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Title of Project:

Cost-Effective Treatment of Produced Water Using Co-Produced Energy Sources

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ABSTRACT

The objective of this project was to upscale the humidification dehumidification (HDH) process tested successfully at field scale in RPSEA Project 07123-05, "Cost-Effective Treatment of Produced Water Using Co-Produced Energy Sources for Small Producers," and to demonstrate a viable and cost effective process using solar energy or waste heat to augment the process for continuous operation. Increased automation and maintenance parameters were evaluated and put in place to allow unattended operation for several days or even weeks at a time and a full-scale prototype was constructed and operated at a field gathering site for a period of four months with the goal of reducing disposed water to less than 20% of the original volume. Technology transfer efforts focused on commercialization of the technology.

This research targeted produced water purification at the wellhead and beneficial use in oil production, i.e., drilling fluid, stimulation fluid, and waterflooding. The project was completed in a single Phase. Year 1 focused on optimizing the existing process to determine maximum throughput and optimal scaling of individual as well as series, or parallel units. Addition of automation, solar panels and banked heat via insulated tanks were implemented to allow for continuous operation. A thorough study of the corresponding latent heat recovery, heat and mass balances on the system, and overall efficiencies was made. Preventive maintenance schedules for the prototype were established and continuous improvements on the process were carried out using an optimization approach, with regard to process costs, packing material, inlet water temperature and other important parameters as established in the previous work on this subject. An optimized prototype for handling higher quantity of produced water with increased automation was assembled, and tested in the field using solar panels for process heating. After testing, the scaled and automated production prototype was demonstrated at a well site. Insulated storage tanks for collecting the heated produced water provide for 24 hour operation. Prolonged operational tests were used to establish preventive maintenance schedules and associated process and operation costs.

Submitted and Signed February 29, 2015 by:

Robert S. Balch
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LIST OF ACRONYMS

NMT	New Mexico Tech aka New Mexico Institute of Mining and Technology
PRRC	Petroleum Recovery Research Center
HLLC	Harvard Petroleum Company LLC
ACC	Air Cooled Condenser
CFM	Cubic Feet per Minute
PMMA	Polymethylmethacrylate (Plexiglass)
PW	Produced Water

EXECUTIVE SUMMARY

This report presents field testing results and economics analysis at pilot scale for a humidification dehumidification (HDH) process, and demonstrates that the process is viable and cost effective process using solar, latent geothermal, and waste heat to augment the process for continuous operation.

The HDH process drops produced water heated to 145-185°F down chambers with upblowing ambient air which humidifies the air at elevated temperature to relative humidity >99%. The water laden air then drops into adjacent cooling chambers and fresh water condenses out. Additional fresh water yield is achieved by using a secondary air-cooled condenser. To accomplish pilot test goals, a field scale prototype was constructed and tested at a field test site near Artesia, New Mexico, to determine operational parameters with solar heating, and then at the Federal 00 well in Eddy County, New Mexico, an oil well that produces ~20 bbl/d of water, to test unattended operation and economics.

The HDH unit was sized for the Federal 00's water production and can process 50 bbl/d of produced water. The field setup utilizes latent geothermal heat in the produced and heat is added to the water using an array of 16 flat plate solar panels. Heated water passes into a storage vessel which then feeds the HDH unit. When the solar panels are not generating heat, produced water is fed directly into the heated storage. At night or on cloudy days additional heat can be supplied to the storage tank by burning waste gas. An Arduino controller manages the process flow, and switches fluid flow as needed, and monitors tank levels. The HDH unit can purify ~20% of the inlet water on each pass, and the outlet concentrate at ~135°F, is cycled back into the hot water storage tank.

The system was tested in summer and winter conditions. Winter conditions have drier inlet air, but less solar energy, and conversely summer has wetter inlet air, but more available solar heating. Summer tests yielded ~7 bbl/d of purified water, and winter tests produced ~11 bbl/d, for an annualized average of ~9 bbl/d, cutting the disposal needed for the Federal 00 in half. Purification costs is from electricity use of small pumps, a blower, and an air-cooled condenser costs $3.60 per day, corresponding to ~$0.51 per barrel in summer and ~$0.34 per barrel in winter to purify water. Cost offsets from selling the fresh water, and reduced disposal costs yielded an 85% reduction in annualized produced water handling costs.

REPORT DETAILS

This project represents the upscale of a humidification dehumidification (HDH) process that was tested successfully in RPSEA Project 07123-05, "Cost-Effective Treatment of Produced Water Using Co-Produced Energy Sources for Small Producers," and to demonstrate a viable and cost effective process using solar energy or waste heat to augment the process for continuous operation.

This project expands on results from the prior project, providing additional research work on integrating solar and other supplemental heat sources, field scale demonstration of full automation, and determining appropriate scaling to suit any small to mid-sized size water disposal operation.

Objectives

The primary objective of the research was to further test the HDH process that was tested successfully in RPSEA Project 07123-05, "Cost-Effective Treatment of Produced Water Using Co-Produced Energy Sources for Small Producers," and determine operational parameters for the process under a commercial scale application.

The existing field prototype had been tested at up to 20 bbl/8 hr or 50–60 bbl/d when prorated to a 24-hour basis, using somewhat arbitrary inlet rates. Additional testing to determine maximum throughput and most efficient throughput rates needed to be performed. Additionally, a system for on-site heat management using solar panels, waste heat, and on-site insulated storage implementation needed to be implemented and tested to allow the system to run at night and during cloudy days and to allow unattended operation for several days or even weeks at a time. The prototype needed to be adapted for commercial operation and operated at a field gathering site for several months with the goal of reducing disposed water to half of the original volume. A thorough study of the corresponding latent heat recovery, heat and mass balances on the system, and overall efficiencies was needed. Preventive maintenance schedules for the prototype needed to be established and allow for continuous improvements on the process using an optimization approach, with regard to process costs, packing material, inlet water temperature and other important parameters.

Previous HDH Development

Humidification-dehumidification is a thermal water desalination process. The HDH process is governed by relative humidity, where the water carrying capacity of the inlet air stream in the prototype is optimized for maximum condensate recovery. From a perspective of partial pressures, water saturated air at 30°C and 80°C has a water partial pressure of 31.8 mm Hg and 355.1 mm Hg respectively; this demonstrates an increase in the water carrying capacity at elevated temperatures. The HDH prototype developed in the predecessor to this project, **RPSEA 07123-05 "Cost-Effective Treatment of Produced Water Using Co-Produced Energy Sources for Small Producers,"** took advantage of this effect by loading air with water at heightened temperatures at the inlet near the top of the system. As temperature decreases while the water drops through the system, distilled water and concentrate drop out in separate streams. The process is optimized by using co-produced energy sources (solar, hot formation inlet water, use of waste gas for heat, etc.) and the heat generated from internal condensation, which releases latent heat to further evaporate the inlet produced water stream. In the prototype, a marked temperature gradient exists within the unit from the top to the bottom, with the highest temperature at the top of the unit where heated inlet water enters the system.

Experiments conducted on the prototype included laboratory scale, bench scale and field scale prototype tests, and a large amount of data were collected. The laboratory and bench scale tests were conducted to prove the concept and field scale tests were aimed at optimizing the process parameters and maximizing the yield. A wide range of produced water concentrations were tested in the laboratory and the field. Bench scale test results showed salt removal efficiency of over 92% and field scale test results from a test site in SE New Mexico for inlet produced water concentrations of 182,000 to 210,000 ppm resulted in water with total dissolved solids (TDS) between 80–245 ppm, which is lower than many municipal water supplies. That project demonstrated that the HDH process was viable and inexpensive relative to other saltwater disposal technologies at laboratory bench scale and field scale.

1. Experimental Methods

This work comprises four major components: the optimization of the prototype HDH unit developed in the first RPSEA project; deployment and optimization of passive solar heating to

preheat the inlet stream; adaptation (or fabrication) of a full-scale production prototype and its assembly in a portable trailer unit; and field validation with a full-scale field test held at the well-head of a producing well. Section 1.1 discusses the optimization of the unit size and throughput. Section 1.2 discusses the maximum volume testing and Section 1.3 discusses HDH module scale optimization. Wellhead testing of the HDH system is summarized in Section 2.

1.1 Optimization of HDH Unit Size and Throughput

A prototype, 80 ft^3 HDH unit (shown in Figure 1) consisting of 11 compartments was constructed in a previous project [Muraleedharan, 2009; Balch et al., 2012; Balch and Muraleedharan, 2014] and was tested successfully at field scale in RPSEA Project 07123-05, "Cost-Effective Treatment of Produced Water Using Co-Produced Energy Sources for Small Producers." This unit was field-tested using short duration tests and an electric steam generator.

In this project, additional calibration and long term testing were completed and produced water (PW) was heated with inexpensive and environmentally friendly solar energy (Figure 1); of the 11 compartments, six are evaporation chambers and the remaining five are used for condensation; heated PW is pumped into the six evaporation chambers and ambient air is blown into those chambers in an opposite direction to the fall of the heated inlet water. To increase residence time and interphase mass transfer between the fluids, corrugated materials were inserted into the evaporation chambers. The humidified air moves into the subsequent condensation chamber where fresh water condenses out as it cools. Additional water can be extracted using an air-cooled condenser to improve yield. Water quality depends on the volumes pushed through the system and can be as lows as 50 ppm TDS. At an optimized operational rate, TDS is around 400 ppm.

1.1.1 Preparation for Volume Testing

The existing prototype was cleaned up, minor repairs were made and stress testing of the unit was accomplished. Section 1.1.2 describes the results of this parametric testing of the HDH unit.

1.1.2 Performance of Maximum Volume Tests

Optimization of the HDH unit size and maximum throughput is a critical milestone of the project that was set for summer of 2013. The HDH unit was set up at a field site near Artesia, New Mexico. The two week test was started in late July and ended in the first week of August 2013. The goals of the tests were accomplished despite rain, extremely strong winds and varying humidity during day and night testing.

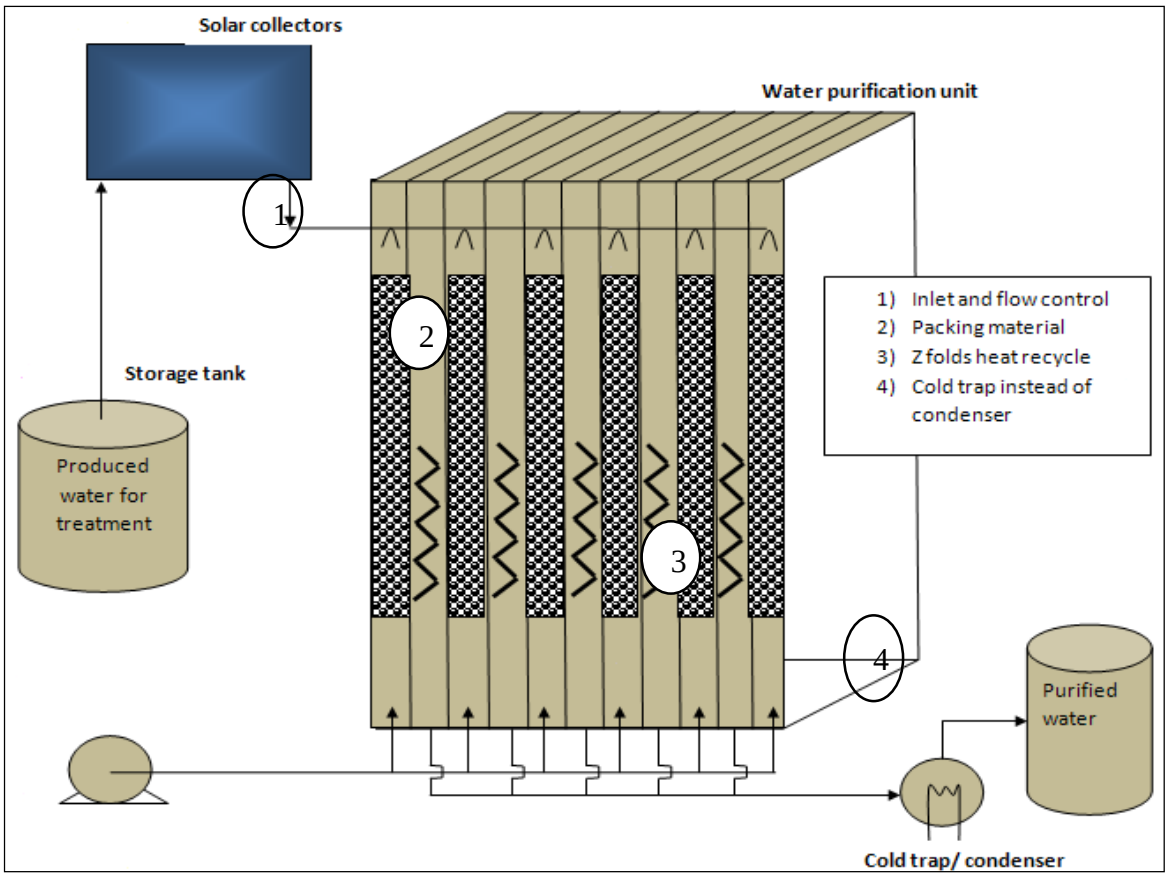


Figure 1. Schematic diagram of the HCH Process (Balch, 2012).

The main goal of this test was to successfully determine the maximum throughput that the existing unit (built in Phase1), sized 72 in. × 48 in. × 39 in., can process effectively. In addition, the optimum inlet rate of fluids (heated produced water and air) was to be established with the goal of understanding sizing constraints for the process. Finally, the maximum volume of water that could be evaporated into the air (reduction of waste stream while not optimizing purified water production) needed to be determined. The tests and testing schedule were designed to meet these objectives.

Primary parameters that affect the efficiency of the HDH unit are the humidity and temperature of the ambient air (dry bulb) so the tests were conducted at the time of the year when these two main parameters are at their zenith; thus, the higher the temperature and humidity of the surrounding air, the lower the efficiency of the unit. The test that was conducted in this period (high temperature and high humidity) provided invaluable information about the operation and efficiency of the system under a worst case scenario. Similar tests were also performed in the winter when it is both cold and dry, representing optimal operating conditions.

1.1.2.1 Optimum Feed Rate Determination

Tests 1-5: Optimum feed rate determination

The goal of the test series from Test one (1) to Test five (5) was to determine the optimum inlet water and inlet air feed rate that produced the highest yield of condensate and also to establish a relationship between the inlet air rate in Hertz (revolutions per second of the air blower) and total dissolved solids in the produced condensate. This was achieved by incrementally varying the feed rate from 0.5 gal/min (Test 1) to 2.5 gal/min (Test 5) and 30 Hz to 50 Hz for untreated inlet water and inlet air rate respectively. Table 1 shows average environmental parameters for Tests 1–5. Table 2 gives a conversion from fan HZ to ft^3/min of air flow.

Table 1. Environmental Parameters for Tests 1-5	
Average Ambient Air Temperature and Relative Humidity: 90°F and 50%	Total Dissolved Solids of Inlet Produced H_20 : 200,000 ppm
Range of Inlet Water Temperature: 170°F–180°F	Duration of Each Test : 20 minutes

Table 2. Air Inlet Conversion from Frequency to Volumetric Flow Rate		
Diameter:	2.25	in
Cross sectional area:	0.02761084	Ft^2
Pump frequency (Hz)	Velocity (ft/min)	Volumetric flow rate (ft^3/min)
30	4200	116.0
35	4450	122.9
40	5010	138.3
45	5450	150.5
50	5800	160.1

Test 1- Water Inlet Rate of 0.5 Gal/Min, Varying Air Inlet Rates

Test 1 was designed to determine how much air could be pushed through the system. A series of three test runs at each air inlet rate was used to verify consistency of test results. Table 3 shows the results of varying air inlet rates at a constant produced water feed rate of 0.5 gal/min. Results from Table 3 are also shown graphically in Figures 2-3.

Table 3: Test 1- Water Inlet Rate of 0.5 gal/min, Varying Air Inlet Rates

H_2O feed rate (gal/min)	Inlet air rate (Hz)	Volume (gal) of conden-sate (test run 1)	Volume (gal) of conden-sate (test run 2)	Volume (gal) of conden-sate (test run 3)	TDS (ppm) of conden-sate (test run 1)	TDS (ppm) of conden-sate (test run 2)	TDS (ppm) of conden-sate (test run 3)
0.5	30	0.5	0.65	0.63	50	63	55
0.5	35	0.61	0.70	0.68	70	90	85
0.5	40	0.70	1.0	0.95	250	280	300
0.5	45	0.68	1.0	0.98	320	375	320
0.5	50	0.7	0.98	0.97	412	418	421

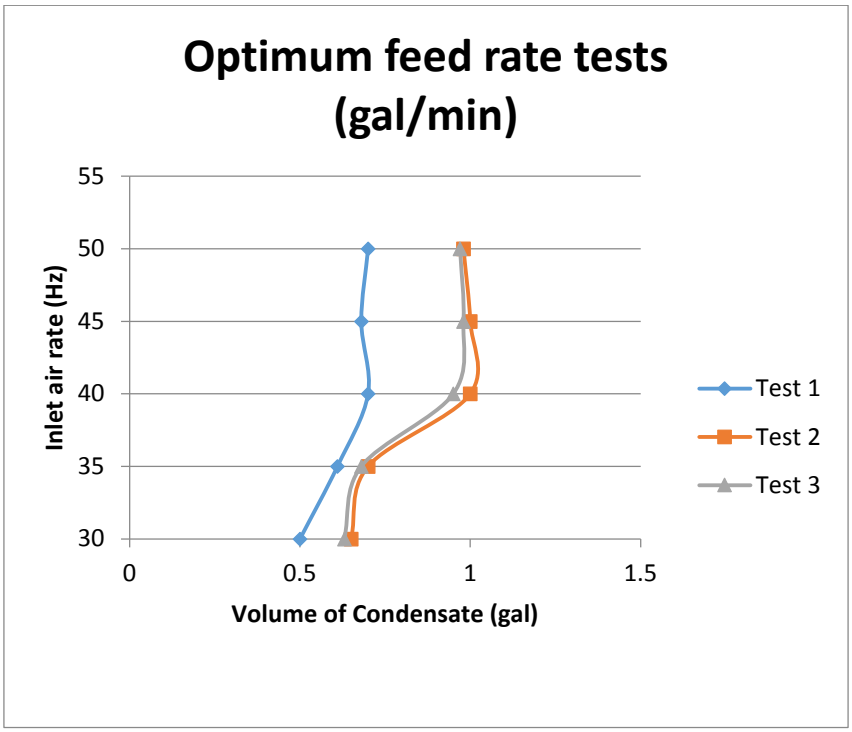


Figure 2. Condensate volume as a function of air inlet rate at 0.5 gal/min inlet water rate.

