SUMMARY TEST REPORT

SYLVAN SOURCE CORE^{TM} WASTEWATER PURIFICATION WITH CLEAN-IN-PLACE

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DOCUMENT PURPOSE

This report summarizes the results of field testing conducted at the Southern California Edison (SCE) Mountainview Generating Station located in Redlands, CA. The document "SYLVAN SOURCE CORE™ WASTEWATER PURIFICATION WITH CLEAN-IN-PLACE FIELD TEST PLAN" describes the field test objectives and detailed testing procedure.

EXECUTIVE SUMMARY

Between June 16 and July 6, 2018 a field test of the Sylvan Source (SSI) Core was conducted at the Southern California Edison (SCE) Mountainview Generating Station located in Redlands, CA. The SSI Core is a multi-stage thermal water purification system that incorporates; 1) proprietary heat transfer technology that enables a lower stage-wise temperature differential (ΔT) than conventional multiple-effect (MED) thermal systems, and 2) proprietary Clean-In-Place (CIP) technology that enables purification of high hardness water without pre-treatment. The field test objectives and corresponding results were:

1. To demonstrate the feasibility of SSI's clean-in-place procedure in a field setting.

   The SSI Core mobile unit treated blowdown (CTB) stream directly from the power plant cooling tower for 300 hours (12.5 days) without pre-treatment. A total of 12 CIP cleaning cycles were performed during the 300-hour test *with the Core remaining in operation*.

   The CTB feed stream had total hardness of 341 ppm $CaCO_3$, 41 ppm silica and 1200 ppm sulfate. Chemical analysis showed that scale was formed during operation of the SSI Core. This level of scale buildup would be unacceptable for conventional RO and some types of thermal systems such as MED or MSF. The SSI Core with CIP demonstrated operation for 300 hours while maintaining the output of purified water.

2. To evaluate the performance of the SSI Core.

   The nominal SSI Core mobile unit capacity with 6-stage configuration is 250 gpd (0.17 gpm). During the 300-hour test, the SSI Core operated in 5-stage configuration (while one stage was being cleaned) at an 86% product water recovery rate on a volumetric basis requiring only pH adjustment to the CTB stream. In contrast, the CTB stream is currently going through multiple steps at SCE's plant today (precipitation clarifier, gravity filter, ion-exchange polishing softener, decarbonator, and reverse osmosis) requiring significant amounts of chemicals and maintenance operations.

   The SSI Core product water was of high purity: specific conductance was 2.9 microS/cm (which corresponds to a calculated TDS of 1.9 ppm) and all analyzed metals were below detection limits.

3. To evaluate the thermal performance of the SSI Core and obtain data that can be used to model the thermal efficiency of larger-scale systems.

   A comparison of the ΔT data between stages that were periodically cleaned and stages that were not cleaned at all was undertaken. While ΔT in stages with CIP were kept within an expected operating range, ΔT in stages without CIP increased steadily during the whole run. This difference confirmed that CIP was successful in eliminating scale from heat transfer surfaces.

   In addition, ΔT benchmark tests were run prior to the 300 hour CTB testing. In those benchmarks, a 5-stage SSI Core configuration demonstrated a 5.5 °F (3.1 °C) ΔT. These values are consistent with thermal performance values used in modeling of larger SSI systems.

BACKGROUND

Water sources in the US, and in particular in the West, are increasingly being stressed due to a combination of population growth and drought conditions. As a result, desalination is becoming increasingly attractive, not only from seawater but also to reclaim water from municipal treatment plants, agricultural areas, industrial waste streams or produced water from oil and gas industry. Reverse osmosis (RO) is the most widespread technology for applications such as municipal water reclamation or sweater desalination. However, RO has several limitations:

- It can only treat waters with relatively low total dissolved solids (TDS), which limits its range of applicability with many industrial and oil & gas water sources.
- It can only concentrate the feed (by separating clean water) to a limited TDS value (for example to 70,000 ppm for seawater desalination), which leaves a large fraction of water in the form of a brine stream that needs to be either disposed of as waste or further treated using thermal processes (i.e. evaporators and crystallizers).
- It requires electrical power, which makes it not suitable for remote applications without access to transmission lines.
- It requires costly pre-treatment (i.e. water softening and highly efficient filtration) to reduce the rate of scale formation that can foul membranes. Highly efficient filtration is also required to prevent fouling of membrane surfaces from particulate matter.

