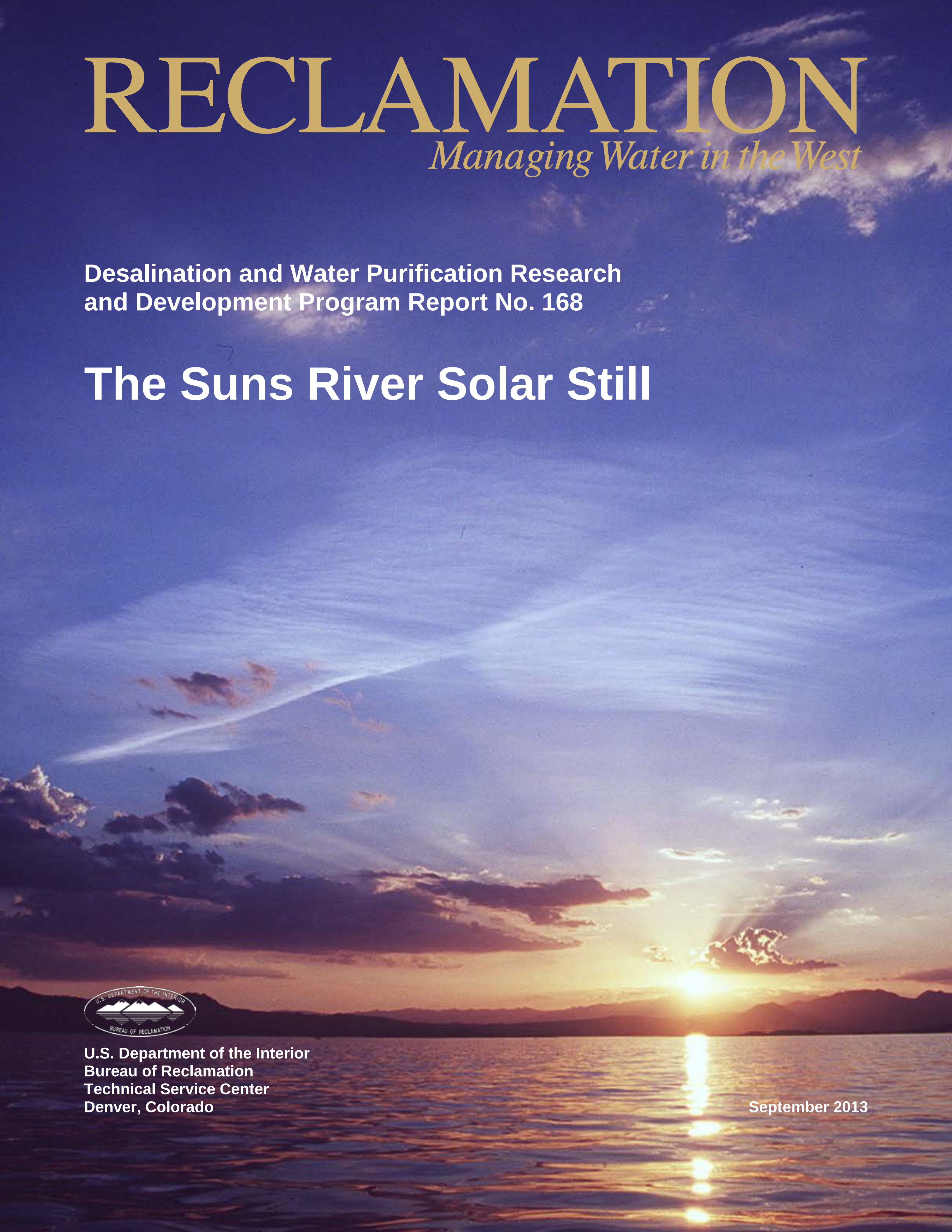

RECLAMATION

Managing Water in the West

Desalination and Water Purification Research and Development Program Report No. 168

The Suns River Solar Still

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

September 2013

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14. ABSTRACT The Sun's River Solar still was tested at the Brackish Groundwater National Desalination Research Facility (BGNDRF). The still produces distillate during both daytime and night time operations and has the ability, during the night cycle, to create the next day's cooling water. This still was tailored for inland desalination based on a previously patented solar still (US Patent 8,088,257, Australian Patent 2008317021, KII, Inc.). Test results affirmed that the solar still has a capacity sufficient to meet residential needs.							
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Prepared for the Bureau of Reclamation Under Agreement No. R11AC81450

by

Hillery Kemp, KII/Suns River

U.S. Department of the Interior
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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

The views, analysis, recommendations, and conclusions in this report are those of the authors and do not represent official or unofficial policies or opinions of the United States Government, and the United States takes no position with regard to any findings, conclusions, or recommendations made. As such, mention of trade names or commercial products does not constitute their endorsement by the United States Government.

