Saltworks

SaltMaker Evaporator Crystallizer Pilot Report

United States Bureau of Reclamation (USBR)

Upper Colorado Region, Paradox Valley Unit

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1. SALTMAKER PILOT RESULTS SUMMARY

Saltworks Technologies Inc. (Saltworks) completed a 30 day on-site SaltMaker pilot for the United States Department of the Interior, Bureau of Reclamation (USBR) at the Paradox Valley Unit (PVU) in Bedrock, Colorado. The SaltMaker pilot (full scale SaltMaker shown in Figure 1) operated 24/7 on hypersaline groundwater, producing freshwater and solids. The solids (Figure 1) were accepted for final disposal at the Broad Canyon Landfill in Naturita, Colorado. The pilot results confirm that a low temperature SaltMaker crystallizer can meet USBR's objectives for the PVU to reduce the saline groundwater to a solid waste product.

The key results from the SaltMaker pilot testing are:

- Solids passed the required paint filter tests for final landfill disposal.
- Produced freshwater with ~500 mg/L total dissolved solids from the hypersaline groundwater.
- Pretreatment with sodium hypochlorite can remove hydrogen sulfide to less than 0.5 mg/L concentrations.
- Tuned the SaltMaker's automated self-cleaning systems to maintain reliable operation with a highly scaling brine chemistry and in a solids producing regime.
- Heat exchanger and packing inspections saw no irreversible scale demonstrating the effectiveness of the SaltMaker's cleaning systems.
- Air sample results showed non-detectable concentrations of hydrogen sulfide and ammonia in the water vapor emissions.
- Completed SaltMaker pilot testing while meeting all health, safety, and environmental on-site requirements.

The pilot results inform the design basis of a full scale 300 gpm SaltMaker saline groundwater treatment plant. An overview of the SaltMaker is included in Appendix A and a product sheet is included in Appendix D. A general arrangement drawing for full scale plant is in Appendix E. This report will disclose the pilot testing data and results.

Figure 1: Full Scale SaltMaker (left); Solids Produced from PVU's Saline Groundwater (right)

2. PILOT TREATMENT TRAIN AND RAW GROUNDWATER CHEMISTRY

The SaltMaker pilot is a two effect machine and has a freshwater removal capacity of up to 40 GPD (150 L/day). Please refer to the SaltMaker Technology Overview section in Appendix A for an explanation of the SaltMaker effects. A description of the differences between the pilot and the full scale SaltMaker is provided in Appendix B. The pilot was installed at USBR's PVU site and operated for over 30 days from February 5 to March 9, 2018. The complete treatment train consisted of a pretreatment skid to remove hydrogen sulfide (H_2S) and a SaltMaker (Figure 2). A simplified process flow diagram is presented in Figure 3.

Figure 2: SaltMaker Pilot at Site (left), H_2S Pretreatment Skid (middle), SaltMaker Pilot (right)

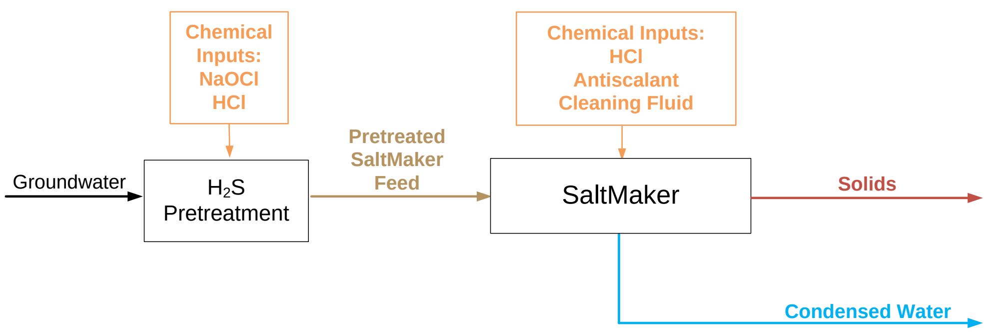


Figure 3: Simplified Process Flow Diagram of Pilot Groundwater Treatment System

The pilot treated a total of 1,089 gal (4,122 L) of the saline groundwater. The raw water chemistry has a total dissolved solids (TDS) of 260,000 mg/L, consisting predominantly of sodium and chloride. The detailed analytical results are provided in Table 1. The groundwater has high scaling potential for calcium carbonate ($CaCO_3$), calcium sulfate ($CaSO_4$), and calcium phosphate ($Ca_3(PO_4)_2$). The scaling compounds are near or at their solubility limits.

The SaltMaker does not require chemical softening pretreatment to remove scaling potential. It can be fed water at any salinity and almost any water chemistry. Expensive chemicals that increase solids load such as soda ash are avoided. The SaltMaker is able to operate with PVU's scaling water chemistry due to:

1) The SaltMaker is predominantly built from plastics, namely gel-coated, fibre-reinforced plastics with low surface energy that provides resistance to corrosion and scale.
2) The plant operates with high circulation rates to provide scouring flows and all wetted surfaces are exposed to continuous dynamic salinity gradients for salt saturation relief.
3) The SaltMaker has intelligent automated operations and self-cleaning processes. The plant's self-cleaning modes prevent irreversible scaling or fouling. It intelligently triggers the appropriate level of cleaning, from 'light rinse' to 'heavy scrub'. The SaltMaker uses condensed water as the cleaning fluid, which can be chemically augmented based on the type of scaling compounds and foulants in the brine. For the PVU brine, the cleaning fluid was augmented with sodium hydroxide to clean for any $CaSO_4$, $BaSO_4$, and $SrSO_4$ scaling. The cleaning fluid is reused multiple times before being fed back to the SaltMaker for treatment once it has been spent.
4) pH adjusting the groundwater to pH 5.5 to mitigate $CaCO_3$ and $Ca_3(PO_4)_2$ scaling risk.

Table 1: Summary of Raw Saline Groundwater Analytical Results

Date Sampled:	Feb 05, 2018	Feb 18, 2018	Feb 25, 2018
Hours of Operation:	0	216	377
Parameter	Raw Saline Groundwater		
Units:	mg/L	mg/L	mg/L
pH	7.04	7.35	7.1
H2S	79.6	49.1 (a)	53.5 (b)
Total Dissolved Solids	260000	263000	263000
Total Suspended Solids	130	22	50
Total Solids	260130	263022	263050
Total Hardness (as CaCO3)	10700	10000	10300
Alkalinity (as CaCO3)	212	216	212
Aluminum	<0.5	<0.25	<0.25
Ammonia (as N)	15.8	23.4	16.6
Antimony	<0.05	<0.025	<0.025
Arsenic	<0.01	<0.005	<0.005
Barium	<0.05	0.037	0.048
Beryllium	<0.005	<0.0025	<0.0025
Bicarbonate (as CaCO3)	212	216	212
Boron	7.1	7.1	7.7
Bromide	38	20	87
Cadmium	<0.001	<0.0005	<0.0005
Calcium	1400	1320	1350
Carbonate (as CaCO3)	<1	<1	<1
Chloride	146000	151000	147000
Chromium	<0.05	<0.025	<0.025
Cobalt	<0.005	<0.0025	<0.0025
Copper	<0.05	<0.025	<0.025
Fluoride	<2	<2	<2
Hydroxide (as CaCO3)	<1	<1	<1
Iron	<0.5	<0.5	<0.5

(a) Samples were collected on February 11, 2018
(b) Samples were collected on February 18, 2018

Table 1: Summary of Raw Saline Groundwater Analytical Results (Continued)

Date Sampled:	Feb 05, 2018	Feb 18, 2018	Feb 25, 2018
Hours of Operation:	0	216	377
Parameter	Raw Saline Groundwater		
Units:	mg/L	mg/L	mg/L
Lead	<0.005	<0.0025	<0.0025
Lithium	0.25	0.305	0.302
Magnesium	1750	1630	1690
Manganese	0.49	0.47	0.46
Mercury	<0.00001	<0.0001	<0.0001
Molybdenum	<0.01	<0.005	0.008
Nickel	<0.05	<0.025	<0.025
Nitrate (as N)	<0.5	<0.5	<0.5
Nitrite (as N)	<0.5	<0.5	<0.5
Phosphorus	3.3	<2.5	<2.5
Phosphate (Ortho)	0.07	0.06	0.042
Potassium	4870	4390	4760
Selenium	<0.05	<0.025	<0.025
Silica (Reactive)	2.74	3.62	2.62
Silicon	<5	<5	<5
Silver	<0.02	<0.010	<0.010
Sodium	91600	83100	87200
Strontium	26.6	30.6	30.1
Sulfate	5700	5310	5890
Sulfide	117	84.5 (a)	78.5 (b)
Thallium	<0.002	0.0015	<0.0010
Tin	0.081	<0.0025	<0.0025
Titanium	<0.1	0.27	<0.05
Uranium	<0.001	<0.0005	<0.0005
Vanadium	<0.1	<0.05	<0.05
Zinc	<0.5	<0.25	<0.25

3. H_2S PRETREATMENT

Sodium hypochlorite effectively reduced H_2S to less than 0.5 mg/L and sulfide to laboratory non-detectable concentrations. The H_2S pretreatment skid was manually operated on a batch basis. The site operators dosed a 264 gallon (1,000 L) tank of raw groundwater with 6% sodium hypochlorite to oxidize sulfide to sulfate (Reaction 1).

$$H_2S + 4NaOCl + 2NaOH \rightarrow 4NaCl + Na_2SO_4 + 2H_2O \qquad \text{Reaction 1}$$

A 3:1 hypochlorite to sulfide dosage rate by molar basis was used for the oxidation reaction. The dosage rate was predetermined by beaker tests completed at Saltworks using representative raw groundwater provided by USBR. The dosed groundwater was mixed with a circulation pump for ~10 minutes to ensure the reaction was complete. Thereafter, the groundwater was pH adjusted with 31% hydrochloric acid (Reaction 2) to pH 5.5 and fed to the SaltMaker.