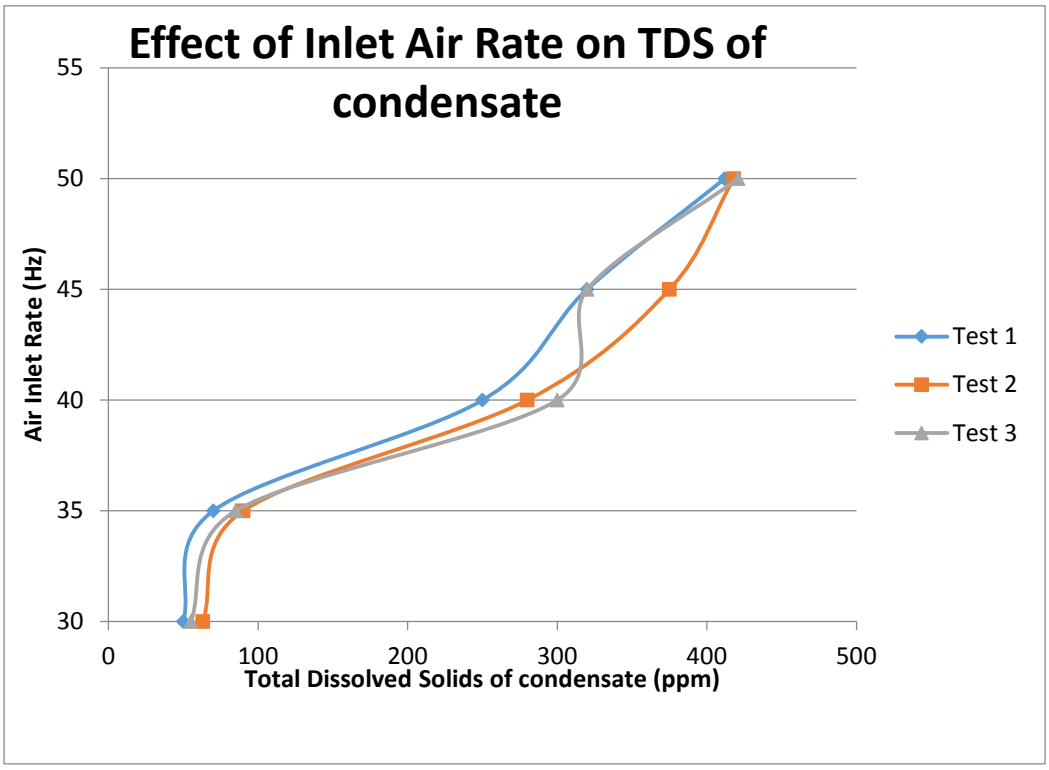


Figure 3. Variation of TDS in the concentrate as a function of air inlet rate at 0.5 gal/min inlet water rate.

The results of Test 1 show that it is possible to increase the throughput of the system by 50% by pushing more air through the system, with a resultant increase in TDS in the purified water stream. This series of tests did not push the purified water above safe drinking water limits.

Test 2- Water Inlet Rate of 1.0 Gal/Min, Varying Air Inlet Rates

Test 2 was also designed to determine how much air could be pushed through the system, though with a greater water inlet rate than in Test 1. A series of three test runs at each air inlet rate was used to verify consistency of test results. Table 4 shows the results of varying air inlet rates at a constant produced water feed rate of 1.0 gal/min. Results from Table 4 are also shown graphically in Figures 4-5.

Table 4: Test 2- Water Inlet Rate of 1.0 Gal/Min, Varying Air Inlet Rates							
H_2O feed rate (gal/min)	Inlet air rate (Hz)	Volume (gal) of condensate (test run 1)	Volume (gal) of condensate (test run 2)	Volume (gal) of condensate (test run 3)	TDS (ppm) of condensate (test run1)	TDS (ppm) of condensate (test run 2)	TDS (ppm) of conden-sate (test run 3)
1.0	30	0.7	0.8	1.1	65	63	75
1.0	35	1.0	1.1	1.98	200	190	400
1.0	40	1.25	1.20	1.5	280	380	420
1.0	45	2.6	2.8	3.2	320	400	450
1.0	50	2.25	2.60	2.60	435	480	450

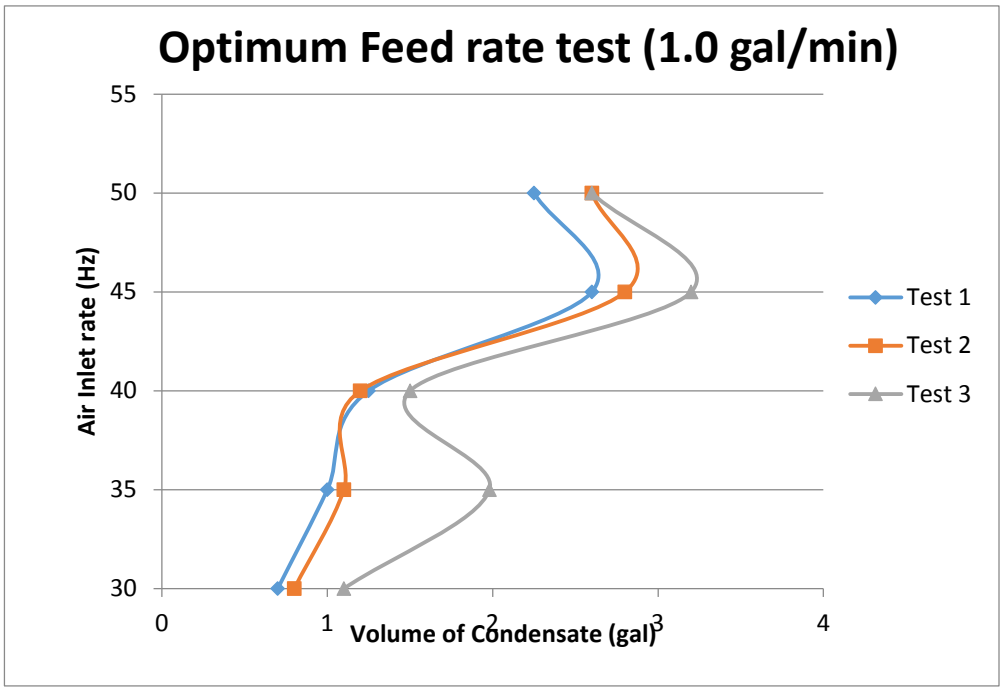


Figure 4. Condensate volume as a function of air inlet rate at 1.0 gal/min inlet water rate.

The results of Test 2 show that it is possible to increase the throughput of the system by 300% by pushing more air through the system and by doubling the produced water inlet rate. The resultant increase in TDS in the purified water stream did not push the purified water above safe drinking water limits.

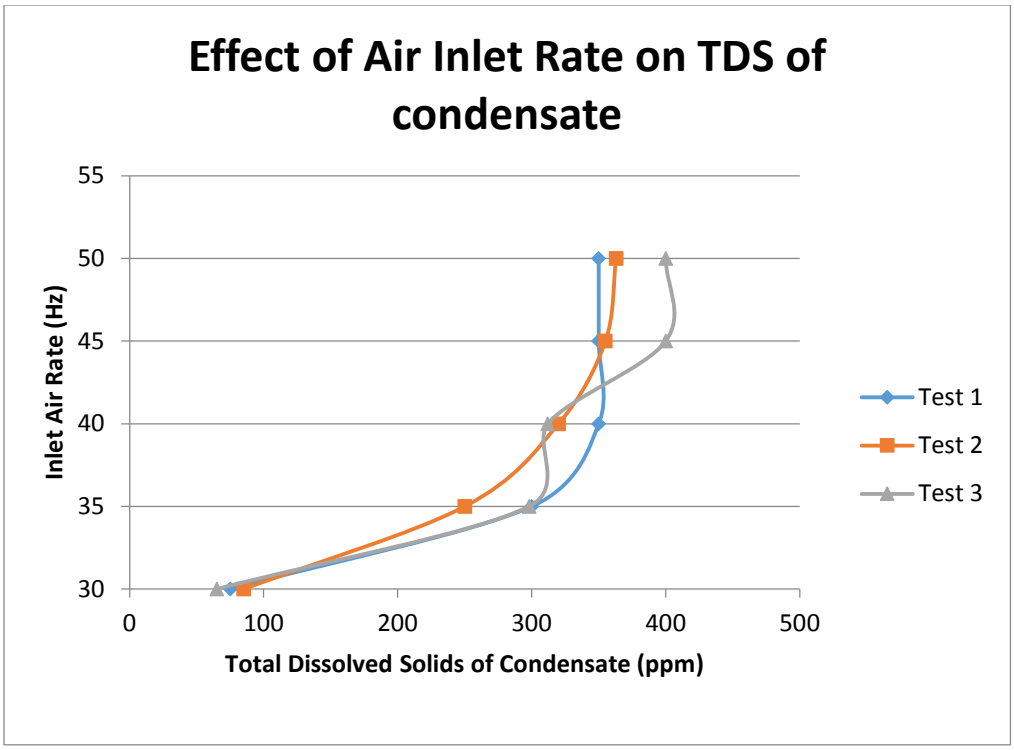


Figure 5. Variation of TDS in the concentrate as a function of air inlet rate at 1.0 gal/min inlet water.

Test 3- Water Inlet Rate of 1.5 Gal/Min, Varying Air Inlet Rates

Test 3 was designed to determine how much air could be pushed through the system. A series of three test runs at each air inlet rate was used to verify consistency of test results. Table 5 shows the results of varying air inlet rates at a constant produced water feed rate of 1.5 gallons per minute. Results from Table 5 are also shown graphically in Figures 6–7.

Table 5: Test 3- Water Inlet Rate of 1.5 Gal/Min, Varying Air Inlet Rates

H_2O feed rate (gal/min)	Inlet air rate (Hz)	Volume (gal) of condensate (test run 1)	Volume (gal) of condensate (test run 2)	Volume (gal) of condensate (test run 3)	TDS (ppm) of condensate (test run1)	TDS (ppm) of condensate (test run 2)	TDS (ppm) of conden-sate (test run 3)
1.5	30	0.8	0.7	1.1	60	65	70
1.5	35	1.1	1.0	1.98	195	400	230
1.5	40	1.20	1.25	1.5	380	450	312
1.5	45	3.0	2.9	3.4	350	400	400
1.5	50	2.5	2.25	2.4	410	400	470

The results of Test 3 show that it is possible to increase the throughput of the system by 200–300% by pushing more air through the system and by tripling the produced water inlet rate. The resultant increase in TDS in the purified water stream did not push the purified water above safe drinking water limits.

Test 4- Water Inlet Rate of 2.0 Gal/Min, Varying Air Inlet Rates

Test 4 was designed to determine how much air could be pushed through the system. A series of three test runs at each air inlet rate was used to verify consistency of test results. Table 6 shows the results of varying air inlet rates at a constant produced water feed rate of 2.0 gallons per minute. Results from Table 6 are also shown graphically in Figures 8–9.

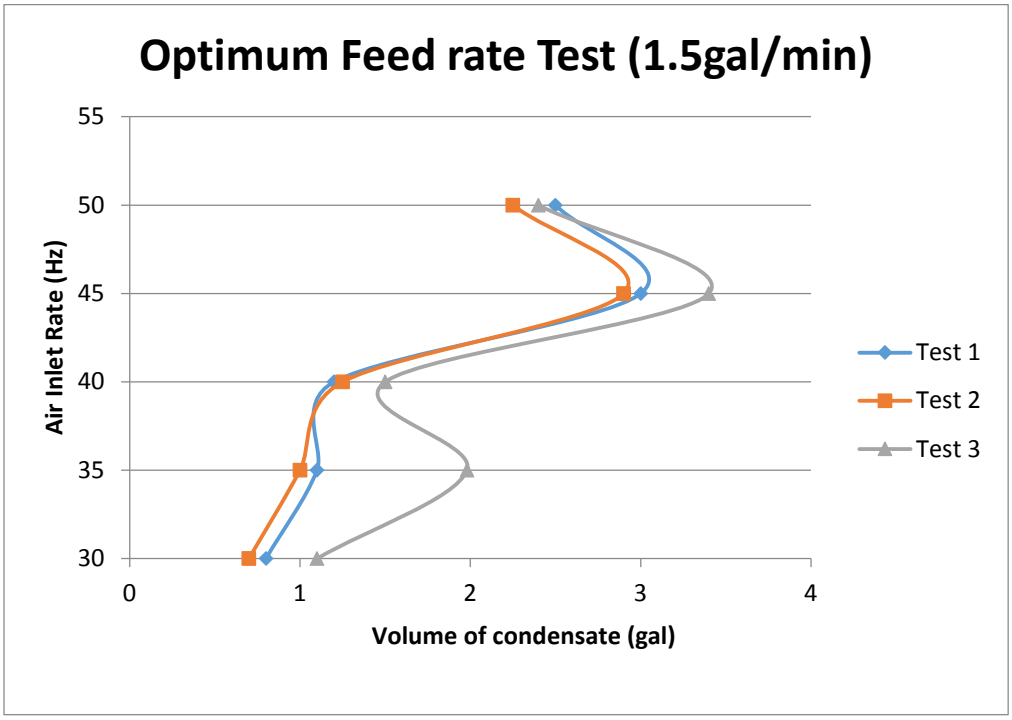


Figure 6. Condensate volume as a function of air inlet rate at 1.5 gal/min inlet water rate.

The results of Test 4 show that it is possible to increase the throughput of the system by more than 500% by pushing more air through the system and by quadrupling the produced water inlet rate. Note that purified water production at lower air rates are lower than those found for lower water inlet rates (Tests 1–3). The resultant increase in TDS in the purified water stream did not push the purified water above safe drinking water limits.

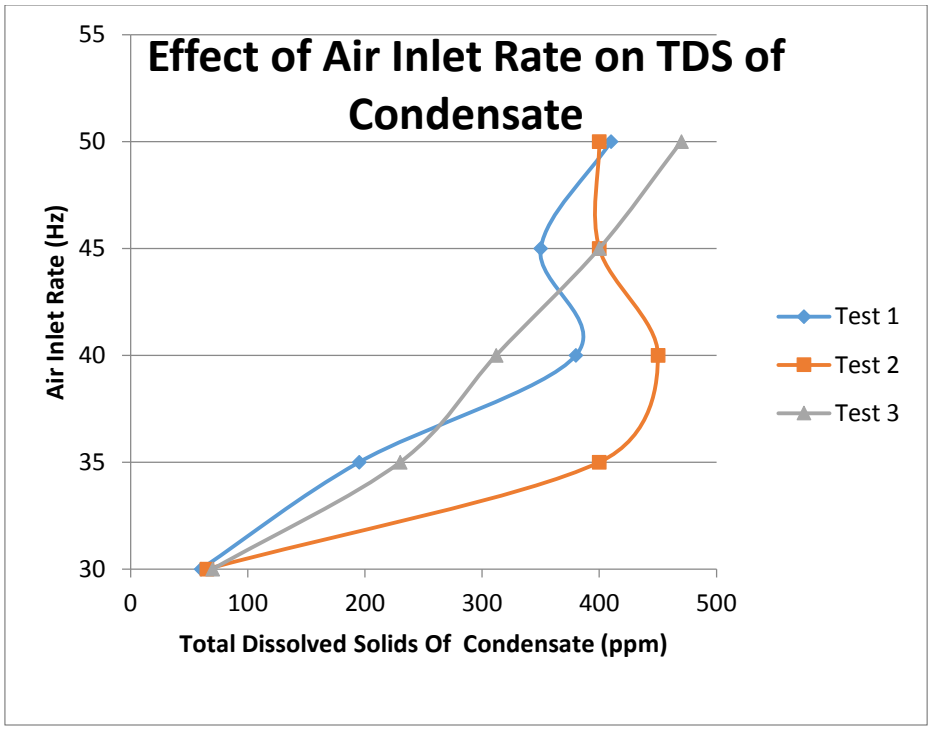


Figure 7. Variation of TDS in the concentrate as a function of air inlet rate at 1.5 gal/min inlet water.

Table 6: Test 4- Water Inlet Rate of 2.0 Gal/Min, Varying Air Inlet Rates							
H_2O feed rate (gal/min)	Inlet air rate (Hz)	Volume (gal) of condensate (test run 1)	Volume (gal) of condensate (test run 2)	Volume (gal) of condensate (test run 3)	TDS (ppm) of condensate (test run 1)	TDS (ppm) of condensate (test run 2)	TDS (ppm) of conden-sate (test run 3)
2.0	30	0.5	0.5	0.48	45	62	89
2.0	35	0.96	0.90	2.0	235	200	90
2.0	40	1.36	1.15	1.69	260	325	355
2.0	45	3.2	3.0	3.50	378	435	400
2.0	50	2.78	2.8	3.0	432	440	424

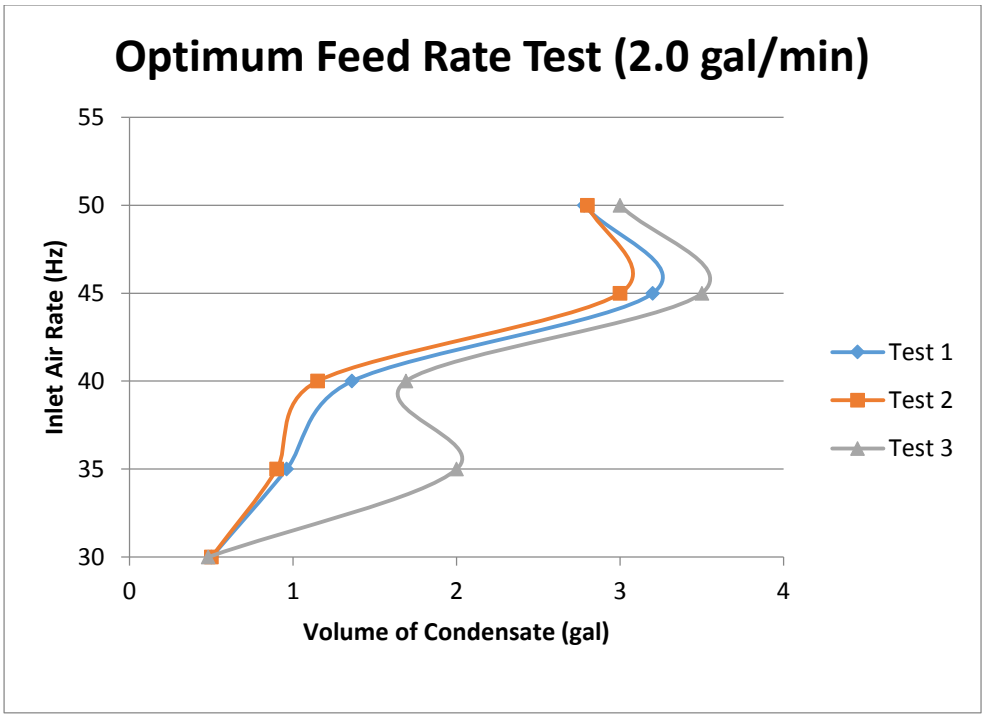


Figure 8. Condensate volume as a function of air inlet rate at 2.0 gal/min inlet water rate.

