Sigma Expert Solutions LLC

# SKID-BASED AUTOMATED FLASH EVAPORATOR SYSTEM (SAFES)

The proposed solution is a set of water purification skids generating municipal quality water from brackish water or RO concentrate. SAFES can be employed for temporary installation or during disaster recovery to a provide rapidly deployable and scalable water purifying solution.

The descriptive video can be found at: https://youtu.be/YkNZjv1CCao and
http://www.sigmaexpertsolutions.com/design/desal

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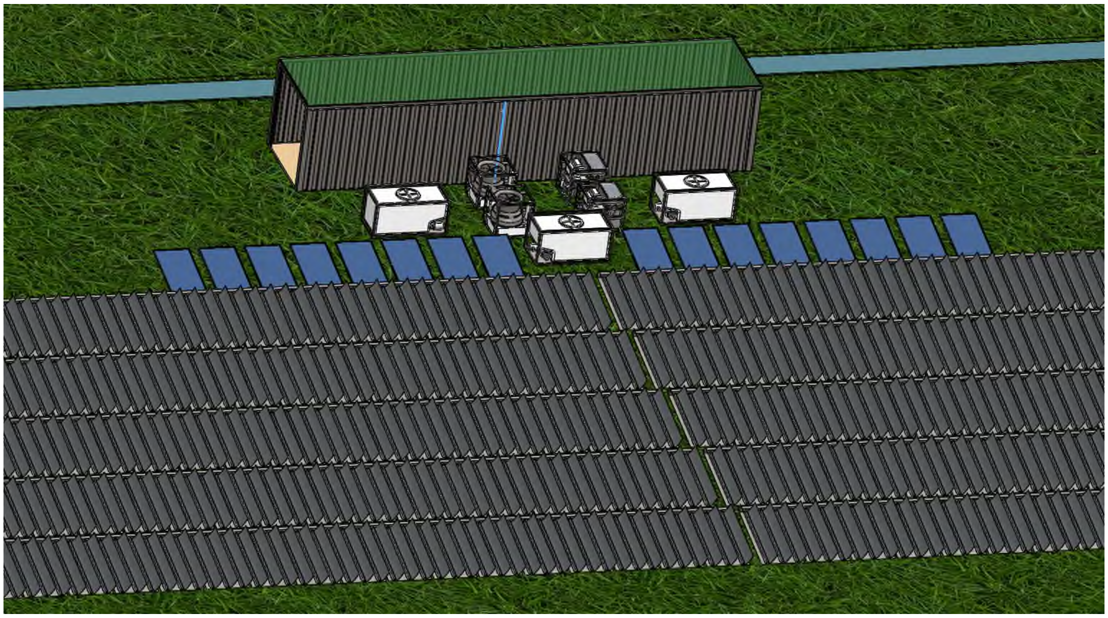
Disaster Response Potable Water System, SAFES, Skid-based



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# 1. INTRODUCTION

## 1.1. Background

Desalination is generally performed in large, permanent, and complex facilities. This approach is effective with availability of abundant salinated water and energy supplies. In the United States, clean, potable water for population centers is generally available from less salinated sources. The exception generally coincides with a natural disaster or temporary condition. In these cases, a quickly deployable and scalable solution is required to process "dirty" water into potable water for cleaning, cooking, and ingestion.

## 1.2. Proposed Concept

The proposed concept is a Skid-based Automated Flash Evaporator System (SAFES) that can transform almost any water source to municipal quality water. Each component is transportable with standard vehicles or hand carried to remote or difficult to access sites. A single skid set provides potable water for a few households. Operation of skid sets in parallel provides infinite scalability.

The target market is municipal drinking water from brackish water or RO concentrate. This aligns with a concept of operations where water is sourced from inland waterways, or supplementing RO systems during disaster recovery or temporary water shortages.

Critical features of SAFES are:

1. Portable – SAFES consists of small skids easily maneuvered into normally inaccessible locations.
2. Self-Supported – Skids operate off-grid. Solar thermal energy is used for the desalination process while photovoltaic panels provide electrical power to pumps and process management equipment.
3. Source Water Flexibility – Staged filtration and purification is used to enable purification of water from almost any source without costly membrane exchanges, heavy maintenance loads, or difficult to manage waste streams.
4. Low capital investment – Customers procure only the equipment needed and expand capability later. This lowers the initial cost of ownership and expands the market to those without a large amount of initial capital.
5. Easily Disposable Waste Stream- The waste stream is concentrated at the bottom of a centrifugal separator in a removable and landfill disposable container.

## 1.3. Concept Evaluation Results

Section 2.2 details how the technical merits of SAFES were evaluated. This section reports the results of the evaluation and the conditions used to run simulations.

Three scenarios where considered for the evaluation: recovery from hurricane Matthew, during the California drought season, and during maintenance of the Flint, MI municipal water system. The table below shows the environmental conditions used as a basis for the study.