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O \qquad \text{Reaction 2}$$

To confirm the effectiveness of H_2S removal by the sodium hypochlorite, samples of the pretreated groundwater were collected each time the SaltMaker's 264 gallon raw groundwater feed tank was refilled. A total of four samples were collected and submitted to an independent third party laboratory for analysis of pH, H_2S, and sulfides. The results are summarized in Table 2 and Figure 4. The detailed laboratory results are included in Appendix F.

Laboratory results show that sodium hypochlorite removed H_2S and sulfide from the groundwater to laboratory non-detectable concentrations. The February 5, 2018 sample had H_2S concentration approximately 30 mg/L higher than the subsequent raw groundwater samples. The cause of the difference is unknown. The February 5, 2018 H_2S treated sample had concentrations of H_2S and sulfide of 4.38 mg/L and 7.55 mg/L, respectively. The slightly elevated sulfide concentrations in this sample was due to unoptimized dosing at start-up and also due to a higher H_2S concentration in the raw than expected. Subsequent to this, the dosing was tuned and all sulfides and H_2S were removed during the pretreatment.

Table 2: Summary of Analytical Results for H_2S Pretreatment

Date Sampled:	Feb 05, 2018	Feb 11, 2018	Feb 18, 2018	Feb 25, 2018	Feb 05, 2018	Feb 11, 2018	Feb 18, 2018	Feb 18, 2018
Hours of Operation:	0	68	216	377	0	68	216	377
Parameter	Raw Groundwater				H2S Treated and pH Adjusted Raw Groundwater			
Units:	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
pH	6.55	6.39	6.54	6.76	5.48	5.18	5.12	5.51
H2S	79.6	49.1	53.5	49.5	4.38	0.423	<0.05	0.28
Sulfide	117	84.5	78.5	90.0	7.55	<1	<1	<1

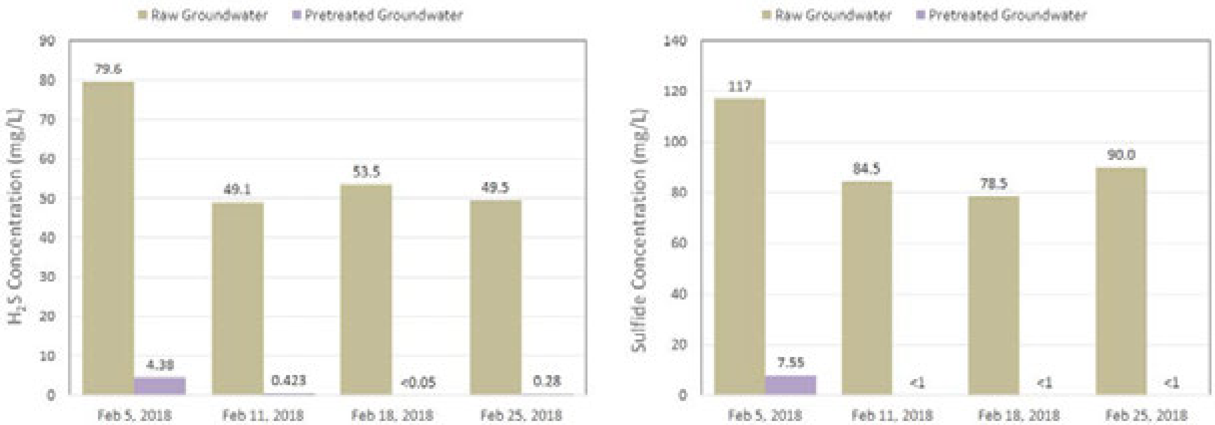


Figure 4: Summary of H_2S and Sulfide Removal

Based on the results, the expected chemical dosing rates for pretreatment for full scale design basis are:

- 12% Sodium Hypochlorite as solution 6,142 mg/L (6.1 kg/m^3) inlet
- 36% Hydrochloric Acid as solution 90 mg/L (0.09 kg/m^3) inlet

Calcium hypochlorite could also be used for the oxidation reaction to reduce the chemical costs for H_2S removal. This was not within the scope of the pilot but can be tested should USBR decide to explore operating cost reduction opportunities. Saltworks notes that though calcium hypochlorite may be a lower cost chemical, it increases calcium concentrations, a scaling ion, in the feed water and may introduce challenges with managing a solid chemical at full scale.

4. SALTMAKER OPERATION

The SaltMaker pilot operated 24/7 for the entire 30 days. Throughout the operating period, the SaltMaker pilot produced freshwater and solids without experiencing irreversible scaling, fouling, or plugging. The features of the machine to operate on USBR's highly challenging groundwater were summarized in Section 2. The data collected during the pilot operation demonstrates that the SaltMaker is effective in mitigating reliability risks associated with scaling water chemistry and operating in a solids producing regime. An overview of data collection during the pilot is included in Appendix C.

The SaltMaker pilot operated at steady state conditions once solids were produced after 37 hours of operation. The SaltMaker brine conductivity for Effects 1 and 2 is summarized in Figure 5. There are sudden downward spikes in the conductivity data. The 'noise' in the data is due to, and evidence of, the cleaning systems. There are two types of cleaning cycles periodically employed by the SaltMaker: (1) the pump, heat exchanger and pipework; and (2) evaporator packing. Both are washed with the cleaning fluid (pH 11, using sodium hydroxide [NaOH]), resulting in a drop in the conductivity (the downward spike). It is noted that the cleaning fluid was re-used multiple times until the conductivity reached 270 mS/cm (~330,000 mg/L TDS), at which point the solution was considered spent and sent back to the SaltMaker for treatment. These cleaning cycles result in the 'noise' in the brine conductivity data and also enable the operator to confirm that the cleaning systems are functioning.

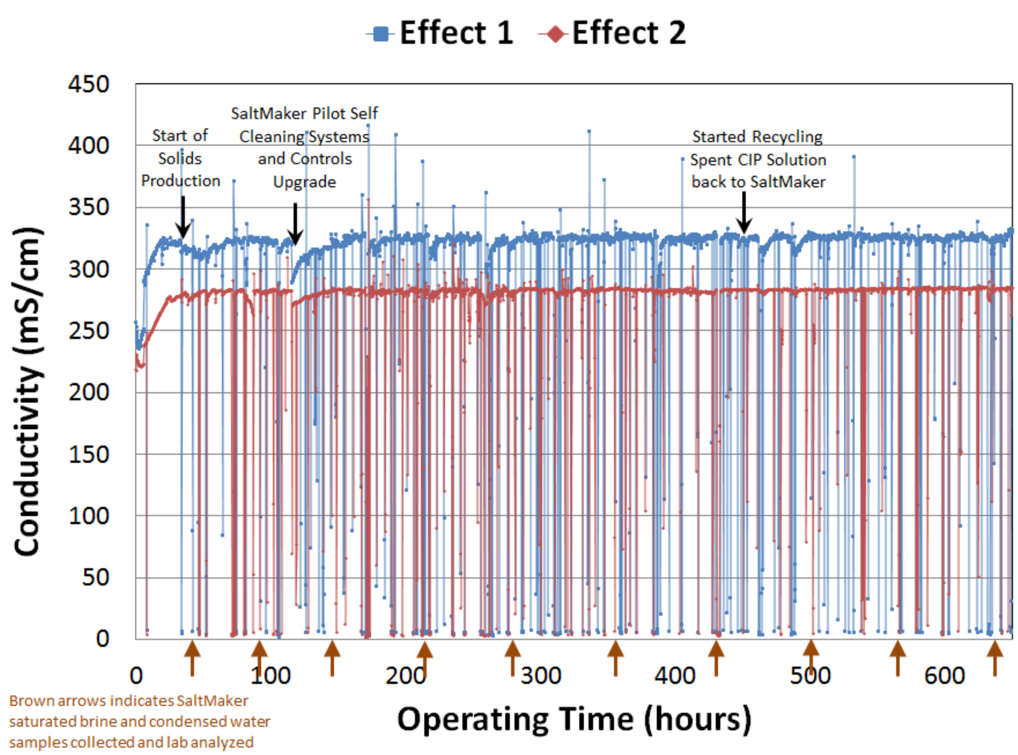


Figure 5: SaltMaker Pilot Effect 1 and 2 Conductivity Data

To confirm effective cleaning, daily inspections of the heat exchangers and packing were completed. As shown in Figure 6 and Figure 7, no irreversible scaling or fouling were observed on the heat exchanger or packing surfaces, further demonstrating the effectiveness of the cleaning cycles.

Start of Pilot | After Week 1 | After Week 2 | After Week 3 | End of Pilot

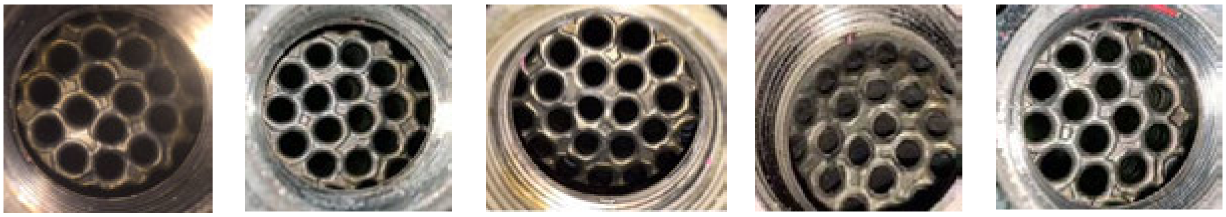


Figure 6: SaltMaker Pilot Heat Exchanger Inspections

Start of Pilot | After Week 1 | After Week 2 | After Week 3 | End of Pilot

Figure 7: SaltMaker Pilot Packing Inspections

After 112 hours of operations, the SaltMaker was shut down for one day to implement improvements to the plant's self-cleaning automation. The upgrades enable self-cleaning optimization so the plant cleans just the right amount, not too frequent (impacting capacity) and not too little (scale buildup). The improvements consisted of installation of sensors and an algorithm to inform cleaning cycle optimization. An extra day of piloting was added to compensate for this temporary shutdown.