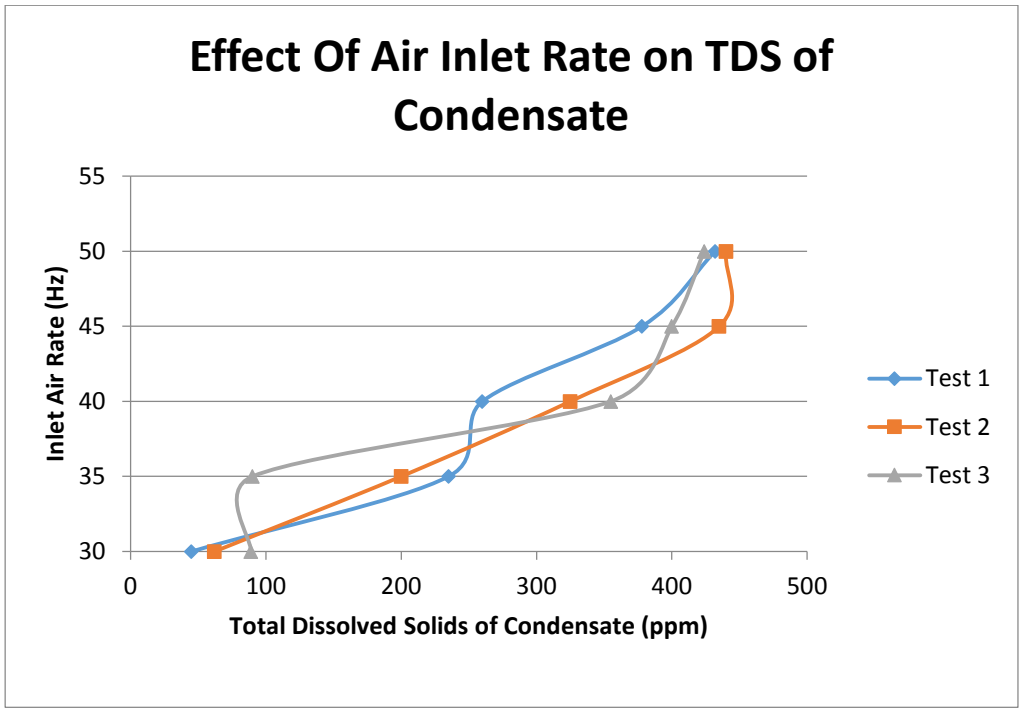


Figure 9. Variation of TDS in the concentrate as a function of air inlet rate at 2.0 gal/min inlet water.

Test 5- Water Inlet Rate of 2.5 Gal/Min, Varying Air Inlet Rates

Test 5 was the final test designed to determine how much air and water could be pushed through the system. A series of three test runs at each air inlet rate was used to verify consistency of test results. Table 7 shows the results of varying air inlet rates at a constant produced water feed rate of 2.5 gallons per minute. Results from Table 7 are also shown in Figures 10–11.

Table 7: Test 5- Water Inlet Rate of 2.5 Gal/Min, Varying Air Inlet Rates

H_2O feed rate (gal/min)	Inlet air rate (Hz)	Volume (gal) of condensate (test1)	Volume (gal) of condensate (test2)	Volume (gal) of condensate (test3)	TDS (ppm) of condensate (Test1)	TDS (ppm) of condensate (Test2)	TDS (ppm) of condensate (Test3)
2.5	30	0.4	0.6	0.55	90	112	120
2.5	35	1.75	1.80	1.68	270	190	175
2.5	40	1.80	2.1	2.6	378	255	395
2.5	45	2.5	2.8	2.9	397	470	462
2.5	50	2.62	3.0	3.0	520	483	491

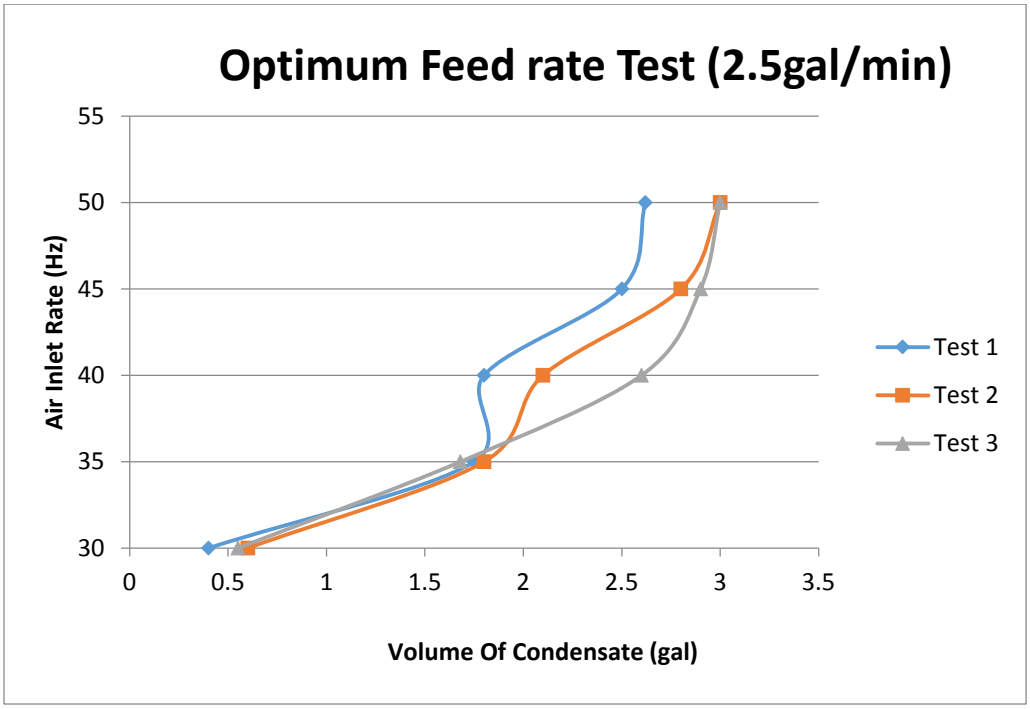


Figure 10. Condensate volume as a function of air inlet rate at 2.5 gal/min inlet water rate.

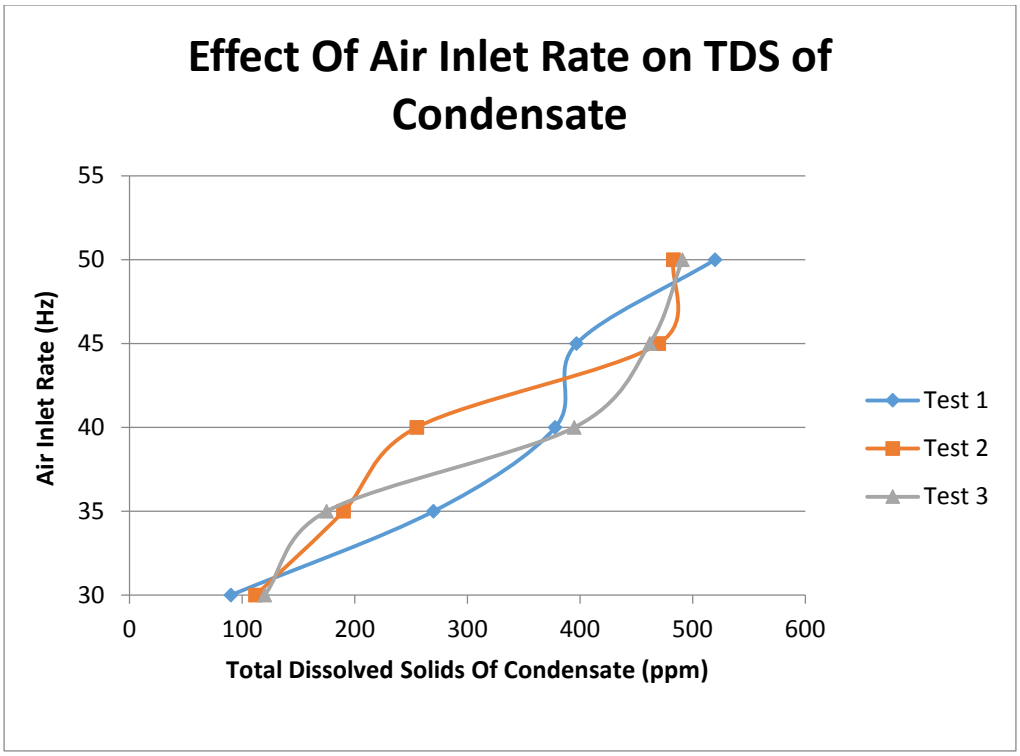


Figure 11. Variation of TDS in the concentrate as a function of air inlet rate at 2.5 gal/min inlet water.

The results of Test 5 show that it is possible to increase the throughput of the system by more than 500% by pushing more air through the system and by quintupling the produced water inlet rate. Note that purified water production at lower air rates are lower than those found for lower water inlet rates (Tests 1–3). The resultant increase in TDS in the purified water stream did not push the purified water above safe drinking water limits.

Test 6- Maximum Throughput Test

Test 6 was designed to observe the operation of the HDH system with large air and water throughput over extended periods of time, in order to better understand sizing and operational constraints and scaling of unit size for production units.

As shown in the feed rate tests (Tests 1–5), optimum operating feed rates were 1.5–2.0 gal and 40–50 Hz (139-161ft^3/min) for heated produced water rate and blower rate or inlet air rate respectively. These rates were selected for extended testing and were successfully employed for the maximum throughput test. The temperature and humidity at the test site are highest in the summer; consequently this is the least efficient time to operate the unit (see attached psychrometric

chart) and represents a worst-case scenario for southeast New Mexico operation of the system. A similar test was run during winter when the ambient conditions are cooler and drier in order to bracket the operational range of the HDH unit.

The tests were conducted on five consecutive days to ensure confirmation of the unit's efficiency at different times of the day with varying temperature and humidity. Test 6 had sustained operational periods of 12 hours, which was accomplished by recirculating the concentrate outflow, which has an average temperature of 125°F. The temperature value of the concentrate in real time is somewhat contingent on the temperature of the dry bulb thermometer. The 12 hour tests with an inlet water rate within the range of 1.5 gal/min to 2.0 gal/min were conducted at different times of the day, from dawn (4 a.m.) to dusk (4 p.m.) and dusk (4 p.m.) to dawn (4 a.m.), which when combined gives information on how the system will respond over continuous 24 h/d operations. From Table 8, the average volume of condensate the unit can treat effectively with TDS in the neighborhood of 400 ppm is 130 gallons in 12 hours (or about 8–9 bbl/d fresh water produced). Nevertheless, this happens to be the least efficient operating period (summer) of the unit. These tests were conducted again with the solar loop to sustain higher inlet water temperatures and increased yield.

Table 8: Test 6- Maximum throughput for 12 hour stress tests.

Test Run	DURATION (HOURS)	Average Relative Humidity (%)	Average Ambient Temperature (^{o}F)	Volume of Condensate (Gallons)
1 (Day)	12	50	90	125
2 (Night)	12	40	70	140
3 (Day)	12	48	100	120
4 (Night)	12	36	75	137
5 (Day)	12	42	103	128

Test 7- Efficiency of the Air-Cooled Condenser

The air-cool condenser (ACC) that provides a supplementary drop in dew point temperature for the condensation of the humidified air consists of two main parts: stainless tube heat exchangers and an electric fan. The copper tubes act as heat exchangers and the fan provides the

requisite ambiance temperature drop for condensation. The efficiency of the air-cooled condenser depends on the dry bulb temperature.

Test 7 was designed to assess the efficiency of the air-cooled condenser. It was interesting to note that the copper tubes that act as heat exchangers are reasonably efficient, even if the fans are not operational, which provides another option for power (cost) savings.

Tests were conducted with and without the air-cooled condenser in operation to assess the efficiency of the electricity powered fans of the air-cooled condenser under similar or the same operational conditions (constant inlet water and air rate, surrounding temperature and relative humidity). Results of the test are shown in Table 9 and Figure 12. Overall, there is about a 50% reduction in efficiency of the ACC without the electric fan. This could reduce operational cost of the process remarkably since it would reduce the waste stream by the same amount, though reducing the yield of fresh water as additional water vapor would be vented. On average the air cooled condenser can double the yield of condensate.

Table 9: Test 7- Air-Cooled Condenser Tests

TEST	Inlet Air Rate (Hz)	VOLUME OF CONDENSATE (WITHOUT ACC) GALLONS	VOLUME OF CONDENSATE (WITH ACC) GALLONS
1	30	1.25	2.5
2	35	2	2.25
3	40	1.0	2.25
4	45	0.9	2.1
5	50	1.5	2.2

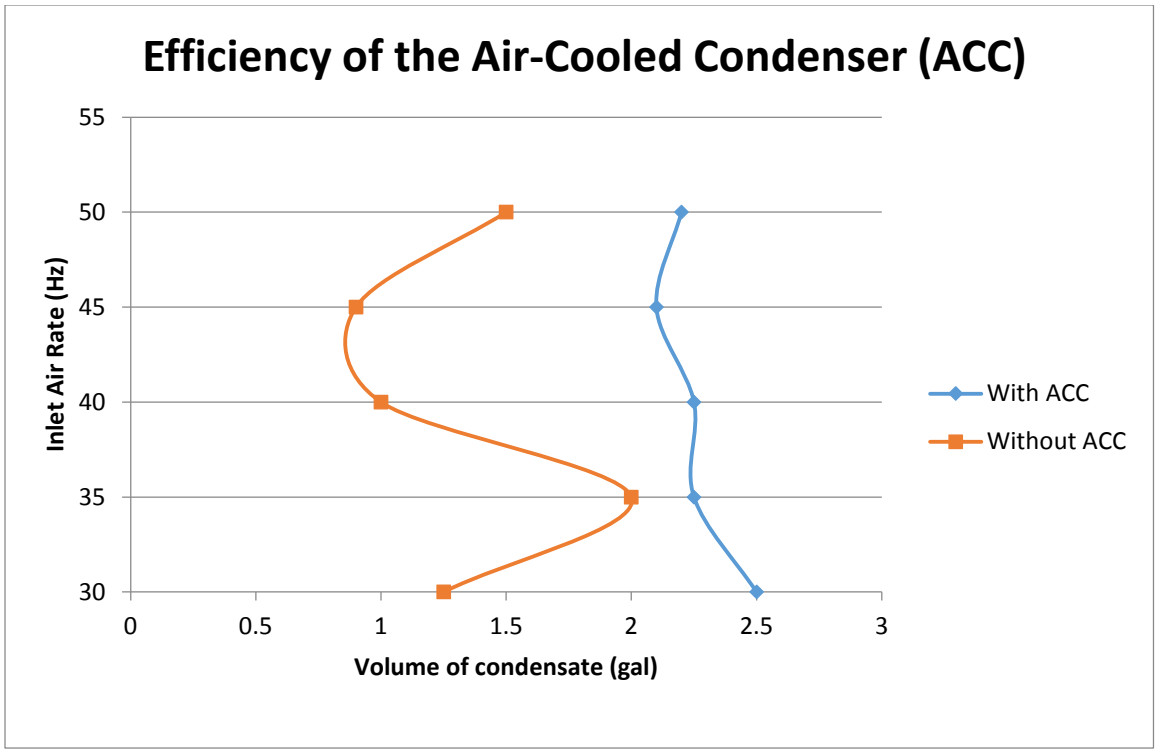


Figure 12. Efficiency of operation with and without the ACC.

1.1.2.9 Summary of Summer Test Results

Table 10 is a summary of the inlet feed rate determination tests, showing the optimum inlet rate for both heated produced water and ambient air. The HDH unit could treat produced water effectively with any rate between 1.5–3.5 gal/min and 40–50Hz (138–160 ft^3/min) for water and air respectively. However, at higher rates (>2.5 gal/min), the rate at which the concentrate volume fills in the unit is too high for efficient recirculation. Hence the recommended optimum inlet rate is between 1.5–2.5 gal/min. The optimum inlet rate is therefore contingent on the volume of the unit (in this case 80ft^3); these rates would change accordingly with changes in volume of the unit.

Using the optimized rates, five longer tests were conducted to establish purification rates for summer conditions. Table 11 shows the summary of these longer 12 hour tests. Tests were run both at night and during the day as temperature and humidity conditions can vary.

Table 10: Summary of Results from Tests 1–7 on Air and Water Inlet Rates		
Test	Observation	Inference (Feed Rate)
1 (0.5 gal/min)	a. Maximum volume of condensate 1 gallon b. Most suitable air inlet rate 40–45Hz c. It takes considerable period of time for the unit to reach saturation.	Good
2 (1.0 gal/min)	a. Maximum volume of condensate 3.2 gallon b. Most suitable air inlet rate 45–50 Hz	Very good
3 (1.5 gal/min)	a. Maximum volume of condensate 3.4 gallons b. Most suitable air inlet rate 45–50Hz c. Optimum inlet rate	Excellent and most efficient inlet rate
4 (2.0 gal/min)	a. Maximum volume of condensate 3.5 gallon b. Most suitable air inlet rate 45–50Hz c. Concentrate volume rises quickly	Excellent (but energy demanding and less efficient)
5 (2.5 gal/min)	a. Maximum volume of condensate 3.0 gallon b. Most suitable air inlet rate 45–50Hz c. Concentrate volume rises or fills up very quickly	Very good

6 (3.0 gal/min)	a. Maximum volume of condensate 3.10 gallon b. Most suitable air inlet rate 45–50Hz c. Concentrate volume fills too quick for effective recirculation	Not recommended for the existing HDH volume (concentrate volume does not make recirculation effective)
7 (3.5 gal/min)	a. Maximum volume of condensate 3.10 gallon b. Most suitable air inlet rate 45-50Hz c. Concentrate volume fills too quick for effective recirculation	Not recommended for the existing HDH volume (concentrate volume does not make recirculation effective)

Table 11: Maximum Throughput for 12 Hour Stress Tests (summer)

Test Run	Duration (Hours)	Average Relative Humidity (%)	Average Ambient Temperature (^{O}F)	Volume Of Condensate (Gal)
1 (Day)	12	50	90	125
2 (Night)	12	40	70	140
3 (Day)	12	48	100	120
4 (Night)	12	36	75	137
5 (Day)	12	42	103	128

From Table 11, the average volume of condensate the unit can treat effectively with total dissolved solids around 400 ppm is 130 gallons in 12 hours (or about 6–7 bb/d fresh water produced). Nevertheless, this happens to be the least efficient operating period (summer) for the HDH unit.

