2.500 Desalination and Water Purification
Spring 2009

A Potable Water System for Paulette and Phaeton, Haiti

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1 Introduction

1.1 Motivation

Water is essential to the health and well-being of individuals, and therefore to the health and well-being of entire communities. The largest water shortage problems exist in the developing world, thereby stunting possible improvement to quality of life and societal well-being. Most of the world's water is salt-water, and only a fraction of a percent of the total water on the planet is accessible freshwater. In order to supply sufficient water to developing communities around the world, it has become increasingly clear that desalination and purification must play a larger part. Desalination plants in the developed world are often large-scale, require significant capital and infrastructure, and rely on advanced technology with teams of experts available to operate and maintain the plants. Much of the developing world, however, consists of small towns, coastal and otherwise, that face harsher restrictions and needs.

Phaeton and Paulette are two such towns located in the sparsely populated North of Haiti in the Caribbean (Fig 1). Phaeton is the larger of the two villages, with a population of 2450 people comprising about 500 families, and Paulette has approximately 1750 people, or 350 families. Phaeton and Paulette are poor towns with little opportunity for non-agrarian employment. Their freshwater needs are equal to those of anyone in the developed world, but their capacity to invest in a standard desalination plant is severely limited. This project is motivated by the desire to provide these people with the same opportunities for healthy living as are available and believed to be acceptable in the developed world. Their need is equal, but their limitations require designing and tailoring a unique, acceptable freshwater system.

1.2 Location and Climate

Haiti is located at 19N and 72W. It's area is slightly smaller than that of Maryland. It borders the Dominican Republic, but mostly consists of Caribbean coastline. It has a tropical, semi-arid climate and rough, mountainous terrain, though this mostly does not apply to the flatter coastal villages of Paulette and Phaeton. Haiti is currently experiencing severe deforestation, soil depletion, ineffective overfarming, and political consternation. All of these lend to the general instability of the small nation. Haiti also suffers from a lack of potable drinking water, medical, and social services and a very high urbanization rate, contributed to by a growing population of youth in Haiti, where the median population age is in the early 20s.

As a near equatorial country, Haiti experiences very little variation in average monthly temperatures which ranges, on average, from 26 to 29 degrees Celsius. There are, however, very distinct wet and dry seasons, as is visible in Fig. 2. Haiti has a high rate of insolation and is well-suited to applications of solar technology.

1.3 Water Quality and Quantity

Paulette is supplied with water by 1 pumped freshwater system, 3 community wells, and 8 hand-dug bucket wells while Phaeton has 1 pumped freshwater system, 1 community well,

Courtesy of the CIA Factbook.

Figure 1: Haiti.

and 7 hand-dug bucket wells. The pumped freshwater system has acceptable drinking water, while the community and hand-dug wells supply brackish water that needs to be purified in order to be healthy. Table 4 in the appendix shows the levels of contaminants in the pumped systems and one of the community wells, along with maximum contaminant levels (MCL) allowed by the EPA for drinking water in the US. Testing showed that all of the water supplies have elevated levels of calcium and magnesium, indicating extreme hardness, silica, dissociated sodium chloride, or salinity, and heightened levels of alkalinity, nitrites, carbonate, and bicarbonate. These qualities most closely resemble those of brackish water with low salinity and high total dissolved solids (TDS).

Families need between 10 and 35 gallons of potable water per day for cooking, drinking, and bathing. Fresh water obtained from the pumped system is currently transported in 3-5 gallon jugs. These jugs are replenished by family members throughout the day from the pumped well at a cost of 0.20 gourde/gal. A gourde is the Haitian currency with an exchange rate of approximately 2.5 cents per gourde. In order to meet demand, therefore, between 13 and 65 m^3/day must be supplied to the two towns. These figures are outlined in Table 5 in the appendix.

1.4 Prior Art

Water purification and desalination is a broadly studied field with many applications, particularly in the developing world. There are four main methods to purify water from brackish or high-salinity water, two of these are membrane processes – reverse osmosis (RO) and elec-

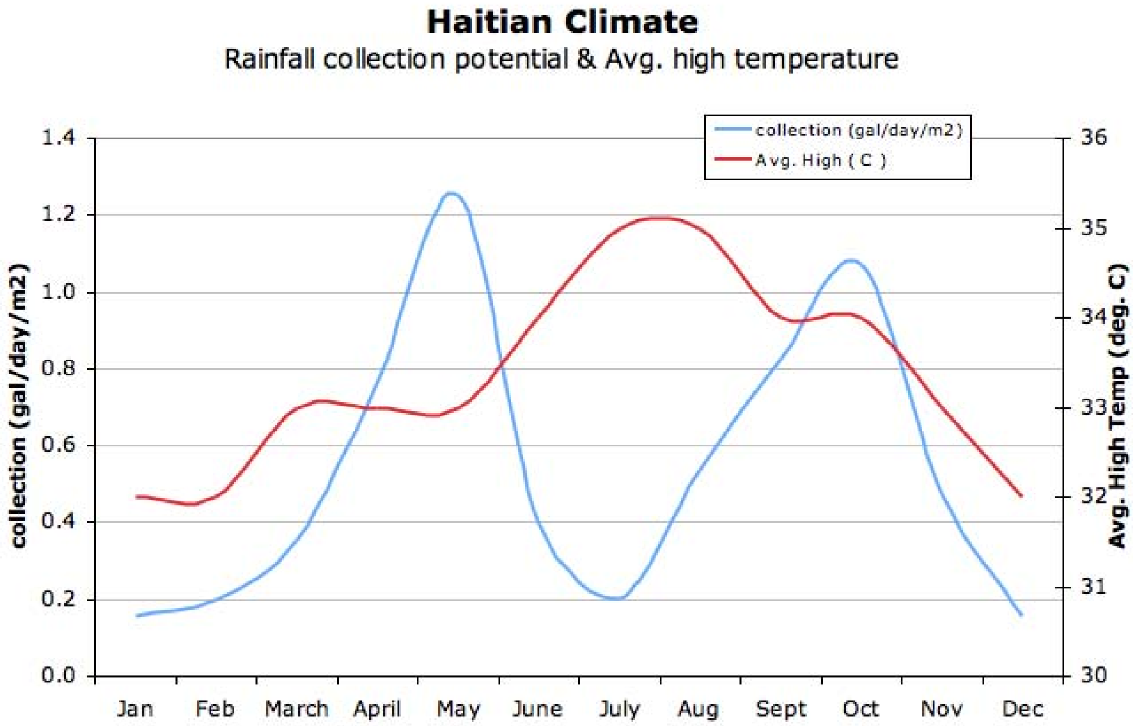


Figure 2: The temperature in Haiti does not vary greatly, though precipitation fluctuates with two dry and two wet seasons per year.

trodialysis (ED) – and two are thermal – multistage flash (MSF) and multieffect distillation (MED). Each of them has a primary energy sink, or process step that requires the most energy. For RO, this sink is the high pressure pumping, for ED it is the passing of electrical current through the anion-cation stack, and for the thermal processes it is the energy needed to change the phase of water [1]. A number of different technologies currently exist for desalinating water in the developing world. These are briefly described below.