5. SOLIDS PRODUCTION

The SaltMaker pilot produced approximately 705 lbs (320 kg) of solids (≤ 10% moisture) from the saline groundwater (see Section 8 for mass balance). The solids passed paint filter testing and were disposed at the Broad Canyon landfill. The SaltMaker pilot started solids production and extraction at 37 hours of operation. The extracted solids were dewatered over a period of 48 hours (Figure 8). The dewatered solids had a low moisture content that was sufficient to pass paint filter tests for landfill disposal based on field screening (Figure 9).

Figure 8: SaltMaker Extracted Solids (left) and Dewatered Solids (middle, right)

Figure 9: Field Paint Filter Screening Test for Solids - Passed after 48 hours of Dewatering

A total of three dewatered samples over the course of piloting were submitted to an independent third party laboratory. The samples were analyzed for:

- Paint filter test: The Broad Canyon Landfill only requires the solids to pass a paint filter test for acceptance.
- pH
- Ignitability
- Radionuclides: Thorium (228, 230, 232), Uranium (233/243,235/236, 238), and Radium (226 and 228)
- Toxicity Characterization Leaching Procedure (TCLP) for semi-volatiles, volatiles, pesticides, herbicides, and metals.

The analytical data is summarized in Table 3 with detailed analytical reports in Appendix F.

Table 3: Summary of SaltMaker Solids Paint Filter Test and TCLP Analytical Test Data

		Date Sampled:	Feb 25 2018	Feb 28 2018	Mar 8 2018
		Hours of Operation:	**337**	**445**	**664**
	Parameter		**SaltMaker Solids**	**SaltMaker Solids**	**SaltMaker Solids**
	Free Liquid (Paint Filter Gravimetric)	-	Passed	Passed	Passed
	pH	-	6.77	6.73	7.24
	% Dry Solids	%	96.1	90	97.7
RCI	Ignitability	°F	>140	>140	>140
RCI	Reactive Cyanide	mg/kg	<0.100	<0.100	<0.100
RCI	Reactive Sulfide	mg/kg	0.0500	0.0600	0.130
Metals	Alkalinity, Bicarbonate as CaCO3	mg/kg dry	83.2	77.8	20.5
Metals	Alkalinity, Carbonate as CaCO3	mg/kg dry	<10	66.7	102
Metals	Alkalinity, Hydroxide as CaCO3	mg/kg dry	<10	<10	<10
Metals	Alkalinity, Total as CaCO3	mg/kg dry	83.2	144	123
Metals	Chloride	mg/kg dry	588000	560000	588000
Metals	Sulfate	mg/kg dry	7210	10800	7240
Metals	Aluminum	mg/kg dry	23.3	<20.9	<20.9
Metals	Antimony	mg/kg dry	<20	<20	<20
Metals	Arsenic	mg/kg dry	<29	<29	<29
Metals	Barium	mg/kg dry	<0.490	<0.490	0.516
Metals	Beryllium	mg/kg dry	0.733	0.718	0.66
Metals	Boron	mg/kg dry	<33.1	<33.1	<33.1
Metals	Cadmium	mg/kg dry	<1.22	<1.22	<1.22
Metals	Calcium	mg/kg dry	3870	4510	1560
Metals	Chromium	mg/kg dry	2.18	0.877	0.802
Metals	Cobalt	mg/kg dry	<0.840	<0.840	<0.840
Metals	Copper	mg/kg dry	<1.17	<1.17	<1.17
Metals	Iron	mg/kg dry	21.2	<17.6	<17.6
Metals	Lead	mg/kg dry	<5.76	<5.76	<5.76
Metals	Lithium	mg/kg dry	<29.9	<29.9	<29.9
Metals	Magnesium	mg/kg dry	266	1060	378
Metals	Manganese	mg/kg dry	1.69	1.3	1.18
Metals	Molybdenum	mg/kg dry	2.88	<2.01	2.36
Metals	Nickel	mg/kg dry	<2.13	<2.13	<2.13
Metals	Potassium	mg/kg dry	795	2780	913
Metals	Selenium	mg/kg dry	<14.2	15	<14.2
Metals	Silicon	mg/kg dry	<53.3	<53.3	<53.3
Metals	Silver	mg/kg dry	<1.91	<1.91	<1.91
Metals	Sodium	mg/kg dry	356000	368000	376000
Metals	Strontium	mg/kg dry	77.3	90.1	21.3
Metals	Thallium	mg/kg dry	<2.37	<2.37	<2.37
Metals	Tin	mg/kg dry	<500	<500	<500
Metals	Titanium	mg/kg dry	1.85	0.815	0.747
Metals	Vanadium	mg/kg dry	13	17.7	26.8
Metals	Zinc	mg/kg dry	1.74	1.85	1.76
Volatiles	Vinyl chloride	mg/L	<0.050	<0.050	<0.050
Volatiles	2-Butanone	mg/L	<0.500	<0.500	<0.500
Volatiles	1,1-Dichloroethene	mg/L	<0.050	<0.050	<0.050
Volatiles	Chloroform	mg/L	<0.050	<0.050	<0.050
Volatiles	Carbon tetrachloride	mg/L	<0.050	<0.050	<0.050
Volatiles	Benzene	mg/L	<0.050	<0.050	<0.050
Volatiles	1,2-Dichloroethane	mg/L	<0.050	<0.050	<0.050
Volatiles	Trichloroethene	mg/L	<0.050	<0.050	<0.050
Volatiles	Tetrachloroethene	mg/L	<0.050	<0.050	<0.050
Volatiles	Chlorobenzene	mg/L	<0.050	<0.050	<0.050
Volatiles	1,4 Dichlorobenzene	mg/L	<0.050	<0.050	<0.050

Table 3: Summary of SaltMaker Solids Paint Filter Test and TCLP Analytical Test Data (continued)

		Date Sampled:	Feb 25 2018	Feb 28 2018	Mar 8 2018
		Hours of Operation:	337	445	664
	Parameter		SaltMaker Solids	SaltMaker Solids	SaltMaker Solids
Pesticides	alpha-BHC	µg/l	<5.0	<1.0	<1.0
	gamma-BHC (Lindane)	µg/l	<5.0	<1.0	<1.0
	beta-BHC	µg/l	<5.0	<1.0	<1.0
	delta-BHC	µg/l	<5.0	<1.0	<1.0
	Heptachlor	µg/l	<5.0	<1.0	<1.0
	Aldrin	µg/l	<5.0	<1.0	<1.0
	Heptachlor epoxide	µg/l	<5.0	<1.0	<1.0
	gamma-Chlordane	µg/l	<5.0	<1.0	<1.0
	alpha-Chlordane	µg/l	<5.0	<1.0	<1.0
	Endosulfan I	µg/l	<5.0	<1.0	<1.0
	4,4´-DDE	µg/l	<5.0	<1.0	<1.0
	Dieldrin	µg/l	<5.0	<1.0	<1.0
	Endrin	µg/l	<5.0	<1.0	<1.0
	4,4´-DDD	µg/l	<5.0	<1.0	<1.0
	Endosulfan II	µg/l	<5.0	<1.0	<1.0
	4,4´-DDT	µg/l	<5.0	<1.0	<1.0
	Endrin aldehyde	µg/l	<5.0	<1.0	<1.0
	Endosulfan sulfate	µg/l	<5.0	<1.0	<1.0
	Methoxychlor	µg/l	<10.0	<2.0	<2.0
	Endrin ketone	µg/l	<5.0	<1.0	<1.0
	Toxaphene	µg/l	<200	<20	<20
	Chlordane (tech)	µg/l	<10.0	<1.0	<1.00
Herbicides	2,4,5-T	µg/l	<3.98	<0.20	<0.20
	2,4,5-TP (Silvex)	µg/l	<3.98	<0.20	<0.20
	2,4-D	µg/l	<9.96	<0.50	<0.50
	2,4-DB	µg/l	<9.96	<0.50	<0.50
	3,5-Dichlorobenzoic acid	µg/l	<3.98	<0.20	<0.20
	4-Nitrophenol	µg/l	<9.96	<0.50	<0.50
	Acifluorfen	µg/l	<3.98	<0.20	<0.20
	Bentazon	µg/l	<19.9	<1.00	<1.00
	Chloramben	µg/l	<9.96	<0.50	<0.50
	Dalapon	µg/l	<19.9	<1.00	<1.00
	DCPA diacid	µg/l	<3.98	<0.20	<0.20
	Dicamba	µg/l	<3.98	<0.20	<0.20
	Dichloroprop	µg/l	<9.96	<0.50	<0.50
	Dinoseb	µg/l	<9.96	<0.50	<0.50
	Pentachlorophenol	µg/l	<3.98	<0.20	<0.20
	Picloram	µg/l	<19.9	<1.00	<1.00
Semi Volatile	Pyridine	mg/L	<0.010	<0.010	<0.010
	1,4-Dichlorobenzene	mg/L	<0.005	<0.005	<0.005
	2-Methylphenol	mg/L	<0.005	<0.005	<0.005
	4-Methylphenol	mg/L	<0.005	<0.005	<0.005
	Hexachloroethane	mg/L	<0.005	<0.005	<0.005
	Nitrobenzene	mg/L	<0.005	<0.005	<0.005
	Hexachlorobutadiene	mg/L	<0.005	<0.005	<0.005
	2,4,6-Trichlorophenol	mg/L	<0.005	<0.005	<0.005
	2,4,5-Trichlorophenol	mg/L	<0.005	<0.005	<0.005
	2,4-Dinitrotoluene	mg/L	<0.005	<0.005	<0.005
	Hexachlorobenzene	mg/L	<0.005	<0.005	<0.005
	Pentachlorophenol	mg/L	<0.005	<0.005	<0.005

