AMERICAN MADE
SOLAR DESAL PRIZE
U.S. DEPARTMENT OF ENERGY

American-Made Solar Desalination Prize

SUBMISSION FOR TEAMING

Mobile PFAS Treatment Team

Robust treatment of PFAS contaminated wastewaters using solar thermal and low temperature distillation

Integrated Compound Parabolic Concentrator (ICPC), LTDis®

TEAM

Winston Cone Optics (WCO) – Merced, CA

- **Roland Winston**, President and Founder
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- **Bennett Widyolar**, Chief Technology Officer
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Crystal Clearwater Resources (CCR) – Dallas, TX

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PARTNERS AND AMERICAN-MADE NETWORK

- Brackish Groundwater National Desalination Research Facility (BGNDRF)
- Naval Systems Engineering Command Engineering and Expeditionary Warfare Center (EXWC)

https://youtu.be/8xot5cVP-88

Question 1: Team

The **Mobile PFAS Treatment Team** is comprised of

- **Winston Cone Optics** - solar thermal technology developer
- **Crystal Clearwater Resources –** thermal desalination technology developer

This multi-disciplinary team came together as part of the American-Made Solar Desalination Prize and is particularly well-suited for success by combining our low cost solar thermal technologies with a robust desalination technology capable of treating a diverse range of hard-to-treat water sources (e.g. oil & gas produced water and PFAS contaminated wastewater). The team is supported by water management service providers in the oil & gas industry as well as the New Mexico Produced Water Research Consortium. We have identified the Brackish Groundwater National Desalination Research Facility (BGNDRF) as our host site for the pilot project demonstration, and have engaged the U.S. Navy and Oil & Gas industries to understand their PFAS problem and solution space.

Winston Cone Optics (WCO)

Winston Cone Optics (WCO)[1] is based out of Merced, California and is spinning out several solar thermal technologies developed at the University of California, Merced (UCM). The core team includes:

- **Dr. Roland Winston** – President and founder, inventor of nonimaging optics, distinguished professor at UC Merced, director of UC Solar
- **Dr. Lun Jiang** – CEO and expert in vacuum-tube technologies
- **Dr. Bennett Widyolar –** CTO and expert in the design, operation, and analysis of solar thermal systems.

The team has worked together for the past 10 years using expertise in *nonimaging optics* and *vacuum tube technologies* to develop advanced solar thermal technologies which generate low cost solar heat in the 100-200 °C temperature range. Our mission at WCO is to take these technologies out of the lab and deploy them in industry.

The team first developed the external compound parabolic concentrator (XCPC) back in 2009[2] for medium-temperature solar thermal process heating up to 250 °C[3,4]. By 2011 the team installed a 23 kW array and used it to drive a double effect absorption chiller[5]. By 2015 we had developed the next-generation East-West XCPC, installing a 30 kW array at UCM to drive a

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[1] https://winstonconeoptics.com/

[2] Winston, R., 2009. Design and Development of Low-cost. High-temperature, Solar Collectors for Mass Production. California Energy Commission PIER Public Interest Energy Research Program Report: CEC-500-05-021.

[3] Jiang, L., Widyolar, B. and Winston, R., 2015. Characterization of novel mid-temperature CPC solar thermal collectors. Energy Procedia, 70, pp.65-70.

[4] Widyolar, B., Jiang, L., Ferry, J. and Winston, R., 2018. Non-tracking East-West XCPC solar thermal collector for 200 celsius applications. Applied energy, 216, pp.521-533.

[5] Winston, R., Jiang, L. and Widyolar, B., 2014. Performance of a 23KW solar thermal cooling system employing a double effect absorption chiller and thermodynamically efficient non-tracking concentrators. Energy Procedia, 48, pp.1036-1046.

single stage thermal evaporator[6] (providing wastewater volume reduction for several wastewater streams: dairy RO brine, winery post-treatment water, and agricultural water runoff). 10 years later the team has significantly de-risked technology performance, longevity, and modelling capabilities[7].

WCO is now licensing the XCPC technology to Artic Solar in the USA and other entities worldwide. We are installing our first commercial system on a local dairy in Merced, CA to provide solar pre-heating of water for their daily sanitation cycle. This propane-replacing system is expected to have a payback period < 3 years, and will be completed by the summer of 2022.

At the same time, we are exploring pathways for cost reductions and performance enhancement through the development of next-generation collectors. The team recently completed a $1.4 million USD award[8] developing a low cost thermal solar technology specifically for thermal desalination. The collector, which we dubbed the integrated compound parabolic concentrator (ICPC) technology, is a non-tracking, low-cost, and high-efficiency vacuum tube collector designed to operate at temperatures < 150 °C which is modular, scalable, and mobile. As a result of this award, WCO demonstrated > 50% solar-to-thermal efficiencies up to 140 °C from a single module, as well as 43% full-day conversion efficiency of incident global irradiance into heat above 120 °C from a 25 m^2 array[9].

Figure 1 – 10kW ICPC array installed at UCM

WCO is located in California's Central Valley, has close ties with the University of California, Merced, and is actively engaging local food producers, dairies, engineering firms, boiler, evaporator, and desalination companies to develop the business.

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[6] Ferry, J., Widyolar, B., Jiang, L. and Winston, R., 2020. Solar thermal wastewater evaporation for brine management and low pressure steam using the XCPC. Applied Energy, 265, p.114746.
[7] Widyolar, B., Jiang, L., Bhusal, Y., Brinkley, J. and Winston, R., 2021. Solar thermal process heating with the external compound parabolic concentrator (XCPC)-45 m2 experimental array performance, annual generation (kWh/m2-year), and economics. Solar Energy, 230, pp.131-150.
[8] U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office (SETO) Award Number DE-EE0008399, CSP Desalination FOA.
[9] The 43% solar-to-thermal efficiency is the net delivered solar-to-thermal efficiency after including the effects of system warmup and thermal loss in the array.

Crystal Clearwater Resources (CCR)

Crystal Clearwater Resources (CCR)[10] is a veteran-managed company dedicated to providing innovative clean-tech water solutions for efficient purification of water & separation of minerals. CCR focuses on challenging wastewater streams across multiple industries including oil and gas produced water, RO brine streams, industrial wastewater, and solution mining using their leading-edge, patented LTDis® technology.

The patented Low Temperature Distillation technology (LTDis®) is a thermal process that uses specially designed evaporators and condensers for very efficient direct contact heat transfer. The billions of droplets of water in the LTDis® process provide a large surface area for the heat exchange of the evaporation/condensation processes. This eliminates most scaling and fouling risks that plague other thermal evaporator technologies. This technology has the ability to operate at high concentrations (up to and into precipitation of the dissolved solids typically about 330,000 ppm) and achieve high conversion ratios.

Our market focus is on hard-to-treat brine streams which are currently uneconomical to manage using traditional treatment systems. These brine streams are often highly variable in composition and have a very high potential for scaling and fouling. Examples include oil/gas produced water, PFAS containing waters, and brackish reject water from municipal and industrial applications. The desired output water quality standards can be reached in all cases, independent of the feed water composition, producing a distillate of less than 250 ppm total dissolved solids.

Brackish Groundwater National Desalination Research Facility (BGNDRF)

The Brackish Groundwater National Desalination Research Facility (BGNDRF)[11] is a focal point for developing technologies for the desalination of brackish and impaired groundwater found in the inland states. The facility is located in Alamogordo, New Mexico and brings together researchers from Federal government agencies, universities, the private sector, research organizations, and state and local agencies to work collaboratively and in partnership.

The team met with Crystal Bing and Malynda Capelle on January 28, 2022 regarding future installation of the WCO+CCR pilot system for on-site performance testing using PFAS-contaminated well water. BGNDRF has 4 groundwater wells, two of which contain measureable levels of PFAS. The BGNDRF site has 4 outdoor test pads (three 20ft x 60ft pads, and one 60ft x 100ft pad which can host 3 clients). Each pad has a piping manifold for source water piping, and a piping manifold which goes out to the evaporation ponds.

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[10] https://www.ccrh2o.com/

[11] 500 Lavelle Rd, Alamogordo, NM 88310 - https://www.usbr.gov/research/bgndrf/

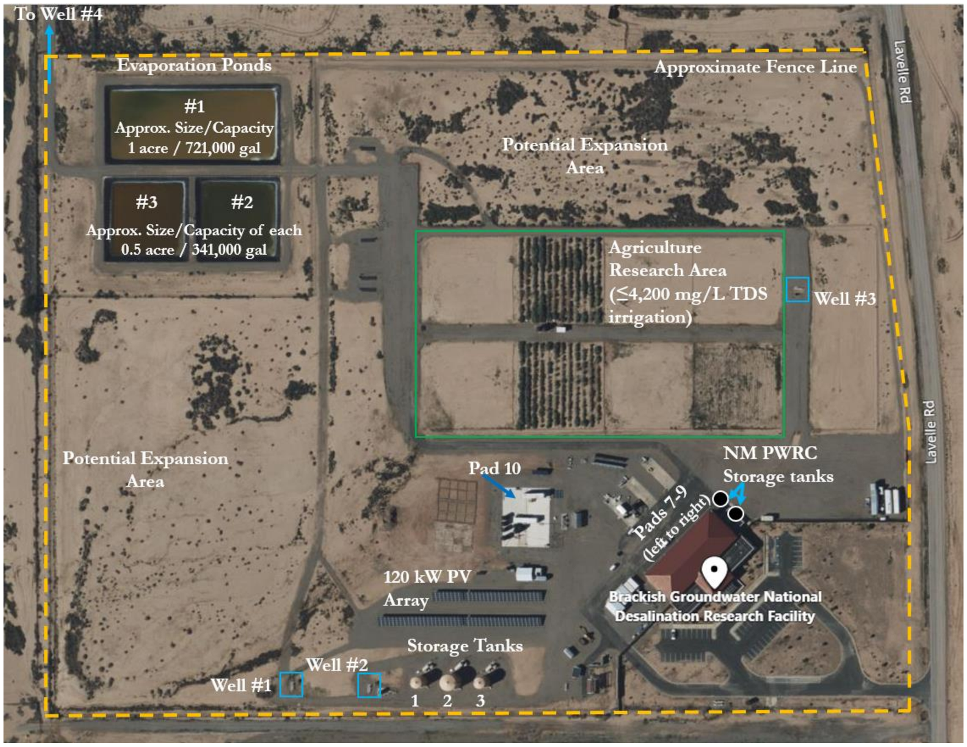

Figure 2 – BGNDRF aerial view

Currently all 3 outdoor pads are in-use, two of which are expected to be in use for the next 18 months to 2 years. There are a series of forms to fill out (the two main forms are the job hazard analysis, and application on system specifications such as flow rate, electrical needs, physical dimensions), to get our place in line, and secure a spot. We expect to be at least 1 year out from installation / testing and so anticipate no issues with this.