Acknowledgments

The author thanks the Bureau of Reclamation's Desalination and Water Purification Research and Development Program and the Brackish Groundwater National Desalination Research Facility.

Acronyms and Abbreviations

BCE	Before Common Era (BCE).
BGNDRF	Brackish Groundwater National Desalination Research Facility
DWPR	Desalination and Water Purification Research (DWPR)
°F	degree Fahrenheit
IR	infrared
kWh/liter	kilowatt hours per liter
LMH	liters per square meter per day
MDT	Mountain Daylight Time
PEX	cross-linked polyethylene
ppm	parts per million
Reclamation	Bureau of Reclamation
RO	reverse osmosis
TDS	Total Dissolved Solids

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Executive Summary

Mankind has pursued an effective and simple way to use direct solar power to economically produce drinking water from salt water for centuries. The Suns River Still tested an innovative method to desalinate water using solar power at the Bureau of Reclamation (Reclamation)’s Brackish Groundwater National Desalination Research Facility (BGNDRF) located in Alamogordo, New, Mexico, USA. The inland version of this still uses a double effect to increase distillate productivity during both daytime and night time operations. The still uses the night cycle to create the next day's cooling water (US Patent 8,088,257, Australian Patent 2008317021, KII, Inc.). Tests at BGNDRF affirmed that the solar still has a capacity sufficient to meet residential needs.

The well water feedstock contained 1,285 parts per million (ppm) Total Dissolved Solids (TDS) and the product distillate contained approximately 20 ppm TDS. Process interference from aerosol gypsum particles originating from the White Sands National Monument required design adaptations. The high summer time productivity of 11.6 liters per square meter per day (liters/m^2/day) is many times the nominal rate of the classic solar still. In winter conditions, the test unit produced 8.4 liters/m^2/day.

1. Introduction

1.1. History of Solar Stills

Aristotle first wrote about using direct sunlight to distill pure water from salt water in 350 Before Common Era (BCE). Archeological evidence indicates that the first people to occupy the desert which is now Iraq around 5000 BCE placed bowls of salt water in stone buildings and collected condensate off the interior walls. Aristotle indicated that the simple process worked but with very poor yield. People have been trying solar stills ever since.

A solar still was installed in the 1870s at Salinas, Chile. It was basically 64 rectangular pools with a greenhouse built over them. Salt water in the pools evaporated into the greenhouse interiors, condensed on the roof and walls and the condensation was captured in gutters placed at the interior base of the walls. The productivity was limited to around 3 to 4 liters per square meter of floor space and, after about 40 years, the site was judged not worth the effort and shut down.

1.2. Classic Solar Stills

The classic solar still involves six major steps in an essentially series process to get from ambient solar energy to distilled water:

1. Solar energy passes through the translucent roof of the greenhouse.
2. Solar energy strikes the black floor of the pool, converting all energy frequency ranges to infrared (IR).
3. The water film next to the floor is heated by IR.
4. The warmer water is lighter, it migrates to the pool surface and some water vaporizes.
5. Water vapor in the hot greenhouse interior is condensed by the lower temperature air outside.
6. Water droplets flow down the sloping roof and are collected in gutters at the walls.

Several parts of this separation mechanism are constrained by heat and mass transfer inefficiencies. The overall process can only produce at the rate of its slowest step.

Fiorenza et al. 2006 examined the classic solar still and compared it to other options and reported that the:

- Classic solar still was limited to a productivity of "around 4 liters/m^2/day."
- Efficiency of solar energy use at 1.5 kWh/liter
- Cost of water from the classic solar still for units sized for small municipal users would be around $10/1,000 gallons.

Several other sources have reported capacity of 3 liters/m^2/day or less which would increase the energy/liter and the unit water cost.

Table 1 shows reported productivity for Classic Solar Stills.

Table 1. Comparable Stills.