Among the larger purification systems, there are two RO units, the SWM 11000 and SSBW 15000, or "Solar cube" capable of producing between 10 and 15 m^3/day. These two systems need 3.84 kWh/m^3 and 2.82 kWh/m^3, respectively, to function. The SWM 11000 costs $38,700 and the SSBW $67,870. These figures come from the company producing these technologies, Spectra Watermakers (http://www.spectralandbased.com/). Cost figures for Spectra Watermakers are given in the Appendix, Fig. 15. Solar electrodialysis provides a clean and convenient way to purify water. One such system, the Eurodia, can process 100 L (26 gal) in full sun in 20 minutes, implying that it has a specific power consumption of only 1.02 kWh/m^3. This is better than the RO systems, but there are still complications in fabrication and maintenance of this system. Nevertheless, this may someday become a viable alternative for small towns throughout the developing world, particularly those blessed with abundant solar energy [2]. Solar water distillation has also been attempted in a variety of different ways. However, there is a basic limitation of using solar power to heat water.

Simply, although solar is abundant, it is also widely dispersed, producing insolation of only 600-1200 W/m^2 for roughly 12 hours daily in sunny areas. For the problem at hand, in order to generate 30 m^3/day of water, an area of 2678m^2 would be required [2]. Attempts at harnessing solar to distill water are numerous, with community-wide efforts, such as the El Paso Solar Energy Association, which encourages the construction of private solar stills in order to create supplemental water for individual families, to the Watercone, which takes advantage of a greater condensing surface in order to attempt to increase the flow rate of distillate. However, these processes are all limited by low-flux solar power and lack of concentration of the power, so none have achieved flow rates about 1-3 L/day.

2 Calculations

The water was approximated with an NaCl solution. In order to correctly perform the calculations, the solution must be made to match the electrical and colligative properties of the water in Haiti. To do this, a range was determined by finding the NaCl solution equivalents for the TDS, the molar sum, and the ionic strength of the water. The resulting NaCl solutions are given in Table 1. The subsequent analyses, then, are based on the best approximated solution based on the properties we needed to match for every technology.

Table 1

Comparing water with NaCl solution

	TDS (ppm)	**sum m** (mol/kg_{H_2O})	**Ionic strength**
Phaeton family well	3860	0.1300	0.0860
Equal TDS	3860	0.1326	0.0663
difference	0.0%	2.0 %	-22.9 %
Equal molar sum	3784	0.1300	0.0650
difference	-2.0%	0.0%	-24.4%
Equal ionic strength	5002	0.1720	0.0860
difference	29.6%	32.3%	0.0%

2.1 Least Work

The theoretical least work to separate freshwater from brackish water is determined using knowledge of the physical properties of the water, and the changes in Gibbs' free energy as a result of extracting pure water from a solution stream. In order to determine the least work, a feed salinity ratio, η, is first defined as the ratio of salt flow ($\dot{N}_{NaCl}$) to pure water in the feed ($\dot{N}_{H_2O}$),

$$\eta \equiv \frac{\dot{N}_{NaCl}}{\dot{N}_{H_2O}} = m_{NaCl}\frac{M_{H_2O}}{10^3} \tag{1}$$

which can then be further defined given the molar masses and fractions of salt and water. Two cases yield different results for the least work needed to extract the pure water. The first case is the extraction of pure water with no remaining salinity from the feed stream (($m_{NaCl,2} = 0$). The least work in this situation is given by

$$\frac{\dot{w}_{least}}{\dot{N}_{H_2O,1}} = \eta(\Delta\bar{G}_{NaCl,3-1}) + (\Delta\bar{G}_{H_2O,3-1}) + (\Delta\bar{G}_{H_2O,2-3}) \tag{2}$$

where $\Delta\bar{G}_{NaCl,3-1}$ is the change in Gibbs energy as a result of changing salt concentration in the output brine and the feed, $\Delta\bar{G}_{H_2O,3-1}$ is the change in Gibbs energy as a result of a different water concentration in the output brine and the feed, and $\Delta\bar{G}_{H_2O,2-3}$ is the change in Gibbs energy due to a difference in the concentration of pure water in the pure output water and the feed. The sum of the energies needed to overcome these chemical changes in the solution yields the least work necessary to extract the water. These chemical energy differences between solutions with different concentrations of certain species are

$$\Delta\bar{G}_{i,a-b} = RT[ln(x\gamma)_{i,a} - ln(x\gamma)_{i,b}] \tag{3}$$

where $x_{i,a}$ is the mol fraction of species i in solution a, and $\gamma_{i,a}$ is the activity coefficient of species i in solution a.

The second and more relevant situation is that in which the output stream is not pure ($m_{NaCl} \neq 0$). In this case, a term accounting for the difference n Gibbs energy as a result of different concentrations of salt between the feed solution and the recovered water must be included,

$$\frac{\dot{w}_{least}}{\dot{N}_{H_2O,1}} = \xi\eta(\Delta\bar{G}_{NaCl,3-2}) + \eta(\Delta\bar{G}_{NaCl,2-1}) + (\Delta\bar{G}_{H_2O,3-1}) + R_p(\Delta\bar{G}_{H_2O,2-3}). \tag{4}$$

Here, a new ratio, that of the recovery ratio, or R_p, is defined. R_p is

$$R_p \equiv \frac{\dot{N}_{H_2O,2}}{\dot{N}_{H_2O,1}} = m_{NaCl}\frac{M_{H_2O}}{10^3} \tag{5}$$

and represents the fraction of of water that is purified. The results of these calculations are given in Fig. 3. The figure also gives the cost for removing the water at a certain recovery ratio. This represents the least cost per m^3. A table summarizing least work calculations is given in the Appendix, Fig. 12.