1.1.2.10 Winter Test Results

The efficiency of the HDH unit is primarily contingent on the prevailing ambient relative humidity and temperature (on dry-bulb). Due to the significant differences between these sensitive parameters among seasons (especially between summer and winter), the efficiency is consequently

affected. A second set of tests, using the optimized parameters from summer testing, were employed to evaluate the system under winter operational conditions.

Due to reduced daylight hours less solar heat was available for winter testing, thus a series of ***6 hour*** tests were employed to determine that an average of 102 gallons of PW could be purified by the HDH Unit in the winter (Table 12), yielding fresh water with TDS around 400 ppm using the prototype. Automating the unit could produce well over 400 gallons of fresh water in 24 hours, and as winter nights are often colder than daytime, this extrapolated rate should represent a conservative estimate. However, an average of 130 gallons (Table 11) is processed effectively by the unit in ***12 hours*** of operation in the summer when the sensitive parameters (relative humidity and temperature) are at their zenith. The volume of daily processed water could be increased by increasing the volume of the HDH unit, i.e, adding additional HDH units in parallel.

Table 12: Results of Maximum Throughput Test of the HDH Unit, Winter

Test (6hr)	Average Daily Relative Humidity (%)	Average Ambient Temperature (°F)	Volume of Condensate (gal)
A	45	50	98
B	48	41	107
C	60	32	111
D	54	45	100
E	68	50	96
F	81	44	102
G	42	53	94
H	39	48	105
I	50	58	98
J	40	35	109

1.1.2.11 General Observations from Testing

Apart from minor variations, which are not uncommon in tests, the higher the blower frequency (inlet air rate), the higher the TDS of the condensate. Subsequently, the blower frequency can be varied to produce condensate with specific TDS when needed.

The unit consists of 11 compartments, of which five are evaporative and the remaining six are condensation chambers. A significant percentage of the condensation takes place in the latter before the humidified airstream moves through the flow lines into the stainless steel heat exchangers of the ACC (Figure 13); because of this the unit did not work effectively when these flow lines were taken out for the reduced condensation tests. Moreover, the test enhanced oxidation and scaling in the unit.

Increasing TDS of the untreated produced water had no significant effect on the efficiency of the process. This was confirmed when the five 12 hour summer tests were sustained by pumping back the concentrate into the heated stream in a cyclical manner. In addition, there were no appreciable changes in the total dissolved solids (TDS) of the condensate when the TDS of heated untreated produced water was increased incrementally by the addition of the concentrate.

Figure 13. Air-cooled condenser used for improving condensate production.

1.1.3 Optimization of HDH Module Sizes

At an inlet rate of 1.5 gal/min of heated produced water, the 72 in. × 48 in. × 39 in HDH unit (78 ft^3) can process just over 51 stock tank barrels of inlet fluid in a single day, with an approximate yield of 20% fresh water for a single pass. Optimal sizing of the unit can be computed

on a case by case basis, depending on volume of produced water available and the desired rate of fresh water generated by the system. For example, if the goal is to reduce an available amount of produced water by 50% the condensed waste water can be run through the system again after being brought back to process heat levels. This single 78 ft^3 unit can reduce the produced water volume of a 20 bbl/d production well by 50%, by passing the water through the system three times. ((20× 0.8) × 0.8) ×.08). A 40 bbl water producer would require two similarly sized units (156 ft^3) to achieve a 50% reduction.

1.2 Deployment and Optimization of HDH Process using Passive Solar Heating

1.2.1 Prepare for Solar Test

After evaluating the system for optimal inlet water and air flow rates, the test site was prepped for utilizing inlet produced water that was preheated using a passive solar array. This involved installation of the solar array, insulated water storage tanks, a thermostat system to control mixing of heated water, cool water, and concentrate from the outlet of the HDH unit to provide a steady of 170–180° water to the HDH unit.

1.2.1.1 Solar Collector Sizing and Installation

According to the design of this research, flat-plate solar panels, which are corrosion resistant and economical, were sized and procured for heating 15 bbl of water from 60°F (assumed initial temperature for sizing) to 176°F (operational temperature of the HDH process).

Calculation: Thermal Energy Required For Heating 15 bbl of Water at 60°F

$$Q = m.c.\Delta T \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where Q is the thermal energy required (BTU), m is the mass of water at 60°F (lb.), c is the specific heat capacity of water (BTU/lb°F) and ΔT being the temperature difference between the initial and operational temperature (°F).

m (15 bbl) = 8.3378 lb/gal × (42×15) gal

c = 1BTU/lb°F

ΔT = (176-60)°F

About 609k BTU of thermal energy is required to heat 15 bbl of water from ambient air temperature in a day. The thermal performance rating of the flat-plate solar collectors is significantly affected by the temperature of the inlet fluid, ambient air temperature, and the intensity of solar radiation.

The 16 flat-plate collectors purchased from Alternate Energy Technologies LLC (AET) for this phase of the project have a design thermal performance rating for each panel (Table 13).

Table 13: Thermal Performance of Flat-Plate Solar Collectors Based on Temperature of Inlet Fluid		
Low Temperature	**35°C (95 °F)**	33.5k BTU/d
Intermediate Temperature	**50°C (122°F)**	27.5k BTU/d
High Temperature	**100°C (212°F)**	9.2k BTU/d

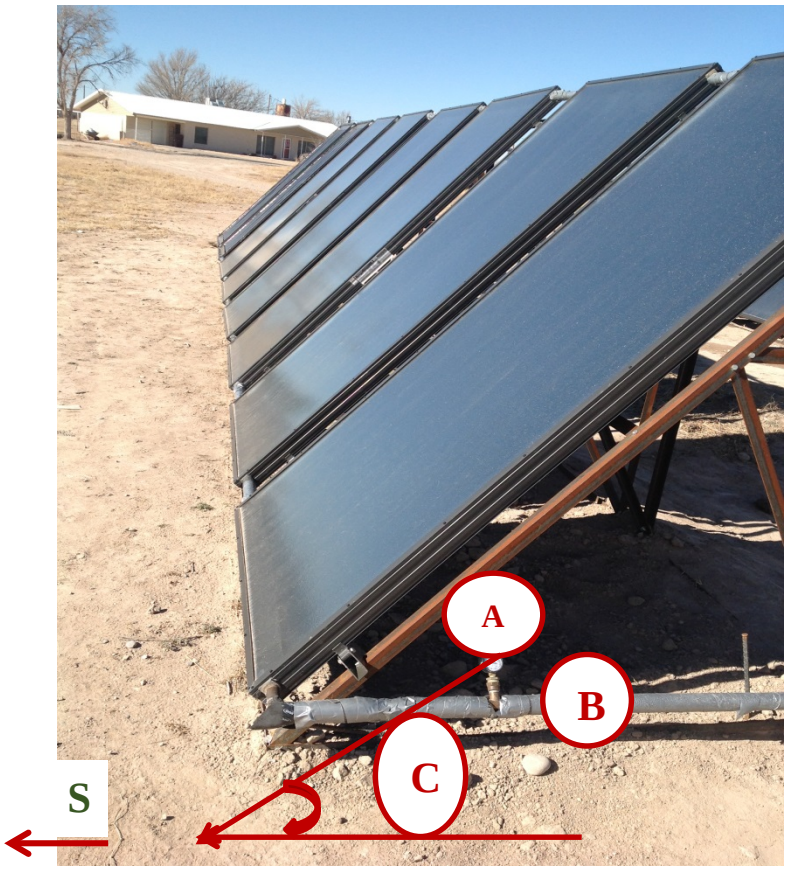
Interpolating the average operational temperature of the HDH process will give about 29k BTU/d per panel. According to AET, this rating is based on an assumed standard day for the state of Florida. This (thermal efficiency) can be improved since the average annual solar radiations in the Southwest United States could be higher than in Florida.

The 16 flat-plate collectors can provide all the energy needed to heat water for the HDH Unit from 60°F to 176°F according to the average solar radiations recordings in the Southwest. Collector sizing can be scaled for specific demands based on volumes of PW to be treated daily on a particular field.

1.2.1.2 Angle of Inclination

For maximum and year-round solar radiation collection, collectors should be tilted at an angle from the horizontal equal to the latitude of the area plus 10° facing True South (taking into account the magnetic declination of the area, letter “S” in Figure 14). This is for countries or areas located in the Northern Hemisphere; collectors should face True North for countries in the Southern Hemisphere (AET 2011).

All 16 collectors were tilted at an angle of 50° (for New Mexico) and installed in a single closed loop with a propylene-glycol water mixture as its circulation fluid. Letter "C" in Figure 15 shows the angle of tilt used for the single closed loop.



A	Pressure gauge
B	Insulated copper piping
C	Angle of tilt to the horizontal (50° True South)

Figure 14. Solar collectors showing angle of tilt (50°), insulated pipe and pressure gauge.

1.2.1.3 Installation

Closed loop installation was used to install the HDH unit's solar collectors. For heating water, there are three methods of installing flat-plate collectors: drainback, open loop and closed loop installation. The drainback and open loop methods circulate by gravity and natural convection or pumping, with the water heated through the copper tubes beneath the copper plates of the solar panels to be heated. The high salinity and organic carbon content in produced water advise against the use of drainback in this application (AET 2011). The closed loop method was chosen as the

most suitable: heat exchangers are used in exchanging heat between heated circulation fluid (anti-freeze with low specific heat) and the PW. Figure 15 shows the closed-loop installation method for the HDH unit.

Figure 15. Solar array collectors installed and connected in a single closed loop at the HDH unit near the Artesia test site.

1.2.1.4 Circulation Fluid

For a fluid to be suitable as a circulation fluid in the closed loop water heating system, two main properties must be considered. The first is the ability of the fluid to absorb heat readily when flowing (low specific heat capacity rate, in this case heat absorbed from copper plates and tubes); the low specific heat capacity rate will also help in reducing the inlet temperature of the circulation fluid after heat exchange, thereby increasing the efficiency of the solar panels. As previously noted, the inlet temperature of the circulation fluid (propylene glycol water mixture) affects the efficiency of the solar panels (AET 2011}.

The circulation fluid must also have a higher boiling point but lower freezing point and must be noncorrosive. Propylene glycol or 1,2-propanediol ($C_3H_8O_2$) is commonly used as anti-freeze and has a boiling point and freezing point of 370°F and -74°F respectively. Moreover, its

specific heat capacity of 0.6 BTU/lb°F makes it an ideal heat exchanger fluid. However, because of its higher specific gravity, water is added as a thinning agent. The circulation fluid used for the panels in these tests consisted of 60% propylene glycol and 40% fresh water.

1.2.1.5 Volume of Circulation Fluid

Each of the sixteen 32 ft^2 flat-plate solar collectors has 10 copper tubes with an outside diameter (OD) of 0.5 in. and 8 ft in length, vertically connected to a 1.25 in. OD, 4 ft horizontal copper pipes. These horizontal (4 ft) pipes are connected on both sides of the tubes to aid fluid circulation, as shown in Figure 16.

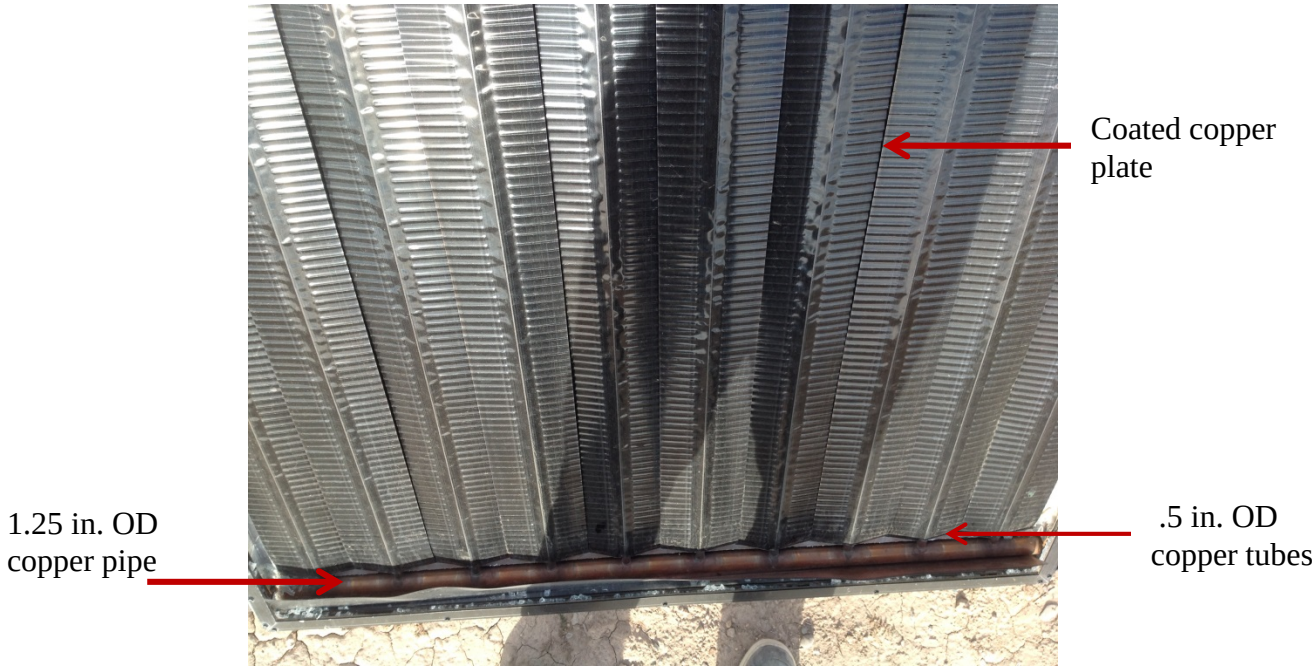


Figure 16. Flat-plate collector with safety glass removed to show copper plates and pipes.

Total collector volume of the 16 panels = 16 × 1.30 gal = 21 gal

Total piping volume = 73 ft × (0.068 gal/ft) = 5 gal

A total of 26 gal antifreeze (glycol–water mixture) was used in filling the solar loop after a positive leakage-free test with freshwater; 60% (or 15.6 gal) of this volume was propylene glycol and the remaining 40% (or 10.4 gal) was fresh water.

1.2.1.6 The Brazed Copper Plate Heat Exchanger

Due to their thermal energy exchange efficiency and durability (Table 14), brazed copper plates were selected and retrofitted into the loop (letter "E" in Figure 17). These consist of varying numbers of brazed copper plates ("E" and "IV" in Figures 17 and 18 respectively); the number of plates selected is primarily contingent on its application. The higher the thermal energy demand of the application, the higher the number of plates needed for maximum heat exchange efficiency. The number of plates currently manufactured ranges from a few tens to several hundred; each plate has thermal energy capacity ratings of about 4kBTU. The thermal energy demand (609 k BTU) for the 15 bbl requires a heat exchanger with at least 100 brazed copper plates (Figure 18). A schematic diagram of the installed heat exchanger is shown in Figure 19.

Table 14: Performance Rating of 100 Brazed Copper Heat Exchanger	
Maximum working pressure	652 psi
Maximum working temperature	437 ^{o}F
Heat exchange area	41.7 ft^2
Maximum flow rate	60 gpm
BTU rating	4000 BTU/ plate

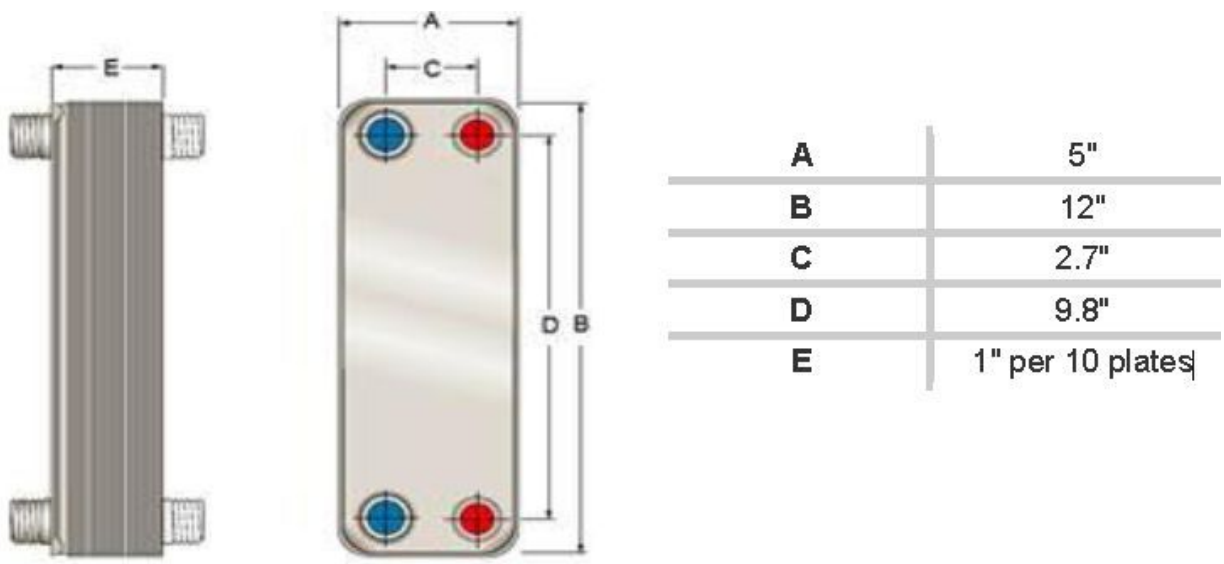
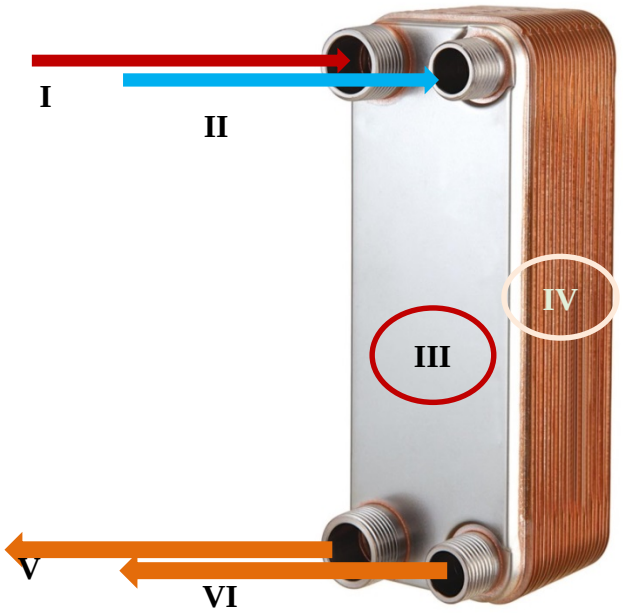


Figure 17. Schematic diagram of the of the 100 brazed copper heat exchanger
www.badgerpipe.com



I	Solar-heated glycol in
II	Cold produced water in
III	316 stainless steel built
IV	100 brazed copper plates
V	Glycol out after heat exchange
VI	Heated produced water out

Figure 18. Schematic diagram of the heat exchanger showing fluid flow directions.

