ppm would provide operators of inland brackish-water RO plants a non-membrane means of reducing concentrate volume by a factor of 10 to 20.

Future Work

As previously noted, AILR will be entering its Brine Zero technology in the Solar Desalination Competition (SDC) sponsored by the Department of Energy. We will first modify the design of a 70-plate stack so that it can operate for long-duration without buckling. The new design will then be thermally proven in a test of a single 70-plate stack that processes a synthetic brine at design conditions (i.e., 95 C peak temperature) for a minimum of one week at our New Jersey lab. Following a successful demonstration of the new design, we will submit our proposal for a field demonstration to the SDC.

In parallel with our entry to the SDC, we are now seeking partners who might have a commercial interest in our technology. We expect discussions with potential partners will help us focus on applications where our technology can be most competitive.

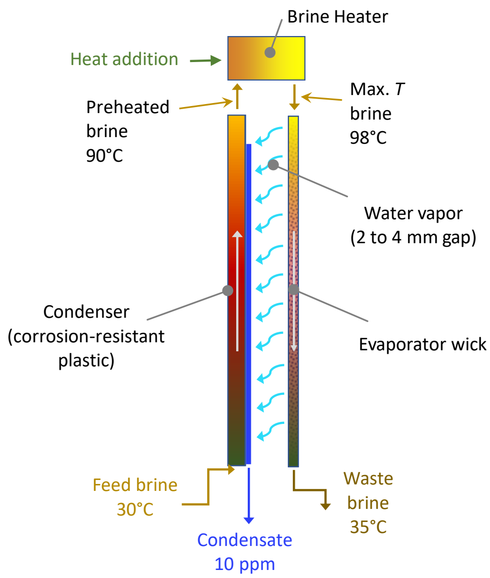