2.2 Reverse Osmosis (RO)

Reverse osmosis works on the principle of overcoming the osmotic pressure that would normally drive diffusion of a solute into a pure solvent and causing the reverse process to occur

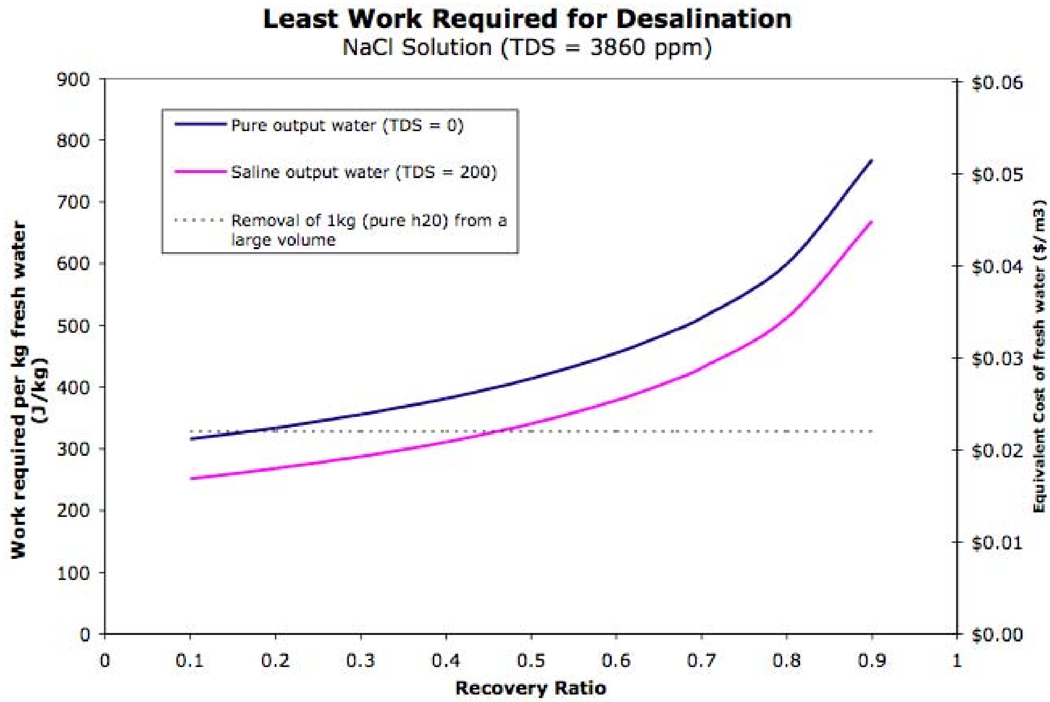


Figure 3: The least work theoretically necessary to extract pure water as a function of recovery ratio. The function is given both for the extraction of pure water, and water with a retained salinity of 200 ppm.

as a result of this driving pressure. The osmotic pressure of a solution into a solute, Pi is given, to a very good approximation, by

$$\Pi = (8.1 * 10^4)(TDS\ in\ PPM) \tag{6}$$

and therefore varies with the amount of dissolved solids in the solution. Therefore, there is less osmotic pressure to overcome in brackish water than in seawater. The volumetric flow rate through a particular membrane can be determined from the difference between the driving pressure and the osmotic pressure, and from the membrane permeability constant, A, as follows

$$Q \equiv A(\Delta p - \Delta\Pi) \tag{7}$$

where A is given for different membranes in $[L/m^2\ h\ bar]$. The power that needs to be provided, then, for reverse osmosis is simply the pressure change that results in the necessary volumetric flow rate. Reverse osmosis has a distinct advantage over thermal processes because it does not require the addition of the latent heat of fusion in order to change the phase of the water. Furthermore, reverse osmosis can be done in several stages, easing the requirements for a single pressure vessel. Reverse osmosis represents the greatest fraction of desalination technologies currently in operation because of its low power needs and low maintenance requirements.

2.3 Electrodialysis (ED)

Electrodialysis involves removing the dissolved ion content in solution away from fresh water. Stacks of alternating cations and anions attract charged particles from the water via electrostatic forces. The power necessary to operate electrodialysis, then, is the voltage that must be places across the cell pairs in order to attract the ions. The ions can pass through the membrane. The specific power, or power divided by fresh water production, is

$$\frac{P}{\dot{m}_{fresh}} = \frac{V_{cellpair} \Delta c F \nu |z|}{\rho \xi} \tag{8}$$

where Δc is the change in concentration between the fresh water and the concentrated water, F is the Faraday constant, $|z|$ is the absolute value of the charge of the ion, ρ is the density of water and ξ is the current utilization efficiency. Electrodialysis is a membrane process, like RO, but the membranes must be precharged and there is mucth less room for error in terms of their stacking and operation. The cation and anion cannot come in contact, or the entire system will not work. Furthermore, only charged particles are removed by electrodialysis, other dissolved solids will remain. Therefore, either a stringent pre- or post-filtration is necessary to remove the remaining particles. Electrodialysis also requires electricity to operate, and electricity is not reliable in many developing world countries.

2.4 Multistage Flash (MSF)

Multistage flash distillation introduces sudden pressure differences to saline streams that cause water to boil and evaporate quickly. The evaporated pure water is then condensed. For the most efficient flashing processes, many stages are necessary, the standard number of stages falling between 20 and 30. The addition of regenerators and brine recirculation can greatly improve the performance of MSF systems. The least heat input necessary for MSF is

$$\dot{Q}_{MSF} = \dot{m}_d (\frac{h_{fg}(T_c)}{N c_p \Delta T_f} + \frac{1}{2}) \tag{9}$$

where where h_{fg} is the latent heat of vaporization of water, 2.29 x 10^6 J/kg, c_p is the specific heat capacity of water, 4186 J/kg, ΔT_f is the temperature difference before and after flashing, and N is the number of stages.