The alternatives to RO are thermal-based processes such as multi-stage flash distillation (MSF) or multiple-effect distillation (MED). While these processes can treat waters with higher TDS and do not require as much electrical power, they have their own set of limitations:

- Current technologies are energy intensive (energy input is steam).
- In seawater desalination applications, current technologies need to operate at low temperature, which means that the system is kept under vacuum, to avoid formation of scale. Operation under vacuum reduces thermal efficiency, increases capital expenses, increases operating costs and increases maintenance costs.
- In wastewater treatment applications, costly pre-treatment (i.e. water softening) is often needed to avoid formation of scale on the heat transfer surfaces.

It is therefore clear that, in order to take advantage of thermal desalination systems, new technologies are needed that overcome present limitations.

SSI has developed the SSI Core, a multi-stage thermal water purification system. The Core has multiple stages in series, each producing steam that is condensed in the downstream stage, so the energy supplied to the first stage is re-used multiple times. Due to the special design of the Core stages, the heat transfer from condenser to boiler can be done using a lower temperature difference (ΔT) than conventional multiple-effect distillation (MED) systems of comparable flows. In numerous independent benchmarks[1], SSI has consistently been in the range of 50% or lower in CapEx and 50% or lower in OpEx compared to conventional competitive systems <u>without requiring any waste heat</u>. The SSI Core OpEx numbers are even more competitive if waste heat is utilized.

[1] Available upon request from Sylvan Source.

SSI recently developed a Clean in Place (CIP) process that enables water purification of scale-containing wastewaters (i.e. waters with high hardness, high sulfate concentration and high silica concentration) without the need of costly pre-treatment unit operations. The CIP process starts with a conditioning step to deposit a very thin layer with negligible thermal resistance. Afterwards, the system can operate treating wastewater normally, with the advantage that scale-forming compounds do not need to be removed in expensive pre-treatment steps. After a certain amount of scale is formed on the heat transfer surfaces, the CIP chemical step is executed to dissolve the conditioning layer and separate scale fragments from the heat transfer surfaces. The CIP can be done one stage at a time, while the rest of the system is in operation, so the overall wastewater treatment operation is not interrupted.

PILOT TEST SITE AND EQUIPMENT

This report summarizes results of a pilot test demonstration of the CIP process. The test was done with SSI's mobile unit. The SSI mobile unit is a 30 ft trailer that contains a 6-stage system capable of treating 250 gal/day of feedwater. The steam to drive the mobile unit is generated in the trailer by an 18 kW boiler. Each stage of the mobile unit is instrumented with temperature probes, pressure sensors, level indicators and flowmeters at the inlet and outlet. Data is continuously recorded. The valves and pumps of the mobile unit are controlled by a computer and can be remotely operated by authorized users. The unit has multiple sampling ports.

The test was conducted at Southern California Edison's Mountainview Generation Station in Redlands, CA. This is a 1,050-megawatt gas-fired power plant that has an existing wastewater treatment plant schematically depicted in Figure 1. The cooling tower blowdown water is first treated in a clarifier where a significant amount of chemicals is needed (ferric chloride for flocculation, sodium hydroxide for pH adjustment, soda ash to supplement carbonate concentration). At the outlet of the clarifier, more chemicals are added before carrying out gravity filtration and water softening using weak acid cation resins (which require chemicals for regeneration every 1-2 days). After another chemical addition to lower pH, the water passes through a decarbonator tower to reduce CO2 levels. Downstream of the decarbonator tower chemicals are added to increase pH, a scale inhibitor is added to prevent membrane fouling and then the water is brought into the reverse osmosis units where 70-75% of the water is recovered, and the rest is discarded as brine.