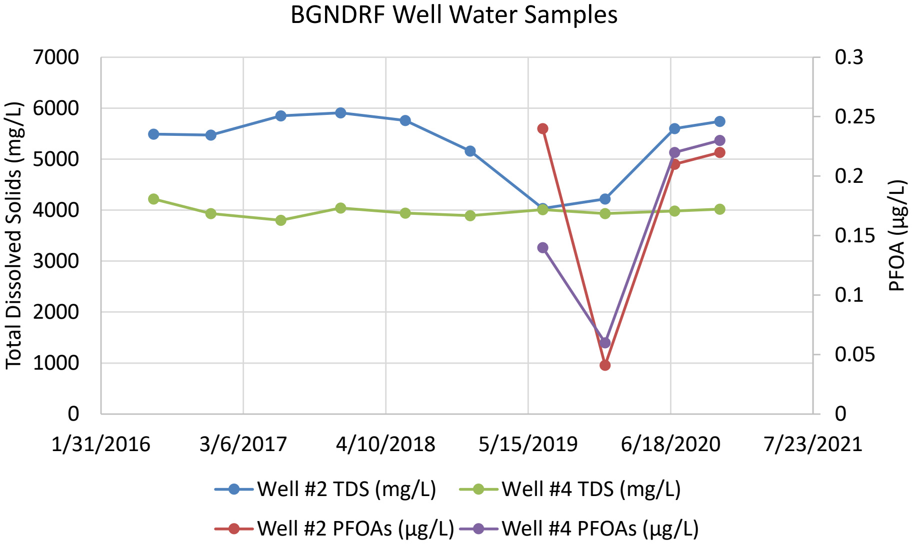

Figure 3 – BGNDRF wells #2 and #4 TDS and PFAS concentration

BGNDRF's discharge permit with the state of New Mexico allows PFAS to be discharged only to their evaporation ponds. This is a potentially limiting factor to the demonstration, as only a single 1-acre evaporation pond is currently available. This limits total discharge to approximately 850 gallons per day. So at this stage we may only be able to operate at partial capacity (e.g. not 24/7) to limit discharge, however, we will continue to work this out with BGNDRF moving forward.

End Users – U.S. NAVY, Oil & Gas Sector

Perfluoroalkyl Substances (PFAS) are a group of long-lasting chemicals that were widely used at military bases and airfields, industry, particularly microchip manufacturing, and in consumer products such as Teflon. PFAS is resistant to typical environmental degradation processes because of the stability of the C-F bonds, which has led to a widespread environmental, social, and health issues.

PFAS/PFOA pollution has become a wide spread challenge for the military[12] and O&G industry[13] and there exists an overwhelming demand[14] for a solution. The team has been discussing this problem with a project engineer at the Navy Engineering and Expeditionary Warfare Center (NFEXWC) who has described the urgent need for an environmentally friendly and easy-to-deploy solution[15,16].

Accidental and emergency discharges from Aqueous Film Forming Foam (AFFF) fire-suppression systems and fire-fighting systems are a large source of PFAS-impacted wastewater representing a serious environmental liability for DoD facilities. These wastewaters contain elevated levels of co-contaminates which decrease the effectiveness of emerging PFAS treatment technologies. Granular Activated Carbon (GAC) is capable of removing Per- and polyfluoroalkyl substances (PFAS) under certain conditions but is limited by several factors including a low loading rate. AFFF wastewater has concentrations upwards of thousands of parts per million (ppm, mg/L), which requires too much GAC to make treatment cost effective. Incineration is currently the only option for high strength AFFF wastewater, which is costly and energy intensive with treatment costs as high as $6-$8/gallon. The cost-savings potential of volume minimization and wastewater treatment is enormous.

The NAVY also needs a solution and could greatly benefit from a solar thermal desalination technology. Decision makers are being asked to choose between saving lives (using AAAF to put out jet fires) and protecting the general public. Current solution spaces still have key issues. Destructive technologies (fully mineralizing the fluorine chemicals) are energy efficient but limited by reaction kinetics. Energy efficient pathways (e.g. low energy plasma reactor, absorbents, ionic exchangers, bio char clay) generate a lot of waste. The EPA is skeptical of current incineration disposal (aerosolized PFAS pollution) as well as absorbents end up in landfills.

The NAVY has outlined the following major requirements:

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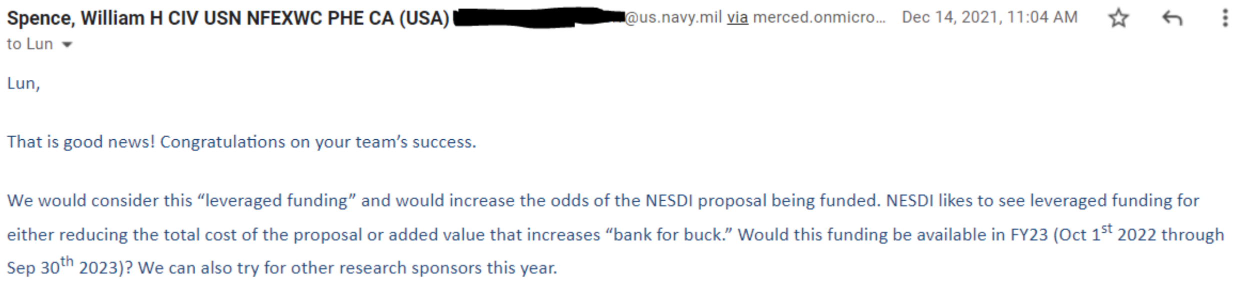
[12] Despite Health Risks, U.S. Military Will Burn Firefighting Foam (theintercept.com)
[13] Mapping PFAS "Forever Chemicals" in Oil & Gas Operations - FracTracker Alliance
[14] Solvay Withholds Data About PFAS Pollution in New Jersey (theintercept.com)
[15] The Military's Toxic Firefighting Foam Disaster (theintercept.com)
[16] U.S. Military Responsible for Widespread PFAS Pollution in Japan (theintercept.com)

- Mobile system – contracted out to individual sites on an as-needed basis:
    - Shipping & installation at host site
    - Water remediation over time period
    - Decommissioning and re-deployment at next site.
- Must enable local sewer discharge of product water without additional permitting

If awarded, we would leverage the American Made Solar Desalination funds for additional funding out of NESDI (see e-mail excerpt).



Spence, William H CIV USN NFEXWC PHE CA (USA) [redacted]@us.navy.mil via merced.onmicro... Dec 14, 2021, 11:04 AM

to Lun

Lun,

That is good news! Congratulations on your team's success.

We would consider this "leveraged funding" and would increase the odds of the NESDI proposal being funded. NESDI likes to see leveraged funding for either reducing the total cost of the proposal or added value that increases "bank for buck." Would this funding be available in FY23 (Oct 1st 2022 through Sep 30th 2023)? We can also try for other research sponsors this year.

Furthermore in the O&G sectors, there are 2,854 sites in the 50 states and two US territories that have identified PFAS contamination, spending over $2 Billion dollars a year to remediate.

Key Components / Vendors

- ICPC solar field (provided by WCO)
- LTDis® desalination/distillation unit (provided by CCR)

The team does not anticipate any issues sourcing the required components.

Question 2: Impact

Performance Enhancements over Existing

Solar Thermal – ICPC

The ICPC consists of an evacuated glass tube and an internally supported aluminum minichannel absorber. The bottom half of the glass tube is silver-coated to reflect incident light towards the absorber, which is selectively coated to maximize solar absorption and minimize thermal emission. A heat transfer fluid (HTF) is circulated through the pores of the minichannel absorber to move the generated heat from the solar field to the desalination system.

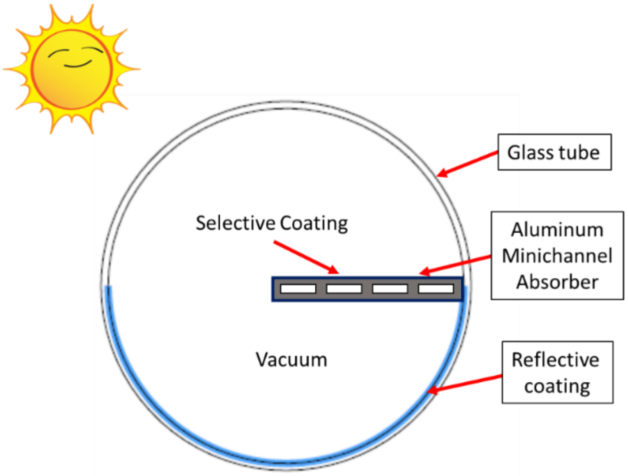


Figure 4 – Cross-section schematic of ICPC

A reflective coating applied on the inside bottom half of the glass tube directs light from the left side of the collector to the bottom surface of the absorber. The absorber material cost is halved and replaced by a low cost silver coating. In this way we are also dually utilizing the glass tube for both the vacuum AND the nonimaging optic so there is no need for additional reflector material or structure. Because the reflector is inside the vacuum tube, it is a high-reflectance first-surface mirror (e.g. 89% for PVD aluminum, 94% for chemically deposited silver) and protected from dusting. In fact there is only a single dusting surface as light enters from outside the glass tube into the optical system which reduces the effect of soiling compared to optical systems with two external surfaces like the XCPC or parabolic troughs. Finally, the 1X nonimaging optical concentrator is wide-angle collector, gathering all light entering the aperture ±90° and directing it to the absorber. This provides year-round passive sun-tracking from a *stationary* position while still collecting all available diffuse light.