Reported Productivity	URL Location	Comments
2.5 liter/m^2	https://www.engineeringforchange.org/solution/library/view/detail/Water/S00026	International Engineering Forum
3.1 liter/m^2	http://econpapers.repec.org/article/eeerensus/v_3a11_3ay_3a2007_3ai_3a3_3ap_3a543-549.htm	International Economics Forum Swedish Business School
4.5* liter/m^2	http://pdf.usaid.gov/pdf_docs/PNABC961.pdf 64 stills, 4,459 m^2, Salinas, Chile, 1878	US AID Report *Based on design of 20,000 liter/day
2.3 liter/m^2 2.2 kWh/liter	http://www.solucionespracticas.org.pe/fichastecnicas/pdf/solar_distillation.pdf	Technology Development Center Great Britain

* The only site reported to be above 4 liters/ m^2 productivity for the Classic Still is based on its design rate of 20,000 liters/day. Actual operating performance data is not available.

1.3. KII. Inc./Suns River Innovations

The KII/Suns River process makes several innovations on these steps de-bottlenecking the key restrictions and adding a second effect:

- At Step 1, Suns River uses a double layer translucent roof eliminating condensation on the interior and increasing solar insulation to the still.

- At Step 2 the Suns River design incorporates a black surface, tilted toward the sun and with a thin, falling film of salt water for evaporation.

- At Steps 5 & 6 the Suns River design includes an interior, water cooled condenser to produce distillate.

- Finally, the Suns River 2nd Effect re-uses the solar energy captured in the condenser cooling water during the day to harvest additional distillate using the cold air as a heat sink at night. This step also cools the water for use as condenser cooling water the next day.

The combined impact of these changes to the process has the potential to raise the distillate yield by a factor of 4 to 5 times that of the classic solar still. The system has a low pressure water pump that will also require small amounts of energy and slightly increase the complexity of the process. The Suns River still capital cost is about 50 percent more than the classic still per unit area, and water costs are projected to be in the range of $4 - $7/1,000 gallons.

2. Equipment and Methods

The Suns River process was developed using “semi-works” pilot plant-sized units operated in northwest Louisiana. Preliminary testing, performed before the DWPR award, in Louisiana indicated performance far better than the classic solar still. The author believed that adding a second effect could increase productivity in a desert climate like that in New Mexico.

With the Desalination and Water Purification Research (DWPR) Program grant from Reclamation, we began the engineering design in November, 2012 for the solar still installation at BGNDRF. This phase also included specification and acquisition of equipment and supplies not readily available in the local Alamogordo market.

Construction of the structure began on February 6, 2012. The structure, assembly, and piping were complete at the end of March. Tanks and pumps were also set in March. Sub-components of the cross-linked polyethylene (PEX) tubing coils and frames holding the clear plastic film roof were assembled at an offsite location and brought to the site. Strong wind gusts compromised the joints between frames holding the translucent film roof, requiring a redesign of those joints and erection of a wind break to protect the structure. The still was fully assembled and ready for operation by the end of March 2012.

The First Effect of the Suns River solar still with a 1.4 m^2 footprint is mounted on a frame which allows adjustment of both the angle of inclination and compass facing direction. The still is built with 3-inch thick walls with an estimated “R” value of 20 on all sides, except the glass solar receiver face. The glass solar receiver is constructed with two layers of tempered glass and sized based on commercially available glass panels (Figure 1). The solar receiver and enclosure are built to be airtight. The process includes two key water flow subsystems.

Figure 1. Home-Sized Solar Still at BGNDRF.

In the first water subsystem, hot brine is introduced at the top of a sloped black floor, the solar absorber, creating a falling film of salt water on the black, absorber floor surface exposed to direct sunlight. Hot brine exiting the still at the bottom of the sloped floor is pumped back to the top of the absorber. The solar energy absorbed by the black floor evaporates pure water from the salt water elevating dew point to over 110 °F inside the still (summer). Temperatures inside the still were sustained about 45 °F above outside ambient temperature.

In the second water subsystem of the day cycle, cold water flows inside tubing in a box enclosure mounted at the top of the sloped floor. The condensing tubes consist of loops of ½-inch PEX tubing enclosed in an R-20 insulated enclosure. Cold water is pumped through the PEX, heated by condensation, and then stored in either the insulated lower part of the Second Effect or in insulated tanks.

Product distillate from the First Effect, which condenses on the looped tubing, is collected in an internal tray below the looped tubing and withdrawn from each side of the still.

The Second Effect is a stagnant pool of hot PEX outlet water built with a high-surface, pyramid roof. Principal production from the Second Effect comes in cooling the pooled water during the unattended overnight period although there is some production during daylight operation. Distillate is collected in small gutters at the interior base of each roof panel of the pyramid. The overview flow diagram shown in Figure 2 indicates the flow patterns.