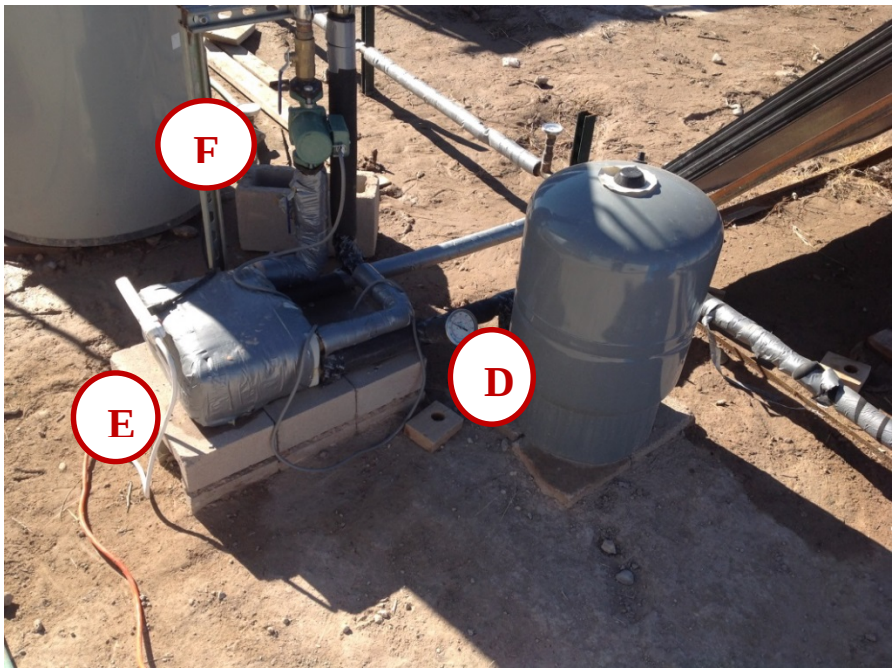


Figure 19. Brazed copper heat exchanger (E), expansion tank (D), and a Taco 007 1/25 hp pump, (F).

1.2.1.7 Circulation Pumps

All design and installation in the system were carried out to optimize cost reduction without compromising efficiency. All 16 solar panels were installed and operated in a single loop; this reduced the need for additional pumps, which would have increased power costs.

There are two main circulation pumps in the entire loop. A Taco 001 1/8 hp pump which circulates heated glycol in the solar loop (letter "G" in Figure 20) and a Taco 007 1/25 hp (letter "F" in Figure 19) model which circulates water from the storage tanks (letter "H" in Figure 21) and the heat exchanger (letter "E" in Figure 19). The solar panels, when mounted on their stands are 9 ft high; circulation pumps with capacity of circulating that amount of hydraulic head was needed, hence the Taco 001 1/8 hp was selected (Figure 22). The storage tanks, on the other hand, were only about 5 ft high, so a Taco 007 1/25 hp circulation pump was selected (Figure 22).

Figure 20. Solar collector array showing the Taco 001 circulation pump (G).

Figure 21. Picture of insulated storage tanks (H) connected to the solar loop.

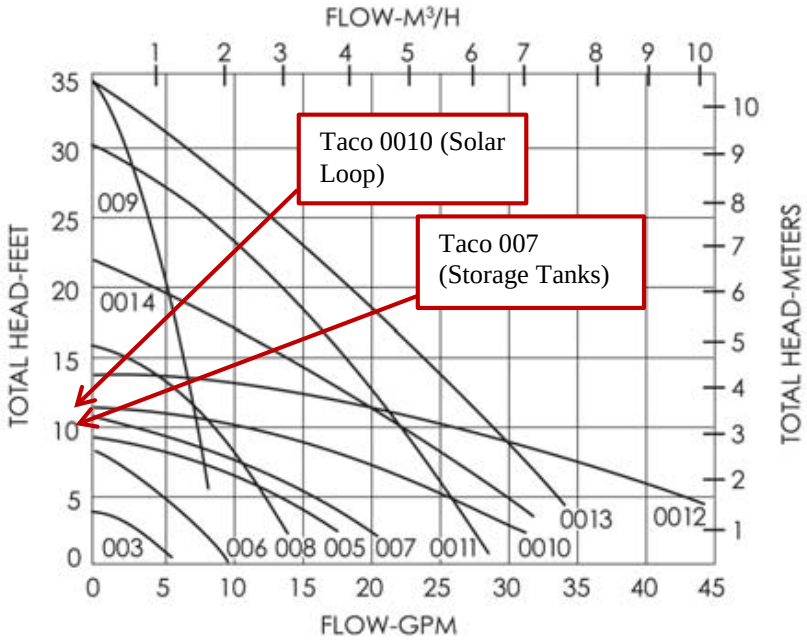


Figure 22. Taco circulation pumps sizing based on flow rate and water head. Source: www.taco-hvac.com

The non-metallic impellers in the Taco pumps have an orientation that makes the pumps operate at their maximum efficiency when installed vertically and more importantly when the pressure in the system is less than 20 psi (as shown in Figure 23). The efficiency of these small pumps positively affects the design and operational costs of the process.

Figure 23. Taco circulation pump and cartridge, showing installation orientation, source: www.taco-hvac.com

1.2.1.8 Solar Loop Operational Safety/Precautionary Measures

1.2.1.8.1 Expansion Tanks

One of the topmost priorities of any engineering design is operational safety of people, environment and the object being designed. Throughout the design and installation, appropriate operational safety measures were strictly observed.

From basic Pressure-Volume-Temperature law, most fluids generally tend to increase in pressure when temperature increases (for a fix mass of fluid). To reduce the effect of uneven pressure and circulation of fluids through the loop as fluids gets heated, diaphragm-type expansion tanks were sized (Figure 24 and letter "D" in Figure 19).

Calculation

$$\boldsymbol{Va = 1.05\,(Vcp + Vp)e + Vcp} \quad \text{---------- (2)}$$

where

$\boldsymbol{Va}$ = expansion volume to be accommodated (gal)

Vcp = total volume of solar panels or collectors (gal)

Vp = total volume of copper piping (gal)

e = Coefficient of expansion of antifreeze (e = 0.045 for water and 0.07 for glycol)

1.05 = 5% volume estimate safety factor

Total collector volume of the 16 panels (***Vcp***) **= 16×1.30 (gal) = 21 gal**

Total piping volume (***Vp***) = **73ft × (0.068gal/ft.) = 5 gal**

From equation (2), total volume of expansion to be accommodated in gallons (***Va***) ***is equal to 22.638 gal.***

The expansion tank maintains pressure by an upward and downward movement of a pre-charged diaphragm. If the pressure in the loop goes higher than the preset pressure (25 psi) or precharged pressure, the diaphragm moves upward to accommodate the added pressure and vice versa.

Therefore two expansion tanks (13 gal each) were retrofitted into the installation.

Figure 24. Picture of a precharged diaphragm-type expansion tank.

1.2.8.1.2 Auxiliary Saftety/Precautionary Measures

Aside from the expansion tank being an essential part of the operational safety measures, other auxilliary safety measures were also taken. Pressure relief valves and air vents which bleed out any added pressure and air from bubbles were also installed.

Thermometers and pressure gauges were installed at strategic positions for safety and process monitoring. Insulated water tanks were used for temporary storage of heated water during testing. Letter "H" in Figure 21 shows the insulated tanks connected to the loop.

1.3 Perform Tests with Passive Solar Heating

1.3.1 Thermal Efficiency of the Solar Collectors in Winter and Summer

When the solar loop was installed (November 2013), the thermal energy output when solar was at its lowest in the northern hemisphere (winter solstice). This test was started in mid-December 2013 and ended in mid-January 2014. Table 15 and Figure 25 are a summary and graphical representation, respectively, of the thermal energy efficiency of the collectors in the winter, whereas Table 16 summarizes results from the summer.

Table 15. Summary of the Thermal Energy Efficiency of Solar Collectors in Winter

Test	Avg. Daily Temp. (^{O}F)	Weather Condition	Daylight Duration (hr)	Initial Temp. of PW (^{O}F)	Final Temp. (^{O}F)	Volume Heated (Gal)	Thermal Energy 'Q' (kBTU)
I	50	Mostly cloudy	10	45	180	168	189.1013
II	41	Mostly sunny	10	47	180	250	277.2319
III	32	Mostly sunny	10	48	180	170	187.1002
IV	45	Mostly sunny	10	50	180	252	273.1463
V	50	Mostly sunny	10	46	180	370	413.3881
VI	44	Partly cloudy	10	50	180	160	173.4262
VII	53	Mostly Sunny	10	50	180	352	381.5377
VIII	48	Mostly cloudy	10	50	180	80	86.71312
IX	58	Sunny	10	50	180	415	449.8243
X	35	Partly cloudy	10	48	180	120	132.0708

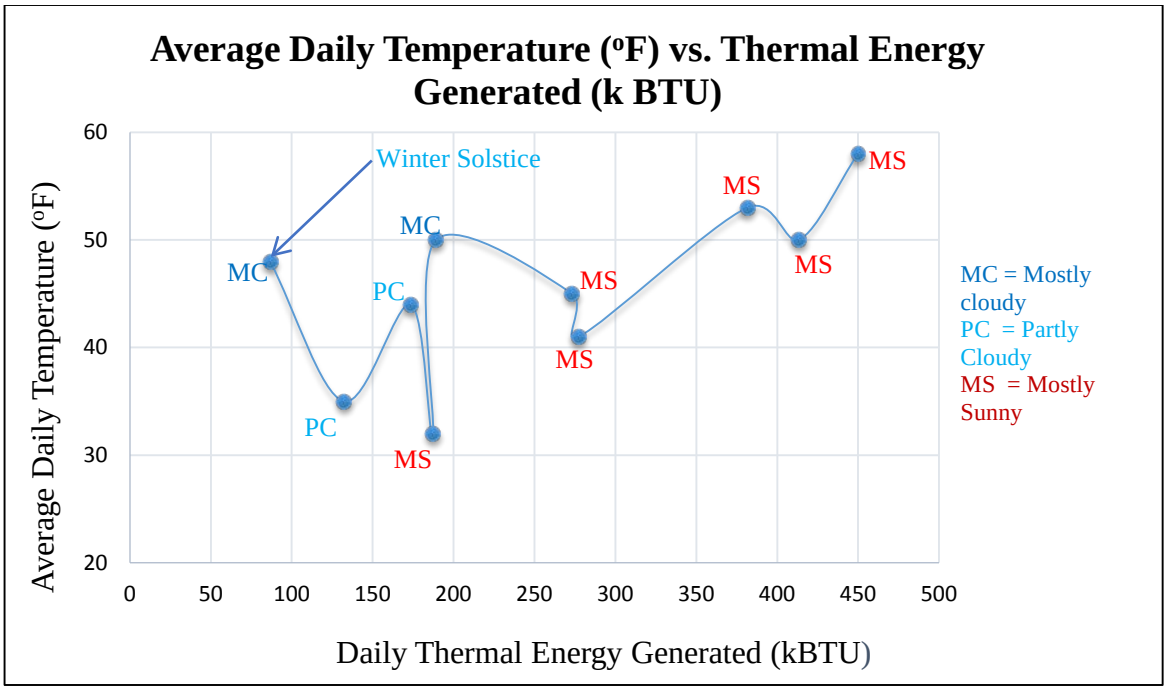


Figure 25. A graphical representation of daily BTU generated by collectors in winter.

These test results clearly show that the weather conditions have a more significant effect on the thermal energy generated by the collectors than does the average daily temperature. This effect is clearly shown between Tests II and VI (Table 15). Even though the average daily temperature of Test VI is 3°Fahrenheit greater than Test II, because the weather conditions were more favorable (mostly sunny) in Test II, there is a significant difference between the thermal energy performance of both tests; the results of Test II is 60% more efficient than Test VI. This is primarily due to the numerical differences between the thermal conductivity of copper (about 231 BTU/hr/°F/ft, since the collectors are made up of copper plates and copper pipes/tubes) and air (about 0.01733BTU/hr/ °F/ft, though dependent on temperature). Consequently, it takes much more time to heat air on a clear day than copper.

From the data shown in Table 15, Table 16 and Figure 25, an average of 256 k BTU and 584 k BTU are generated by the entire solar collectors, which heats close to *6 bbl* and *13 bbl* from initial temperature of about 50°F (dependent on prevailing ambient temperature) to 180°F for winter and summer respectively. However, the temperature of produced water from most oil fields is higher than the ambient temperatures. Therefore, less thermal energy is required to raise the initial produced water to operating temperature when the unit is installed and operating on a wellhead;

overall yields of heated water will be greater if latent geothermal heat is used. For example, on a clear average sunny day (60°F) when the panels (originally sized for 15 bbl in phase 1) are providing about 450 k BTU (as in the case of Test IX from Table 15) of thermal energy, about 32 barrels of produced water initially at 140°F could be heated to operating temperature of 180°F.

Table 16. Summary of the Thermal Energy Efficiency of Solar Collectors in Summer

Test	Avg. Daily Temp. (°F)	Weather Condition	Daylight Duration (hr)	Initial Temp. of PW (°F)	Final Temp. (°F)	Volume Heated (gal)	Thermal Energy "Q" (k BTU)
I	97	Sunny	12	50	180	530	574.4744
II	95	Mostly sunny	12	48	180	520	572.3065
III	101	Sunny	12	52	180	560	597.6535
IV	94	Sunny	12	54	180	512	537.8881
V	90	sunny	12	50	180	508	550.6283
VI	98	Sunny	12	47	180	550	609.9100
VII	103	Sunny	12	49	180	580	633.5060
VIII	100	Mostly Sunny	12	52	180	565	602.9896
IX	98	Sunny	12	52	180	555	592.3173
X	96	Mostly Sunny	12	50	180	528	572.3065

Additional daily thermal energy requirements for the 6 hr tests in the winter were supplied by a steam generator; in late winter and throughout summer and fall, the solar collectors could generate all the energy required to heat produced water to the operational temperature (180°F). The use of an energy-hungry steam generator could be supplanted with waste gas heating on cold and/or cloudy winter days when ambient conditions do not favor ample thermal energy generation by the collectors.

1.4 Design Optimum Field Configurations and Automation:

Optimal operational parameters determined through testing, and an evaluation of the capacity for the solar array to heat water helped to define the field set up and automation requirements needed for extended testing. A stated goal of extended field testing was to test operation of the system on a continuous basis, with no interruptions in service for night time operations and unfavorable weather conditions. Running at optimal parameters the HDH unit can process ~50 bbl/d of produced water. The selected field test site, the Federal 00 #3 well near Carlsbad New Mexico has produced water that enters the separator at ~120°,F, and generates ~20 bbl/d of PW. On a sunny summer day the solar panels could produce enough heat to run the Federal 00's entire production of water through the system three times, resulting in a reduction of produced water by 50% while generating 10 bbl/d of fresh water. In order to accomplish this, the system would require adequate insulated storage, systems to recycle concentrated PW back into the heating process, pumps, fans, the air cooled condenser, and automation to control fluid levels in associated storage tanks to avoid overtopping or overdraining. In order to ensure operations could continue on cloudy days, and longer winter nights a heater treater was converted to utilize waste natural gas for supplemental heating. An Arduino control system was designed and implemented to control the process. The test site automation and configuration is detailed in Section 4 of this report.

1.5 Adapt or Fabricate Production Prototype HDH Module

The existing prototype was already at an appropriate size for the selected field site, so it was determined that it could be adapted for field testing in this project, rather than building a second prototype. One goal of this project is to evaluate commercialization potential for this process. The original unit was constructed using stainless steel, which is an expensive material that requires special welding equipment to manipulate. Although stainless steel has excellent corrosion resistance and heat transfer properties, it should be possible to use alternate materials to reduce the cost of producing commercial HDH units.

1.5.1 Building Material Selection for Commercial HDH Units

Considerations for selecting off-the-shelve building materials, should evaluate the following properties:

I. Yield strength, density and tensile strength only need to accommodate the fairly low pressures of the system primarily resulting from the blower pushing ambient air into the unit.

II. The material should have excellent corrosion resistance.

III. Though the material must be durable (as stated in I.), it should also be affordable.

IV. The material must have a melting point much higher than the operating temperature of the unit (about 180°F).

Table 17 summarizes properties that meet these considerations:

Table 17. Summary of Physical Properties of Building Materials and Pricing

Material	Yield Strength (MPa)	Tensile Strength (MPa)	Density (g/cm^3)	Melting Point (^oF)	Current Cost/ft^2 ($)
Stainless Steel (Cr)	2617	2693	7.45	2700	106
Aluminum (alloy, Zn/Cu)	500	550	2.47	1221	30
PMMA (Plexiglas)	72	114	1.17	392	5

- *Polymethylmethacrylate* (Plexiglas, PMMA) could be used in building the unit; however, the thickness of the Plexiglas should be increased (0.5 in. and above); most importantly, the thickness of the unit's cap must be significantly increased to increase stability when the blower is in operation. The low material pricing of the PMMA is its strength in the materials comparison.
- Aluminum alloyed with either zinc or copper has enough strength (yield and ultimate tensile strength) for building the HDH unit and it would have a materials cost of 70% of the cost of building the original prototype using stainless steel.