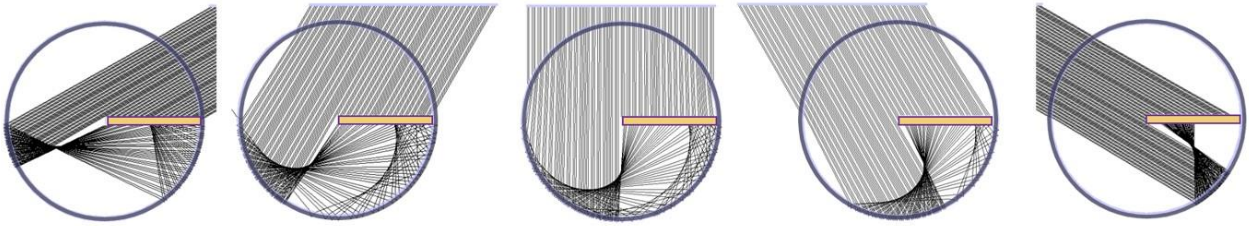


Figure 5 –ICPC ray tracing from -60° to +60° incidence in increments of 30 degrees

The outer surface of the minichannel is selectively coated to maximize solar absorption and minimize thermal emission (radiation). The minichannel design minimizes the thermal resistance between the hot absorber surface and the internally circulated heat transfer fluid (HTF). The absorber surface is thus kept cool to minimize radiation.

The inside of the glass tube is evacuated to eliminate convective losses from the absorber surface. The vacuum is maintained by a hermetic metal-glass seal between the aluminum end-cap and glass tube. This is a critical component, which enables the ICPC tubes to be made almost entirely of aluminum[17] and glass.

As a result, the ICPC readily generates solar-heated HTF at > 50% solar-to-thermal efficiency up to 150 °C. Because the ICPC tubes are made almost entirely from aluminum and glass, they have an extremely low material cost < \$50/m^2 of aperture which is key to providing a low levelized cost of heat.

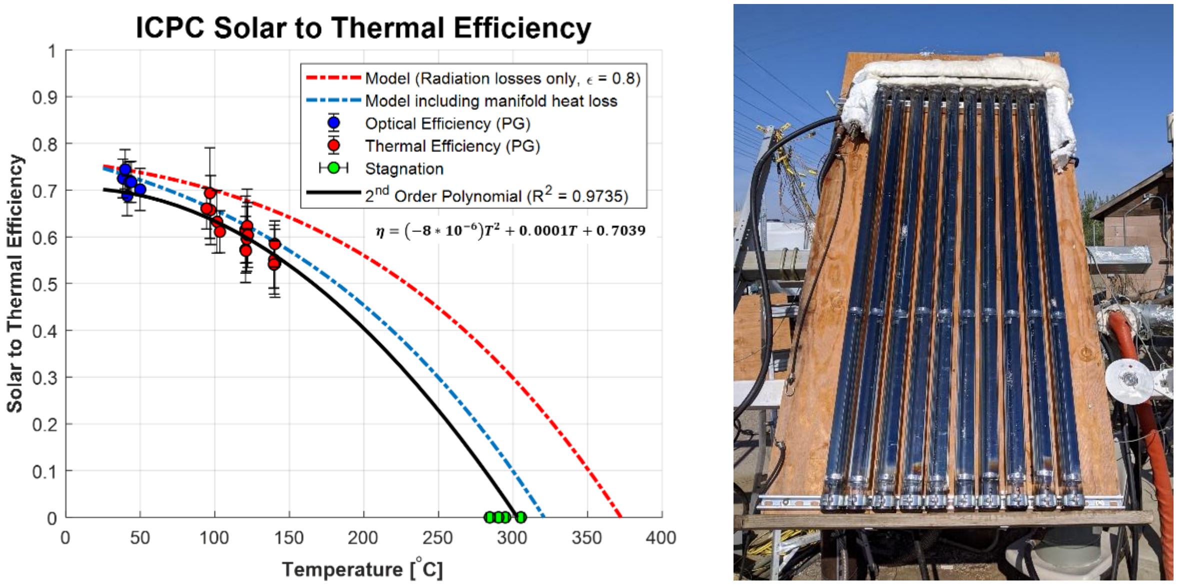


Figure 6 – (left) Experimental solar-to-thermal efficiency. (right) Module under testing.

Individual tubes are joined together in a parallel flow configuration of 20-tubes to form an ICPC module. Modules are approximately 150 lbs each and can easily be handled by a 2-person team. Each tube in the module is rotated ~35 degrees to mirror the latitude of potential site locations within the contiguous U.S. This maximizes the annual solar irradiance on the aperture of each tube, while simultaneously enabling the collector to be installed flat (horizontal) against the ground.

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[17] Aluminum is 1/10th the price per volume compared to traditional copper absorbers

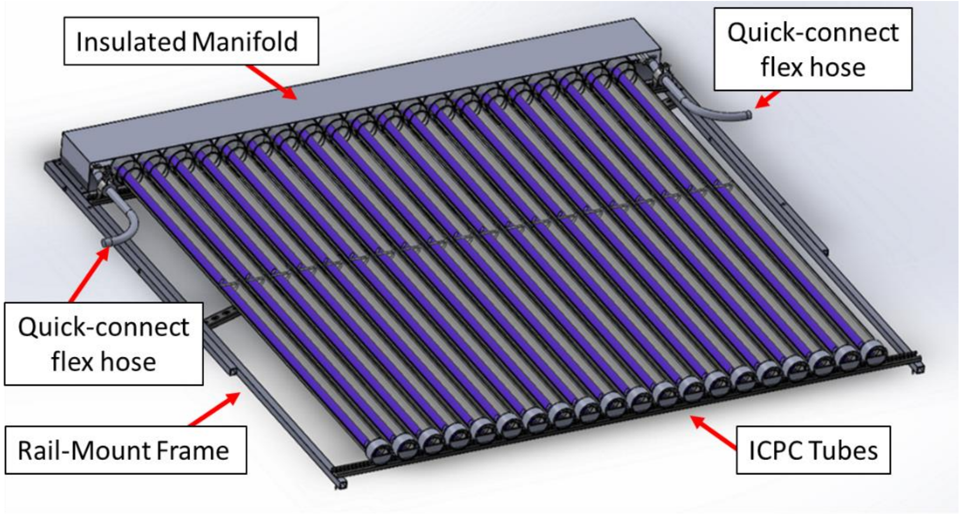

Figure 7 – ICPC module consisting of twenty ICPC tubes

The flat collector has extremely low wind-loading and enables the tubes to be installed on low-cost rail mounts with ballast-weighted foundations. Modules are then tied together to form a solar field using quick-connect fittings and flexible hose. The result is a lightweight technology which is simple to install and tear down can be relocated multiple times (e.g. **mobile**) over its 30 year lifetime.

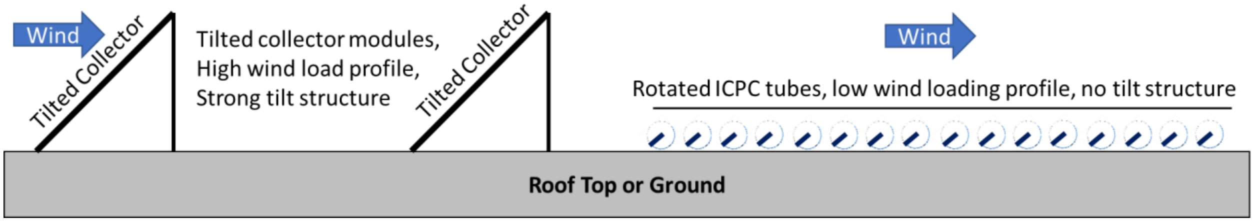

Figure 8 – (left) traditionally tilted collector modules, (right) rotated ICPC module with low wind profile.

The ICPC technology is a next-generation collector which has extremely low-cost potential. It is highly competitive against state-of-the-art solar thermal collectors at temperatures < 150 °C. The current target LCOH (including cost of capital) is 1.5 cents per kWh, which is on-par with industrial (wholesale) natural gas in the U.S. today. Demonstrating cost-parity with fossil fuels in the U.S. will be disruptive for the solar thermal industry worldwide.

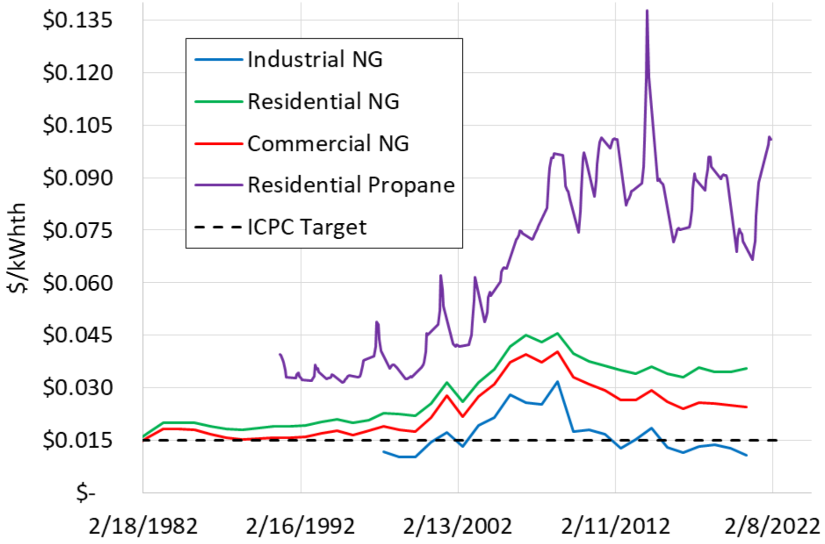

Figure 9 – Natural gas[18] and propane[19] prices - Energy Information Agency (EIA)

Commercial gas prices are currently around 2.5 cents per kWh in the U.S. This enables a low-cost low-carbon heat-as-a-service business model, where WCO would install and operate a system and the customer would pay for the heat delivered at a fraction (e.g. 80%) of the price they are currently paying for natural gas.