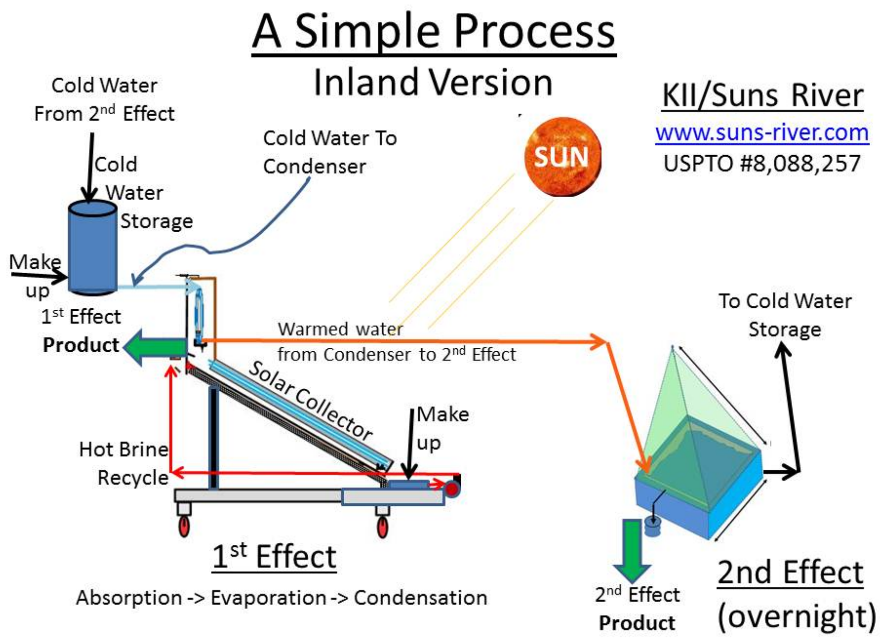

Figure 2. Suns River still overview flow diagram.

3. Results

Initial flow and instrument testing commenced in April. Start up and first distillate production was on April 17. Some effort was required to get the still completely air tight. In tests in April and early May two major process problems emerged. First, the internal temperature of the still ranged from only 21 degrees Fahrenheit (°F) to 24 °F higher than the outside ambient temperature. This was 25 to 30 °F lower than the pilot plant experience in northwest Louisiana. Second, at start-up, a tenacious covering of fine droplets formed on the inside of the clear film roof of the still. Droplets at this location within the pilot unit in Louisiana coalesced into larger drops and ran down the sloped roof to be collected as distillate. But at BGNDRF these droplets formed in the early morning and stayed in place all day.

Other tests from late April to mid-May were short runs evaluating various changes in attempts to increase still productivity. Through these tests, still temperatures were only about 20 °F above outside ambient temperature. Efforts were aimed at clearing the droplet layer in order to increase solar absorption and still performance. In early May, clear film on one of the seven roof panels was coated on the underside with the commercial product Rainex to attempt to establish droplet coalescence. Initially, there was some minor improvement, but that panel soon had the same droplet problem.

It was discovered that vibrating the film at the top of the still would cause the droplets to coalesce and run down the slope, clearing the film as the droplets passed. Several methods of vibrating film were attempted but in all cases the fine droplets re-formed quickly, so the effect on solar transmission was minimal. A trial of spraying distillate on the top underside of one panel did not clear the fogged droplet problem. In mid-May, one of the panels was altered to have two layers of film with an air space between the two. The film on the two-layer panel remained clear of the droplet formation. Also, one panel was changed to a single layer of “No Fog” film from the vendor. To test the impact of the altered panels, a solar radiation profile was run inside the still beneath each panel. The test showed some minor improvement with both the “No Fog” film and the two-layer film but did not account for the large deficiency in solar absorption indicated by low production. The profile indicated that solar radiation readings inside the still were approximately 80% of the ambient radiation measurement.

In further attempts to improve still productivity in late May, we added a frame with an additional 220 feet of ½-inch PEX to the sloped floor. Also electrically-powered 24-inch box fans were placed on the sloped floor to enhance air movement within the still. The fans did not seem to have any measurable impact, but the additional PEX was productive. The run on May 31 still productivity remained well below pilot study rates.

Much of the effort through May was focused on assuring that the still was airtight and vapor loss was eliminated. This was thought, at the time, to be a possible explanation for the low productivity. Later material balances showed that we could account for over 92 percent of the water inventory, so material loss was eliminated as the cause for low productivity.