The SSI Core with CIP is a simpler system (see Figure 2). The cooling tower blowdown only needs a minor pH adjustment (to a value >8.5) before being supplied to the Core, where more than 85% of the water can be recovered. The Core can tolerate formation of scale on heat transfer surfaces, which is an event that would trigger shutdown and cleaning by operators in current evaporators or RO systems. In SSI's system, a stage can be isolated from the rest of the system and a targeted chemical cleaning executed on a regular basis, in a process that can be fully automated.

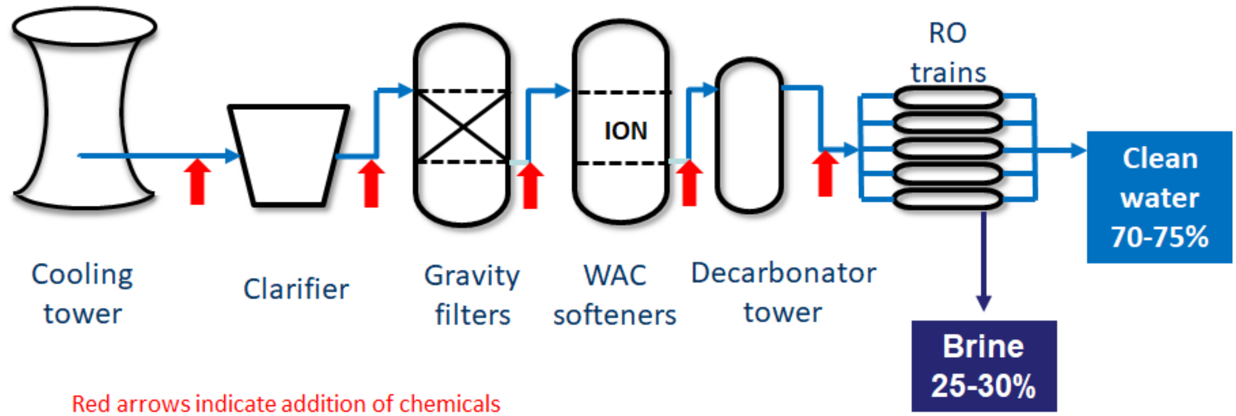

Figure 1 Simplified representation of the current wastewater treatment process at the test site.

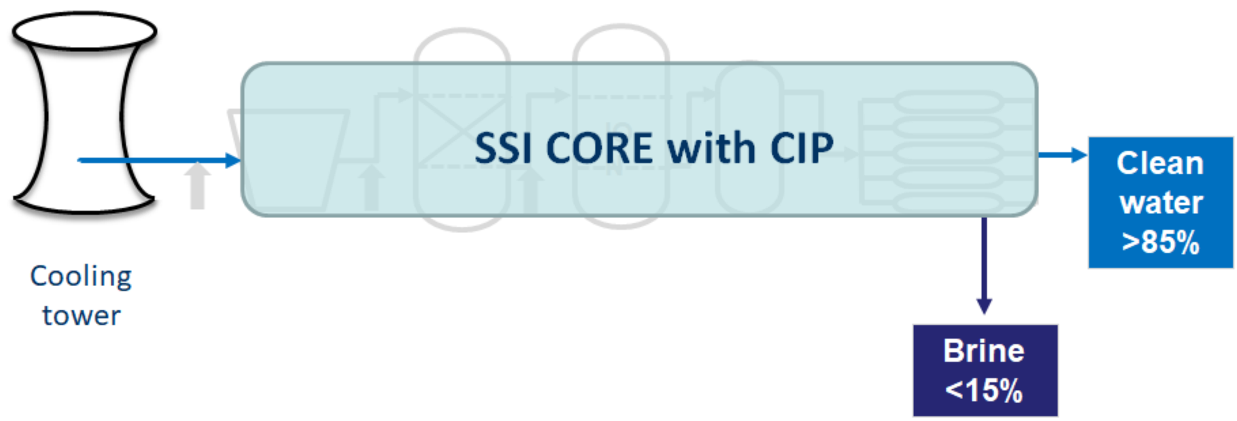

Figure 2 Schematic representation of the SSI Core with CIP process used in this test (recovery is dependent on feedwater chemistry).