### Simulation Environmental Conditions

| **Parameter** | **Cases Run** | | |
|---|---|---|---|
| Location | Kinston, NC | Sacramento, CA | Flint, MI |
| Time Period | October 2016 | July (average) | July (average) |
| Temperature (°C) | 25.6 | 34.44 | 27.8 |
| Humidity (%) | 30 | 1 | 30 |

Based on simulation results shown in Figure 1, a pair of skid sets and 100 solar collectors is proposed to balance production rate, thermal efficiency, and transportability. Figure 2 shows thermal efficiency vs. irradiance, highlighting that the irradiance of 1000W/m$^2$ used to develop Figure 1 results is a worst-case scenario. Results from Figure 1 combined with normalized solar insolation rates for the simulated regions are bounding. Approximately 7 hours of equivalent full sun are available in the most limiting location, resulting in approximately 4m$^3$ of water per day produced per skid pair. To meet a production goal of 100m$^3$/day, a total of 26 ISO containers would be delivered to a minimally prepared site and set up in a matter of days.

Simulations show that flash evaporation with only three stages and at low temperatures to minimize scaling (below 90°C) is thermally inefficient compared to larger, more complex facilities. To meet the production target of 100m$^3$/day, an area roughly equivalent to two football fields is required. So even with this decrease in efficiency, the space requirement is not prohibitive, and is offset by the increased flexibility over more permanent solutions.