The addition of regenerators and brine recirculation can greatly improve the performance of MSF systems. The components necessary to enable this are heat exchangers and compressors, which may be difficult to build and need additional fuel to operate. Furthermore, generating the high pressures necessary to operate the system may be infeasible in Haiti.

2.5 Multieffect Distillation (MED)

Distillation is the vaporization and subsequent condensation of pure water from saline water. Distillation relies on the salt's very low volatility, or tendency to vaporize. Thermal distillation systems require the input of heat to raise the temperature of the saline mix to water's vaporization temperature and the addition of the latent heat of vaporization to water to change its phase from liquid to vapor, and a surface on which the vaporized water can condense. The simplest derivation of the heat input necessary to vaporize water is

$$\dot{Q}_{SED} = \dot{m}_d h_{fg}(T_c) + \dot{m}_f c_{p,f}(T_v - T_g) \tag{10}$$

where h_{fg} is the latent heat of vaporization of water, 2.29 x 10^6 J/kg, $c_{p,f}$ is the specific heat capacity of water, 4186 J/kg, T_v is the vapor temperature, and T_g is the temperature of the feed, which can be raised with heat exchangers or solar pre-heating.

Distillation is much more efficient if it is performed in several stages. In this case, the equation for the least heat necessary for distillation becomes

$$\dot{Q}_{MED} = \dot{m}_d \frac{h_{fg}(T_c)}{N} + \dot{m}_f c_{p,f}(T_v - t_g) \tag{11}$$

where N is the number of stages necessary. Simple calculations show that the number of stages in the distillation process have a much greater effect on the required heat than the difference of the feed temperature and the vapor temperature. This is because the latent heat of vaporization exceeds the specific heat capacity by two orders of magnitude, so changing the first term on the right hand side of the equation has a much greater effect on the least heat required than changing the second term.

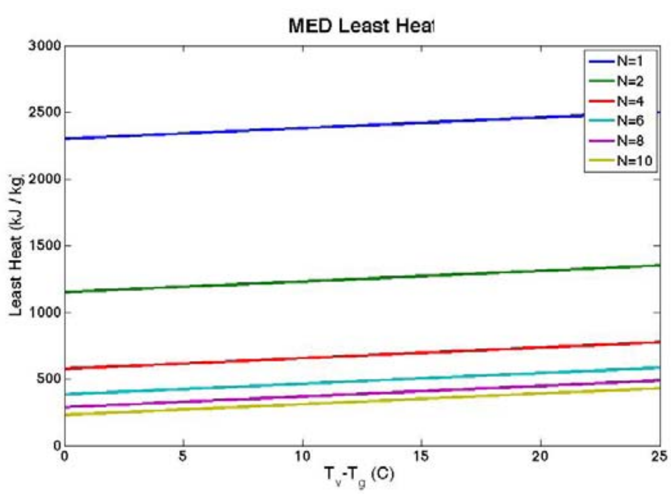


Figure 4: The heat input necessary to distill water varies greatly with the number of stages in the distillation process, but has comparatively minimal variation based on the temperature difference between the temperatures of the feed stream and the temperature at which vaporization occurs.

3 Design and Cost

In order to select an appropriate final proposal and design for a desalination system in Haiti, several functional requirements must be met. The first is that the system must purify water to a TDS value below 300 ppm, starting with a feed contamination level of around 3860 ppm, the maximum contamination of the family wells. Secondly, a flow rate that can supply both towns with enough water is necessary. This implies a low value of 13.2 m^3 per day and a high value of 66.2 m^3 per day. The middle ground was taken, which can supply enough water for the populations of both Paulette and Phaeton. Furthermore, the systems must operate with limited power, as all of the power available comes from a very small number of sources limited to human power, diesel fuel power, solar, wind, and water power. A recovery ratio of more than 50% is desired to reduce the feed flow requirements on the wells. Furthermore, in order to limit the need for tampering with the system, the design should limit daily servicing to below 10 min and monthly servicing to less than 4 hours, boosted by an anti-fouling design. Finally, equipment and operational cost are important factors. Currently, residents pay approximately $0.02/kg of fresh water retrieved from the pumped systems. The overall design of the new desalination system should add as little cost as possible to this amount to be useful and affordable for the residents. Accordingly, the following desalination system is proposed for use in Phaeton and Paulette in Haiti.

3.1 Selection

Table 2

Least Power Input, kWh

	13 m^3/day	**65 m^3/day**
Theoretical	1.185	5.93
RO	7.8	39
ED	24.2	121
SED	17,184	85,920
MED, N=3	5,928	29,616
MSF, N=10	760,080	$3.8*10^6$

Based on figures for the least work necessary to purify the brackish water currently supplied to Phaeton and Paulette, a reverse osmosis system was chosen as the main method of purification. RO requires far less specific power input than the other water purification technologies. Although thermal technologies are attractive because the sun is such an abundant source of energy, the output necessary is simply far too great to be greatly impacted by solar radiation, at best 7.5 kWh/m2/day. As it became evident that a great fraction of the power would have to come from fuel, in this case diesel, minimizing the fuel consumption for inexpensive day-to-day operation became a key factor. As such, Table 2 shows that RO is, in this case, the most economical and practical system. The remainder of this chapter focuses on the specific RO design constructed for use in Paulette and Phaeton.

3.2 Design

3.2.1 RO design

To assist in selecting the proper RO membranes, Dow/Filmtec's reverse osmosis system analysis software (ROSA) was used. Sample program output is shown in the Appendix, Fig. 16. The salinty profile corresponding to a 3860pmm Phaeton family well was input for the feed. A screenshot of the software interface is shown in Fig. 5.