- Steel alloyed with chromium (stainless steel) is an excellent material for building HDH units if the topmost priority for material selection is durability. Nevertheless, it does significantly increase the materials costs

2.0 Results and Discussion

In this section, a full evaluation of the system and its operation is made; final design considerations are enumerated and applied to future production systems. A full evaluation of the economics of the system and its applicability to a variety of small- to medium-scale produced water scenarios has been performed, and system designs using core HDH modules for parallel, serial, or a combination to achieve site specific purification goals are tabulated.

2.1 Full-Scale Field Test with Solar and Heat Storage

A full-scale field test was performed at the wellhead of a producing well. The full-scale production prototype, associated equipment, insulated tanks, and automation system were assembled and integrated with the gathering system and then tested for a period of three months including periods of continuous operation with daily inspection. This section details site preparations and automation of the system.

2.1.1 Electrical and Mechanical Operation of the Humidification-Dehumidification System (HDH)

The system was located at a producing well (Federal 00 #3) northeast of Carlsbad, New Mexico (GPS coordinates Latitude 32°28'55. 35”N Longitude 104°13'41. 59”W). The HDH system was set up to operate independently at the site as an integrated part of the wellhead equipment (Figure 26). Figure 27 shows the major components that make up the HDH system.

2.1.2 Safety and Security

Personal protection equipment was worn at all times. The mechanical and electrical system was designed around personal safety. The control valves in the system safeguards the surface of the ground so that the PW does not come into contact in any way that might constitute a hazard to any fresh water supply. The electrical system was grounded and bonded to ensure a safe environment for trained and untrained personnel that might need to work in and around the system.

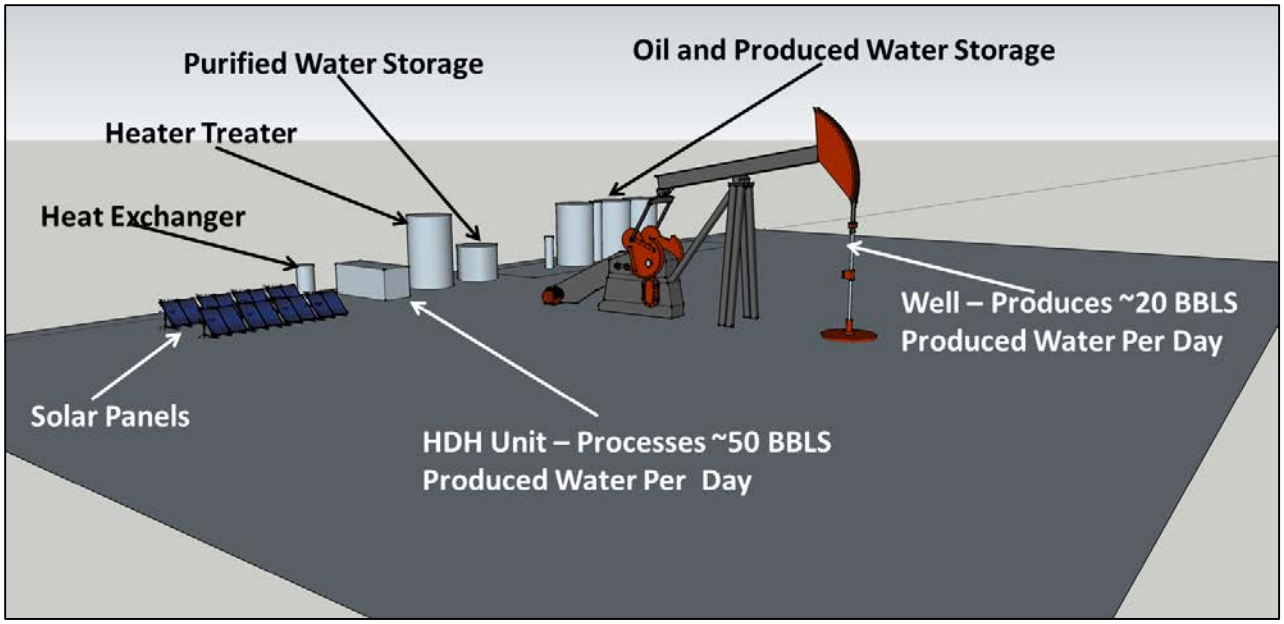


Figure 26. Schematic diagram showing HDH equipment integrated with the wellhead.

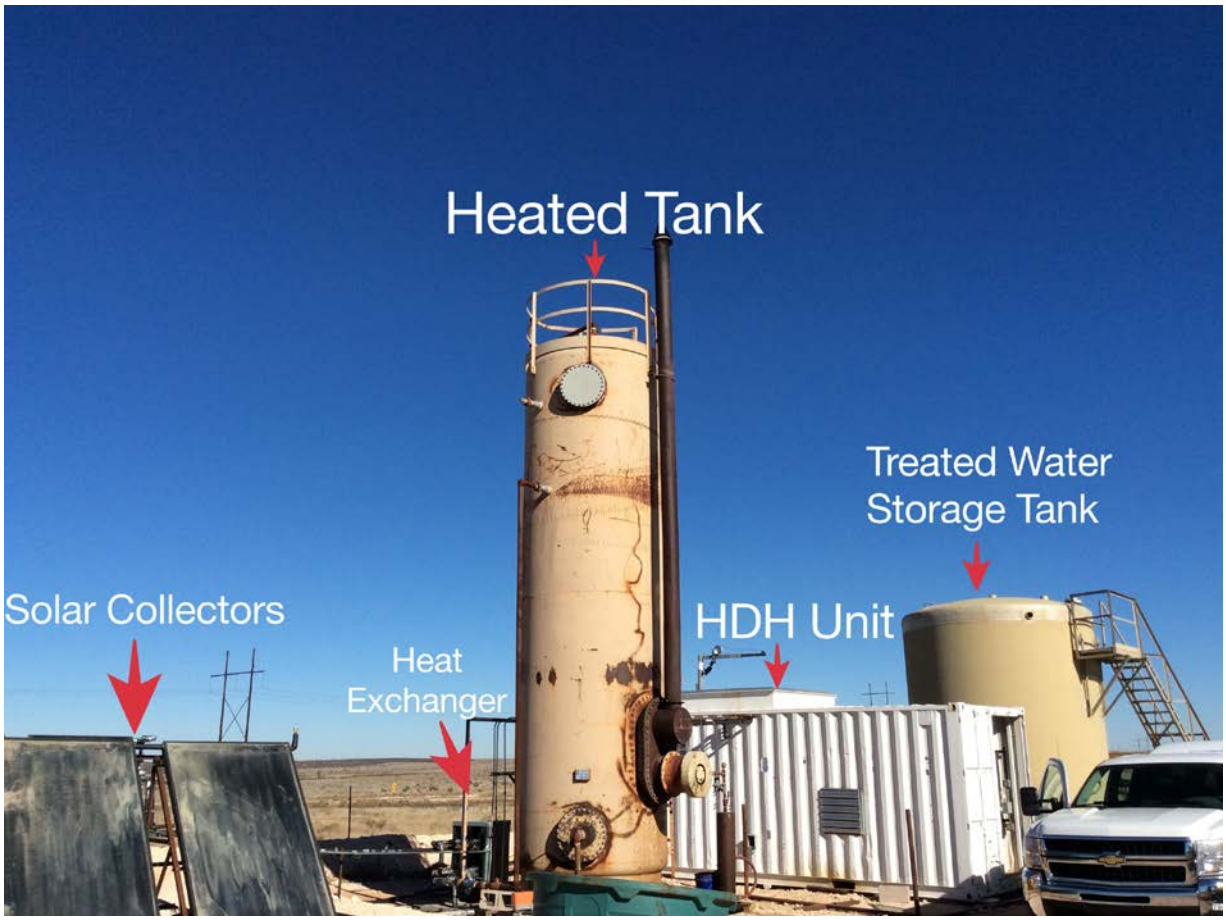


Figure 27. Major components of the HDH system as deployed.

2.1.3 Arduino Controller

The Arduino Uno microcontroller (Figure 28) was selected to control the HDH unit because of its open-source platform. The Arduino Uno controller uses C programming to control the hardware. It has 14 digital input/output pins (of which six can be used as PWM outputs), six analog inputs, a 16-MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. The controller monitors the water in the heated tank, solar system and the HDH unit. There are four different electrical/mechanical valves in the system. A normally closed (NC) valve controls the flow of the produced water into the heated tank. The NC valve ensures that in the event of a power failure, water cannot flow unrestricted. There are three three-way valves installed into the system. One three-way valve operates the flow of water in the solar system. The second three-way valve operates the water that feeds into the HDH unit and the third three-way valve controls the concentrate water in the HDH unit.

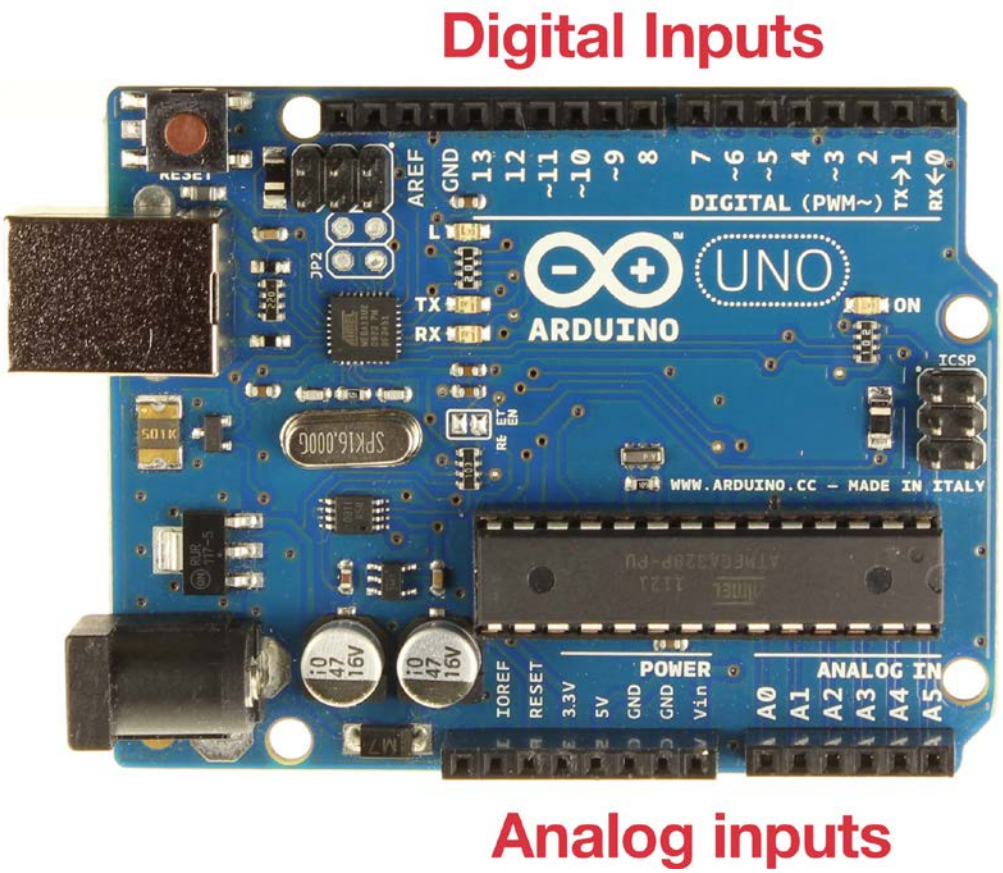


Figure 28. Arduino controller board.

2.1.4 Heated Tank

A float switch located inside of the heated tank (Figure 29) regulates the volume of water in the tank. When the water falls below a predetermined level, the float switch energizes a relay that controls a NC valve and a ½ hp motor. In the energized condition the PW is pumped from the oil well storage tank into the heated tank. When the heated tank has filled to the predetermined level, the float switch de-energizes the relay and shuts down the NC valve and ½ hp. motor. (The NC valve was installed in the system in order to secure the PW in the event of a power failure.)

Figure 29. Heated Tank using a heater treater separator. Waste gas can be used to supplement solar heat.

A proportional gas valve controls the temperature of the water in the heated tank. A thermocouple in the tank monitors the temperature and controls the valve. The gas valve has an operating range from 130°F to 180°F. The Arduino controller monitors the temperature of the water in

the heated tank and controls the water flow to the HDH unit. When the water reaches 140°f (minimum process heat) the controller energizes a three-way valve and diverts the flow of water from the bypass condition to the HDH unit. The water flowing to the HDH unit must be at a minimum of 140°F.

2.1.5 Solar Collector System

The solar collector system (Figures 30–31) is a closed loop system that utilizes a mixture of 60% water and 40% glycol mixture. The glycol use in the system is food grade that poses no threat to the environment in the very unlikely event of an accidental leak. The 18 solar collector (AE32) panels are manufactured by Alternate Energy Technologies. The fluid capacity of each is 1.05 gal and it measures approximately 8 ft × 4 ft × 3 ft. The fluid capacity of the entire system is approximately 20 gal. When the system is charged, the minimum operating pressure should be no less than 26 psi. The solar collectors are connected together with 1in. copper tubing and and the system utilizes a single 120 VAC circulating pump to move the fluid.

Figure 30. Solar collectors.

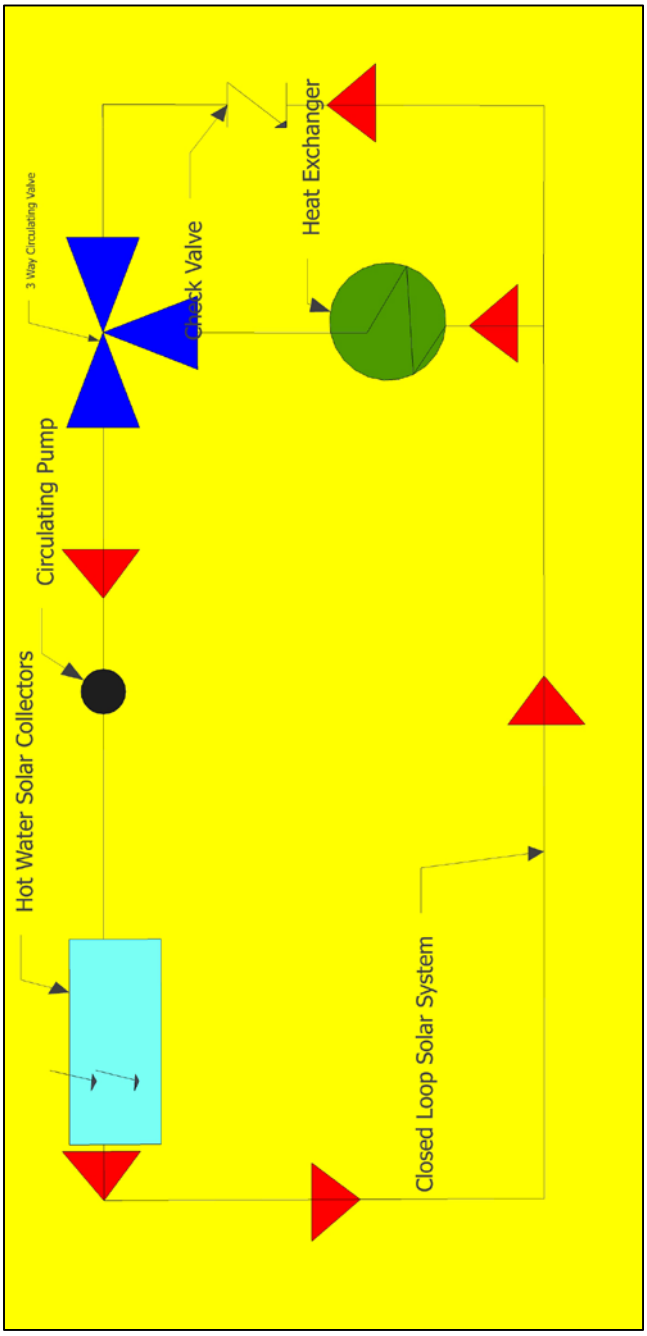


Figure 31. Schematic of the solar collector system and associated valves and controls.

During daylight hours a photocell de-energizes a relay with NC contacts. The photocell used is an off-the-shelf unit that energizes during non-daylight hours. The use of an ice cube relay with NC contacts allows the circulating pump to operate during the day and be off during the night. The Arduino controller monitors the temperature of the liquid in the solar system. When the solar collectors acquire enough heat (minimum 140°F), the Arduino controller energizes a three-way

diverting valve on the solar system. The three-way valve diverts the liquid from the bypass and redirects it to the heat exchange. The heated liquid then flows through two heat exchangers allowing the solar system to augment the natural gas heater in the heated tank. (Due to the large volume of water (18,000 gal) in the heated tank, the solar panels can only be used to augment the natural gas heater.) When the panels are not capable of supplying heated liquid to the heat exchangers, the controller redirects the liquid to the bypass condition by de-energizing the three-way valve.

2.1.6 HDH Unit

The Arduino operates the HDH unit once the water starts to flow into the unit. A humidity sensor will signal the controller to energize two motors (high speed fan and ½ hp motor). The high-speed fan is used to inject ambient air into the unit and forced the heated (condensate) air out of the unit and into a cooling chamber. The cooling chamber is a radiator with a ½ hp motor that operates a fan. The fan circulates air across the fins of the radiator and cools the condensate. When the condensate is cooled it returns in the form of water droplets at the end of the radiator. The water is captured into a 55-gal drum. When the 55-gal drum is filled to a predetermined level a submergible pump will pump the water into a large holding tank. The water is now cleaned and ready for use. Figure 32 shows a schematic drawing of the HDH control process. Figure 33 shows the drip trays for heated produced water located at the top of the HDH unit. The humidity sensor identifies the presence of water in the tank (digital input). The controller energizes two relays that control the high-speed fan motor in the HDH unit and a radiator with a ½ hp motor.

The high-speed motor and the radiator motor are a product of the original HDH design. The motor control circuit was designed around the operation of the HDH unit. The motors only operate when there is humidity in the unit.