The most attractive markets WCO has identified are *mobile* markets which do NOT have existing natural gas hookups. These markets are typically served using liquid propane gas (LPG) at a price of approximately $0.09 / kWh, more than three times the cost of commercial natural gas. This enables payback periods of less than three years and the generation of significant value over a 20 year lifetime.

Desalination - LTDis®

The LTDis® system, is a patented thermal evaporator that works on the principles of direct contact heat transfer. Unlike MED or MSF systems, the heat transfer in the LTDis® system occurs directly on the surface of billions of water droplets in its evaporators and condensers, eliminating the need for costly heat exchangers or tube bundles. Because the phase change takes place on the droplets, there is very little risk for scaling or fouling in our vessels. Additionally, without the need for large-surface area tube bundles or heat exchangers, the size of the vessels is greatly reduced.

This results in a robust, low cost, mobile, and high-efficiency distillation system which is flexible in treating many different highly contaminated feed waters.

The low thermal resistance of the direct contact heat exchange and lower operating temperatures and pressures avoids the costs of exotic metallurgies required by traditional thermal evaporator systems. The use of low-cost non-metallic construction materials such as

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[18] https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm
[19] https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=M_EPLLPA_PRS_NUS_DPG&f=M

polypropylene or fiber reinforced plastics (FRP) allows us to significantly lower the CAPEX below the cost of traditional MED/MSF systems.

Due to our steady thermal efficiency through variable heat input, we are uniquely capable of integrating heat sources such as solar thermal. The availability of solar energy is typically coincident with water-challenged regions in the U.S. therefore we expect solar thermal will become the preferred energy source for most systems in these areas. Furthermore, electricity from Photovoltaics (PV) can be used to provide the electricity demand of the plant pumps, control system and lighting.

The small size afforded by the direct heat exchange enables a mobile containerized system to be designed. LTDis® is modular and scalable, in which several modules can be installed in series to increase water treatment capacity. The modular plant design uses non-corroding materials and durable standardized components manufactured from fiber reinforced plastics (FRP) and/or stainless steel. Piping within the plant is made of polypropylene or FRP. The external plate heat exchangers are made of titanium or stainless steel where they are in contact with feed water.

In contrast to many other thermal desalination technologies, LTDis® is highly tolerant of variable feed water composition without the need for extensive pre-treatment typically required for scale control. LTDis® features an adaptive process that can operate under a wide range of full and partial load conditions and therefore is able to maintain thermal balance despite variability in the solar thermal source.

Distillate recovery rate can be optimized based on the application to minimize the remaining brine output and associated disposal costs. Discharge can either be a defined heavy brine, salt slurry or bulk solids. High conversion ratios and a pure water extraction rate of up to 95% from the feed ensure the preservation of natural water resources and the minimization of waste and its associated handling/disposal impacts.

PFAS Treatment

Current PFAS treatment is performed by concentrating PFAS molecules through carbon adsorption or ion exchange, then disposing of the concentrate in approved landfill or destroying in a thermal oxidizer. Challenges include biofilm formation on adsorbents and breakthrough of short chain PFAS molecules. Adsorbents and resins are unable to remove salts or other total dissolved solids needed for ground discharge of treated brackish or salty contaminated waters, such as in the proposed pilot location.

CCR’s Low Temperature Distillation (LTDis®) technology has demonstrated the ability to take highly contaminated PFAS water and produce clean distillate. These demonstrations proved our system is capable of a 10,000X reduction in contaminates, yielding a distillate with less than 20 parts per trillion, well below the EPA standard of 70 parts per trillion.

Commercially Relevant Outcome

The NAVY described their ideal solution, as a mobile system which can be containerized, shipped, and deployed at multiple locations around the world. The system would be contracted for operation on a site-by-site basis until their local wastewater problems are resolved, then shipped to a new location. The purified distillate should be able to be discharged into the local sewer system without additional permitting requirements, requiring < 70 ppt PFAS to meet EPA standards, and < 17 ppt PFAS to meet certain state requirements. As long as the system can provide overall treatment costs for less than their current disposal cost of \$6-\$8/gallon (\$1,584-2,112/m^3), there is a commercial relevance in this space (this is an excellent entry market).

PFAS treatment in the O&G market currently costs between \$6.60-\$63.00/m^3, depending on the level of contamination. Together, the ICPC + LTDis® technologies will provide a robust automated treatment solution for desalinating/depolluting contaminated waters that is deployable in remote locations

LCOW and Cost Breakdown

Levelized Cost of Heat (LCOH)

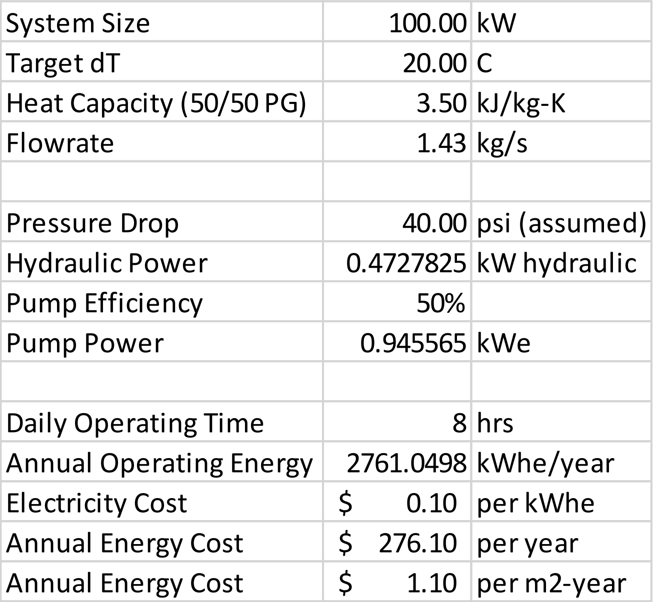
Tube Aperture Length	1.9	m
Tube Aperture Width	0.066	m
Tube Aperture	0.1254	m2
Tubes per Module	20	
Module Aperture	2.508	m2
Number of Modules	100	modules
Array Aperture	250.8	m2
Total number of tubes	2000	tubes

The following numbers were developed for a 250 m^2 aperture solar field (100 kW thermal) of ICPC tubes. Calculations were performed assuming a labor rate of \$50 per man-hour, 6.56 ft of piping required per m^2 of solar field aperture (based on dimensions of module on a per m^2 basis), and a heat transfer fluid volume of 0.46 gallons per m^2 of aperture. Frame and tube assembly is estimated to take approximately 15 minutes per module, and module assembly (connecting all the tubes to the manifold) is also expected to take an additional 15 minutes per module, with remaining balance of system (e.g. plumbing, insulating, jacketing) expected to take 15 minutes per module. Thus, the total additional labor cost on a per square meter basis for the installed solar field is \$14.95/m^2 cumulative installation labor.

ICPC - Glass Tube	$	2.50	per tube	Includes cost of material and shaping of flanged opening and sealed end
ICPC - Aluminum Minichannel	$	0.50	per tube	Previous Quote
ICPC - Selective Coating	$	0.10	per tube	Batch PVD coating on suspended minichannels
ICPC - Absorber Supports	$	0.20	per tube	1/4" Steel strip x 5X diameter (circumference + 2D)
ICPC - Reflective Coating	$	0.59	per tube	Previous Quote
ICPC - Glass-to-metal Seal	$	1.29	per tube	Includes cost of end cap and thermocompression process
	$	**5.18**	**per tube**	Note: All-glass Dewar tubes are $3/tube
	$	**103.60**	**per 20-tube module**	
ICPC Tubes	**$**	**41.31**	**per m2**	
Manifold - Tubing	$	4.16	per m2	3/4" x SCH40 Steel Tubing - 6 ft x 2 x $0.87/ft
Manifold - Insulation	$	3.23	per m2	Fiberfrax - 6ft x 2 ft @ $135/100 sq ft
Manifold - Jacketing / Box	$	4.78	per m2	Aluminum Sheet Metal - 6ft x 2 ft @ $2/sq ft
Manifold - Fittings	$	1.99	per m2	Solder, fittings
Manifold - EPDM Steam Hose	$	1.20	per m2	$3/ft @ 1 ft per module
Manifold - Assembly Labor	$	4.98	per m2	$50/hr @ 1/4 hour per module
Manifolds & Assembly	**$**	**20.35**	**per m2**	
Frame - Rail Mounts	$	6.29	per m2	1"x1"x1/8" Steel Square - 2 rails X 5.8 ft X $27/20ft
Frame - Ballast (Bricks)	$	0.80	per m2	$0.5 per brick x 4
Frame - Angle	$	0.54	per m2	1"x1"x1/8" Steel Angle - 0.5 ft x 4 @ $13.5/20ft
Frame - Fastening	$	1.99	per m2	$5 per module estimate
Frame - Assembly / Installation Labor	$	4.98	per m2	$50/hr @ 1/4 hour per module @ factory OR on-site
Frame & Installation	**$**	**14.60**	**per m2**	
BOS - Pump	$	1.59	per m2	20 degree dT, 1.4 kg/s flow, 40 psi, 50% pump efficiency. Based on prev quote $419.635/kW
BOS - Pipe & Fittings	$	5.71	per m2	3/4" SCH 40 black steel pipe @ $0.87/ft, 6.56 ft pipe per m2 aperture
BOS - Heat Transfer Fluid	$	4.39	per m2	RhoGard Ultra @ $16.7/gal (prev quote), diluted 50/50 with DI water @ $1/gal, 0.5 gal per m2 aperture
BOS - Insulation	$	9.84	per m2	1/2" x 1" thick fiberglass @ $1.5 / ft (prev quote), 2 m pipe per m2 aperture
BOS - Jacketing	$	6.30	per m2	11.5" aluminum pipe jacketing @ $0.96/ft (prev quote), 2 m pipe per m2 aperture
BOS - Instrumentation	$	4.00	per m2	Assuming $1K for instrumentation out of 100 kW (250 m2) system
BOS - Installation Labor	$	4.98	per m2	$50/hr @ 1/4 hour per module on site
Balance of System	**$**	**36.81**	per m2	
Solar Field Total	**$**	**113.07**	**per m2**	

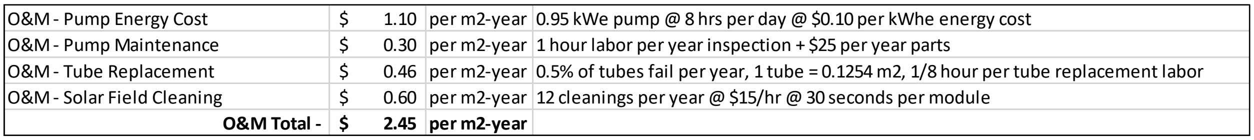
Site preparation was estimated to be \$2.50 per m^2, based on the SAM costs for a parabolic trough collector (PTC) field of \$2.11 per m^2 for site preparation and \$0.44 per m^2 for clearing & grubbing. The current goal of the ICPC solar field is to be installed without any modifications to the site. If necessary, the solar field can be raised off the ground using bricks to prevent any danger of flood damage and to provide rough levelling of the solar array.