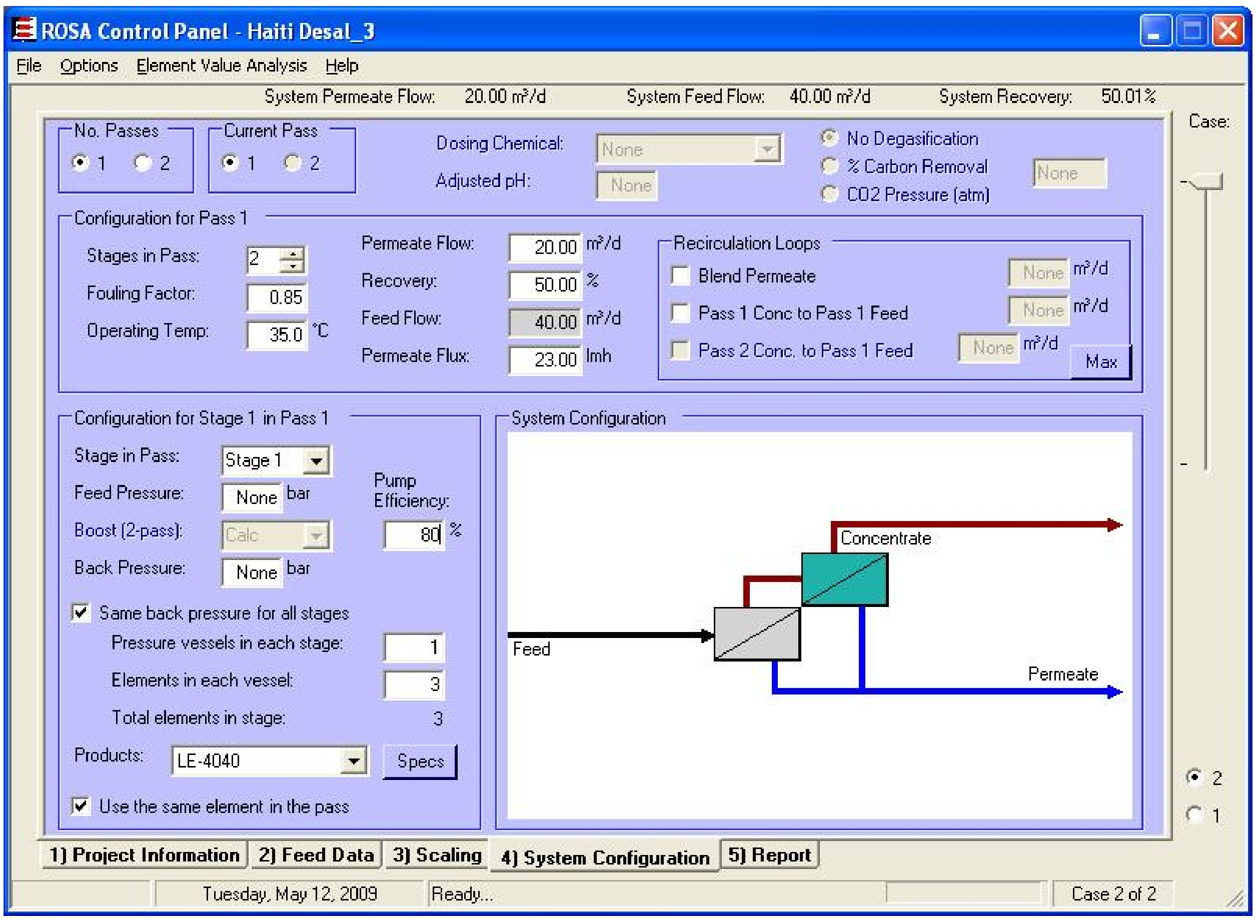


Figure 5: DOW/Filmtec RO Analysis Software (ROSA).

Two RO design layouts were simulated: a single element with concentrate recirculation and a two stage, multiple element design. Both designs were simulated for various feed temperatures and pressures to determine the optimal operating conditions. As Fig. 6 shows, the specific power is reduced for increased feed temperature - at the expense of increased permeate salinity levels - due to the effect of the "temperature correction factor" on membrane permeability. However, care must be taken to avoid the upper feed temperature limit of the RO membranes, typically around 40 °C. Similarly, an optimum feed pressure exists which minimizes the specific energy requirements for the system.

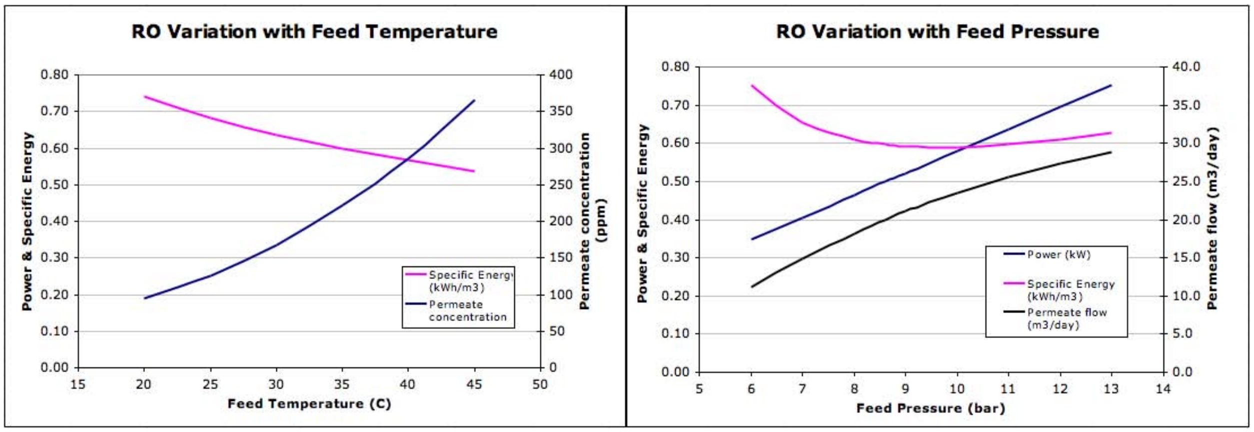


Figure 6: The operation of the chosen reverse osmosis membrane varies as a function both of the temperature of the incoming feed and the pressure. Therefore, the unit can be made more efficient with some preheating, which can be easily accomplished with solar power.

Figure 7 depicts the single element with concentrate recirculation. This recirculating flow is necessary to limit the recovery for the element to 15%, while boosting overall system recovery to 80%. Due to the high recirculated flow rates (120 m^3/day), a large 8" x 40" element is needed for desalting and a second, "booster" pump is required to bring the blended concentrate back up to feed pressure. Since the "blended" feed (feed + recirculated concentrate) is greatly increased in salinity to 15753 ppm, the feed pressure must be quite high (23.4 bar) to overcome the high osmotic pressure. However, the overall feed rate (25 m^3/day) is fairly low, and hence, the specific power of 1.02 kWh/m^3 is reasonable.