A portion of the water that enters the HDH unit will not condense. The HDH must flush the water out as the new water enters. When the water in the unit has reached a predetermined level, a float switch will energize a ½ hp motor. The float switch will energize a relay that controls a pump motor. The excess water in the bottom of the chamber will be pumped back to the heated tank, and as this water retains a temperature of ~130°F, some heat is also recycled. The Arduino controller monitors the time that the return pump operates through a set of normally open (NO) contacts. Periodically the controller operates a three-way valve and flushes a certain amount of produced water into an open air holding tank.

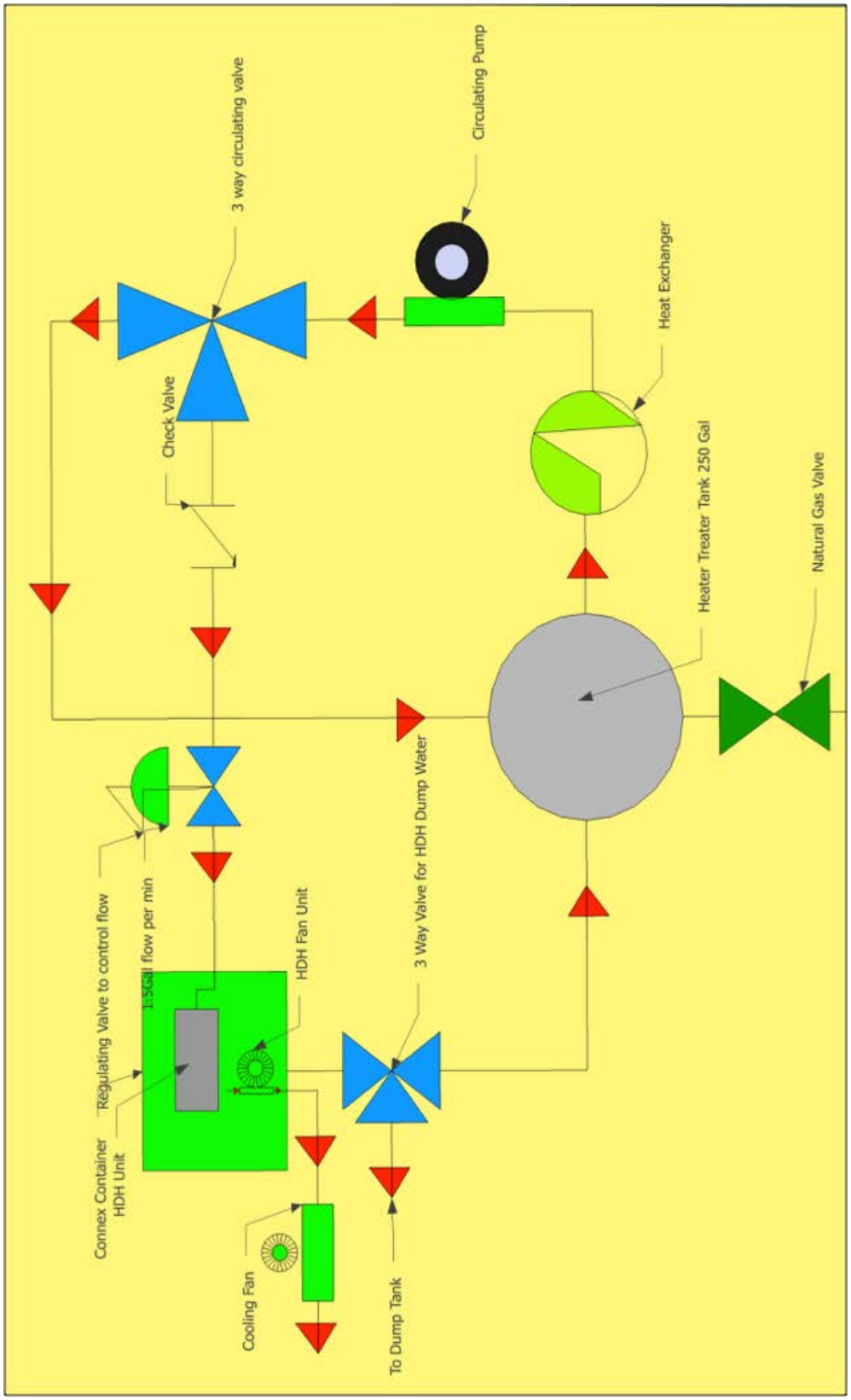


Figure 32. Schematic of the electrical/electronic system controlling the HDH process.

Figure 33. Drip trays at the top of the HDH unit, with access hatch removed. Filler material occupies the humidification chambers directly below each drip tray.

2.1.7 Extended Field Tests

The production prototype was installed at the Federal 00 #3 wellhead during the Fall of 2015 and extended field testing began in December of 2015. Goals of the extended testing were to establish long-term operational parameters for the system, ensure that maintenance schedules and operational parameters were in line with predictions, and troubleshoot equipment, automation, and safety measures that allow for unattended operation.

The system was installed at the field site by early December of 2015 and operational tests began in mid-December. The test site at the Federal 00 #3 provided approximately 20 Bbl of produced water per day. The HDH system was sized and configured to process ~51 Bbl per day and as such could run the water from the test well through the HDH process multiple times in a 24 hour period. Heat from the solar panels was supplemented with waste-gas heating via a heater treater separator to allow for night-time operations and to test the system with continuous throughput.

Problems Encountered

1) **Reliable heating –** The repurposed heater treater used to provide supplemental hot water for full time operations had too large a volume of water to reliably heat to process temperatures of 175–180°F. This was countered by reconfiguring the hot water outflow to have its intake closer to the heater unit, and by pumping recycled discharge water in at the top of the unit to improve circulation.
2) **Filler material –** The cardboard filler material used in testing of the unit had held up quite well to intermittent tests of 6–12 hours, but under continuous operations the filler material had a tendency to break down. At several points the small pump used to re-circulate the discharge to the heated storage became clogged and this caused the HDH unit to fill up with fluid and become less effective. Initially this was countered by cleaning out the strainer more frequently but it became apparent that this would require maintenance approximately every 48 hours. The HDH system was retrofitted with larger discharge valves, flushed to clean out all residual packing material fragments and put back in service. Cleaning of the Y-strainer was only required weekly after the retrofit. **Pump maintenance –** The system utilized inexpensive low horsepower pumps to move fluids. On several occasions pumps needed to be replaced due to wear. In each case the automatic system halted fluid flow and no problems with fluid management occurred. The failed pumps had been used for multiple tests over a period of several years and had been cycled frequently, which added to wear. None of the replacement pumps failed during the extended testing.

The system ran successfully until March 31, 2016 for as many as eight days at a time, with a field technician staying within a short drive of the system and monitoring system operation via internet. On March 31, the system was demonstrated to 12 attendees of the Annual Roswell SPE Leadership Symposium, and to service company personnel from Elite Well Services. At the close of the project, the HDH system was released to the site operator and project partner, Harvard Petroleum Co., LLC (HPCLLC), who intended to keep the system running. A number of recommendations were made to HPCLLC to reduce maintenance and to increase reliability. A switch to a synthetic packing material would reduce the need for maintenance of packing material and allow longer times between site visits. Pumps should be examined for wear quarterly, and spare pumps should be kept on site to minimize down time.

2.2 Economic Evaluation

2.2.1 Equipment and Power Rating

The primary operational costs for the HDH unit are its electrical components. There are four categories of electricity-powered equipment that are operational on the current HDH prototype. These are circulation pumps, centrifugal pump, air blower, and the air cooled condenser.

Circulation Pumps: One of the prime motivations for studying the HDH process is its cost effectiveness. All designs and installations were carried out to optimize cost reduction without compromising efficiency. All 16 solar panels were installed and operated in a single loop; this reduces the need for additional pumps which would increase power costs. There are two main circulation pumps in the entire solar loop: a Taco 001 1/8 hp pump (with power rating: 1.10 A, 115V), which circulates heated glycol in the solar loop and a Taco 007 1/25 hp (with power rating: 0.79A, 115V) model, which circulates heated produced water from the storage tanks and the heat exchanger.

Centrifugal Pump: A ¼ hp electricity-powered (with power rating 1.7A, 115V) centrifugal pump has been included in the HDH process. It pumps heated produced water into the evaporation chambers of the HDH unit.

Air Blower: The air blower (with power rating 3A, 115V) plays an instrumental role in the HDH process. It blows ambient air into the evaporation chambers in a direction opposite to the inlet produced water. The HDH prototype was built to have an air blower with enough working pressure to push the humidified air out into the air cooled condenser, thereby, optimizing cost reduction.

Air Cooled Condenser: Data gleaned from Phases I and II of the project confirmed the efficiency of the HDH process being enhanced with the inclusion of an air-cooled condenser. The air-cooled condenser (with power rating 2.78A, 115V) enhances the condensation of the humidified air made available by the operational pressure of the air blower.

2.2.2 Operational Design of Equipment on the HDH Prototype

As noted, there are two main Taco circulators; the Taco 001 1/8 hp is connected to the solar collectors whereas the Taco 007 1/25 hp is connected to the storage tanks. These run concurrently

every 30 minutes for 15 minutes, after which there is a uniform thermal energy exchange between the heated glycol and the PW (by means of the heat exchanger). The other electrical components run continuously when the unit is operational for as long as heated PW is readily available. The ¼ hp centrifugal pump moves heated produced water into the HDH unit, and ambient air is blown into the unit by the electricity-powered air blower and to enhance the dehumidification of the moist air, and the humidified airline is connected to an air-cooled condenser. The power ratings and energy calculations of these equipment and current price for operating the unit (in New Mexico) with the solar collectors is reported in Table 18 and displayed in Figure 34. Cost per barrel will vary depending on ambient temperature and humidity.

Table 18: Estimated 24 Hour Operational Cost of HDH Unit with the Solar Collectors

Equipment	Current (amp)	Voltage (v)	Power (kWh)	Operation Time (hr)	Current Price /kWh($)	Power Cost ($)
Taco 007	0.79	115	0.0908	3	0.18	0.049
Taco 0010	1.10	115	0.1265	3	0.18	0.068
1/4hp Cent. Pump	1.7	115	0.1931	24	0.18	0.834
Air Blower	3	115	0.345	24	0.18	1.490
Air-Cooled Cond.	2.78	115	0.3197	24	0.18	1.381
Total	**9.37**	**115**	**1.0751**	**24**	**0.18**	**3.82**

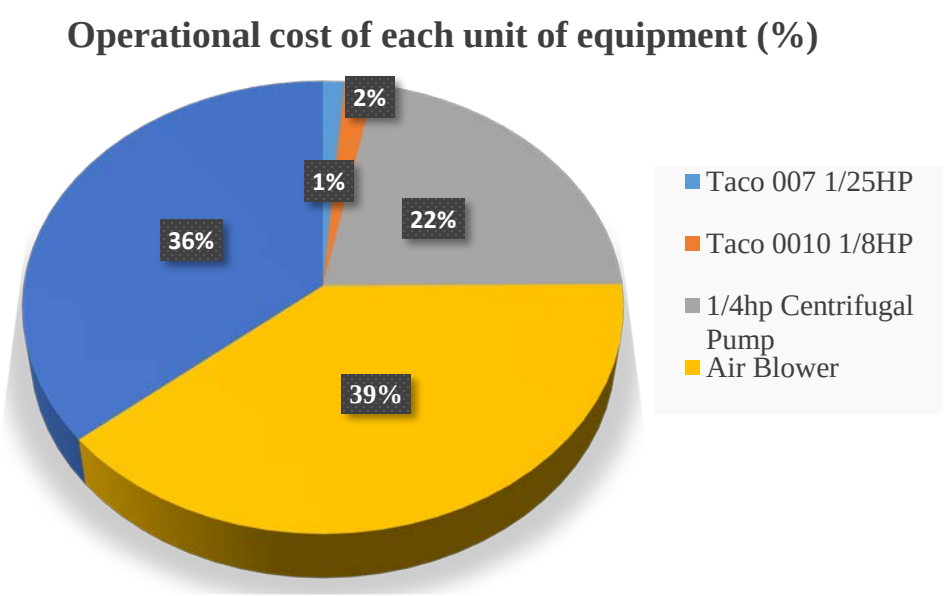


Figure 34. Distribution of power demand for the HDH system.

2.2.3 Summary of Operational Costs

Using the power and energy calculations shown in Table 18, it cost about **$0.12/day** to heat the produced water (OPEX only) with the solar collectors, that is, generating about 256k btu (heating 6 bbl) and 584k btu (heating 13 bbl) for winter and summer respectively. In other words, it cost about **$0.02 and $0.001** to heat a barrel of PW for the HDH unit in the winter (i.e., worst case performance of the collectors) and summer, respectively. This cost is to heat from ambient temperature, and is thus a conservative estimate since PW from oil wells retains geothermal energy and has higher temperatures than the ambient temperatures used in the calibration tests. The total cost of operating the HDH unit for water purification using the solar collectors is about **$3.82** for 24 hr of operation. The annual average efficiency is about 20% (producing close to 9 bbl of freshwater in 24 hrs) for the current 80 ft^3 unit; therefore, the cost of purifying a barrel of produced water is about **$0.42**.

This analysis confirms the essential goal of the HDH process: Its operational cost-effectiveness, making the process a pragmatic means of treating produced water for small scale oil production operations.

2.2.4 Cost of Construction

Material cost is low, using many off-the-shelf components, and is built into an inexpensive surplus Connex container. The largest costs are for labor to assemble the unit, time to install automatic systems, and plumbing to circulate water. Table 19 shows material costs to construct an HDH system with circulating pumps and fans utilizing an existing source of heated produced water. To build the HDH unit and its control systems would take approximately 320 labor hours, of which 40 hours would require specialist skills in electronics. The cost of this could vary significantly by region, but in New Mexico a roughneck crew would cost $15 per hour, and a specialist about $50 per hour. Cost to construct on site in New Mexico would be on the order of $6,200, and the total for the system plus labor would be ~$18,855.

Table 19. HDH Unit Materials Cost			
Item	Amount	$ Cost Each	Item Total
1/2 hp Pump motors	3	300	900
Electrical gear switches	4	200	800
1 in. PVC fittings	10	9	90
1 in. PVC pipe	100	2.25	225
Timer	1	25	25
Arduino controller	1	150	150
Circulating pump	1	350	350
Connex Box 20 ft	1	250	250
Exhaust fan	1	300	300
Sump pump	1	65	65
HDH fan motor w/frequency control	1	400	400
Electrical service	1	3,000	3,000
HDH box	1	6,000	6,000
1 in. ball valves	5	20	100
Total Cost			**$12,655**

If a solar collector system similar to that used by this project were added, the price is increased. An additional 160 labor hours would be needed to install the solar system at a cost of $2,400. In addition the component costs would be increased. Table 20 shows the component costs for an HDH system with solar heating. Total cost to install a system configured with solar heating would be on the order of $38,056, an additional cost of $19,201.

3.0 Impact to Small Producers

This research focused on a humidification-dehumidification process that could be a viable and cost-effective means of treating PW for small producers. Advantages of the HDH method:

I. Use of inexpensive sources of thermal energy and utilization of lower temperature thermal processes in the HDH process significantly reduces per-unit costs of processing PW. Specifically, instead of electric-powered steam generators for heating PW as in the case of some of the thermal desalination methods described earlier in this report, inexpensive passive solar, latent geologic heat, and/or waste gas can be used.

Table 20. Component Costs for an HDH System with Solar Heating			
Item	Amount	$ Cost Each	Item Total
Solar panels	16	780	12,480
1/2 angle iron panel holders	800	3	2,400
1 in. copper pipe	300	3.47	1,041
1 in. copper unions	20	9	180
1 in. ball valves	10	20	200
Heat exchanger	2	300	600
1/2 hp pump motors	3	300	900
Electrical gear switches	4	200	800
1 in. PVC fittings	10	9	90
1 in. PVC pipe	100	2.25	225
Timer	1	25	25
Arduino controller	1	150	150
Circulating pump	1	350	350
Connection box 20 ft	1	250	250
Exhaust fan	1	300	300
Sump pump	1	65	65
HDH fan motor w/frequency control	1	400	400
Electrical service	1	3,000	3,000
HDH box	1	6,000	6,000
Total Cost			**$29,456**

II. The HDH unit is more adaptable to smaller scale operations. It is cost-effective for produced water treatment irrespective of volume. Many other processes require >10,000 bbl/d to reduce per-unit cost to economical levels.

III. Due to the operational flexibility and small footprint of the HDH unit, it can easily be installed at an individual wellhead or field gathering site, whereas due to the large volumes required by the other methods, PW must be transported from oil fields to treatment sites, increasing treatment cost due to transportation costs.

IV. Materials used to construct the HDH unit include inexpensive materials, like cardboard or straw cooler pads that are used for interphase mass transfer and to extend residence time. Low-capital cost is a very important factor in favor of the HDH process when working with smaller volumes of PW.

An ideal scenario for the HDH process is a well or facility that is remote from disposal wells, where transportation cost to dispose of PW can impact economics of the well, where latent geothermal energy is high, and where free heating (solar, waste gas) is viable. In its simplest configuration an HDH unit could purify 10% of the waste in a continuous stream using only separator output water, and just running the air blower and two small pumps.

Small producers can operate in more remote areas and in smaller fields than larger companies, and may have less access to private salt water disposal wells, and thus can be more strongly impacted by disposal costs. Many desalinization technologies only become cost-effective at large scales of operation due to high infrastructure costs. Essentially, the less PW that a producer has, the more it costs to purify using large-scale commercial processes. This system provides a reduction in waste disposal costs using scalable equipment that can purify smaller volumes of PW at low capital expenditures, and thus provides a useful tool to small or remote operations.

The system can be operated in many areas of the country during winter (Figure 35) and most areas west of the Mississippi year round (Figure 36), and is fully functional in the southwest and Rocky Mountain States, where conditions are dry and water supply is stressed.

Analysis of Impact to Harvard Petroleum Federal 00 #3 Site

Harvard Petroleum Co. LLC operated the Federal 00 #3 well, which was the site of the full-scale field testing of the HDH system. An analysis of costs to operate the system is shown in Figure 37. Water from the Federal 00 is disposed of in a remote salt water disposal well; trucking and disposal costs are $2.30/bbl of produced water. The well produces ~20 bbl/d of PW, for an annualized disposal cost of $16,790. The HDH system as deployed was able to reduce the disposal volume by 50% and hence the water that needed to be hauled and disposed of by 50%, reducing disposal costs to $8,395.