		Date Sampled:	Feb 25 2018	Feb 28 2018	Mar 8 2018
		Hours of Operation:	337	445	664
	Parameter		SaltMaker Solids	SaltMaker Solids	SaltMaker Solids
Radiochemistry	Radium 226	pCi/g	<0.5	<0.3	<0.3
	Radium 228	pCi/g	<0.7	<0.5	<0.5
	Radium (total)	pCi/g	<0.7	<0.5	<0.5
	Thorium 232	µg/g	<0.266	<0.241	<0.253
	Thorium 230	µg/g	<1.42E-06	<1.28E-6	<1.35E-6
	Thorium 228	µg/g	<3.54E-11	<3.20E-11	<3.36E-11
	Thorium (total)	µg/g	<0.266	<0.241	<0.253
	Uranium 238	µg/g	<0.3	<0.3	<0.3
	Uranium 235	µg/g	<0.001	<0.001	<0.001
	Uranium 234	µg/g	<00002	<0.00002	<0.00002
	Uranium (total)	µg/g	<0.3	<0.3	<0.3

The solids produced consists of ~97% sodium chloride, ~2% calcium sulfate, <1% other salts based on a sample submitted to the laboratory to determine the composition. The results are summarized in Table 4.

Table 4: Summary of SaltMaker Solids Composition Analytical Data

Parameter	SaltMaker Solids Composition
Aluminum	0.003%
Barium	0.0001%
Bicarbonate	0.66%
Cadmium	0.000002%
Calcium	0.63%
Chloride	58.9%
Chromium	0.0001%
Copper	0.0005%
Iron	0.004%
Lead	0.0001%
Magnesium	0.042%
Manganese	0.0003%
Molybdenum	0.00001%
Nitrate	0.0003%
Phosphorus	0.019%
Phosphate (Ortho)	0.013%
Potassium	0.086%
Silica	0.004%
Sodium	38.0%
Strontium	0.017%
Sulfate	1.61%
Tin	0.00005%
Titanium	0.0001%
Uranium	0.000001%
Zinc	0.001%

6. CONDENSED WATER AND BRINE CHEMISTRY

The SaltMaker pilot produced condensed water (freshwater) with total dissolved solids (TDS) of ~500 mg/L. The freshwater quality remained consistent throughout the pilot testing. This is demonstrated by the field conductivity measurements of the condensed water as summarized in Figure 10. There were a couple of conductivity spikes in the condensed water. The increased conductivity was due to field operator inspections of the SaltMaker heat exchanger. It is suspected that after inspections, the PVC connector either did not have enough Teflon tape or was not sufficiently re-tightened. This resulted in seepage of brine into the freshwater, increasing the TDS. At 420 hours of operation mark and thereafter, the operators ensured that the connector was sufficiently tight. The freshwater quality was then consistently less than 1 mS/cm.

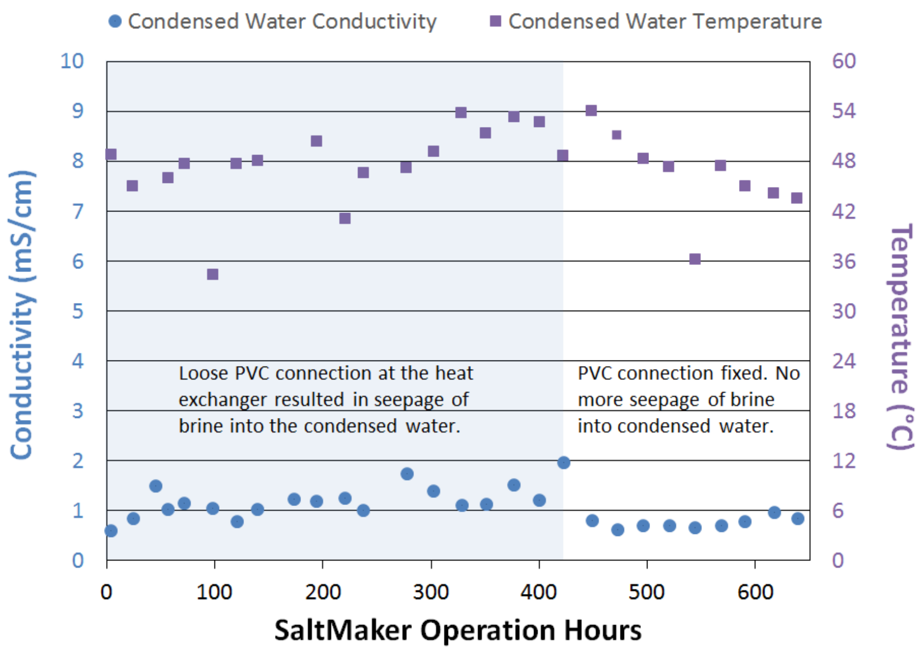


Figure 10: SaltMaker Condensed Water Conductivity and Temperature

The temperature of the condensed water was ~48°C as measured directly at the SaltMaker pilot discharge. At full scale operation, this water can be cooled to ambient conditions.

The pH of the condensed water as measured by field measurements is summarized in Figure 11. The pH varied between 6 and 9. At full scale operation, this water can be pH adjusted to the required pH.

No total solids field analysis was conducted on the condensed water. The field total solids analysis has a detection limit of 1,000 mg/L, which is higher than the total solids of the condensed water.

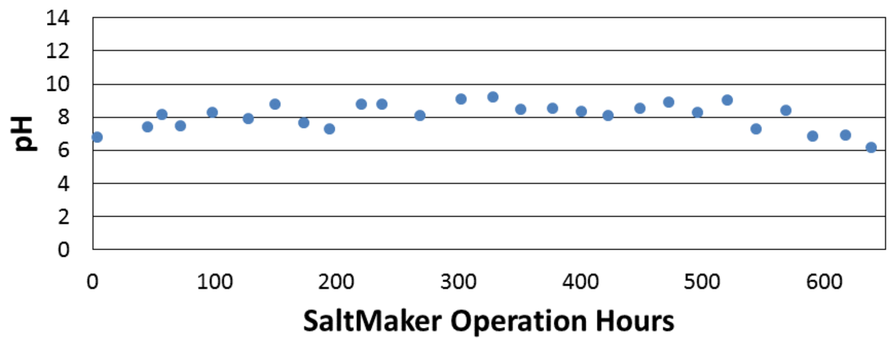


Figure 11: SaltMaker Condensed Water pH

Samples of the SaltMaker condensed water were collected and submitted to an independent laboratory for analysis on an every three day frequency as shown in Figure 5. The analytical results are summarized in Table 5. The main results are:

- TDS is less than 500 mg/L, noting that the elevated TDS results were due to the loose connection as described above.
- The TDS comprises of mostly sodium and chloride
- The pH of the condensed water varied between 4.5 and 7.6. The variation is likely due to low alkalinity with no buffering capacity of the water. The condensed water could be augmented with alkalinity, such as sodium bicarbonate, to maintain the pH between 6.5 and 7.5.

Table 5: Summary of SaltMaker Condensed Water Analytical Data

Date Sampled:	Feb 09, 2018	Feb 12, 2018	Feb 15, 2018	Feb 18, 2018	Feb 21, 2018	Feb 24, 2018	Feb 27, 2018	Mar 03, 2018	Mar 05, 2018	Mar 08, 2018
Hours of Operation:	41	98	145	216	280	354	421	520	568	664
Parameter	SaltMaker Condensed Water									
Units:	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
pH	6.18	7.59	7.15	6.46	6.34	6.08	6.51	5.13	4.49	5.27
Total Dissolved Solids	538	518	288	608	920*	522	1030*	222	210	292
Total Suspended Solids	<2	<2	<2	<2	5	<2	3	<2	<2	<2
Total Solids	538	518	288	608	925	522	1033	322	210	292
Total Hardness (as CaCO3)	21	10	14	24	47	27	55	15	13	18
Alkalinity (as CaCO3)	3	14	7	3	3	2	5	2	<1	2
Aluminum	(0.165) <0.05**	(0.24) <0.05**	(0.28) <0.05**	(0.26) <0.05**	(<0.05) <0.05**	(0.13) <0.05**	(0.32) <0.05**	(0.089) <0.05**	(0.536) <0.05**	(0.26) <0.05**
Ammonia (as N)	0.6	3.1	2.1	3.7	0.3	0.4	0.45	0.22	0.1	0.25
Antimony	<0.0005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.0005	<0.0005	<0.005
Arsenic	<0.0001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0001	<0.0001	<0.001
Barium	0.0014	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.0006	0.0007	<0.005
Beryllium	<0.00005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.00005	<0.00005	<0.0005
Bicarbonate (as CaCO3)	3	14	7	3	3	2	5	2	<1	2
Boron	0.154	0.18	0.29	0.22	<0.05	0.43	0.24	0.312	0.321	0.66
Bromide	0.83	<0.05	<0.05	0.16	0.78	0.47	0.76	0.18	0.13	0.2
Cadmium	<0.00001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.00001	<0.00001	<0.0001
Calcium	2.27	0.6	1.6	1.9	3.7	1.94	3.39	0.87	0.88	1.02
Carbonate (as CaCO3)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Chloride	323	327	183	374	552	308	585	130	123	160
Chromium	0.0007	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.0005	0.0008	<0.005
Cobalt	0.00235	0.0015	0.0019	0.0045	<0.0005	0.0035	0.0039	0.00247	0.00335	0.0048
Copper	0.0016	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.0005	0.0011	<0.005
Fluoride	<0.02	<0.02	<0.02	<0.02	<0.02	<2	<0.02	<0.02	0.09	0.03
Hydroxide (as CaCO3)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Iron	0.02	<0.1	<0.1	<0.1	<0.1	0.01	0.03	0.05	0.02	0.01

* Elevated TDS concentrations due to a loose connection at the heat exchanger. This resulted in seepage of brine into the condensed water, elevating the TDS.