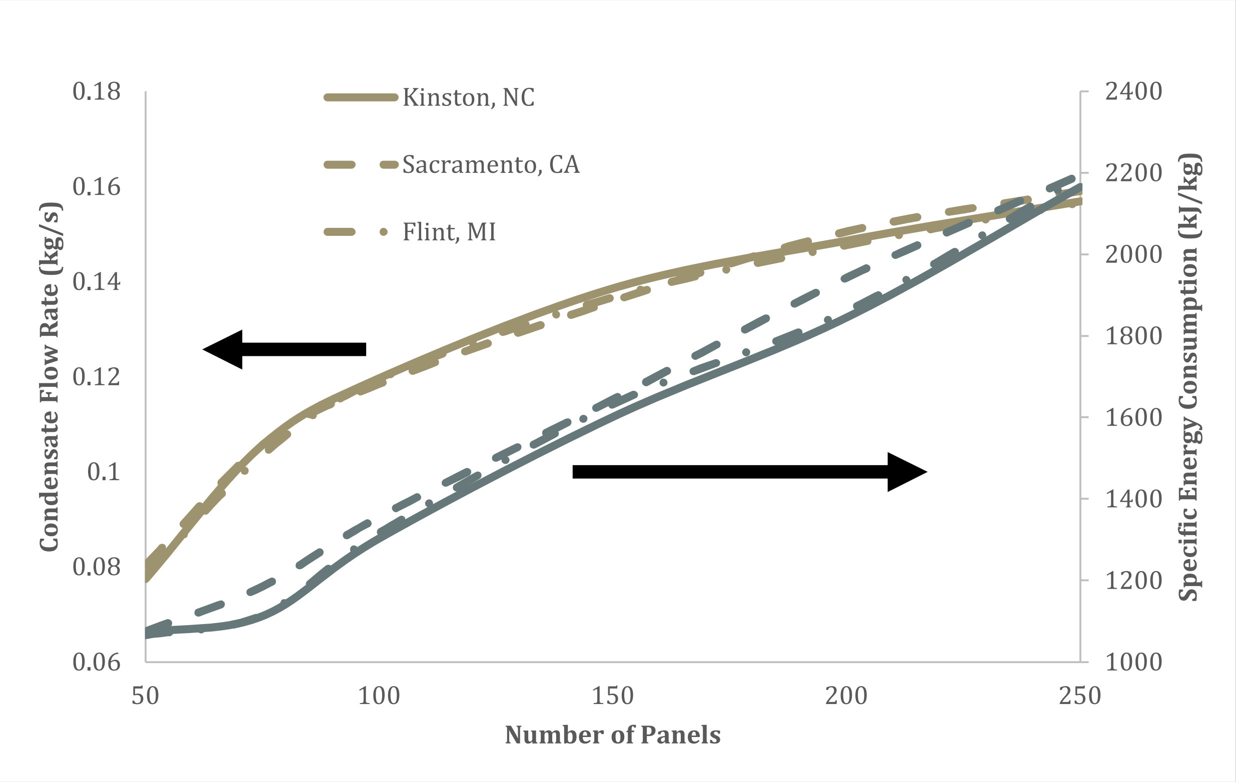


*Figure 1. Condensate Flow and SEC vs. Solar Field Size*

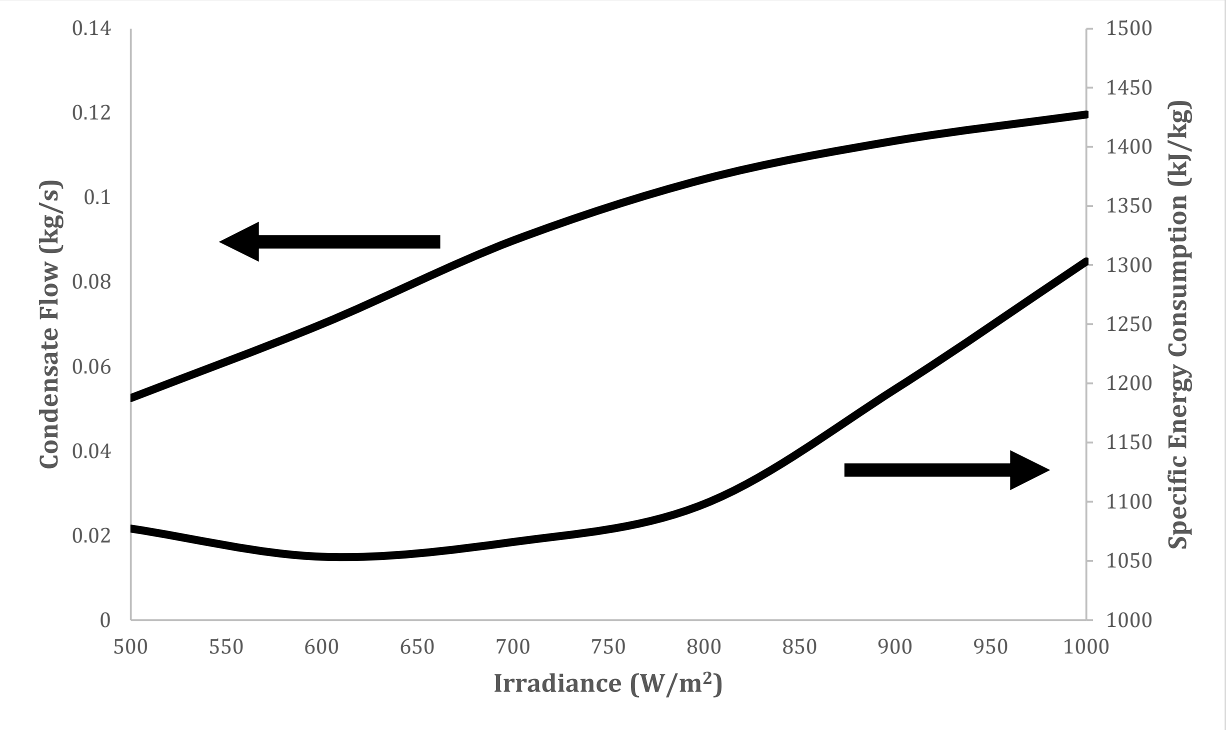


*Figure 2. Condensate Flow and SEC vs. Irradiance*

# 2. TECHNICAL NARRATIVE

## 2.1. Novel Aspects

### 2.1.1. Advancements

#### Use of Miniaturized Thermal Water Desalination

SAFES is a transportable system requiring minimal oversight and is compatibility with various water sources. Transportable skids allow access to areas otherwise not accessible. Unlike an RO system, thermal desalination is less impacted by source water quality, and less likely to degrade in capacity/capability due to membrane fouling or high differential pressures.

#### Flexibility of Capacity and Installation

Only the amount of water purification required is installed and can just as easily removed. The evaporator technology is modular, and configuration changed in the field to extract additional efficiency and/or throughput.

#### Low Operational Burden

Operation is almost entirely automated and requires minimal maintenance. Process monitoring and control is performed by an onboard processor. Disposable media are only used downstream of distillation, and the waste stream is concentrated in a single location, minimizing the volume of waste and simplifying waste management.

### 2.1.2. Building a Prototype

Commercially available components comprise most of the design. Due to low operating temperatures, pressures, and flows, exotic materials will not be required. Construction of prototypes can be performed in multiple shop facilities in parallel to accelerate schedule. Completed systems are stored in shipping containers until needed at the test facility. Validation testing with only a few skids pairs would prove out the concept, removing the need for a large testing program prior to commercialization.

### 2.1.3. Reducing Cost

Low maintenance requirements and exclusive use of solar energy result in minimal operational cost. Novel integration of pre-filtering, brine cooling, and automation allow for extended unsupported operation. Cleaning, when required, can be done in the field with common tools. Only the amount of production required is installed, further minimizing cost.

## 2.2. Concept Feasibility

### 2.2.1. Technical Feasibility

To determine technical feasibility, critical characteristics of SAFES are identified below.