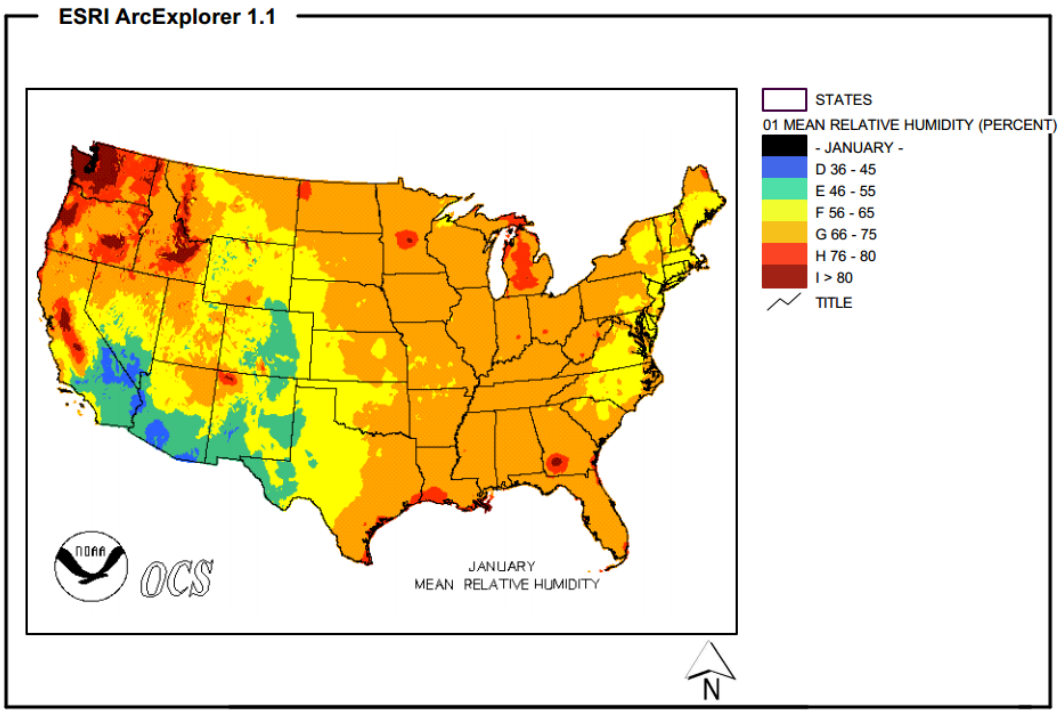


Figure 35. Mean relative humidity in January for United States. The system runs best under 70% relative humidity, a majority of the country in winter.

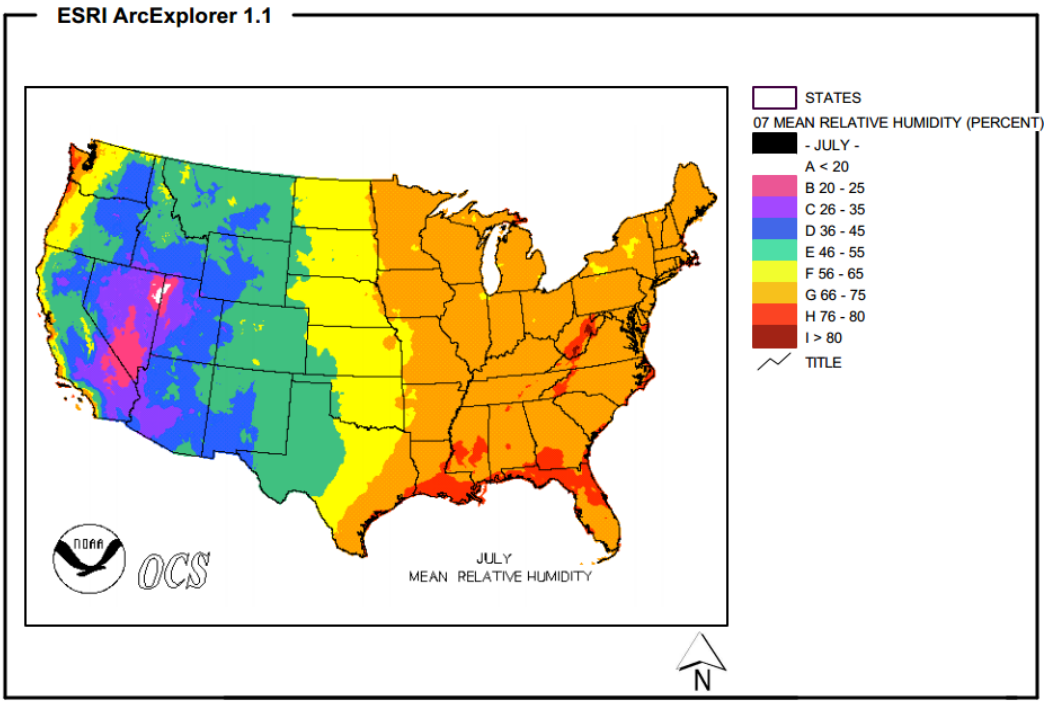


Figure 36. Mean relative humidity in July for United States. The system runs best under 70% relative humidity.

The HDH unit costs about $1,394 per year to operate with an average electrical cost of $3.82 per day. Disposal costs are the sum of the condensed waste stream and the electrical costs ($8,395 + $1394 = $9,789). The disposal cost is offset by selling purified water at $2.00/bbl, for a total annual added value of $7,300. Net disposal costs after selling purified water is the total disposal cost, less the value of the purified water ($9,789 – 7300 = $2,489). This represents a savings of $14,301 per year. As configured with the solar collector system and accounting for labor to set up the system as described in Section 2.2.4, the total capital expenditure would be $38,056. It would take 32 months for the system to pay for itself.

In a location with free heated water, such as the hot PW in the Bakken (~180°F) or if process heating using waste gas is used in place of a solar array, the capital expenditure would be reduced to $18,855 and the system would pay for itself in only 13 months, assuming similar value to the purified water.

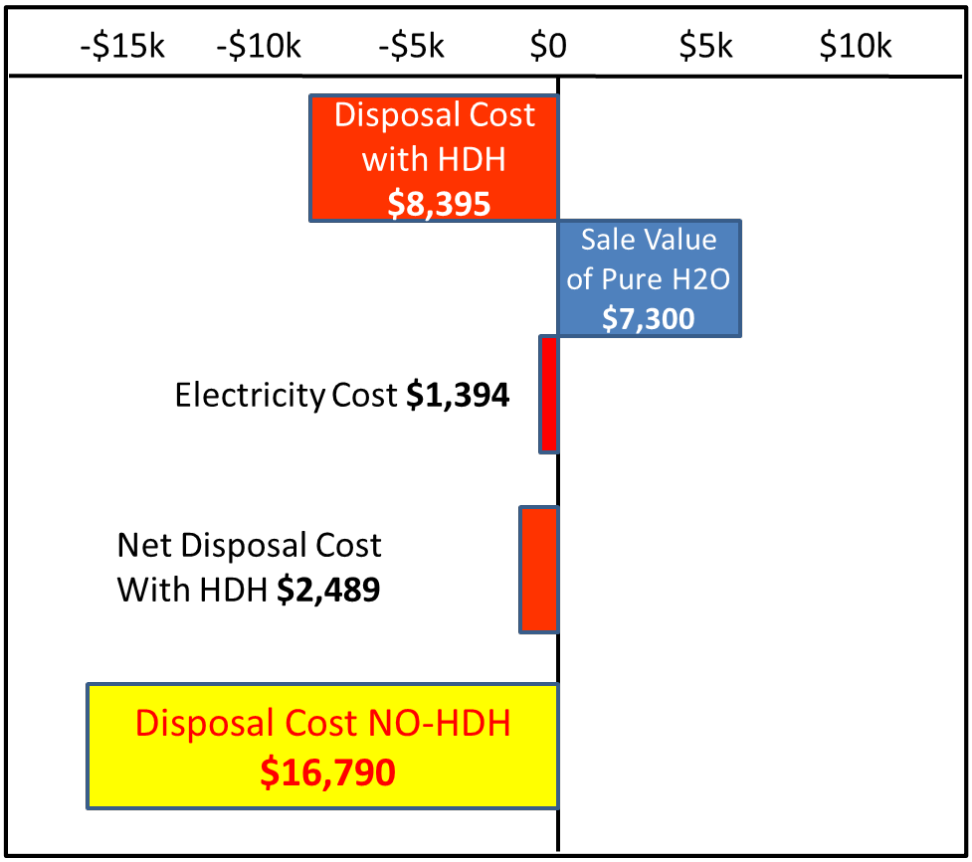


Figure 37. Impact of HDH water purification on the Federal 00 #3's water disposal costs.

4.0 Technology Transfer Efforts

The objective of technology transfer was to aggressively transfer technology to independent oil companies and service companies. This was accomplished through direct contact with companies, discussions at regional trade associations such as the New Mexico Oil and Gas Association, and the Independent Petroleum Association of New Mexico, and through the following direct technology transfer activities:

Patent:

At the time of this report a US patent for this process was pending.

Thesis:

1. Abdallah, I.:"Optimization and Testing of a Humidification-Dehumidification Process using Passive Solar Heating," M.S thesis Petroleum Engineering, New Mexico Institute of Mining and Technology, August 2015.

Presentations:

2. Balch, R., (2015):"Cost-Effective Treatment of Produced Water using Co-Produced Energy Sources: Phase II Field Scale Demonstration and Commercialization," Invited to Uinta Basin Working Group Meeting, Vernal, Ut, January 8.
3. Balch, R., (2014): "Cost-Effective Treatment of Produced Water using Co-Produced Energy Sources: Phase II Field Scale Demonstration and Commercialization," Unconventional Hydrocarbon Reservoirs and Produced Water Management, Salt Lake City, Utah, September 10.
4. Balch, R. (2014): "Cost-Effective Treatment of Produced Water using Co-Produced Energy Sources," Invited speaker, Independent Petroleum Association of New Mexico, Albuquerque, NM, August 6-8.
5. Balch, R., (2014): "Cost-Effective Treatment of Produced Water using Co-Produced Energy Sources: Phase II Field Scale Demonstration and Commercialization," RPSEA Onshore Production Conference, Houston, Texas, June 17.
6. Balch, R. (2014): "Cost-Effective Treatment of Produced Water using Co-Produced Energy Sources," Invited speaker, American Association of Mechanical Engineers Energy

Live Forum, San Diego, California March 17-19.

7. Balch, R., (2013): “Cost-Effective Treatment of Produced Water using Co-Produced Energy Sources: Phase II Field Scale Demonstration and Commercialization,” RPSEA Onshore Production Conference, Long Beach, California, October 17.
8. Balch, R., (2013): “Cost-Effective Treatment of Produced Water using Co-Produced Energy Sources: Phase II Field Scale Demonstration and Commercialization,” RPSEA Onshore Production Conference, Wichita Kansas, June 28.
9. Balch, R., (2012): “Cost-Effective Treatment of Produced Water using Co-Produced Energy Sources: Phase II Field Scale Demonstration and Commercialization,” RPSEA Onshore Production Conference, Houston, Texas, November 29.
10. Balch, R. (2011): “Cost-Effective Treatment of Produced Water using Co-Produced Energy Sources"An Oil and Gas Regulatory Data Mapping Portal,” Presented at RPSEA small producer forum, Bakersfield, CA, October 10.

Papers:

11. Balch, R., and Muraleedharan, S., (2014): “Cost-Efficient Well-Head Purification of Produced Water using a Humidification-Dehumidification Process,” paper SPE 169526-MS presented at 2014 SPE Western North America and Rocky Mountain Joint Regional Meeting 16-18 April 2014 in Denver, Colorado.
12. Balch, R., Abdallah, I., Garcia, L., and Cercone, D. (2016):” Pilot Test and Economic Analysis of a Wellhead Produced Water Purification System based on Humidification and Dehumidification using Co-Produced, Solar, and Waste Heat”, Paper SPE 180409-MS presented at 2016 SPE Western Region Meeting, May 23-26, in Anchorage Alaska.

A target goal of RSPEA is to spend 1.5% of project funds on technology transfer activities. Figure 35 tracks the progress of that goal.

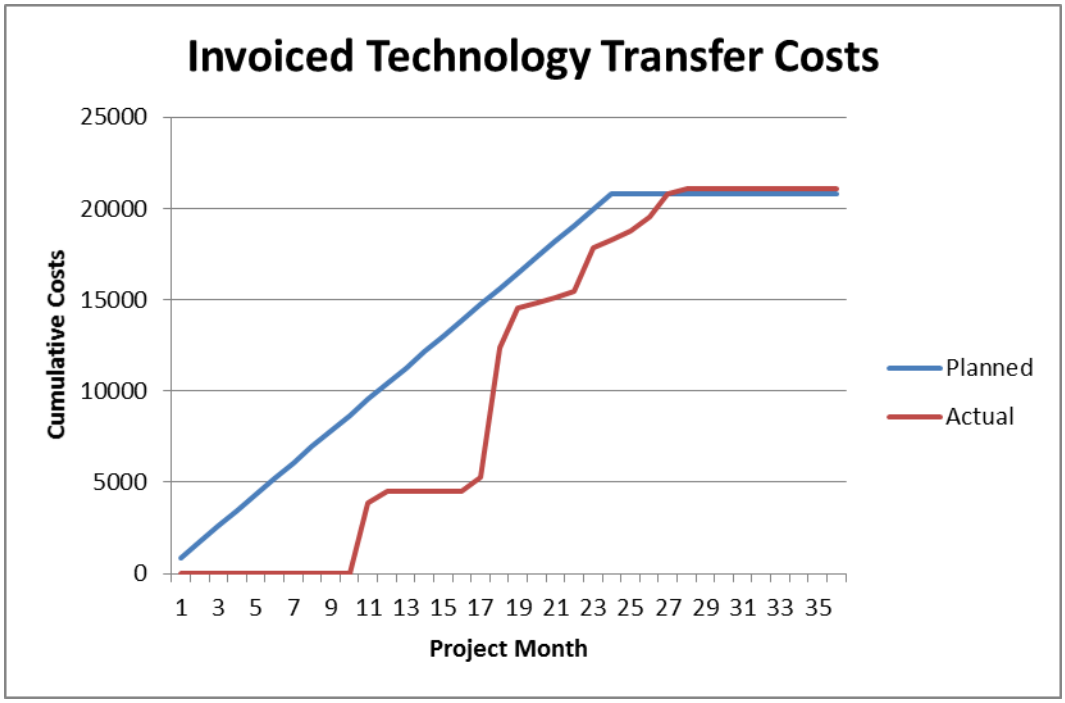


Figure 38. Invoiced technology transfer by project month.

5.0 Conclusions

The HDH unit built in the Phase 1 of the project was successfully optimized with passive solar heating. The 80 ft^3 unit treats about 50 bbl of PW with optimized rate of 1.5–2.5 gal/min and 150–160ft^3/min for produced water inlet rate and ambient air respectively. This reduces the produced water to condensate freshwater and concentrated waste stream with varying efficiency due to seasonal variability in the sensitive parameters of the HDH process: ambient temperature and relative humidity.

It was observed that the air inlet rate of the blower has a somewhat linear relationship with the TDS of the condensate freshwater. This effect, however, should be studied in a controlled environment to clearly define the relationship with higher levels of confidence.

It was determined that the sixteen 8 ft × 4 ft flat plate solar collectors that were fitted into the system could provide the required thermal energy for the unit's operation, with the exception of cold winter days. Additional daily thermal energy requirements for a series of six hour tests in the winter were supplied by a steam generator; in late winter and throughout summer and fall, the solar collectors could generate all the energy required to heat produced water to the operational temperature (180°F). The use of an energy-hungry steam generator could be supplanted with waste

gas heating on cold and/or cloudy winter days when ambient conditions do not favor ample thermal energy generation by the collectors.

The temperature of produced water from most oil wells is higher than the ambient temperature. Adequate thermal insulation methods to reduce heat loss in real time will be strictly observed resulted in a significant increase in hot water generation from the solar panels.

The HDH unit was moved from its location in Artesia and re-installed at a wellhead provided by industry partner Harvard Petroleum LLC near Carlsbad, New Mexico. The HDH unit is sized for the Federal 00's water production and can process 50 bbl/d of PW. The field setup utilizes the latent geothermal heat in the PW and heat is added to the water using an array of 16 flat plate solar panels. When the solar panels do not generate sufficient heat, at night or on cloudy days, additional heat is supplied to the storage tank by burning waste gas. An Arduino controller manages the process flow, switches fluid flow as needed, and monitors tank levels. The HDH unit can purify ~20% of the inlet water on each pass, and the outlet concentrate at ~135°F, is cycled back into the hot water storage tank.

The system was tested in summer and winter conditions. Winter conditions have drier inlet air, but less solar energy, and conversely summer has wetter inlet air, but more available solar heating. Summer tests yielded ~7 bbl/d of purified water, and winter tests produced ~11 bbl/d, for an annualized average of ~9 bbl/d, cutting the disposal needed for the Federal 00 in half. Purification costs are from electrical use of small pumps, a blower, and an air-cooled condenser, costing $3.82 per day, corresponding to ~$0.55 per barrel in summer and ~$0.35 per barrel in winter to purify water. Cost offsets from selling the fresh water and reduced disposal costs yielded an 85% reduction in annualized produced water handling costs.

The HDH unit could be upscaled to treat larger volumes of produced water as conditions (PW production rates) on a field demand. This could be done by adding condensation and evaporation chambers in parallel.

The HDH process is insensitive to varying TDS concentration and also treats organic waste. The fresh water generated by the unit meets the requirement of potable water. Therefore, low humidity regions in the United States and beyond could employ the inexpensive HDH process for water treatment; the fresh water generated by the unit is safe for most basic water needs

6.0 Recommendations

Operational recommendations were addressed in Section 2. An evaluation of operational constraints and advisable locations was made in Section 4. An analysis of system costs makes it possible to evaluate if the capital expenditures and payoff of the system make sense for a particular operation.

In general, in areas with high water disposal costs, especially those with very distant operations to conventional disposal operations are candidates for use of this system. Areas with latent geothermal heat can reduce process costs and an HDH system could be placed in-line with current disposal systems to reduce waste volumes by ~20% while yielding an equivalent amount of fresh water.

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