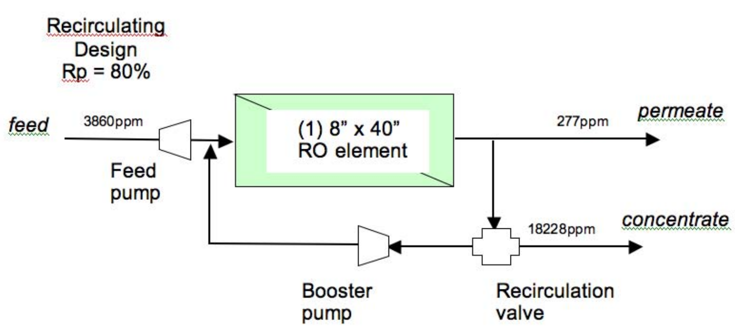


Figure 7: Recirculating design schematic.

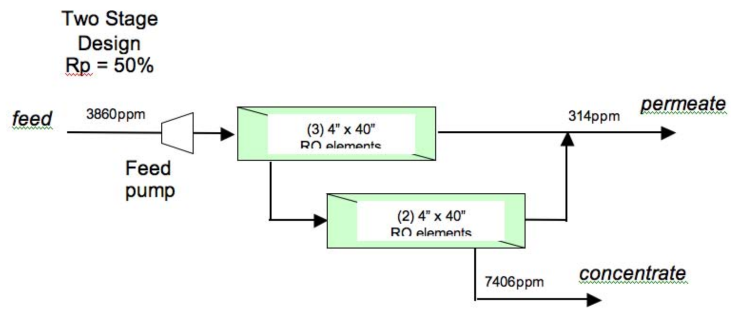


Figure 8: Two-stage design schematic.

A conventional 2-stage design is depicted in Fig. 8. Smaller 4" x 40" elements can be used, but 5 membranes are needed to keep the recovery-per-element below 15%. The lower feed pressure (8.2 bar) is somewhat offset by the increased feed flowrate (40 m^3/day), resulting in a specific power of 0.60 kWh/m^3. This design, although requiring less energy to operate, is physically larger, has more elements and has a higher capital cost than the recirculating single element design. Table 3 summarizes the flow parameters for each element in the various systems.

Table 3

RO System Details						
Stage 1		Perm Flow	Perm TDS	Feed Flow	Feed TDS	Feed Press
Element	Recovery	(m^3/day)	(mg/l)	(m^3/day)	(mg/l)	(bar)
1	0.15	5.99	118.56	40.00	3860.03	8.27
2	0.15	4.98	162.48	34.01	4518.73	8.16
3	0.14	4.00	226.14	29.03	5265.73	8.07
Stage 2						
1	0.11	2.84	340.71	25.03	6072.10	7.65
2	0.10	2.19	470.79	22.19	6805.95	7.60
Recirculating						
	0.14	20.00	277.10	144.99	15752.58	23.09

3.2.2 Prefilter

The feedwater coming from the wells needs to be prefiltered to remove turbidity and suspended colloids. A 50 micron filter is sufficient to remove particulates without imposing a large pressure drop.

3.2.3 Preheater

Owing to the increased production rate at higher feed temperature, a combined solar-waste heat preheater is used to raise the feed water temperature. The feedwater is assumed to be extracted at a temperature of 30 °C, which is around the average temperature in the area. An optimal operation temperature for the reverse osmosis system is 35 °C, meaning a temperature increase of only 5 degrees is necessary. The power needed to raise the water temperature is given by

$$\dot{Q}_{in} = \dot{m} c_p \Delta T \tag{12}$$

where c_p is the specific heat of water, taken to be 4186 J/kg K. In this case, the heating will be a combination of solar power and waste heat from the generator used to drive the RO system. Furthermore, the hot brine will be recirculated through the preheating element, implying that the only temperature difference will lie in the extracted water. Therefore, $\dot{m}$ is the distillate flow rate. Inserting all the previously derived values and performing the described thermodynamic balance yields a need for 14.5 kW to sufficiently preheat the feed. Of these 14.5 kW, 6 kW will come from waste heat from the generator. The remaining 8.5 kW will come from solar heating. The solar water heater can be constructed entirely

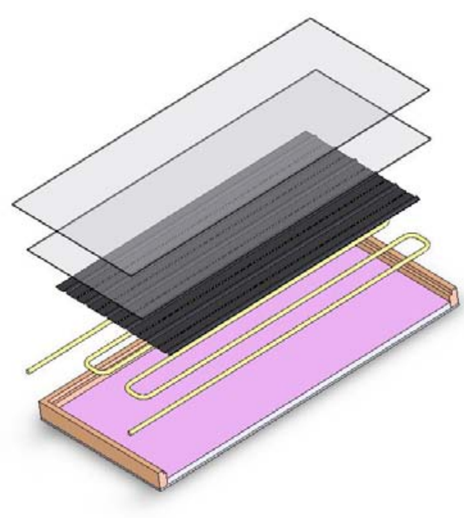


Figure 9: The solar collector consists of a 2x4 support, two spaced panes of glass, an off-the-shelf radiant floor heat transfer layer, copper pipes, and simple rigid foam insulation. The whole mechanism is easy to assemble and all the components can be easily found in marketplaces for a low cost.

of locally available materials. It will consist of a 1x2m wood-frame, lined with low-cost rigid foam insulation board, to which tubing and heat transfer plates are attached. The tubing, standard copper pipe or low cost PEX plastic tube (used in radiant floor heating applications) is in direct thermal contact with preformed sheet aluminum absorber plates (also used in radiant floor heating applications). These absorber plates can be painted matte black for increased absorptivity and collection efficiency. The entire collector is insulated from convective, conductive and most radiative losses by double glazing layers of plate glass (Fig. 9). The collector plate, assumed to have an efficiency of approximately 65%, a standard average efficiency of simple heating collector plates, will need to cover an area of 13 m^2, assuming an insolation of 1000 W/m^2 for 12 hours per day, in order to generate this power. Seven collection modules will accomplish this task. For maximum efficiency, they should be installed facing south, inclined at Haiti's latitude, approximately 19 degrees.