** Aluminum concentrations are expected to be non-detectable as the raw saline groundwater has non-detectable concentrations. The analytical data showed detectable concentrations of aluminum. This is due to leaching from the radiator when the freshwater condenses on the aluminum fins. This only happens in the SaltMaker pilot unit. Full scale SaltMakers radiators fins are hersite coated, so it will not leach aluminum in the freshwater.

Table 5: Summary of SaltMaker Condensed Water Analytical Data (continued)

Date Sampled:	Feb 09, 2018	Feb 12, 2018	Feb 15, 2018	Feb 18, 2018	Feb 21, 2018	Feb 24, 2018	Feb 27, 2018	Mar 03, 2018	Mar 05, 2018	Mar 08, 2018
Hours of Operation:	41	98	145	216	280	354	421	520	568	664
Parameter	SaltMaker Condensed Water									
Units:	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Lead	0.00017	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	0.00027	0.00143	0.0009
Lithium	0.0008	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.0011	0.0011	<0.005
Magnesium	3.84	2.1	2.5	4.6	9.1	5.31	11.3	3.08	2.69	3.66
Manganese	0.003	<0.01	<0.01	<0.01	<0.01	0.004	0.006	0.002	0.001	0.001
Mercury	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
Molybdenum	0.0002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.0002	0.0002	<0.001
Nickel	0.0033	<0.005	<0.005	0.006	<0.005	<0.005	0.01	0.0038	0.0056	<0.005
Nitrate (as N)	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.007	0.011
Nitrite (as N)	<0.005	<0.005	0.039	<0.005	0.035	<0.005	0.033	<0.005	<0.005	<0.005
Phosphorus	0.06	<0.5	<0.5	<0.5	<0.5	<0.05	0.11	<0.05	<0.05	0.06
Phosphate (Ortho)	0.010	0.003	0.002	0.002	0.005	0.014	0.026	0.001	0.011	<0.001
Potassium	8.8	6	6	12	21	12.7	25.6	6.8	5.9	8
Selenium	<0.0005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.0005	<0.0005	<0.005
Silica (Reactive)	0.05	0.03	0.06	0.06	0.07	0.06	0.09	0.05	0.06	0.09
Silicon	0.3	<1	<1	<1	<1	0.4	0.4	0.4	0.5	0.9
Silver	<0.0002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.0002	<0.0002	<0.002
Sodium	184	93	129	187	335	179	334	76.4	67	89.3
Strontium	0.0355	0.027	0.024	0.032	<0.005	0.031	0.056	0.0113	0.012	0.01
Sulfate	11	9.6	8.1	12.3	20.2	11.3	25.3	5.1	14.9	6
Thallium	<0.00002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.00002	<0.00002	<0.0002
Tin	0.00432	0.0034	0.0093	0.008	<0.0005	0.0135	0.0136	0.0147	0.0306	0.0438
Titanium	0.001	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.003	0.004	<0.01
Uranium	<0.00001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.00001	<0.00001	<0.0001
Vanadium	<0.001	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.001	<0.001	<0.01
Zinc	0.049	<0.05	<0.05	0.06	<0.05	<0.05	<0.05	0.056	0.071	<0.05

The SaltMaker concentrated the saline groundwater to brine saturated conditions within 37 hours of the pilot startup. This was confirmed by observing solids production within the plant. Reaching solids production within two days of pilot startup was expected as the raw saline groundwater has high TDS of 260,000 mg/L. Figure 12 and Figure 13 summarize the conductivity results and field total solids results, respectively, for the saturated brine. The saturated brine temperature was ~ 55°C (Figure 12) and the pH varied from 4.5 to 7.5 (Figure 14).

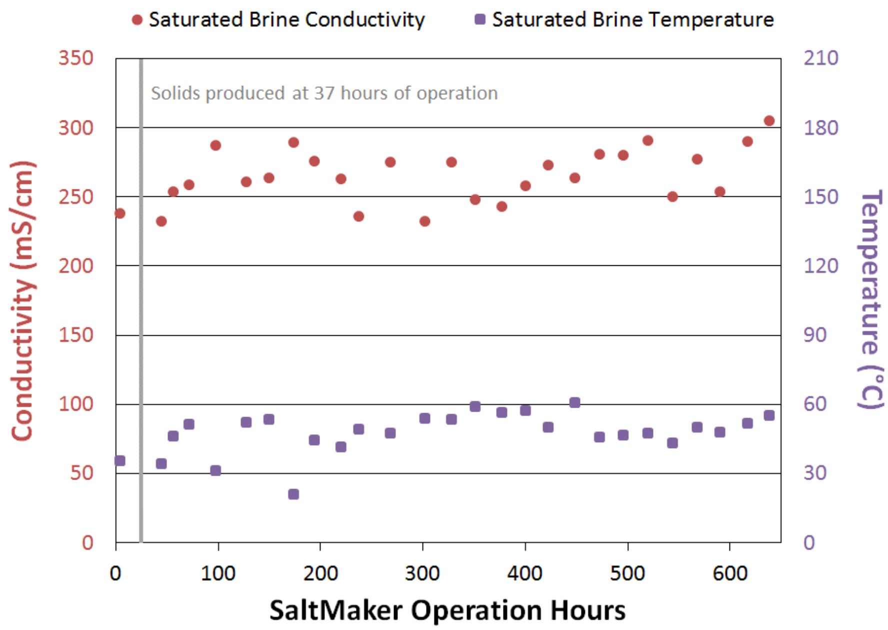


Figure 12: SaltMaker Saturated Brine Conductivity and Temperature

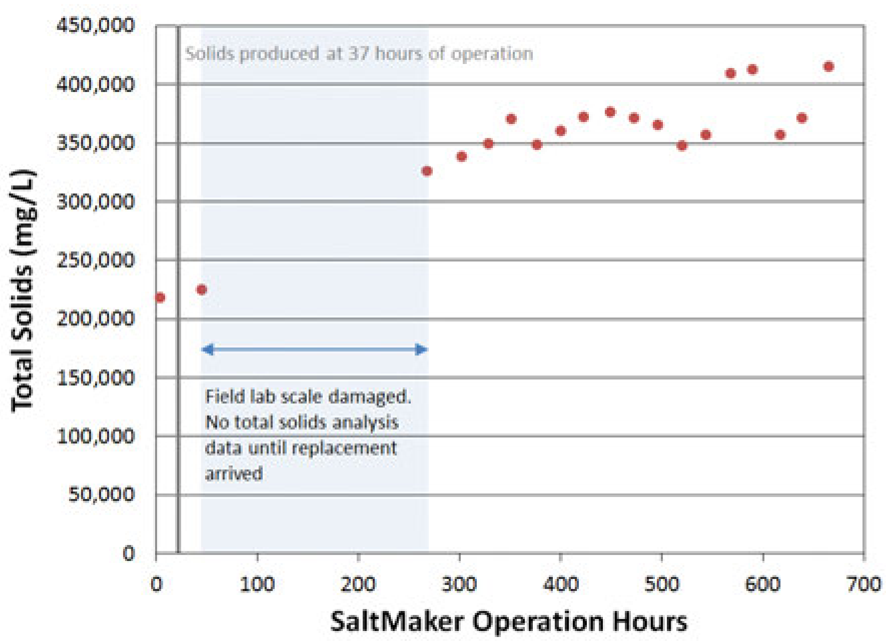


Figure 13: SaltMaker Saturated Brine Total Solids

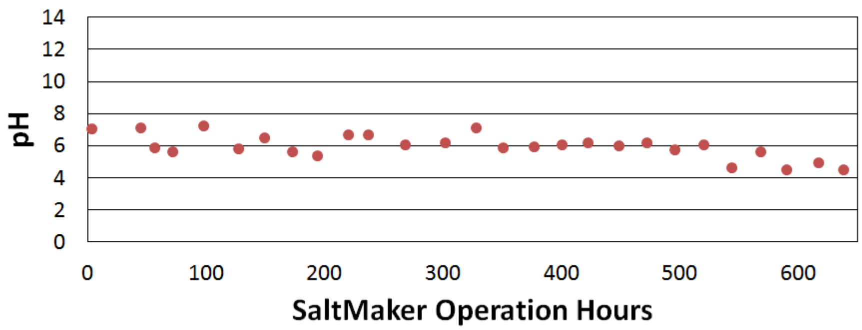


Figure 14: SaltMaker Saturated Brine pH

Samples of SaltMaker saturated brine were collected and submitted to an independent laboratory for analysis on an every three day frequency as shown in Figure 5. These samples were collected at the same time as the condensed water samples. The analytical results are summarized in Table 6. The main results are:

- Saturation of the brine was reached at 330,000 mg/L TDS
- The saturated brine is a highly scaling fluid with $CaSO_4$, $Ca_3(PO_4)_2$, $SrSO_4$, and $BaSO_4$ compounds all at concentrations greater than their solubility limits.

These results further support the importance of the SaltMaker's automated self-cleaning system to maintain reliable operation in a highly scaling and solids producing regime.