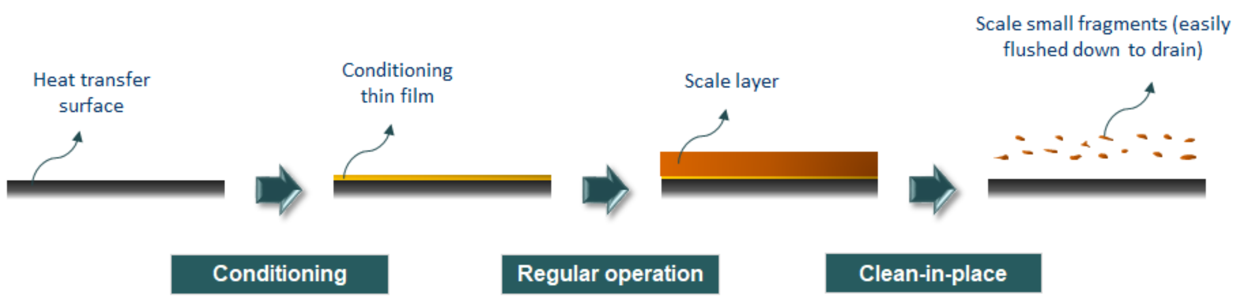

Figure 3 Schematic representation of the SSI CIP process.

RESULTS AND DISCUSSION

Prior to the long run with cooling tower blowdown, two ΔT benchmark tests were run. In those benchmarks, a 5-stage SSI Core configuration demonstrated a 5.5 °F (3.1 °C) ΔT at feed rate of 0.10 gpm, and a 6-stage SSI Core configuration demonstrated a 6.2 °F (3.4 °C) at feed rate of 0.15 gpm. These tests provided a baseline for the system when all heat transfer surfaces were clean.

A 300-hour test was done using SSI's 6-stage mobile unit with 5-stages in operation and one stage out of service for cleaning. Each stage has a condenser and a boiler. The unit has two possible stage input vessels (Stage 1A and Stage 1B) that can receive steam from a steam generator in their condenser. These are the hottest stages and more prone to mineral fouling. The mobile unit has four regular stages (Stage 2 to Stage 5). After a recent upgrade from previous pilot tests, stages 1A, 1B and 2 can be brought out of service ("valved-out") for cleaning while the rest of the system is operating normally. Stages 3, 4 and 5 did not have the capability of being valved-out and cleaned. At several points during the 300-hour test, a clean stage was brought back in service and one of the operating stages was taken out of service for cleaning. This was done without interruption of the test, as is expected to happen in full size units.

The feed water to the system was untreated cooling tower blowdown (it was taken before it enters the multiple pre-treatment steps required for reverse osmosis). The pH of the feed was adjusted in batch mode using two totes with an approximate capacity of 250 gal. While a pH adjustment to >8.5 would be sufficient for Core operation, it was decided to adjust the pH to >10 to ensure that operation took place inside the defined window of operation. In future systems with better pH control, pH will be kept at lower values to minimize use of chemicals. The average TDS of the feed during the run was approximately 3100 ppm.

The system operates in counterflow mode (reverse flow), which means that feedwater and product (purified) water move in counterflow through the system. The adjusted feed water ("feed to SSI Core" in Table 1 below) was pumped into the system through a heat exchanger in counterflow with the product. This was done to recover heat from the clean water exiting the system. Next, the feed was introduced to a pre-heater, a stage that recovers heat of vaporization of condensing water from steam produced in the last boiling stage. After that, feedwater passed through a degasser that can be used to strip volatile species (like VOCs, volatile organic compounds); due to the lack of VOCs in the cooling tower blowdown water, steam was not supplied to this unit. Non-condensable gases dissolved in the feed (mainly nitrogen and oxygen) were removed from the system by continuously venting the last condenser in the system. After exiting the degasser, the feedwater was pumped through all boilers starting at Stage 5 (lowest temperature) and exiting at one of the heat input vessels (Stage 1A or 1B). Clean water produced in the condensers was flowing from the condenser of Stage 1B to all other condensers (2 to 5) and the combined flow was collected after the heat recovery heat exchanger.