1. Source water is dosed with chemicals, then circulated through a centrifugal separator to remove precipitates. Feasibility of chemical treatment and mechanical separation is common and not addressed during the concept stage.
2. A unique multi-stage flash distilling unit is used for purifying the feedwater. This is the major technology of the concept and requires verification that flash evaporation can be performed at this scale. Feasibility is demonstrated through creation of a simulation discussed in detail below.
3. Salinated input to the flash distiller is heated using solar thermal collectors. This technology is mature, so feasibility is not addressed in the concept stage.
4. Recycled brine is cooled with an evaporative cooler prior to re-introduction into the pre-treatment tank. The simulation discussed below demonstrates feasibility of this type of cooling in various climatic conditions.
5. Downstream of the flash distiller, distillate is processed through various filters and a UV sanitizer. This is mature technology and feasibility is not addressed in the concept stage.
6. SAFES is operated by an onboard computer using sensor inputs and various control sub-systems. Process sensing and control technology is mature and feasibility is not addressed during the concept stage.
7. Power for electrical components is provided by photovoltaic cells. The amount of power required for the skid system is determined by the simulation to verify that the power supplied by photovoltaic cells is sufficient.
8. Packaging is a primary characteristic of SAFES. Detailed modeling of SAFES components is performed to ensure the target space envelope can be achieved.

### Small Scale Multi-Stage Flash Evaporator Feasibility

A three stage flash evaporator is the core technology. To meet packaging requirements, unique construction and flow paths were required. The evaporator is comprised of three identical stages, stacked vertically, and separable. A breakaway of the top stage is shown in Figure 3. The flow through the evaporator is shown schematically in Figure 4.