3.2.4 Storage tank

A tank capable of storing enough water for lulls between fillup times is also necessary. Assuming the biggest interval between fillups is 15 minutes, a tank that can hold 163 gallons is necessary. 200 Gallon storage tanks are available here for between $150 and $1,000. It is assumed that simpler storage units can be found in Haiti and can be procured for a much smaller sum. Since the water kept inside of it will be of much higher quality, it will likely be less corrosive than the water currently housed in storage tanks at the site.

3.2.5 Generator

A 2kW diesel to electric generator is more than sufficient to power the system, and they are readily available for minimal costs. Alternatively, a diesel engine can be directly coupled to the high pressure pumps, but this method creates additional integration issues.

3.3 Design integration

Fig. 10 shows a schematic of the complete design. Individual components are listed in Table 6 in the Appendix. Pictures of sample components for the design are given in the Appendix, Fig. 18 - 24.

3.4 Operation and Maintenance

The proposed water purification system will need daily supervision. An attendant will need to replenish fuel in the generator tank 2-3 times per day. Alternatively, a larger diesel tank of appropriate size can be incorporated into the system, necessitating weekly fill-ups. At the beginning of each day, the attendant may need to prime the pumping units by opening an air-relief valve in the pressure lines. At the end of the day, the prefilter unit should be flushed and valves should be closed to keep the membranes wet.

More infrequent maintenance may include: flushing/replacement of the RO membrane, cleaning of the solar collector preheater, repair/replacement of pipes, valves, pumps,

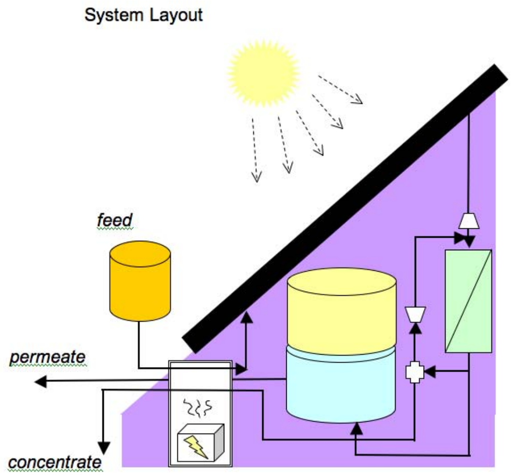


Figure 10: System layout.

etc. The BW30-365 FR RO membrane is selected for it's fouling resistance and should give 2-5 years of service before replacement is needed.

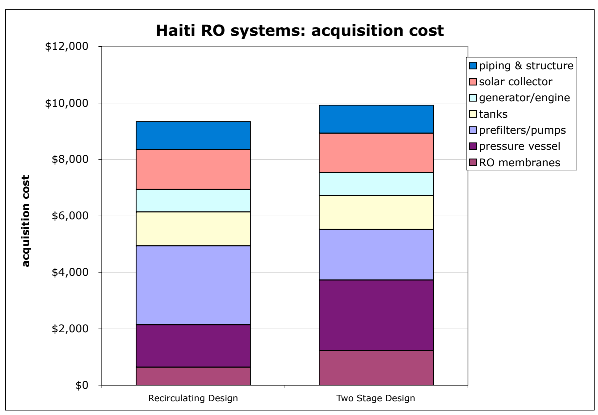


Figure 11: System cost breakdown.

A simplified economic analysis shows a reasonable hardware cost and minimal operational costs, not including wages to the attendant already present at the well site (Fig. 11 and Appendix: Table 7, Fig. 13, 14). A discount rate of 10% and service lifetime of 7 years were assumed to calculate the minimum sales price of purified water, 0.48/m^3. This works out to less than 1 cent per 5 gallons additional to the Haitian villagers.

4 Conclusions

The proposed design appears to be feasible, both technically and economically; however additional calculations and simulations should be performed to fully characterize its performance under varying conditions. The single membrane design is attractive for its low footprint and overall membrane/pressure vessel cost, and the locally fabricated structure and solar collectors further decrease system cost. However, the pump selection is critical to the systems reliability and efficiency. The proposed multistage centrifugal booster pumps may not be the best choice; additional alternatives should be explored.

Below is a list of possible failure modes, should this system be implemented:

4.1 Mechanical failure

- Pump failure
- Membrane fouling
- Pipe fouling
- Connector leaks
- Generator failure

4.2 Operator-induced failures

- Recirculating valve set improperly resulting in fouled membrane
- Feed pressure/flow settings wrong
- Failure to clean prefilter
- RO membranes ”pumped dry”
- Lack of solar collector maintenance (cleaning)

4.3 Other

- Theft of generator
- Vandalism/damage to collector glass

5 Appendix

Table 4

Water characteristics

	Pumped System	**Phaeton Well**	**molality, m mol/kg H_2O**	**EPA MCL**
Pumped system particulate	450	650		
Community Wells	3000	1200		
Private bucket wells	2300	3500		
Calcium	50.3	128	0.0031936	None
Magnesium (S)	64.8	192	0.0078980	None
Sodium	181	2080	0.0904741	None
Chloride (S)	115	904	0.0255007	250 ppm
Nitrate (as N) (P)	0.09	0.5	0.0000081	10 ppm
Sulphate (S)	77.6	280	0.0029148	250 ppm
Phosphate	0.21	0.31	0.0000033	None
Aluminum	0.002	2.7		200 ppb
Arsenic (P)	<0.002	1.8		5 ppb
Iron (S)	<0.01	1.0		300 ppb
Silicon (SiO_2)	63.8			None
Color (S)	0 CPU	3 CPU		0-14 CPU
Alkalinity (S)	730	420		None
Conductivity	1440 umhos/cm	7720		None
Hardness	392	320		150+ hard
pH (S)	7.2	7.1		6.5-8.5 pH units
Turbidity	0.63 NTU	0.17		0-5 NTU
TDS	838	3860		500 ppm