The system was operated at 86% recovery rate on a volumetric basis. This was chosen to match the operating conditions of the EPRI-sponsored test in late 2016, but recovery rates higher than 95% are possible. The chosen recovery rate was achieved by adjusting the brine flow by means of a needle valve to match 14% of the total feed flow into the system (which was determined as the sum of volumetric flows of brine and purified water, also referred as product). The average TDS of the brine during the test was approximately 21,000 ppm.

The average temperature of the steam stream from the steam generator was 254 °F in the first 125 hours of test and then it was increased to 274°F over a transition period of 30 hours; this temperature was maintained until the end of the test. The need for higher temperature was to balance the increase in temperature drop caused by scale formation in those stages that did not have cleaning capability (Stages 3, 4 and 5), as discussed below.

Table 1 presents hardness and silica measurements done on-site by SCE staff (averages of 10 measurements taken over 5 days during the run). The top row shows values for the feed stream going into the Core (after pH adjustment). The second row presents values for the brine at approximately 86.4 % recovery rate (concentration factor feed-to-brine = 7.4). The third row includes expected values in the brine if there was no scale crystallization inside the Core. In the last row the percentage of hardness/silica that crystallized in the Core as scale is presented. As seen in the data, the total hardness in the feed to the Core was 341 ppm $CaCO_3$ and the silica content was 41 ppm SiO_2. As shown in Table 1, a large fraction of the hardness (almost 2/3) and most of the silica stayed inside the system as solids, most likely as calcium sulfate and carbonate, magnesium/calcium silicates and amorphous silica. Overall, the data presented in Table 1 illustrates that operating under these conditions resulted in a difficult challenge that was ideal to validate the feasibility of SSI's CIP process.

Table 1 Hardness and silica measurements, maximum possible values and percentage staying inside the Core as solids.

	Ca Hard	**Total Hard**	**SiO_2**
	ppm CaCO3	ppm CaCO3	ppm
Feed to SSI Core	300	341	41
Measured in brine	813	861	16
Max. possible in brine	2209	2511	302
% as scale inside Core	63.2 %	65.7 %	94.7 %

Figure 4 shows flows of influent cooling tower blowdown feed water and effluent purified water and concentrated brine starting after reaching steady state (4 hours after operation start-up). An interesting pattern can be seen in the first 125 hours of the test, in which the heat input conditions were kept constant (same temperature of the steam generator supplying steam to the Core) and the amount of scale in the stages without cleaning capability was still low. The formation of scale in all stages resulted in a decrease in the system output over time, from a starting output value slightly below 0.12 gal/min of purified water to an output around 0.09 gal/min of purified water after two days of operation.

Between elapsed time 48 hours to 125 hours, by periodically cleaning stages the purified water output was recovered and stayed in the range 0.10-0.12 gal/min. During the period marked as "steam input pressure adjustment" in the plot, the increase in product output is not significant because the pressure of the steam generator was being adjusted. After this point, the effect of scale formation on Stages 3, 4 and 5 (stages without CIP capability) can be seen in the slightly lower overall output. Nevertheless, from 155 hours to 225 hours there were several recovery periods that prevented a steady output reduction, as it would be expected in a system without any CIP capability.

From 225 hours to 300 hours the system was left to operate without carrying out any CIP in any of the stages, in a planned "stress test" designed to test the operational limits of the CIP. After that period, the system was stopped for several hours to carry out simultaneous CIP of stages 1B and 2, and then briefly restarted to assess the performance recovery. During this validation period (8 hours after reaching steady state), the feed was switched to a solution of sodium sulfate with approximately the same conductivity as the cooling tower blowdown feed. The reason to choose a sulfate salt was to reduce the chemical transfer of scaling compounds that takes place from colder to hotter stages due to thermodynamic driving force, which over time can mask the results in the validation test.