A 100 kW-thermal system with a dT of 20°C and heat capacity of 3.5 kJ/kg-K requires a 1.43 kg/s flow rate. Assuming a 40 psi pressure drop through the array requires a hydraulic power of 0.47 kW and a pump electric power of 0.95 kWe (50% pump efficiency). The pump is operated 8 hours/day for 365 days/year, requiring 2,761 kWhe/year. For an electricity cost of \$0.10/kWh$_e$, this costs \$276/year or \$1.1/m^2-year.



System Size	100.00	kW
Target dT	20.00	C
Heat Capacity (50/50 PG)	3.50	kJ/kg-K
Flowrate	1.43	kg/s
Pressure Drop	40.00	psi (assumed)
Hydraulic Power	0.4727825	kW hydraulic
Pump Efficiency	50%	
Pump Power	0.945565	kWe
Daily Operating Time	8	hrs
Annual Operating Energy	2761.0498	kWhe/year
Electricity Cost	$ 0.10	per kWhe
Annual Energy Cost	$ 276.10	per year
Annual Energy Cost	$ 1.10	per m2-year

The total operating and maintenance cost is calculated using the annual energy cost of operating the pump, an assumed maintenance cost of 1 hour labor per year and \$25 per year in parts, an estimated tube replacement cost assuming 0.5% of tubes fail per year (based on current estimates from past 8 years of test array operation and the general experience of similar commercial product over the last 30 years), and a 7.5-minute per tube time for replacing tubes (\$50/hr labor rate). Finally, a simple cleaning cost is included by estimating it takes 30 seconds to spray down each module for a cleaning labor cost of \$15/hr and cleaning is performed 12 times a year. The result is an annual O&M cost of \$2.45/m^2-year, half of which comes from the pump energy cost.



O&M - Pump Energy Cost	$ 1.10	per m2-year	0.95 kWe pump @ 8 hrs per day @ $0.10 per kWhe energy cost
O&M - Pump Maintenance	$ 0.30	per m2-year	1 hour labor per year inspection + $25 per year parts
O&M - Tube Replacement	$ 0.46	per m2-year	0.5% of tubes fail per year, 1 tube = 0.1254 m2, 1/8 hour per tube replacement labor
O&M - Solar Field Cleaning	$ 0.60	per m2-year	12 cleanings per year @ $15/hr @ 30 seconds per module
O&M Total -	**$ 2.45**	**per m2-year**	

The resulting LCOH is calculated using the capital recovery factor (CRF) of 0.08139 per the technical appendices of the Solar Thermal Desalination prize (assuming a period n=30 years and a discount rate i=7%).

In Merced, CA the annual global tilt solar irradiances is 2026 kWh/m^2-year. Assuming a 43% annualized solar-to-thermal efficiency (as achieved in our previous technical demonstration of the 10 kW field at UCM), each square meter of solar field will deliver 871 kWh of heat at 120 °C each year. This results in a levelized cost of heat of **1.36 cents per kWh** over its lifetime.

Site improvement cost	$ 2.50	per m2	
Solar field cost	$ 113.07	per m2	
O&M cost	$ 2.45	per m2-year	
CRF	0.0814	FROM TECHNICAL APPENDICES for i=7% and n=30	
Annual Site Solar Resource	2026.00	kWh/m2-year (global tilt irradiance in Merced, CA)	
Annual Solar Efficiency	43%	based on experimental data from 10 kW solar field	
Annual Thermal Generation @ 120 C	871.18	Solar resource x annual efficiency	
Levelized Cost of Heat	**$ 0.0136**	**per kWh**	

At the BGNDRF site, the annual global tilt solar irradiances is 2215 kWh/m^2-year. Assuming the same 43% annualized solar-to-thermal efficiency, each square meter of solar field will deliver 952 kWh of heat at 120 °C each year. This results in a levelized cost of heat of **1.25 cents per kWh** over its lifetime.

Site improvement cost	$ 2.50	per m2	
Solar field cost	$ 113.07	per m2	
O&M cost	$ 2.45	per m2-year	
CRF	0.0814	FROM TECHNICAL APPENDICES for i=7% and n=30	
Annual Site Solar Resource	2215.00	kWh/m2-year (global tilt irradiance in Merced, CA)	
Annual Solar Efficiency	43%	based on experimental data from 10 kW solar field	
Annual Thermal Generation @ 120 C	952.45	Solar resource x annual efficiency	
Levelized Cost of Heat	**$ 0.0125**	**per kWh**	

Our current optical and thermal models predict a 58% annualized module-level solar-to-thermal efficiency. We are using the lower experimental results for this analysis which also includes thermal losses in the solar field (manifold, plumbing, pump skid) as well as the parasitic thermal losses which are consumed to warm the system up to operating temperatures. Moving forward, part of our tasks will be to improve our modelling capabilities of the integrated technology at scale.

Levelized Cost of Water (LCOW)

The LTDis® has the following performance metrics:

- Product water flow: 100 m^3/day
- Recovery ratio: 95%
- Feed water flow: 105 m^3/day
- Brine flow rate: 5 m^3/day
- Specific Thermal Energy Consumption: 180 kWh/m^3
- Specific Electrical Energy Consumption: 3.145 kWh$_e$/m^3
- Heat Source Temperature: 95 °C, ~90 °C in plant
- Capacity factor: 100%
- Capital cost: $165,000 per m^3/hr capacity
- Fixed O&M cost: 2.5% of capital cost annually

Variable O&M cost is calculated by multiplying the specific thermal energy consumption by the levelized cost of heat, and the specific electrical energy consumption by the cost of electricity.

$$LCOW = \frac{overnight\ capital\ cost * capital\ recovery\ factor + fixed\ O\&M\ cost}{8760 * capacity\ factor * desalination\ plant\ capacity\ per\ hour} + variable\ O\&M\ cost \quad (1)$$

For an electricity cost of 10 cents per kWhe and a levelized cost of heat of 1.5 cents per kWh provides a LCOW of \$5.02/m^3. Increasing the LCOH to 3 cents per kWh provides a LCOW of \$7.7/m^3. Reducing it to 1 cent per kWh provides a LCOW of \$4.10/m^3. This highlights the importance of low cost solar thermal heat to reduce the LCOW, but also describes a commercially relevant solution for both the Oil & Gas sector as well as the U.S. Navy.

System / Market / End-user	Treatment Costs
ICPC/LTDis® System	\$5.02-\$7.7/m^3 (projected)
Oil & Gas	\$6.60-\$63.00/m^3 (current)
U.S. Navy	\$1,584-2,112/m^3 (current)

Question 3: Target Performance Metrics

Technical performance of the ICPC collector technology has already been established by the previous work done at UC Merced. Remaining milestones include establishing long-term integrity of vacuum tube seals (20+year) and developing robust tube-to-manifold connections.

Technical Milestones prior to Demonstration

Milestone	Test Description	Success Metric	Test conditions, justification
M0.1 Vacuum stability	Vacuum tubes thermally cycled to approximate 20 year lifetime. Vacuum integrity confirmed by measuring heat loss from absorber to determine convection coefficient	No convection by comparing heat loss before and after, every equivalent 4 years of testing, until 20 years.	Minimum number of tubes tested: 10 40°-150°C cycle 7,300 cycles (approximate 20 year lifetime of 1 thermal cycle per day) 30 min cycles, each 4 year equivalent takes 1 month
M0.2 Tube-To-Manifold Connection	Tube-to-Manifold connection thermally cycled at 150 psi internal.	Pressure loss of < 10% for > 90% of tubes after 4 equivalent years to thermal cycling to proceed with design submission.	See test conditions of M1.1.

Performance Metrics of Demonstration

Key performance metrics of the 100 m3/day pilot are focused on unlocking the Navy PFAS treatment market.