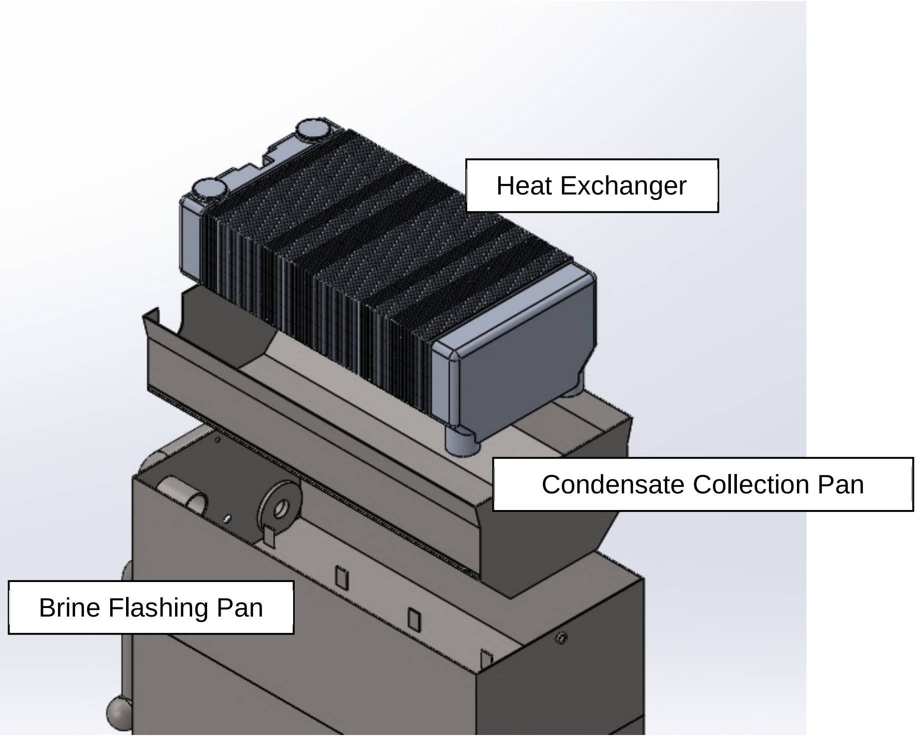


*Figure 3. Breakaway of Top Stage*

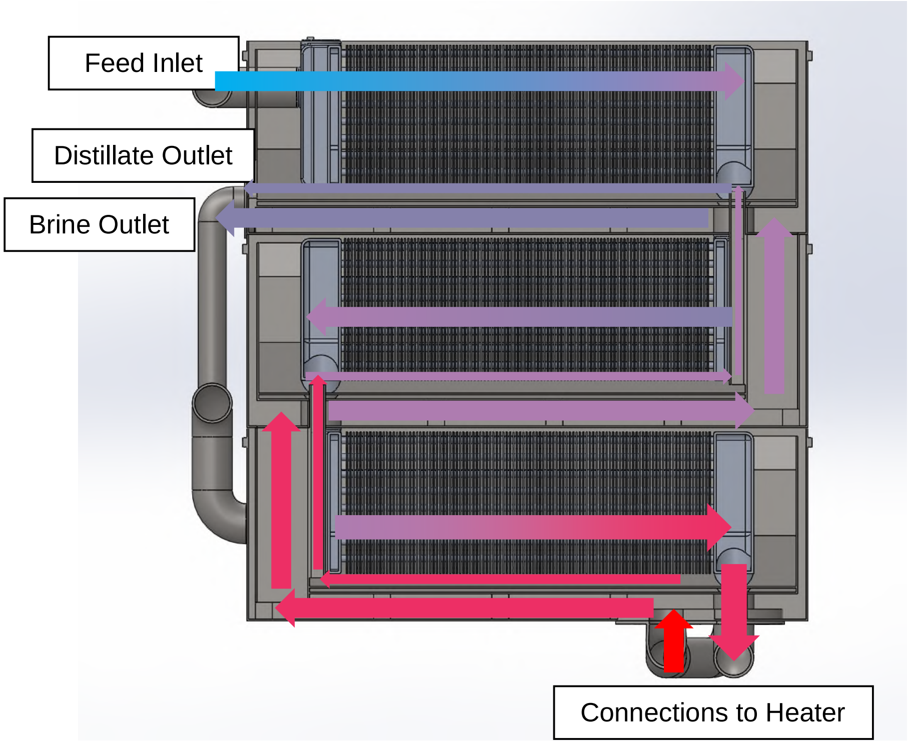


*Figure 4. Flow Through the Flash Evaporator*

A simulation of the SAFES system was developed, capturing all of the thermodynamic processes and fluid flow characteristics. An iterative solution is required to capture the co-dependence of sub-systems. The flow chart below outlines the approach.

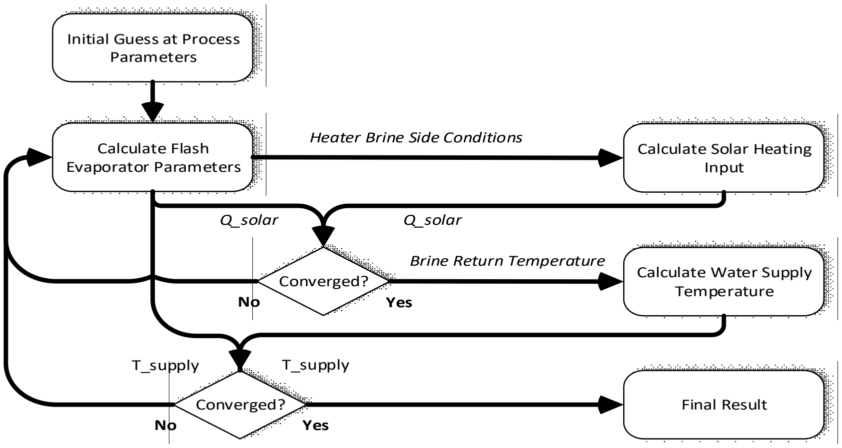


*Figure 5. Simulation Iterative Flow*

Results of the simulation validate technical feasibility of SAFES. A summary of the results is provided in Section 1.3. A white paper with more calculation details and results will be posted at www.sigmaexpertsolutions.com/design/. Methods and assumptions used in each simulation block are summarized below.

### *Calculate Flash Evaporator Parameters*

A model of the flash evaporator balances the heat absorbed during feedwater pre-heating and condensation energy of flashed steam. Process conditions from other systems that impact operation are initially guessed.

*Assumptions:*

- There is a 5°C temperature elevation required (temperature of the brine must be at least five degrees over saturation temperature) in the evaporating liquid to drive the flash process.
- Water properties are not significantly impacted by contaminants in the water stream.

### *Calculate Solar Heating Input*

The amount of heating required by the evaporator is balanced against heat transfer rate from the solar collectors. The heater inlet temperature on the brine side is iterated until convergence is met between the two calculations.

*Assumption:*

- High temperature solar heating panels provide water temperatures much higher than the maximum brine temperature.

### *Calculate Water Supply Temperature*

Brine discharge from the evaporator is sent to the evaporative cooler model. Combined with user input of environmental conditions (temperature and humidity) an updated evaporator supply temperature is determined. Supply temperature is iterated until convergence is met.

*Assumptions:*

- The source water is at ambient temperature.
- The evaporator is capable of saturating the incoming air to 90% humidity.

### Evaporative Cooler

The simulation performed above demonstrates feasibility of the evaporative cooler modeled at modeled environmental conditions.

### Electrical Power Requirements

Pumping power is calculated during the simulation based on differential pressure and flow rate for each of the process pumps. The electrical power requirements for the fan and vacuum pump are based on manufacturer's data. Auxiliary, sensing, and control power is estimated as constant based on experience. Simulation results show that 600W bounds the power consumption of a skid set. Assuming 15% efficiency of photovoltaic panels, a minimum of $4m^2$ meters is required. Packaging studies showed that $16m^2$ of panels can be easily accommodated.

*Assumptions:*

- Pumps are 75% hydraulically efficient and 90% electrically efficient.
- The brine return pump will not cavitate.
- The vacuum pump selected is sufficient in size to remove condensable gases.

### Packaging

To support the concept of operations, two skid sets and related support equipment must fit within a single ISO container. Solid modeling of SAFES components (skids show in Figures 7 and 8) is performed and shown integrated into a container (Figure 6).