Figure 1 – One-Gap Representation of DGD Process

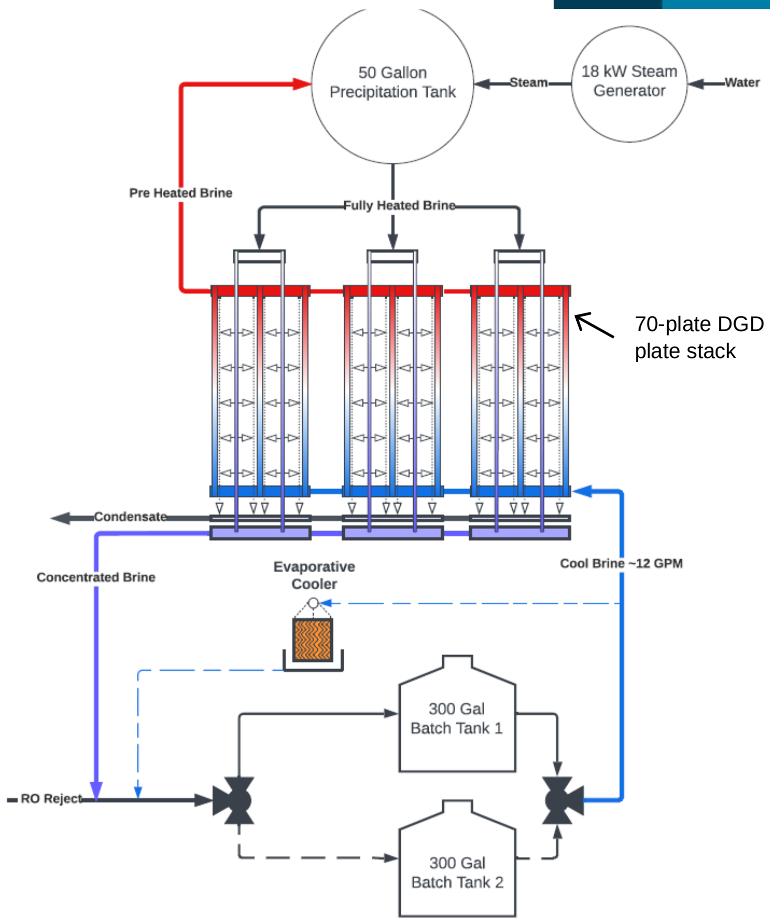

Figure 2 – Schematic Layout of Brine Zero Yuma Installation

Figure 3 – Three Uninsulated, 70-plate Modules for Brine Zero

Figure 4 – Failure Mode for Plate Assemblies

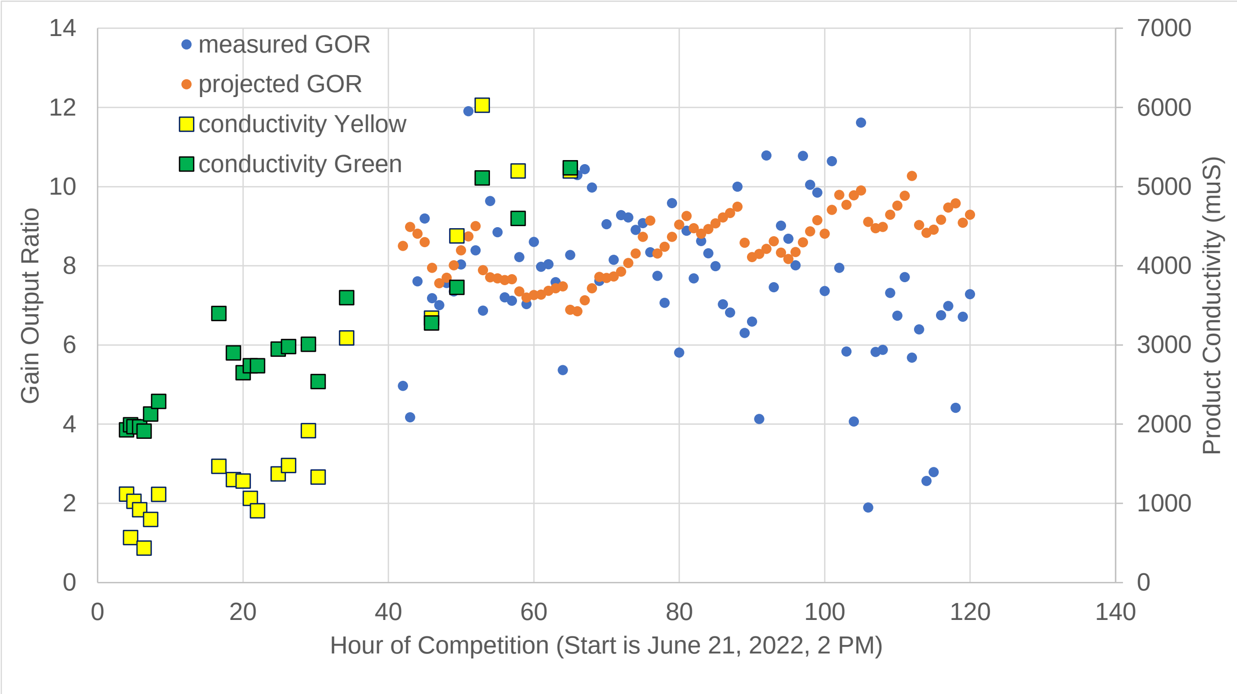

Figure 5 – Early Performance of Yellow and Green Stacks

Figure 6 – Eight Panel Array of AILR Steam-Generating Solar Collectors

Table 1 – Seven-Stage Operation of 100,000 gpd Brine Concentrator

Stage		1	2	3	4	5	6	7	Total
Brine Feed	gpm	69.4	28.7	16.0	8.9	5.7	4.1	3.4	
C Input	ppm	8,000	19,327	34,729	62,289	98,208	135,064	162,235	
C Output	ppm	19,327	34,729	62,289	98,208	135,064	162,235	193,306	
BPE	degC	0.30	0.65	1.30	2.20	3.20	4.00	5.00	
condensate	gpm	40.7	12.7	7.1	3.3	1.5	0.7	0.6	
Stage GOR		18.94	17.28	14.46	11.14	8.24	6.52	5.12	0.00
Q Thermal	kW-th	314.7	108.0	71.7	42.9	27.4	15.5	15.7	
Brine Recirculation	gpm	414.9	135.3	81.0	41.6	22.3	11.0	10.1	
nAssemblies		41	13	8	4	2	1	1	70
								recovery	95.9%

BPE - Boiling Point Elevation of Brine