Performance Metric	Goal	Justification
M1 - Levelized Cost of Heat delivered by solar field	≤ 1.5 cents / kWh_{th}	Cost-parity with industrial gas
M2 – Feed Water Quality	TDS >1,000 mg/L PFAS	Key to unlocking NAVY's PFAS contaminated wastewater market
M3 – Product Water TDS concentration	Meets requirements for either surface discharge or beneficial use designation	Enable surface water discharge or beneficial-use designation
M4 – Product Water PFAS concentration	< 20 PPT	Enable sewer discharge for NAVY sites
M5 – Combined LCOW	LCOW < $10/m3	Enable commercial relevance for entry-system which can treat PFAS contaminated wastewaters

Question 4: Planning and Documentation

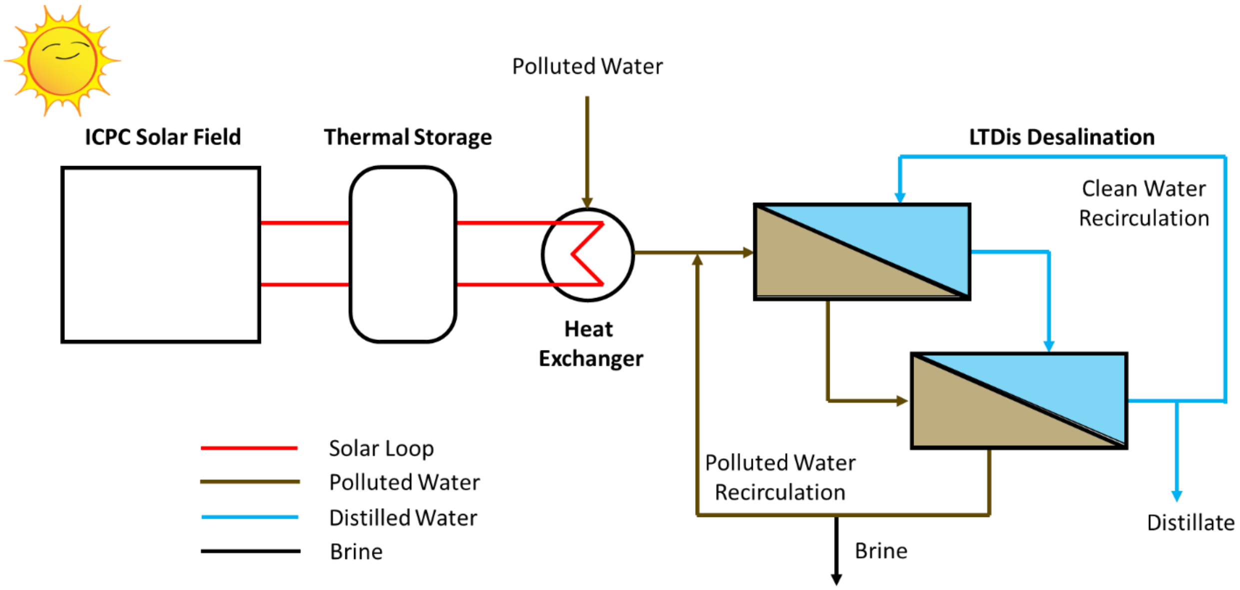


Figure 10 – ICPC Solar Field + Thermal Storage + LTDis® schematic

The solar field will contain the following equipment:

- Solar field ICPC modules
- Thermal energy storage tank
- Pipe, fittings, & valves
- Insulation & jacketing
- Pump, expansion tank, & heat transfer fluid
- Controls & instrumentation
    - PSP (solar) & wind Sensors
    - Thermocouples
    - Flow meters
    - Data logger & controller

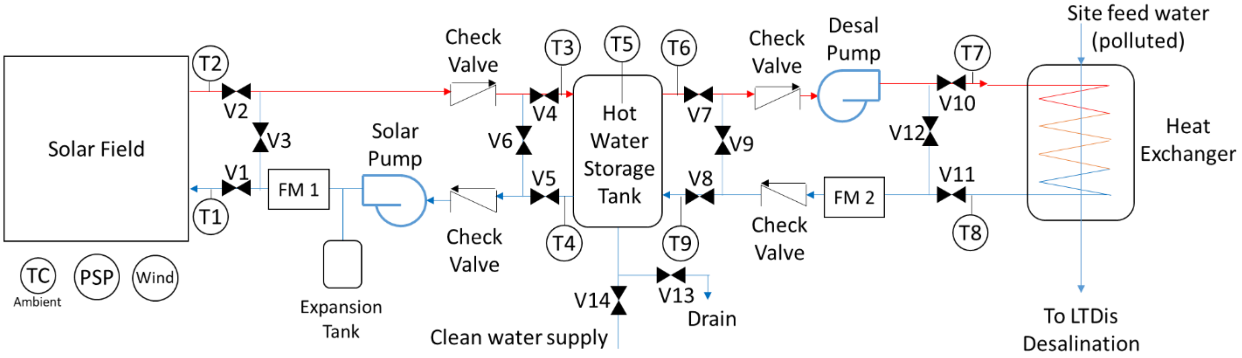


Figure 11 – ICPC Solar Field + Thermal Storage to LTDis® process diagram

The solar loop will be operated during the day, raising the hot water storage tank temperature. The desalination loop will continuously draw from the hot water storage tank. A third redundant backup heating loop (e.g. propane heater, not shown) can be implemented to maintain required temperatures in the hot water storage tank during cloudy days.

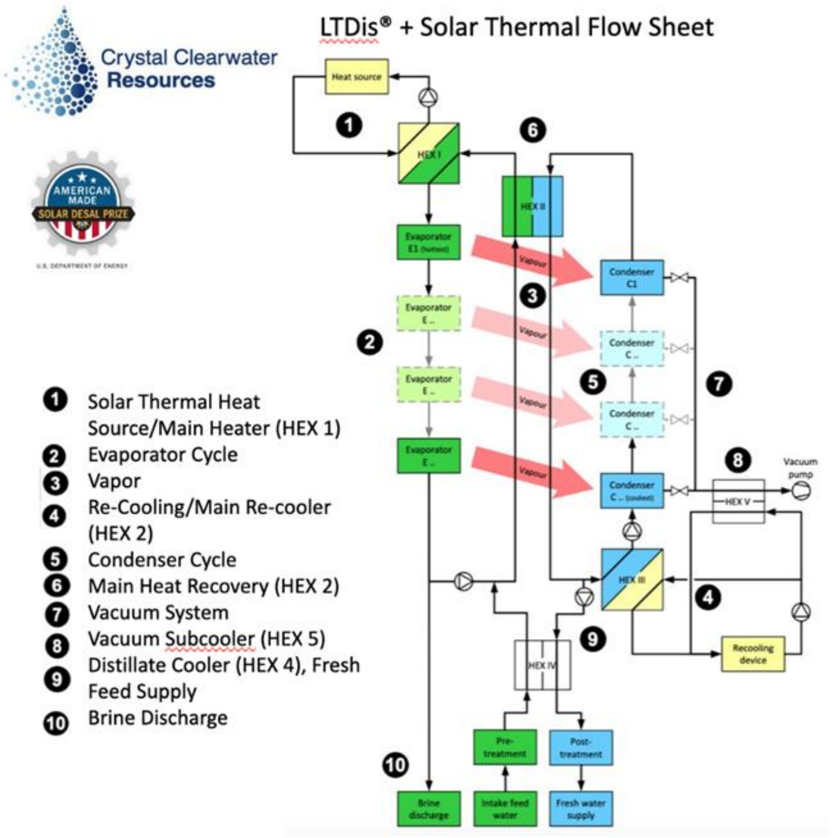
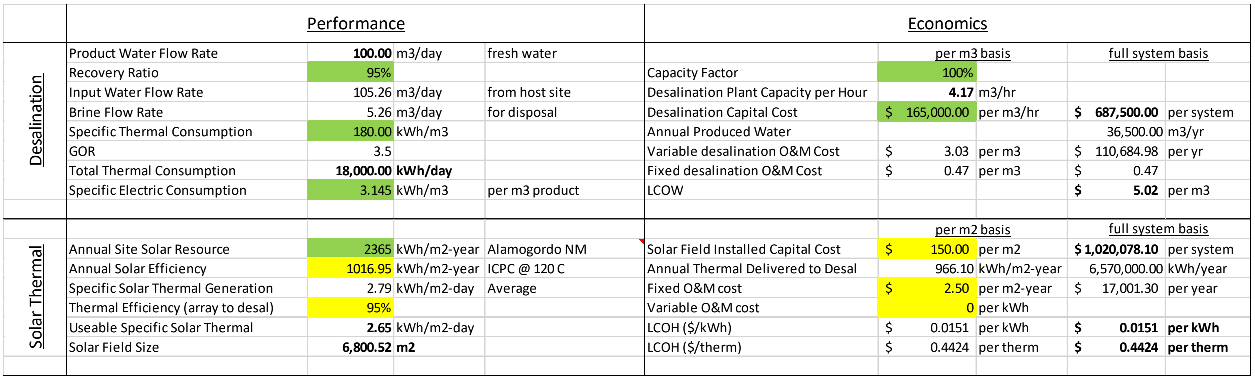