Table 6: Summary of SaltMaker Saturated Brine Water Analytical Data

Date Sampled:	Feb 09, 2018	Feb 12, 2018	Feb 15, 2018	Feb 18, 2018	Feb 21, 2018	Feb 24, 2018	Feb 27, 2018	Mar 03, 2018	Mar 05, 2018	Mar 08, 2018
Hours of Operation:	41	98	145	216	280	354	421	520	568	664
Parameter	SaltMaker Saturated Brine									
Units:	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
pH	6.92	7.51	5.95	5.26	5.87	5.11	5.29	5.18	4.91	4.48
Total Dissolved Solids	322000	335000	331000	328000	341000	343000	337000	346000	343000	344000
Total Suspended Solids	118	228	677	176	220	86	100	188	52	206
Total Solids	322118	335228	331677	328176	341220	343086	337100	346188	343052	344206
Total Hardness (as CaCO3)	14600	14600	13500	13100	15200	17000	18600	19800	21700	21700
Alkalinity (as CaCO3)	18	77	14	8	12	7	7	8	5	<1
Aluminum	<0.5	<0.5	0.47	0.29	0.6	0.37	0.32	<0.5	<0.5	0.9
Ammonia (as N)	0.9	3.7	6	10.4	6.4	5.8	4.2	4.42	6.51	7.8
Antimony	<0.05	<0.05	<0.025	<0.025	<0.025	0.026	<0.025	<0.05	<0.05	<0.05
Arsenic	0.01	0.01	0.01	0.007	0.01	0.011	0.006	0.01	0.03	<0.01
Barium	0.22	0.28	0.227	0.199	0.205	0.289	0.174	0.25	0.28	0.24
Beryllium	<0.005	<0.005	<0.0025	<0.0025	<0.0025	<0.0025	<0.0025	<0.005	<0.005	<0.005
Bicarbonate (as CaCO3)	18	77	14	8	12	7	7	8	5	<1
Boron	8.8	10.7	10.8	10.1	12.8	14.4	15.8	18.5	20.5	17.8
Bromide	36	37	<5	34	137	163	173	211	211	207
Cadmium	<0.001	<0.001	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.001	<0.0005	<0.001
Calcium	1590	1260	1390	1160	1170	1150	1080	925	1000	1070
Carbonate (as CaCO3)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Chloride	183000	196000	186000	168000	191000	190000	190000	191000	208000	190000
Chromium	<0.05	<0.05	<0.025	<0.025	0.036	0.06	0.048	<0.05	<0.05	0.06
Cobalt	<0.005	0.009	0.0072	0.0065	0.0098	0.0147	0.0136	0.023	0.029	0.03
Copper	<0.05	<0.05	<0.025	<0.025	<0.025	<0.025	0.03	<0.05	0.09	<0.05
Fluoride	<2	<2	<2	<2	<2	18	<2	<2	<2	<2
Hydroxide (as CaCO3)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Iron	<0.5	<1	<0.5	<0.5	0.8	0.6	<0.5	0.7	<0.5	0.7

Table 6: Summary of SaltMaker Saturated Brine Water Analytical Data (continued)

Date Sampled:	Feb 09, 2018	Feb 12, 2018	Feb 15, 2018	Feb 18, 2018	Feb 21, 2018	Feb 24, 2018	Feb 27, 2018	Mar 03, 2018	Mar 05, 2018	Mar 08, 2018
Hours of Operation:	41	98	145	216	280	354	421	520	568	664
Parameter	SaltMaker Saturated Brine									
Units:	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Lead	0.016	<0.005	<0.0025	0.0064	0.0059	<0.0025	<0.0025	<0.005	<0.005	<0.005
Lithium	0.38	0.46	0.431	0.44	0.535	0.651	0.583	0.71	0.84	0.72
Magnesium	2580	2780	2440	2470	2990	3430	3860	4250	4660	4630
Manganese	0.19	0.3	0.47	0.58	0.68	0.64	0.65	0.61	0.73	0.8
Mercury	0.00001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	0.0002
Molybdenum	<0.01	<0.01	0.006	0.008	0.028	0.04	0.069	0.11	0.128	0.09
Nickel	<0.05	<0.05	0.046	0.08	0.178	0.277	0.426	0.69	0.84	0.73
Nitrate (as N)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.6	<0.5
Nitrite (as N)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Phosphorus	17.5	21	13.7	10.9	9.4	15.4	6.3	11	10.9	20.5
Phosphate (Ortho)	4.57	3.04	8.00	10.9	8.82	11.9	4.68	13.3	10.4	16.8
Potassium	5740	7140	5640	5600	7450	8450	7740	10200	10600	8200
Selenium	<0.05	<0.05	<0.025	<0.025	<0.025	<0.025	<0.025	<0.05	<0.025	0.18
Silica (Reactive)	7.99	10.1	8.28	7.76	8.36	9.47	9.05	11.3	11.1	12.2
Silicon	6	<10	6	<5	5	6	6	8	8	8
Silver	<0.02	<0.02	<0.01	<0.010	<0.010	<0.010	<0.010	<0.02	<0.02	<0.02
Sodium	114000	104000	94800	105000	113000	99100	88400	90300	101000	80600
Strontium	22.8	22	27.1	23	21.9	21.8	16.1	28.8	15.6	10.8
Sulfate	6050	6260	6190	6040	6480	7100	7220	7960	8030	7680
Thallium	<0.002	<0.002	<0.001	<0.0010	<0.0010	<0.0010	<0.0010	<0.002	<0.002	<0.002
Tin	0.01	0.011	0.0151	0.015	0.0174	0.0252	0.0202	0.025	0.044	0.039
Titanium	<0.1	0.2	0.16	0.29	0.07	0.11	<0.05	0.2	<0.1	<0.1
Uranium	<0.001	<0.001	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.001	<0.001	<0.001
Vanadium	<0.1	<0.1	<0.05	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.1
Zinc	<0.5	0.5	0.44	0.57	0.82	1.4	1.29	1.8	2.3	2.5

7. AIR QUALITY

Air sample testing demonstrated no hydrogen sulfide or ammonia emissions from the SaltMaker. Full scale SaltMakers have the last effect open to atmosphere. The last effect operates as a cooling tower to complete final heat rejection. Air sampling was conducted to characterize for any potential emissions at full scale. The pilot SaltMaker normally operates with two closed effects; however, the plant includes the ability to open the second effect and emulate open operation.

Two air samples were collected for analytical testing and submitted to an independent third party laboratory for analysis. One sample was collected during the third week of operation and the other sample was collected during the last week of operation. The results are summarized in Table 7. The results show that there were no detectable concentrations of either hydrogen sulfide or ammonia in the air sample.

Table 7: SaltMaker Open Effect Air Sample Analytical Data

Date Sampled:	Mar 2/4, 2018	Mar 8, 2018
Parameters	**ppm_v**	**ppm_v**
Hydrogen Sulfide	<1.83	<1.83
Ammonia (10 L Sample)	<1.4	<1.4
Ammonia (50 L Sample)	<0.27	<0.27
Ammonia (100 L Sample)	<0.14	<0.14

8. MASS BALANCE

The total mass balance (solids and water) and solids only balance were within 10% (Table 8), which is appropriate considering the small capacity of the pilot. During piloting, there was a need for internal inspections that result in some lost fluids in order to meet one of the key pilot objectives: confirm no irreversible scale or build-up. As a result, field measurements and fluids lost during investigative inspections affect closing the balance fully. There was 578 kg of solids removed from the system during cleaning optimization testing. This occurred early in the piloting when more frequent washes were completed to maintain reliable operation with the highly scaling water prior to reducing and optimizing cleaning cycles. The pilot then underwent cleaning optimization testing. During the last week of operation, the cleaning system was optimally tuned to the water chemistry and all cleaning fluid was recycled back into the SaltMaker Pilot. The mass retained in the table represents the brine that stayed in the SaltMaker pilot after plant shutdown.

Table 8: SaltMaker Pilot Mass Balance

	Total Mass Balance (Kg)	Solids Balance (Kg)
Mass In		
Saline Groundwater	4782	1072
Mass Out		
Condensed Water	3823	1.9
Solids	320	288
Laboratory Samples	54	8.5
Cleaning Optimization Testing	578	578
Mass Retained		
Brine in SaltMaker	454	246
Mass Difference (Mass In - Mass Out - Mass Retained)	-447	-50
Percent Difference	-9.4%	-4.7%

APPENDIX A: TECHNOLOGY OVERVIEW

SaltMaker Evaporator Crystallizer

The following provides a general overview of the SaltMaker, non specific to the USBR PVU project. The SaltMaker evaporator crystallizer is a one-step brine treatment plant for volume minimization and zero liquid discharge (ZLD) applications. Its unique evaporative crystallizer design is built to treat the toughest waters and to simplify brine treatment.

The SaltMaker overcomes challenges that face conventional crystallizers:

- **Reliable Solids Production:** A circulating slurry continuously forms and grows crystals. Solid salt is discharged to an automated bagging or binning system.
- **One Step Treatment:** No pre-treatment required. For ZLD applications, solids are produced without the need for extra process equipment, such as centrifuges or filter presses.
- **Resists Corrosion, Plugging, and Scaling:** High circulation rates, constantly changing saturation gradients, and non-corroding, non-stick wetted surfaces prevent reliability challenges that plague conventional crystallizers
- **Intelligent Automation and Self-Cleaning:** The plant has automated start, stop, and hibernate for immediate ramping from 0 to 25% capacity in one step. It operates at any capacity between 25% to 100% in dynamic capacity control mode and will detect and initiate cleaning cycles.
- **No Single Point of Failure:** The SaltMaker is built from redundant process sets, unlike MVR evaporators that rely on a single vapour compressor inhaling moisture into a high-speed rotating machine. Even with the loss of one process set during maintenance, the plant keeps running at 92% capacity.
- **Modular Build and Scale Up:** The plant is built around ISO container frame modules, for ease of delivery, installation, and expansion to suit growing project capacity needs by adding process blocks.
- **Low Temperature Air Humidification Dehumidification:** The SaltMaker operates with an air cycle humidification dehumidification process (< 90°C), which avoids the use of pressure vessels and enables its construction from fiber reinforced plastics that withstand severely corrosive fluids. Multiple effects efficiently recycle thermal energy, opening a wide range of waste heat energy source options.