The data presented in Figure 4 shows that during the stress test (from 225 hours to 300 hours) the purified water output steadily decreased from around 0.11 gal/min to a value close to 0.085 gal/min. After CIP of 2 stages, during the validation period the purified product output was recovered to a value higher than 0.10 gal/min. In summary, the results show that under some conditions it is possible to maintain the system output by periodically carrying out CIP of stages, even when a stage has been in operation for multiple days.

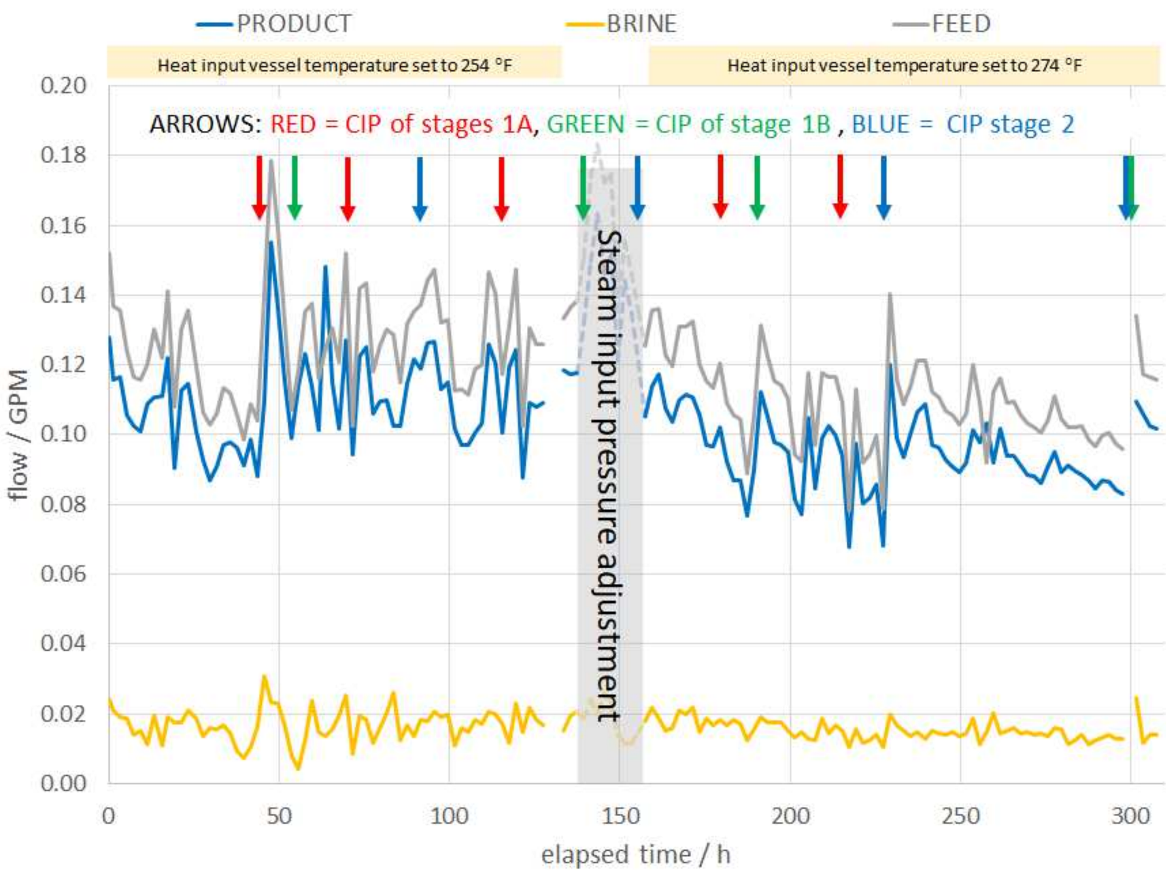

Figure 4 Flows of influent cooling tower blowdown (FEED), effluent purified water (PRODUCT), and effluent brine (BRINE).