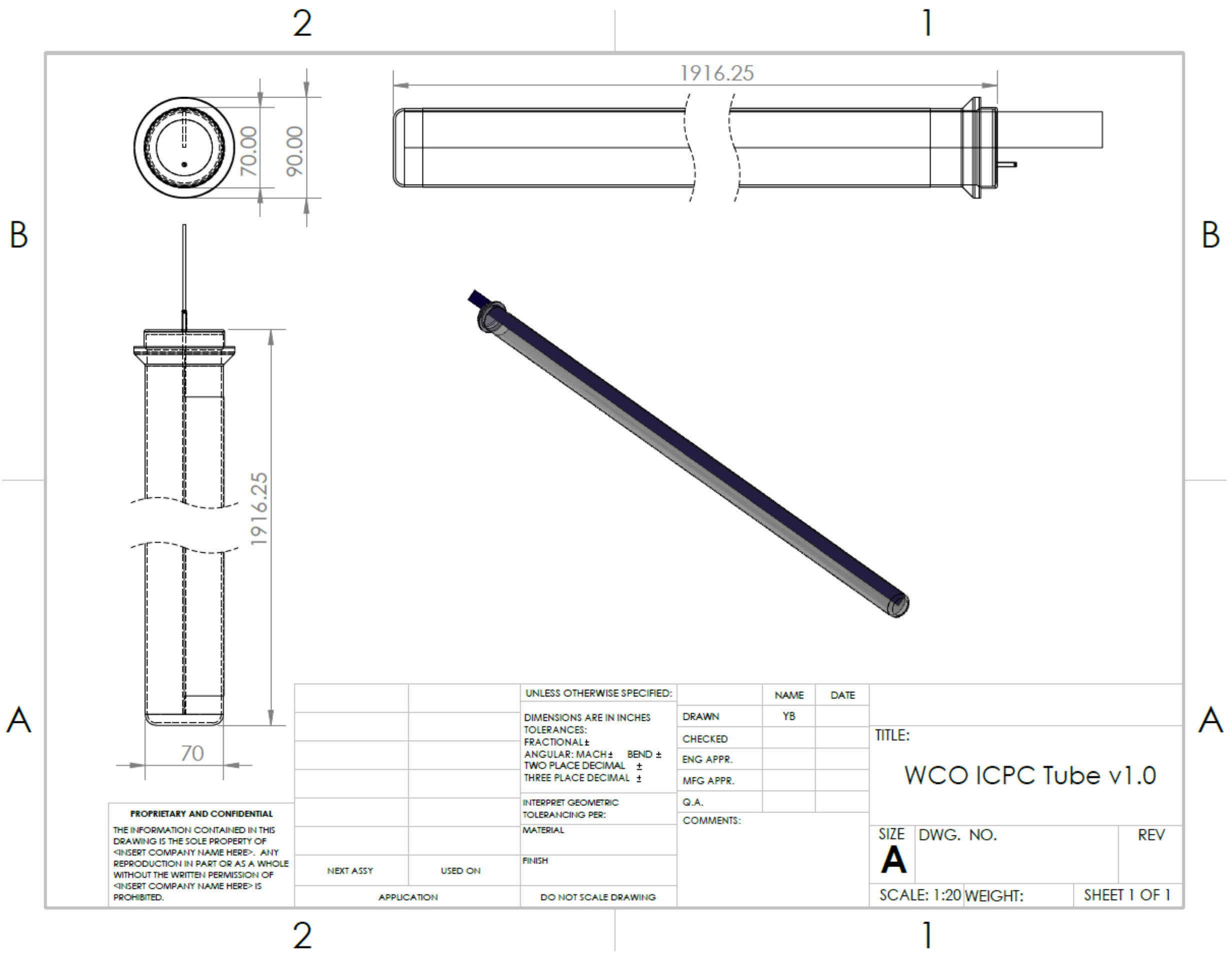
Figure 12 – LTDis® Process diagram



	Performance				Economics				
Desalination	Product Water Flow Rate	**100.00**	m3/day	fresh water		per m3 basis		full system basis	
	Recovery Ratio	95%			Capacity Factor	100%			
	Input Water Flow Rate	105.26	m3/day	from host site	Desalination Plant Capacity per Hour	**4.17**	m3/hr		
	Brine Flow Rate	5.26	m3/day	for disposal	Desalination Capital Cost	$ 165,000.00	per m3/hr	**$ 687,500.00**	per system
	Specific Thermal Consumption	180.00	kWh/m3		Annual Produced Water			36,500.00	m3/yr
	GOR	3.5			Variable desalination O&M Cost	$ 3.03	per m3	$ 110,684.98	per yr
	Total Thermal Consumption	**18,000.00**	**kWh/day**		Fixed desalination O&M Cost	$ 0.47	per m3	$ 0.47	
	Specific Electric Consumption	3.145	kWh/m3	per m3 product	LCOW			**$ 5.02**	per m3
						per m2 basis		full system basis	
Solar Thermal	Annual Site Solar Resource	2365	kWh/m2-year	Alamogordo NM	Solar Field Installed Capital Cost	$ 150.00	per m2	**$ 1,020,078.10**	per system
	Annual Solar Efficiency	1016.95	kWh/m2-year	ICPC @ 120 C	Annual Thermal Delivered to Desal	966.10	kWh/m2-year	6,570,000.00	kWh/year
	Specific Solar Thermal Generation	2.79	kWh/m2-day	Average	Fixed O&M cost	$ 2.50	per m2-year	$ 17,001.30	per year
	Thermal Efficiency (array to desal)	95%			Variable O&M cost	0	per kWh		
	Useable Specific Solar Thermal	**2.65**	kWh/m2-day		LCOH ($/kWh)	$ 0.0151	per kWh	**$ 0.0151**	**per kWh**
	Solar Field Size	**6,800.52**	**m2**		LCOH ($/therm)	$ 0.4424	per therm	**$ 0.4424**	**per therm**

Based on our current estimates, the 100 m^3/day pilot system would cost $1.7 million USD.

- LTDis® System Capacity: 4.17 m3/hr
- LTDis® System Cost: $687,500
- ICPC Solar Field Capacity: 6,800 m2 (3.4 MW)
- ICPC System Cost: $1,020,078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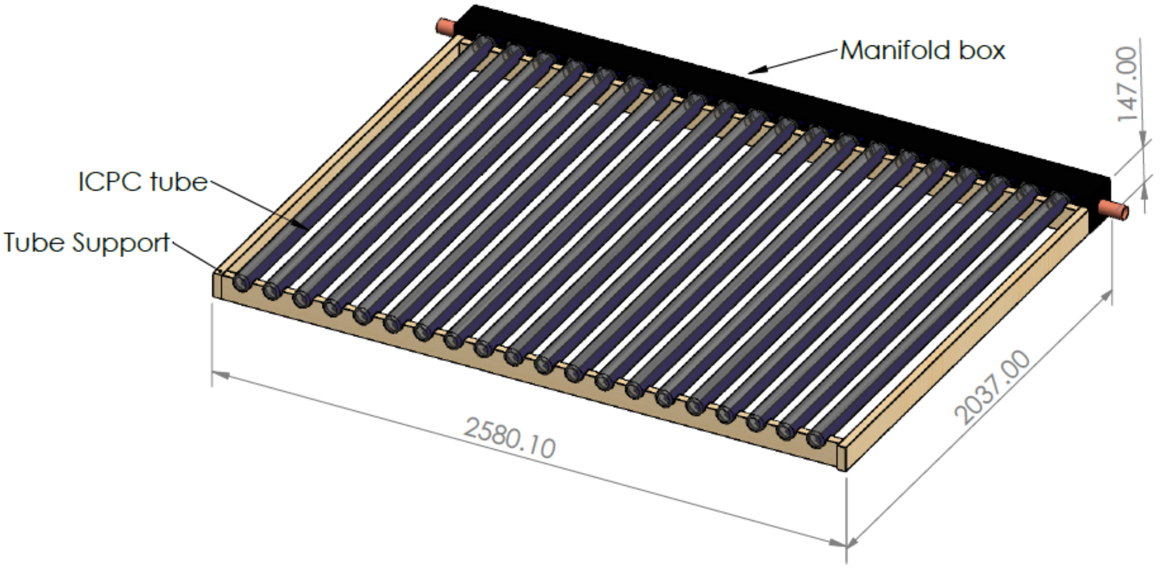
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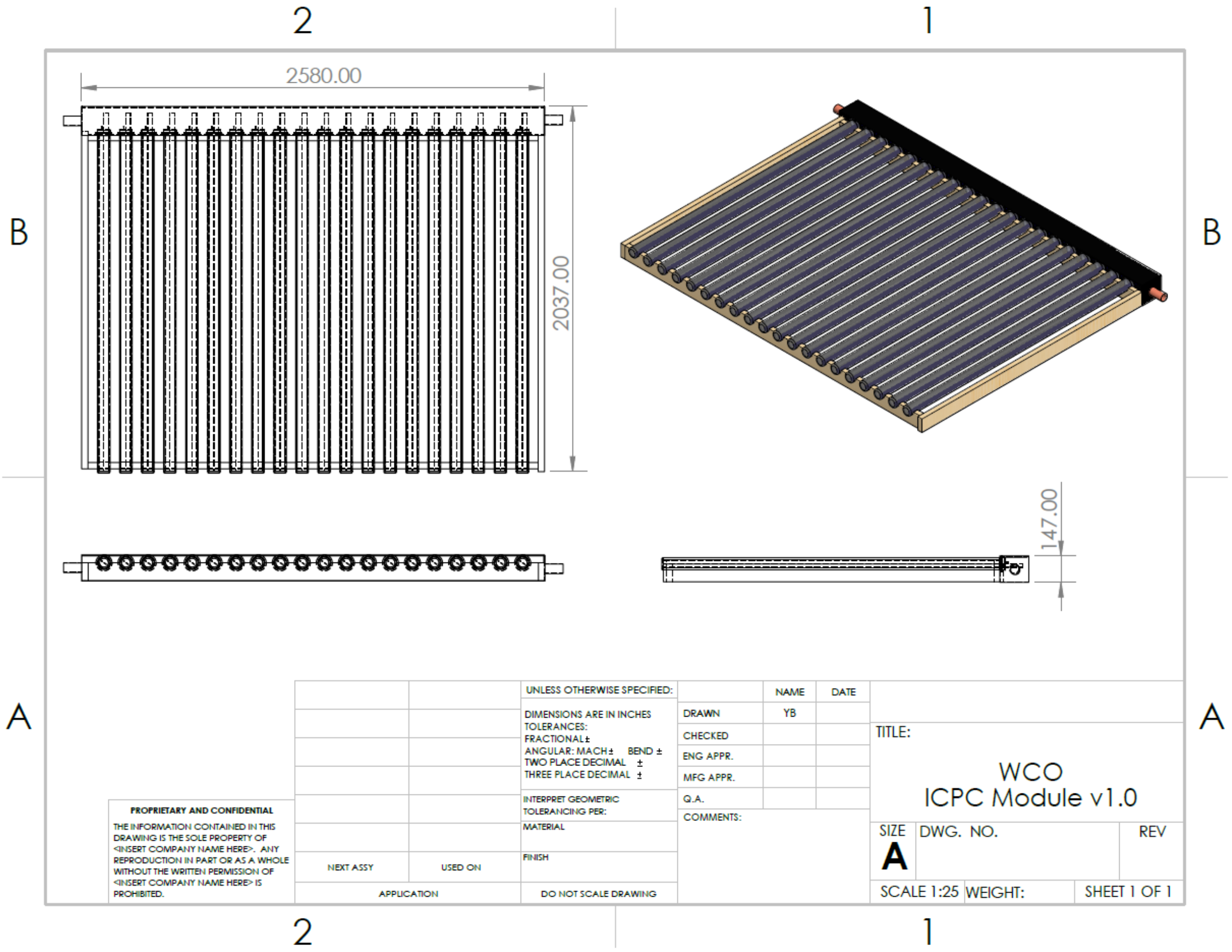
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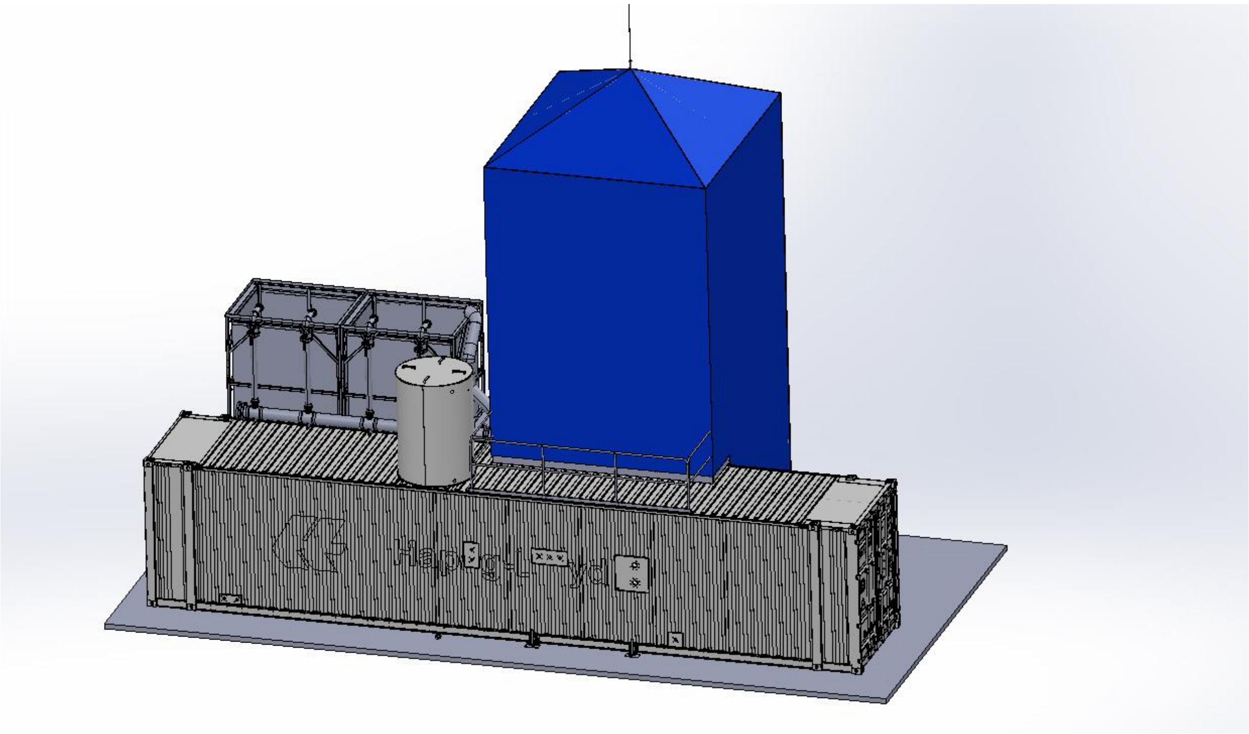