A major turning point came on June 6 when laboratory results from the May 17th run indicated that while distillate product contained only 14.4 ppm TDS (Total Dissolved Solids), 9.5 ppm was calcium sulfate (gypsum). The normal windy conditions created a regular dusty environment so minor solids contamination of the product was not surprising. But the TDS in the distillate had only small traces of silica, iron, etc. —the make-up of desert dust. Since the simple still process has no way to segregate one component of the dust, the TDS make-up of $^2/_3$ calcium sulfate presented an anomaly.

To investigate this, we changed the product collection from the roof film so that distillate could be collected off each of the seven panels individually instead of the collective total. Analysis of distillate from individual panels indicated that new, retail film showed good droplet coalescence, maintained moderate clarity, had fair productivity, and had a distillate containing only 3 – 5 ppm gypsum. Distillate from film which had been in service from start-up showed gypsum of 20 to 25 ppm, and those panels had the characteristic fogged droplet coating and very low productivity. Further observation over several days showed that the new, retail film developed the same fog droplet problem and gypsum in its distillate product rose to the 15 to 20 ppm level. A sample of Alamogordo rainfall indicated a gypsum level of 65 ppm and only trace amounts of other minerals.

The BGNDRF location, with its prevailing west-southwest wind, is directly downwind of the White Sands National Monument. According to Monument literature, while the heavier gypsum particles settle out to form the famous white dunes, lighter aerosol gypsum particles continue in the wind. At BGNDRF, the solar still absorbed them from the air. Literature research indicated that most minerals act as hygroscopic[1] dust and enhance atmospheric droplet formation as rain or fog. But, unexpectedly, calcium sulfate actually operates as hydrophobic dust in similar circumstances, changing the surface tension of the water and causing fine droplets to form but impeding coalescence.

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[1] Hygroscopic is the ability of a substance to absorb or adsorb moisture/water from its surroundings.

In June, we installed new retail polyethylene film on all 7 panels. Tests conducted on new film showed productivity up to 2.9 liter/m^2/day – continuing well below expected performance. At this best productivity for the 40-foot still the solar energy use was estimated at 2.0 kWh/liter. The new film stayed clear for a short time, but in a matter of days developed the fogged droplet problem. Several methods were tried to clean the gypsum off the inside of the film including: washing with detergent, washing with household ammonia solution, and mechanically cleaning the underside of the film with a high pressure hydro blaster. Nothing had any noticeable impact on the droplet fog.

Also in late June there was one attempt at the night cycle, circulating heated cooling water from the day cycle over the still at night in an attempt to both produce more distillate and cool the water for reuse. With the low solar absorption, the hot water temperature was only 103 °F and the desert night only cooled to 78 °F. The night cycle trial showed very little productivity.

It was decided that further tests were needed to try a range of possible configurations and materials to address the gypsum interference. Testing those bigger changes at the scale of the 40-foot still did not make economic sense. In the first week of July the 40-foot still was secured for a period of no operation and efforts shifted to design and construction of a smaller, more flexible still to permit a wide range of possible configurations to investigate methods to handle the gypsum contamination and low productivity.

The design focused on a still with a 1.4 square meter (m^2) footprint. The 1.4 m^2 still was designed to accommodate a two or three layer translucent roof, changeable floor material/configurations and other adaptations. The equipment was fully insulated to prevent heat loss from the non-translucent parts. The still was designed to allow tracking of the sun in both horizontal and vertical planes. This was necessary since the end effects on such a short still would impair performance if it were in a fixed position.

For the night cycle/second effect, the 1.4 m^2 still was designed for air flow between the two glass panels. Air from a swamp cooler was ducted to two ports at the lower end of the still. Tests circulating heated water on the still floor while passing cold air between the glass panes proved not to accomplish either the desired distillate production or cooling of the circulating water. In another attempt to recover distillate from the heated water, a small packed tower was put under vacuum to effect vacuum flash of the heated cooling water. This, too, was not effective.

Finally, we placed the heated cooling water in an insulated pan with a pyramid cover of thin polyethylene film for second effect processing. The pan and pyramid were designed so that humidity evaporating from the surface of the water would condense on the inside of the film, run down the film, collect in special gutters built into the pan rim and collect in containers set to drain distillate from all four sides. This design, similar to a classic solar still, proved to produce some distillate during daytime storage of the hot water. Importantly, the pyramid design, unattended, produced distillate overnight and cooled the water inventory to within 5 °F of the ambient low temperature. Water cooling is critical for the inland version of the process.