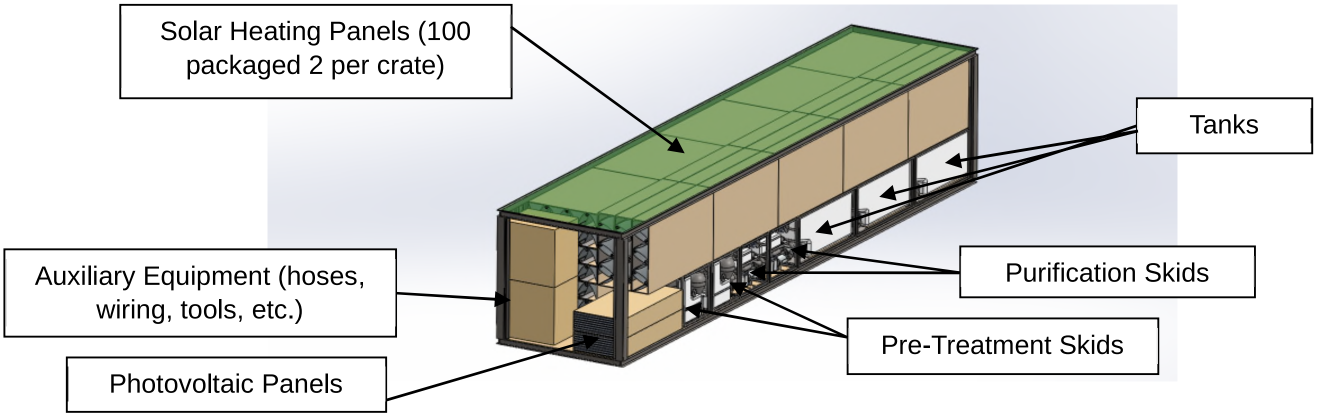


*Figure 6. Packed Pair of Skids with Support Equipment*

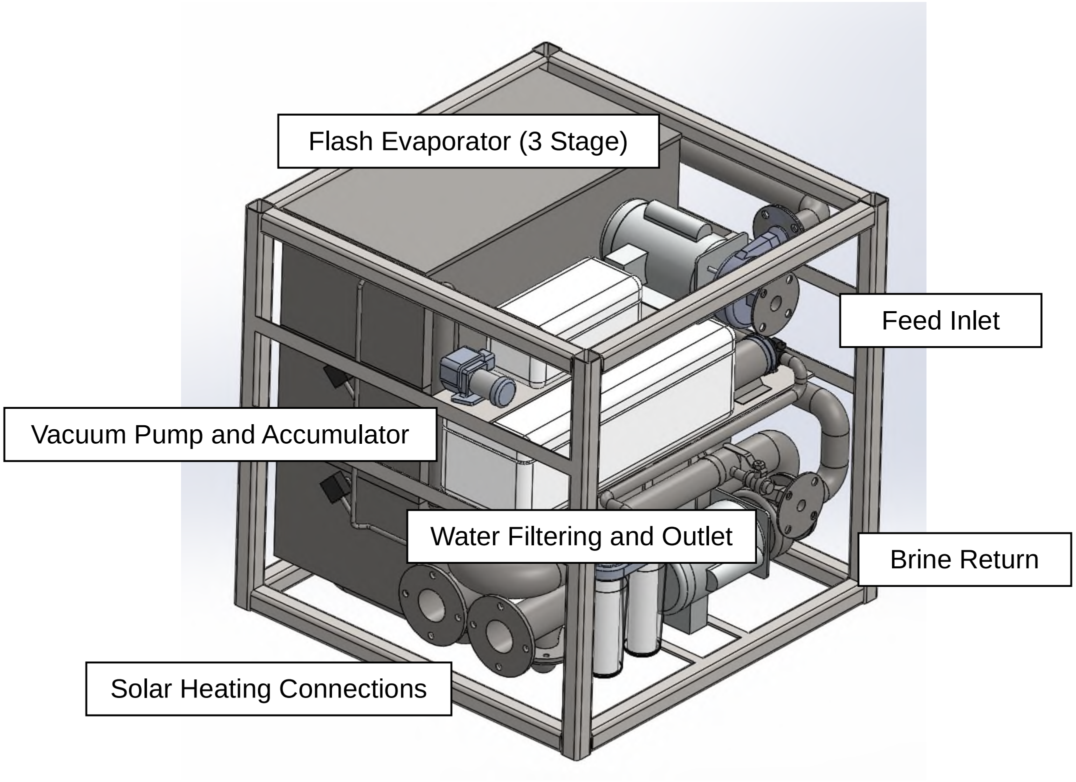


*Figure 7. Purification Skid*

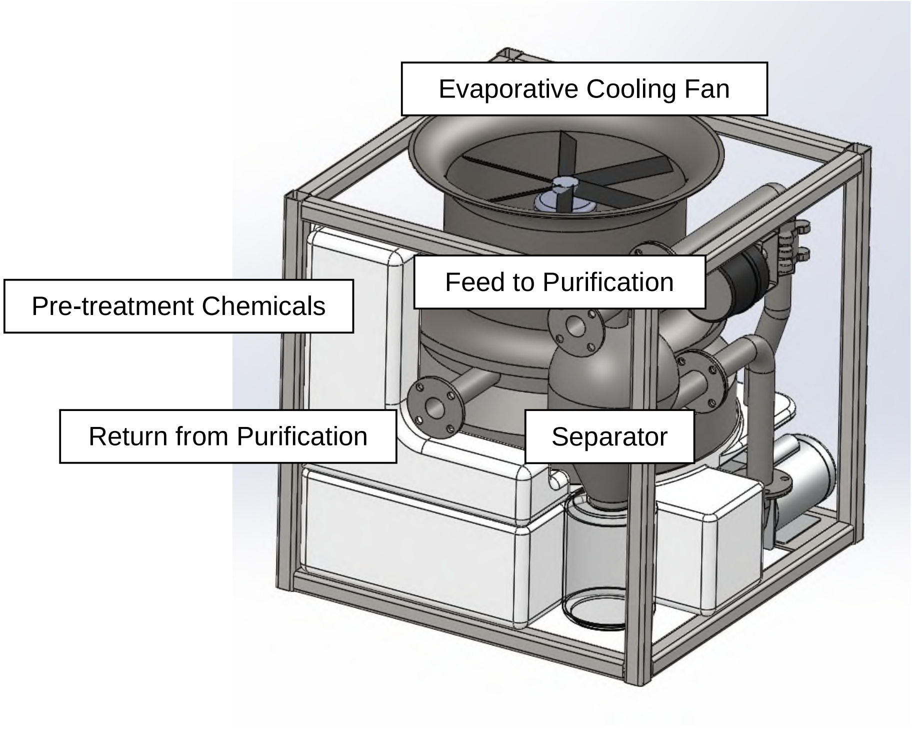


*Figure 8. Pre-Treatment Skid*

### 2.2.2. Implementation Feasibility

To establish implementation feasibility, a logic driven schedule was built with critical activities and key milestones. A rolled-up version of this schedule is shown in Figure 9.