Reliable Solids Production and Extraction

The SaltMaker produces solids by circulating a brine slurry to continuously form and grow crystals. Salts preferentially grow on suspended seed crystal nucleation sites rather than on heat transfer surfaces. The larger crystals settle and are discharged to a Solids Management System for automated bagging or binning. Concentrated liquor, including smaller salt seeds, is recycled back to the SaltMaker while solid salts remain behind in the bags or bins. The system notifies the operators when the bags are full and ready to be transported to a drainage rack by forklift.

The solids are then drained and can pass the paint filter test, often within 24 to 48 hours of draining. Afterwards the bag can be sent for disposal or re-use depending on the application. The Solids Management System takes the guess work out of management and improves reliability. The plant flushes and purges slurry lines to prevent clogging, discharges thick slurry to the bags only when necessary, and automatically recycles rich liquor brine and notifies operators when to change bags.

Automated Bagging System

Bag Removed by Forklift

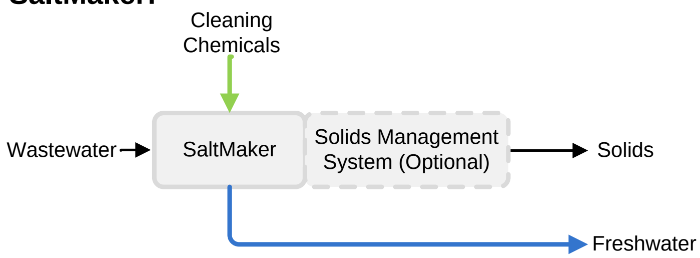
Bag of Solids

One Step Treatment

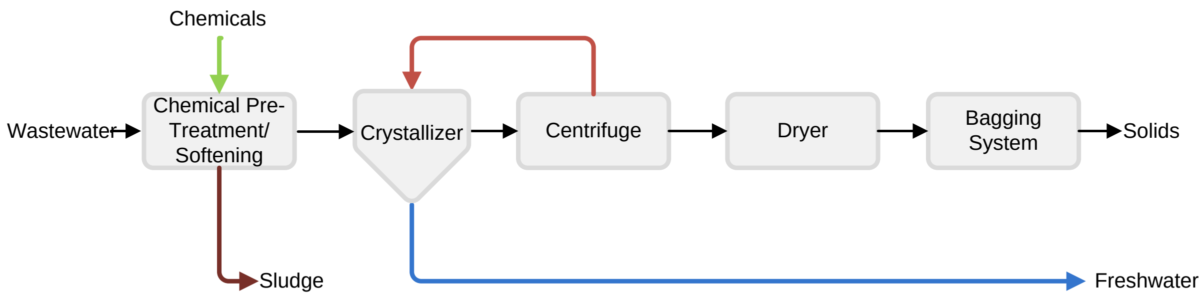
Traditional treatment technology requires multiple steps with different technologies to treat wastewater with high salinity levels. This includes separate systems for pretreatment, evaporation, crystallization, solids production and dewatering. The SaltMaker combines these steps into a single system that requires no pretreatment unless the water contains H_2S, which must be treated upstream the SaltMaker for safety reasons. The SaltMaker can be fed water at any salinity and almost any water chemistry. Expensive chemicals that increase solids load, such as soda ash, are avoided in the front end.

For ZLD applications, the Solids Management System can be added to the SaltMaker. Brine enters the plant, which produces freshwater and solids in bags or bins. No extra processing equipment, such as centrifuges or filter presses, is required. A simplified process flow diagram comparing the SaltMaker and a conventional process used to achieve ZLD is provided below.

SaltMaker:



Conventional:



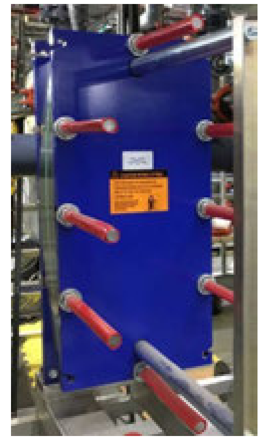
Built to Resist Corrosion, Plugging, and Scaling

The SaltMaker is predominantly built from plastics – namely gel-coated, fibre-reinforced plastics – with low surface energy that provides resistance to corrosion and scale. The plant also operates with high circulation rates to provide scouring flows and all wetted surfaces are exposed to continuous dynamic salinity gradients for salt saturation relief. Combined with sound engineering design, the SaltMaker prevents plugging and reliability challenges that frequently affect conventional evaporators and crystallizers.

Pipework
UPVC and CPVC

Pumps
Engineered Plastics

Modules and Tanks
Fiber Reinforced Plastics



Heat Exchanger
Titanium (non-boiling)

Intelligent Automated Operation and Cleaning

The SaltMaker has intelligent automated operations and self-cleaning processes. The plant can automatically (1) start; (2) stop and flush; and (3) hibernate in circulation mode and ramps to 25% capacity in one step. Dynamic capacity control allows the SaltMaker to operate anywhere from 25% to 100% of the rated capacity while being remotely managed via a secure internet connection.

The plant's self-cleaning modes prevent irreversible scaling or fouling by regularly monitoring key performance metrics. It will then automatically trigger the appropriate level of cleaning, from 'light rinse' to 'heavy scrub'. The SaltMaker uses distilled water as the cleaning fluid, which can be chemically augmented based on the type of scaling compounds and foulants in the brine. The cleaning fluid is reused multiple times before being fed back to the SaltMaker for treatment once it has been spent.

No Single Point of Failure

Unlike mechanical vapor recompression (MVR) technologies, where 100% plant capacity is lost when the vapour compressor goes offline, the SaltMaker has no single point of failure. The plant is built with repeatable and redundant evaporation-condensation process sets. If a process set is down for maintenance, the plant continues to run at 92% capacity.

Evaporation Module | Fan Module | Radiator Module

An Evaporation-Condensation Process Set

There are Multiple Process Sets in an Effect

An Effect

There are Multiple Effects in a SaltMaker

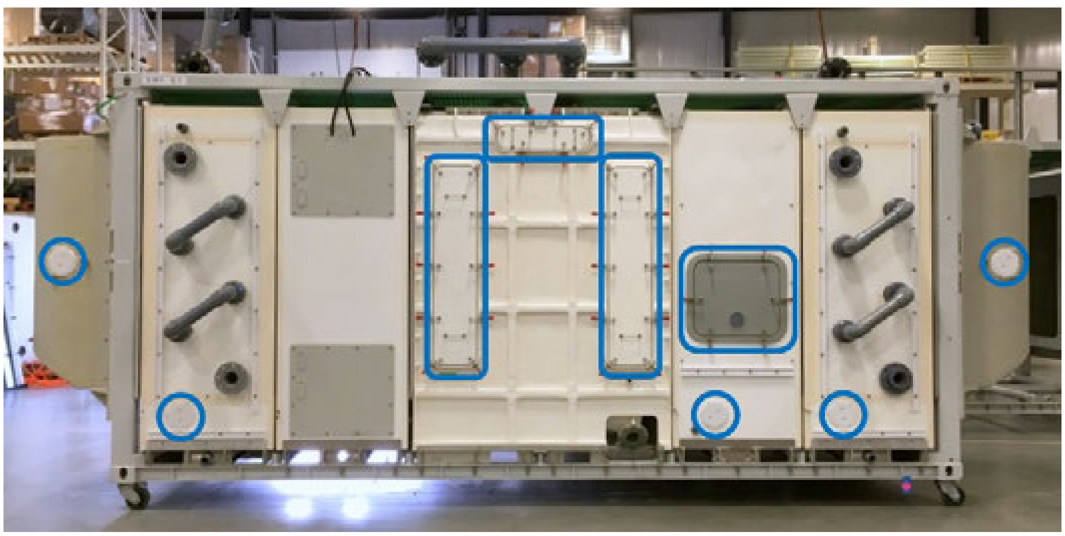
A S100 SaltMaker with Four Effects

Modular Build and Scale Up

The SaltMaker is built into standard ISO container frames. These modules enable factory assured quality production, ease of shipment-installation, and future expansion. The open concept design also allows easy access to processing equipment, such as pumps, for inspection and routine maintenance without any confined space entry.

Modular SaltMaker Plant Built into Standard ISO Frames

Easy Access to Process Equipmment



Effect with Multiple Inspection Hatches and Ports (highlighted in blue)

Multiple inspection ports in each effect allows convenient monitoring for scaling and fouling. Process set modules slide in and out. Cleaning is done with a power washer.

The modular design simplifies transport and assembly; the SaltMaker is sent by standard freight without any permits of oversized loads and assembled by crane on-site.




SaltMakers are built to standardized plant sizes that can be added together to expand capacity as your project grows. The models and their capacities are listed below.

Model	Capacity Based on Freshwater Removed*			
	m^3/day	Gallons per Day	Gallons per Minute	Barrels per Day
S30	30	7,900	5.5	188
S66	66	17,400	12	415
S100	100	26,400	18	630
S125	125	33,000	23	790

* Capacity derated by 20% to produce a 450,000 mg/L total solids slurry and by 40% to produce solids.