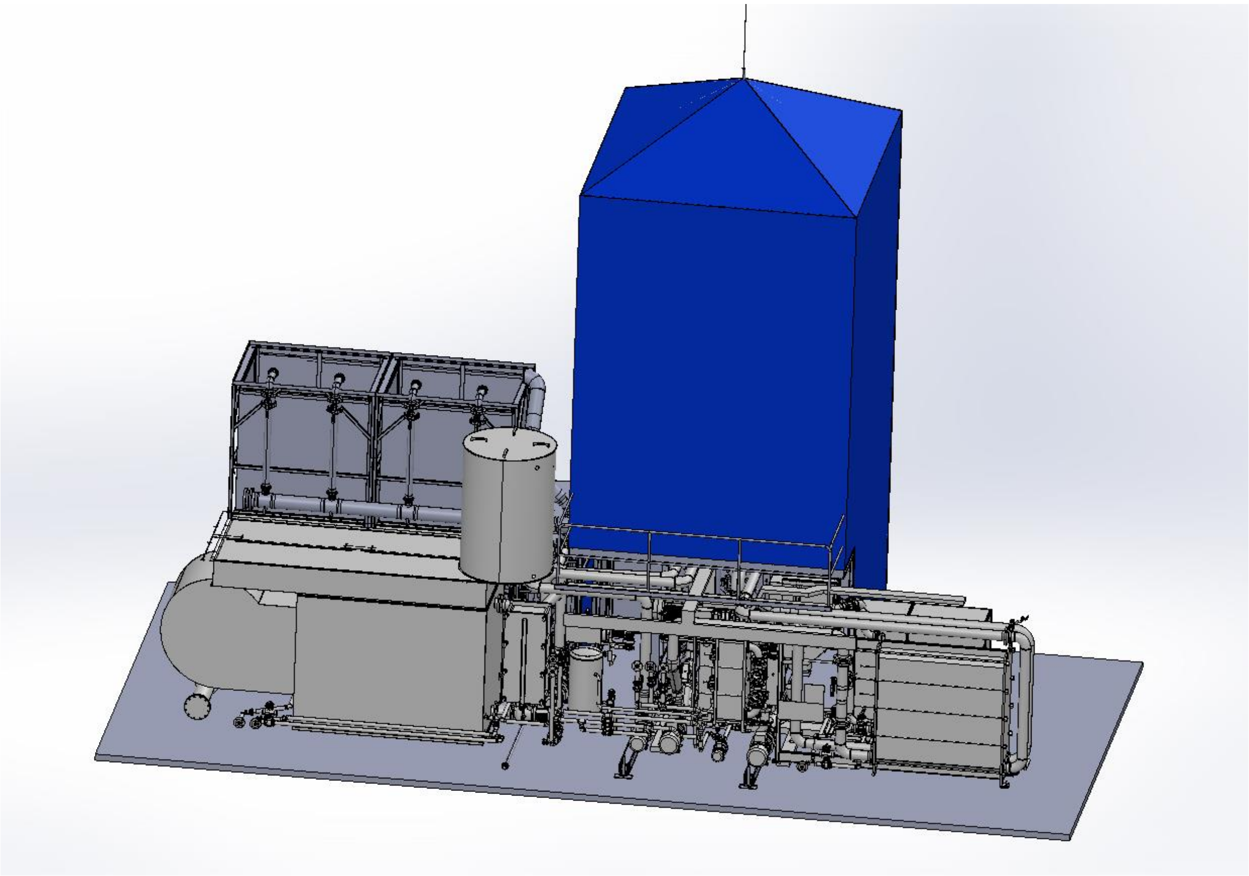

BGNDRF has the following permitting / approval process to use their site.

1. BGNDRF Arrival Check-in Sheet
2. 7-2540 Use Authorization Application
3. Facility Use Authorization Application
4. BGNDRF Job Hazard Assessment Form
5. Emergency Shutdown Form
6. Emergency Notification Form
7. Research Team POC Form
8. Certification of Vaccination for Contractors and Visitors

We will work on these as we proceed to the Design phase to ensure our place in the BGNDRF testing queue and to begin any other procedures as necessary to install the prototype system.

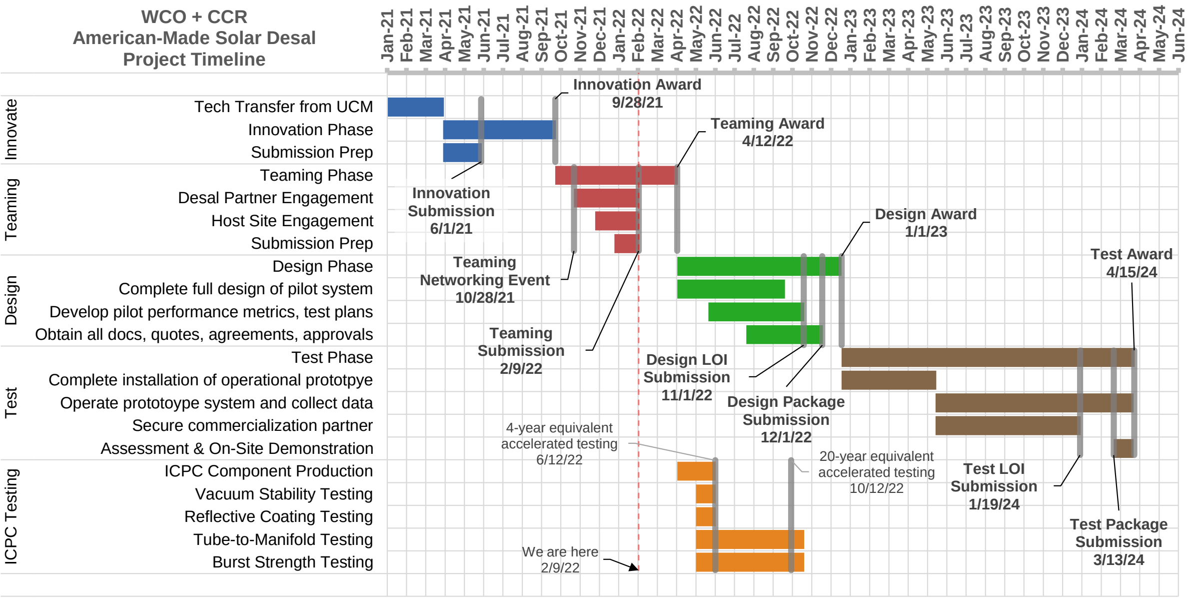

Figure 13 – Project Schedule

We plan to submit our Test-phase submission package in March 2024, which provides 1 year to complete the design phase and 1 year to complete the test phase. This is within the time we would need to fabricate our next generation of tubes, complete all ICPC-relate stress-testing prior to entering our design-phase submission at the end of 2022. It is also a reasonable amount of time to fabricate, install, and TEST the prototype system. If the project is delayed beyond this time frame, we can still complete our TEST submission in April 2025.