#### Technical Milestones

Technical milestones shown in the schedule represent include testing, demonstrations, reviews, and construction.

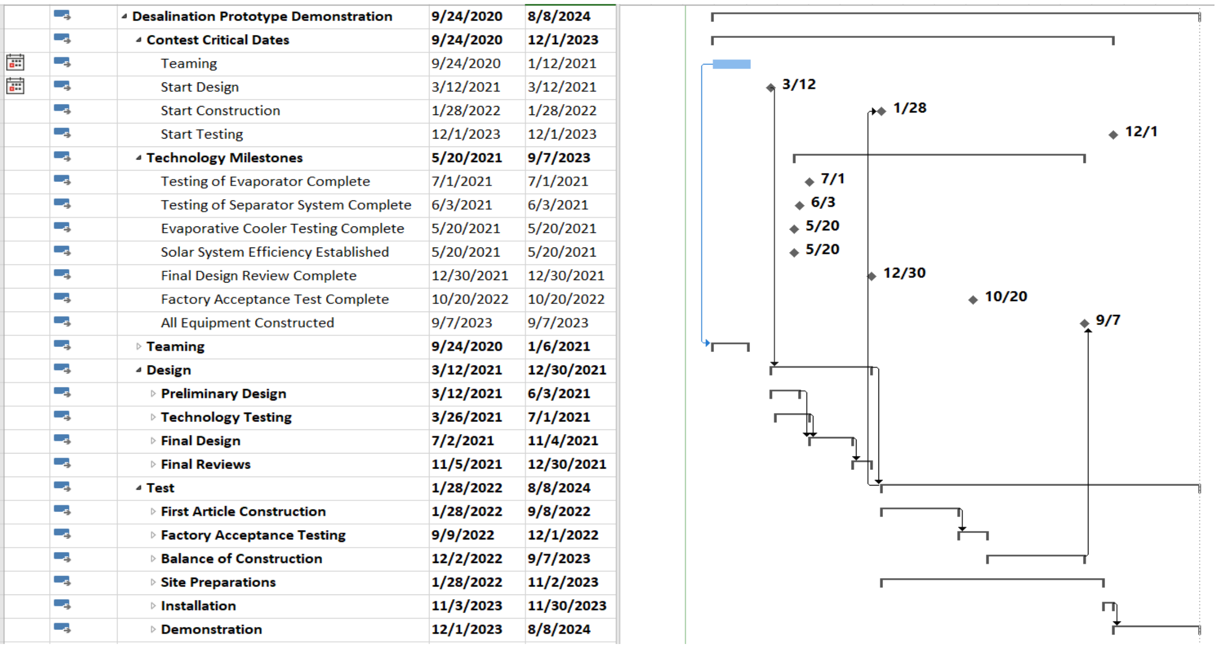
#### Development Cycle

The progression from a preliminary design through the final testing phase and preparations for commercialization is detailed in the schedule. The construction timeline is based on producing enough skids to meet the 100m3/day requirement – a timeline that could be accelerated if testing of only a few skid sets were required.