Another metric of success of the CIP procedure can be seen in the temperature gradient between condenser and boiler in one stage (referred to as delta T or ΔT). For a given amount of heat transferred through the same area, an increase in ΔT is an indicator that scale is being deposited and therefore thermal resistance is increasing. This is analogous to the increase of electrical resistance, which will require a higher voltage (ΔV) in order to have the same amount of current circulating. As seen in Figure 4, due to the periodic CIP of stages the output flows were kept within a range during the full 300 hours of operation. Figure 5 presents ΔT for three of the regular (not heat input) stages in the system: Stage 2, Stage 3 and Stage 4. These are stages that always performed under the same role and are shielded from oscillations of the steam generator on one end, and the variations in the feedwater temperature on the other, so data trends are more clearly observed. As seen in the plot, at the beginning of the test all three stages had ΔT in the range 6-8 °F. As the test progressed and scale was deposited on heat transfer surfaces, the thermal resistance increased and correspondingly higher ΔT were needed to maintain the same product output (hence the adjustment in the heat input temperature described above). The ΔT in Stages 3 and 4 (no CIP) climbed steadily for the 300 hours of test until a value around 16 °F. By contrast, ΔT at Stage 2 dropped every time that the stage was cleaned using SSI's CIP process and it could be maintained inside the initial 6-8 °F range for the whole duration of the test.