The 1.4 m^2 still was operated for several runs in late August and early September. The inner glass pane showed some minor fogging at start-up but quickly cleared. With still internal temperature ranging from 40 – 50 °F above ambient production matched that observed in earlier KII/Suns River pilot testing in Louisiana.

In its initial configuration with the pyramid Second Effect, the 24-hour production from the 1.4 m^2 still reached 16.2 liters or 11.6 liters/m^2. This translated to solar energy use of 0.5 kWh/liter. The inner glass pane showed some minor fogging at start-up but quickly cleared. The still internal temperature ranged from 40 to 50 °F above ambient. PEX water was heated to 25 to 30 °F above ambient. Processing this hot PEX water in the pyramid Second effect accounted for almost 8 liters of the total production.

First Effect summer operations were begun around 8:00 am Mountain Daylight Time (MDT) and continued until around 6:00 pm MDT. A portable insolation meter was mounted adjacent to the still to measure instant and cumulative solar energy. The still was manually maintained pointed to the sun through the progress of the day. The passive Second Effect operation took place overnight—producing distillate and cooling the water inventory for use as cooling water the next day.

The quality of the distillate product in the August-September runs ranged from 3 to 10 ppm TDS. Aerosol gypsum particles (calcium and sulfate) accounted for 5 to 7 ppm of the 10 ppm total TDS. During the December Proof Run, local instrument measurement of TDS was 21 ppm TDS feeding 1,285 ppm well water. The peak production for the First Effect in August was 9.8 liters and 8.3 liters for the Second Effect. This combines for a total production over 12 liters/ m^2/day. Winter conditions in December yielded production of 11.8 liters total or 8.4 liters/ m^2/day, reflecting the lower winter solar power. Even the lower winter yield is almost triple the classic solar still.

Night operation of the Second Effect cooled the water supply to within 10 °F of the nighttime low temperature. This is critical for the inland version of the process as that provided the cooling water for use in the condenser for the next day cycle. Cool water was about 50 to 60 °F below the daytime still interior temperature.

The results of operation in both winter and summer conditions at BRNDRF showed solar production in the 8.5 to 12 liters/m^2/day range. Analysis of these yields shows that winter production is higher than expected given that the length of the solar day in winter was only 85 percent of that during the summer days.

The still operation was stable and required little or no adjustment to flows during the day cycle. The Second Effect produced some distillate during daylight hours but produced 78 percent of its total production during the unattended night period.

The Proof Run produce distillate with a TDS of 20 ppm from feed water with 1,285 ppm TDS. In this example, a blend of 1.6 liters of feed water with 1 liter of distillate would yield 500 ppm TDS in potable water. That blend would be the potable yield equivalent of 21.8 liters/m^2/day in winter and 31.2 liters/ m^2/day in summer. With the unit sized at 1.4 m^2, an average production of 37 liters per day would be generous for daily cooking and drinking needs for one family.

4. Conclusions and Recommendations

This new design should facilitate a re-assessment of solar distillation as part of the portfolio of desalination technologies. The scalability of the solar distillation process means that distributed populations like those of Africa, the American West, and Australian Outback can get pure, safe water from their local saline or contaminated sources, raising water quality and eliminating the current huge water transport and energy costs. The distillation process delivers water free of both mineral and bacterial contaminates.

Further this solar technology, applied at commercial, municipal, or industrial scale, can compete with reverse osmosis (RO) in many applications. The Suns River still may be able to feed RO reject brine, increasing the RO yield and providing good water to blend with RO product helping meet mineral specifications. Meeting current and future water demands with technology using 99+ percent solar energy can be key to meeting recent zero carbon constraints placed on future desalination capacity by the U.S. and Australia.

In an even larger implication, this solar technology can impact atmospheric carbon dioxide and global warming using the principles of oasis forestry in vast deserts adjacent to seas in Africa, Australia, and the U.S.

5. Recommendations

- Conduct tests of this process at commercial/industrial scale to study scalability.
- Conduct testing to analyze and define the thermodynamics of the Suns River solar still process.
- Facilitate efforts to get this water purification technology in use for communities in need.
- Test the equipment with more concentrated feeds including RO reject brine.

- Conduct testing to define scale removal and upper limits to salt concentration.
- Conduct tests of the seaside version of the process feeding seawater and use of seawater for cooling.

6. References

Fiorenza, G., V.K. Sharma, and G. Braccio. 2006. Techno-Economic Evaluation of a Solar Powered Water Desalination Plant. 2006 NATO conference Solar Desalination for the 21st Century