#### Key Performance Parameters

Key Performance Parameters (KPPs) for SAFES are used to demonstrate achievement of the project objectives. The KPPs include:

- Provide water quality from high salinity sources to meet potable water requirements.
- Operate effectively in different environments.
- Have low operating and maintenance costs.
- Install water production capability within days of equipment delivery.



| | | |
|---|---|---|
| **Desalination Prototype Demonstration** | **9/24/2020** | **8/8/2024** |
| **Contest Critical Dates** | **9/24/2020** | **12/1/2023** |
| Teaming | 9/24/2020 | 1/12/2021 |
| Start Design | 3/12/2021 | 3/12/2021 |
| Start Construction | 1/28/2022 | 1/28/2022 |
| Start Testing | 12/1/2023 | 12/1/2023 |
| **Technology Milestones** | **5/20/2021** | **9/7/2023** |
| Testing of Evaporator Complete | 7/1/2021 | 7/1/2021 |
| Testing of Separator System Complete | 6/3/2021 | 6/3/2021 |
| Evaporative Cooler Testing Complete | 5/20/2021 | 5/20/2021 |
| Solar System Efficiency Established | 5/20/2021 | 5/20/2021 |
| Final Design Review Complete | 12/30/2021 | 12/30/2021 |
| Factory Acceptance Test Complete | 10/20/2022 | 10/20/2022 |
| All Equipment Constructed | 9/7/2023 | 9/7/2023 |
| **Teaming** | **9/24/2020** | **1/6/2021** |
| **Design** | **3/12/2021** | **12/30/2021** |
| **Preliminary Design** | **3/12/2021** | **6/3/2021** |
| **Technology Testing** | **3/26/2021** | **7/1/2021** |
| **Final Design** | **7/2/2021** | **11/4/2021** |
| **Final Reviews** | **11/5/2021** | **12/30/2021** |
| **Test** | **1/28/2022** | **8/8/2024** |
| **First Article Construction** | **1/28/2022** | **9/8/2022** |
| **Factory Acceptance Testing** | **9/9/2022** | **12/1/2022** |
| **Balance of Construction** | **12/2/2022** | **9/7/2023** |
| **Site Preparations** | **1/28/2022** | **11/2/2023** |
| **Installation** | **11/3/2023** | **11/30/2023** |
| **Demonstration** | **12/1/2023** | **8/8/2024** |

*Figure 9. Proposed Schedule*

## 2.3. Concept Impact

The ability to provide clean water during disaster recovery, temporary drought conditions, or other temporary water emergencies improve the quality of life and health of the population impacted. Additionally, economic benefits described below could also be realized.

### 2.3.1. Why Investors would be Interested

Small scale desalination has broader applicability and requires less capital investment than large, permanent facilities. This lowers risks for investors and increases the flexibility of implementation. Additionally, federal funding available for disaster relief may provide a steady revenue stream for owners of a portable system.

# A. RESPONSE TO TECHNICAL APPENDIX: PERFORMANCE METRICS

Performance metrics and topics highlighted in the technical appendix are addressed below.

- LCOW=2.51 (See table below for inputs)
- LCOH=2.25 (See table below for inputs)
- Thermal energy consumption is dependent on the environmental conditions and flow rates. See Figures 1 and 2 for more details.
- Continuous circulation is used to facilitate precipitation of contaminants in a mechanical separator. The final recovery ratio for the system will approaches unity, with little liquid discharge from the mechanical separator.
- Annualized Solar Thermal Efficiency is not addressed by this concept.
- Continual mechanical separation and pre-treatment results in a very concentrated (sludge-like) discharge with high chemical efficiency usage (as the chemicals are recirculated with the brine). Waste heat is exhausted to the air and not a water source. Both approaches minimize environmental impact.

**Inputs used for LCOW and LCOH calculation**

| **Parameter** | **Value** | **Units** | **Basis** |
|---|---|---|---|
| Overnight Capital Cost | **64,989.28** | $\$/m^3$ | Class 4 bottoms up estimate with 10% contingency divided by 100m$^3$ of production per day. See breakdown below. |
| Cost of Skid Set Construction | 53,100 | \$ | Bottoms up estimate of one skid set (52 required). |
| Cost of Tank Construction | 14,088 | \$ | Bottoms up estimate of one tank skid (3 per skid set) |
| Cost of Solar Concentrators and Shipping Container | 55,000 | \$ | Estimate for 100 solar concentrators and ISO container (26 required). |
| Cost of Delivery and Installation | 110,000 | \$ | For freight on 26 skid pairs, installation labor, and 2 acres of land area |
| O&M Cost | **4,680**<br>**2.25** | $\$/m^3$-yr<br>$\$/m^3$-hr | Weekly cost developed below as basis for fixed and variable cost. |
| Technician | 8,000 | \$/wk | Perform routine maintenance with two technicians full time. |
| Consumables | 1,000 | \$/wk | For cleaning supplies and carbon filters. |
| Capacity Factor | **0.3** | % | Average anticipated solar availability at 1000W/m$^2$ |
| Desalination Capacity per hour | **14.6** | m$^3$/hr | See main report |
| Solar Plant Energy Capacity per Hour | **1300** | kW-hrs | 26 100 panel installations at 50% efficiency (1000W/m$^2$ irradiance assumed). |