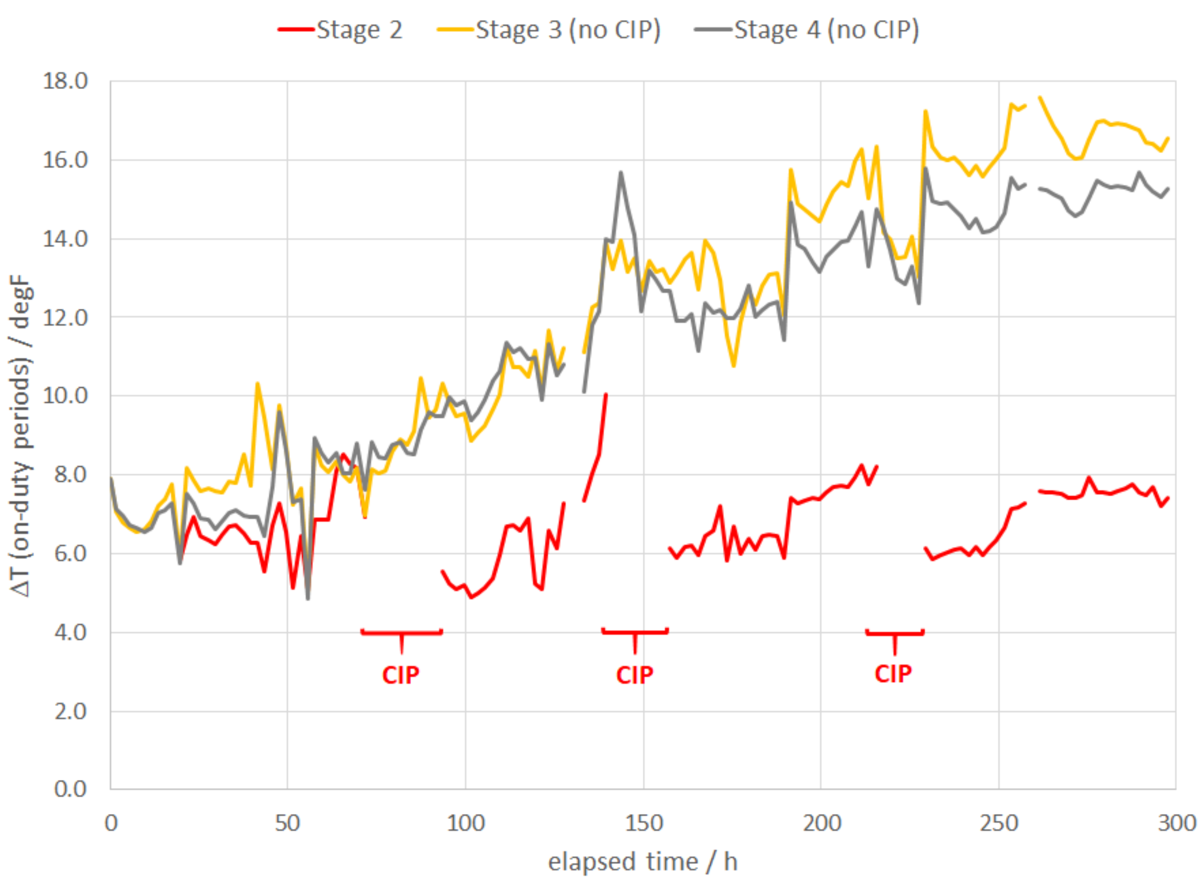

Figure 5 Temperature difference between condenser and boiler in the same stage for three of the regular stages in the Core: Stage 2 (subject to periodic CIP) and Stages 3 and 4 (without CIP capability).

In addition to validation of the CIP process in the field, a second goal of the pilot test was to demonstrate good quality of purified water produced by the SSI Core. As a result, and as shown in Table 2 below, in this test the levels of metals were below detection limit and the specific conductance of the purified water was 2.9 microS/cm (which corresponds to a calculated TDS of 1.9 ppm).

Finally, it is worth noting that, although the mobile SSI Core unit was not originally designed to handle solids inside the unit, it could be operated for 300 hours under conditions in which scale was formed primarily on heat transfer surfaces, but also on other hot surfaces. Moreover, the CIP process generates a significant amount of solids that are drained out. Except for a 2-hour interruption to clear an obstructed drain, the test proceeded normally. On a pilot unit testing a novel process this is a very small amount of down time. The multi-stage nature of the system and the periodic “valving-out” of stages allowed preventive maintenance that gave robustness to the system and gave the SSI team the opportunity to inspect components periodically which provided valuable information for designing future systems.

Table 2 Purified water analytical data (composite of 6 samples taken during 24 hours).

Parameter	Value	Units	Method
Spec. conductance	2.9	microS/cm	SM 2510 B
Al	<100	ug/L	EPA 200.7
Ba	<20	ug/L	EPA 200.8
Ba	<100	ug/L	EPA 200.7
Cr tot	<20	ug/L	EPA 200.8
Cu	<10	ug/L	EPA 200.8
Fe	<50	ug/L	EPA 200.7
Hg	<0.20	ug/L	EPA 200.8 ATP
Ni	<20	ug/L	EPA 200.8
SiO2 tot	<5.0	ug/L	EPA 200.7
Sr	<100	ug/L	EPA 200.7
Ti	<10	ug/L	EPA 200.7
Zn	<10	ug/L	EPA 200.8
TOC	0.88	mg/L	SM 5310B
NH3 nitrogen	0.21	mg/L	SM4500NH3HG
Total P as PO4	<0.15	mg/L	PO4 calc
Total P	<0.05	mg/L	SM 4500P B E
Ca	<1	mg/L	EPA 200.7
Mg	<1	mg/L	EPA 200.7
Na	<1	mg/L	EPA 200.7
K	<1	mg/L	EPA 200.7
Total Alkalinity	<5	mgCaCO3/L	SM 2320B
OH	<5	mgCaCO3/L	SM 2320B
CO3	<5	mgCaCO3/L	SM 2320B
HCO3	<5	mgCaCO3/L	SM 2320B
Cl	<1	mg/L	EPA 300.0
SO4	<0.5	mg/L	EPA300.0

CONCLUDING REMARKS

The main findings in this pilot test were:

- The CIP process allowed operation for 300 hours with untreated cooling tower blowdown water (total hardness 341 ppm $CaCO_3$, 41 ppm silica and 1200 ppm sulfate) while maintaining the output of purified water production.
- Stages that were periodically cleaned using SSI's CIP were able to operate during the full test without a continuous increase in the temperature difference (ΔT) between condenser and boiler.
- Stages that were not cleaned using SSI's CIP required a continuously higher ΔT to maintain system output.
- Distillate with high purity was produced: specific conductance was 2.9 microS/cm (corresponding to a calculated TDS of 1.9 ppm) and all analyzed metals were below detection limits.
- While a new process was tested in a system originally designed to operate without solids, the pilot test proceeded on schedule with only one short interruption to clear an obstructed drain.