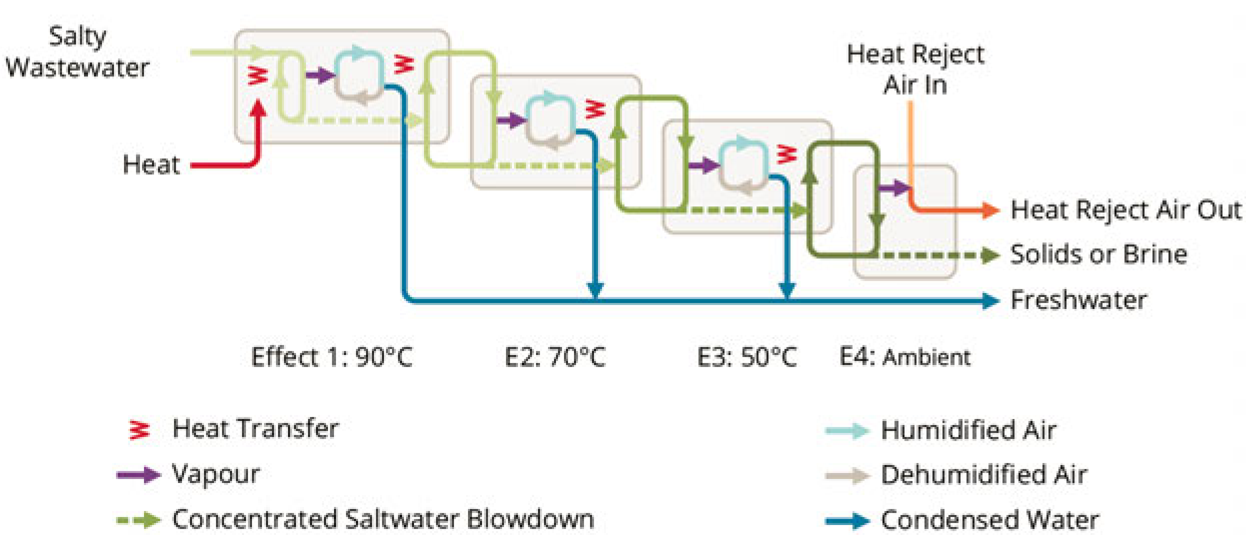
S100 SaltMaker Plant
100 m³/day freshwater removed capacity

S100 + S125 SaltMaker Plants
Capacity Increased by adding a S125 plant block
100 m^3/day + 125 m^3/ day = 225 m^3/day freshwater removed capacity

Low Temperature Air Humidification- Dehumidification

The SaltMaker is a multiple effect, thermally-driven evaporator crystallizer. It can use a variety of thermal sources: steam, low grade waste heat, and gas or liquid fuel fired low pressure water heaters. It operates at atmospheric pressure and temperatures less than 90°C, employing humidification dehumidification air cycles that do not require a vacuum, pressure, or boiling water on any heat transfer surfaces. Steam ticketed operators or pressure vessel certifications are not required.

In each of the effects, thermal energy is recycled, brine is concentrated, and freshwater is produced. Initial heat input to the plant at for example 92°C is used to evaporate and condense water in multiple effects, with the temperature being downgraded in each effect while the heat is recycled. This multiple effect process enables one unit of heat to produce four units of volume reduction as shown the process diagram below.



Warm brine flows at high volumetric velocities through the system and is sprayed onto non-stick packing material of the evaporator modules. Approximately 1-2% of each droplet is evaporated to become freshwater vapour, while the droplet is concentrated and cooled. The droplet is pumped through the system again to recapture heat and further evaporate.

Air is the vapour carrier with the fan module providing the motive force. Water vapor condenses into freshwater liquid at the radiator modules, which also transfer the latent heat of condensation to the next effect for energy efficiency. The final effect can be open or closed to atmosphere, providing cooling and heat rejection.

As water is evaporated, the brine is concentrated. Solid salts form on smaller salt seeds as saturation is exceeded. The smaller salt seeds are recycled from the Solids Management System (SMS), described above, with larger crystals forming and then discharged back to the SMS. This continuous cycling enables salt crystal growth and prevents the need for complex multi-step processes. The SMS is seamlessly integrated into the SaltMaker process, controls, and modular skids so a single package can be delivered and operated.

APPENDIX B: SALTMAKER PILOT OVERVIEW

SaltMaker Pilot

The SaltMaker pilot plant can remove up to 40 GPD (150 L/day) freshwater, can handle varying feed water chemistries and operate reliably at high brine concentrations to produce solids (Figure 15). This is made possible by its proprietary cleaning systems, controls and lack of membranes. It is designed for scalable operations toward full scale SaltMakers. It is noted that the pilot SaltMaker is a two effect closed air loop unit, whereas full scale units are four or five effects. The two effects of the pilot unit are representative of those on the full scale units that experience the most severe operation and are the two effects where solids are produced. The pilot machine has the same process, process components, and controls as full scale SaltMakers.

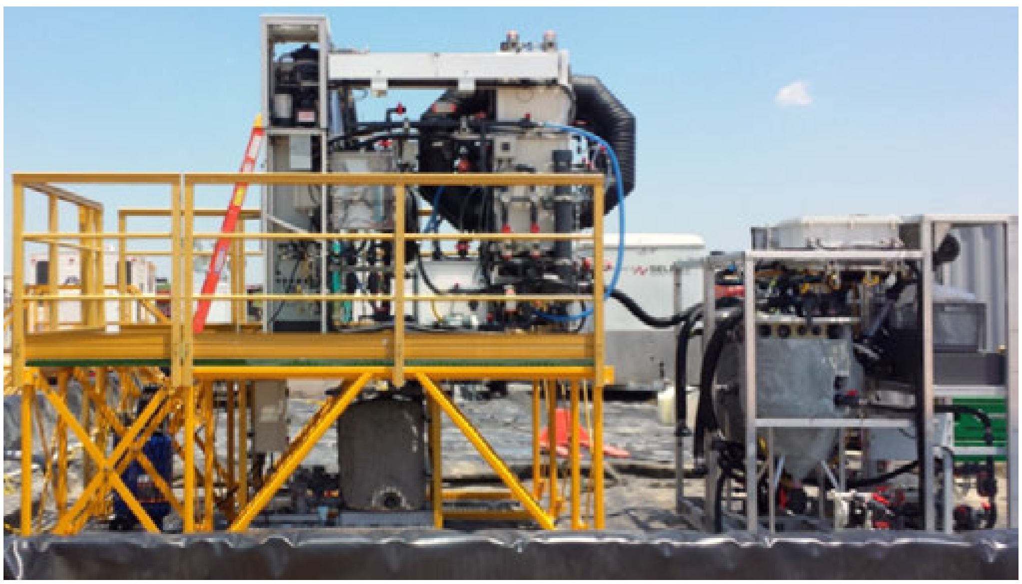


Figure 15: SaltMaker Pilot

For simplicity in the pilot SaltMaker, an electric heater is used to generate the thermal energy and temperature gradients. This prevents the need for a gas or heat source during piloting. Full scale SaltMakers are thermally driven by waste heat or natural gas. Electric energy consumption data from the pilot SaltMaker will not scale to the larger units. This is due to the electric heater in the pilot SaltMaker consuming a lot of power which is not used in the larger units. Scale up estimates for energy performance of full scale units is based on thermodynamics and past performance.

The difference between the pilot SaltMaker and a full scale SaltMaker is summarized in Table 8.

Table 8: Summary of Differences between Pilot SaltMaker and Full Scale SaltMaker

	Pilot SaltMaker	**Full Scale SaltMaker**
# of Effects	2	4 to 5
Thermal Energy Source	Electrical (Heater)	Waste Heat/Natural gas
Emissions	Closed Air Loop	Open last effect for heat rejection Optional: Closed last effect with alternate cooling source
Max Temperature	176°F (80°C)	203 °F (95°C)

The SaltMaker pilot plant for the USBR testing comes equipped with full process automation, self-cleaning systems, and a solids extraction system. The controls are similar as those for the full scale SaltMaker.

All lessons learned, controls, production and water chemistry obtained from the pilot SaltMaker scale up to full scale SaltMakers.

APPENDIX C: DATA COLLECTION

Data was collected during the pilot testing with the intent of providing sufficient data for the evaluation of performance, design and costing of a full scale plant. Three types of data were collected during the piloting: DAQ, manual measurements, and analytical.

Data Acquisition:

The SaltMaker pilot plant comes complete with a 24/7 data acquisition (DAQ) system to record conductivity, temperature, and other parameters.

Manual Measurements:

Manual measurements were completed daily to record parameters not available on the DAQ system and also as a check of DAQ and instrument calibration. Measurements were completed and recorded on operator log sheets. The manual measurements included conductivity, pH, temperature, and solids mass.

Along with the manual measurements, the operator completed:

- SaltMaker pilot check to ensure the plant, cleaning systems, and solids extraction systems are operating on spec.
- Calibration of all probes, sensors and transmitters for accurate HMI readings.
- Measurement of pilot feed consumption, condensed water production, and solids produced by tank volume measurements and solids weighing.

Analytical:

Analytical data are representative of samples collected at specific sampling ports within the pilot plant and analyzed for specific parameters. There were two types of analytical data that was collected during the testing program:

- **Field Screen:** These analyses were completed at Saltworks' onsite field lab as a screen for key parameters of interest. The main analysis completed was for total solids, a proxy for total dissolved solids.

- **Laboratory:** Independent third party laboratories, AGAT Laboratories (Burnaby, British Columbia) and Green Analytical (Durango, Colorado), were used for characterization of water, solids, and air. Samples were collected, stored, and transported to the laboratory in chilled coolers as per the laboratory procedures.

APPENDIX D: SALTMAKER SPEC SHEET

APPENDIX E: FULL SCALE PLANT PRELIMINARY GENERAL ARRANGEMENT

APPENDIX F: DETAILED LABORATORY REPORTS