Table 5

System characteristics		
	Paulette	**Phateon**
TDS		
Pumped System	450	650
Community Wells	3000	1200
Private bucket wells	2300	3500
Population Demographics		
Population	1738	2418
Families	350	500
Water needs	**Low**	**High**
Water need per family (gal/day)	10	35
Water need per family (kg/day)	37.8	132.3
Water need per town (kg/day)	13230	66150
Water need per town (m^3/day)	13.2	66.2
Current price of water (gourde/day)	0.20	
Current price of water ($/kg)	0.0189	
Distiller water flow for 24 hour op (kg/sec)	0.153	0.766
Distilled water flow for 12 hour op (kg/sec)	0.306	1.531
Diesel price ($/gal)	2.25	3.00
Diesel energy content (MJ/gal)	135.5	

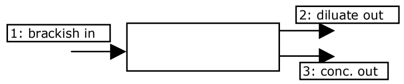
Table 6

Components		
	Recirculating	**Two stage**
Recovery	80%	50%
Specific power	1.02kWh/m^3	0.6kWh/m^3
Permeate TDS (35 °C)	277	314
Pump flow & power 80% efficiency	Feed: 25m^3/day 23.4 bar ΔP 850 W Recirculate 120m^3/day 0.43 bar ΔP 75 W	Feed: 40m^3/day 8.2 bar ΔP 500 W
Pump	Feed: 10GBS10 Booster: 10GBS10	Feed: 10GBS10
Membrane	1X Filmtec BW30-365FR (34m^2)	3X Filmtex LP-4040 (8.1m^2) 2X Filmtec XLP-4040 (8.1m^2)
Pressure Vessel (Fiberglass)	1X Codeline 80A-15-1	1X Codeline 40A-30-3 1X Codeline 40A-30-2

Table 7

Cost Estimates ($)		
	Recirculating	**Two stage**
RO Membrane	638	1,225
Pressure vessel	1,500	2,500
Prefilters/pumps	2,800	1,800
Tanks	1,200	1,200
Solar collector	1,400	1,400
Piping & Structure	1,000	1,000
Generator/engine	800	800
Acquisition price	9,338	9,925
Annual maintenance	600	800
Water price to break even ($/$m^3$)	0.48	0.50

Least Work (Exergetic) calculations: NaCl solution



Diesel cost ($/gal)	Diesel conversion efficiency	Diesel heating value (MJ/gal)
$3.00	33%	135.5

TDS @ 1	m_1 (mol/kg)	x_h20_1	feed salinity ratio	g_1+/-
3860	0.066307	0.99762	0.0011935	0.7928

Pure output water (TDS = 0)

Rp	m_3 (mol/kg)	g_3+/-	x_h20_3	dG_h20 3-1 (J/mol)	dG_h20 2-3 (J/mol)	dG_NaCl 3-1 (J/mol)	Wleast/Nh20 (J/mol)	Wleast/mh20 (J/kg)	Energy per fresh water flow (kWh/m3)	Cost of fresh water ($/m3)
0.1	0.07367	0.7855	0.99735	-0.656	6.571	476.3	0.57	315.9	0.0877	$0.021
0.2	0.08288	0.7773	0.99702	-1.476	7.391	1007.5	1.20	334.1	0.0928	$0.022
0.3	0.09472	0.7678	0.99660	-2.530	8.445	1608.3	1.92	355.6	0.0988	$0.024
0.33	0.09897	0.7646	0.99645	-2.908	8.822	1805.1	2.16	362.9	0.1008	$0.024
0.4	0.11051	0.7567	0.99603	-3.935	9.849	2300.3	2.75	381.5	0.1060	$0.026
0.5	0.13261	0.7436	0.99524	-5.900	11.815	3116.9	3.73	413.7	0.1149	$0.028
0.6	0.16577	0.7275	0.99406	-8.845	14.759	4114.5	4.92	455.2	0.1264	$0.031
0.67	0.20093	0.7139	0.99281	-11.965	17.879	4973.9	5.95	492.9	0.1369	$0.033
0.7	0.22102	0.7072	0.99210	-13.745	19.660	5399.8	6.46	512.2	0.1423	$0.034
0.8	0.33153	0.6804	0.98819	-23.517	29.432	7217.9	8.64	599.5	0.1665	$0.040
0.9	0.66307	0.6454	0.97666	-52.603	58.518	10390.8	12.46	768.5	0.2135	$0.052

Removal of 1kg (pure h20) from a large volume	
dG_h20 1 (J/mol)	Wleast/mh20 (J/kg)
5.914	328.2
5.914	328.2
5.914	328.2
5.914	328.2
5.914	328.2
5.914	328.2
5.914	328.2
5.914	328.2
5.914	328.2
5.914	328.2
5.914	328.2

Saline output water (TDS = 200)

TDS @ 2	m_2 (mol/kg)	x_h20_2	g_2+/-
200	0.003423	0.99988	0.9374

Rp	m_3 (mol/kg)	g_3+/-	x_h20_3	conc. salinity ratio (NaCl_3/NaCl_1)	dG_h20 3-1 (J/mol)	dG_h20 2-3 (J/mol)	dG_NaCl 2-1 (J/mol)	dG_NaCl 3-2 (J/mol)	Wleast/Nh20 (J/mol)	Wleast/mh20 (J/kg)	Energy per fresh water flow (kWh/m3)	Cost of fresh water ($/m3)	difference from "pure" product
0.1	0.07329	0.7859	0.99737	0.99484	-0.622	6.231	-13856.8	14309.7	0.45	251.4	0.0698	$0.017	-20.4%
0.2	0.08203	0.7780	0.99705	0.98968	-1.400	7.009	-13856.8	14817.5	0.97	267.9	0.0744	$0.018	-19.8%
0.3	0.09326	0.7689	0.99665	0.98451	-2.400	8.009	-13856.8	15395.0	1.55	287.5	0.0798	$0.019	-19.2%
0.33	0.09728	0.7659	0.99651	0.98296	-2.758	8.366	-13856.8	15584.7	1.75	294.0	0.0817	$0.020	-19.0%
0.4	0.10823	0.7582	0.99611	0.97935	-3.732	9.341	-13856.8	16063.5	2.24	311.1	0.0864	$0.021	-18.5%
0.5	0.12919	0.7455	0.99537	0.97419	-5.596	11.205	-13856.8	16856.7	3.07	340.4	0.0946	$0.023	-17.7%
0.6	0.16063	0.7298	0.99424	0.96903	-8.389	13.998	-13856.8	17830.7	4.09	378.6	0.1052	$0.025	-16.8%
0.67	0.19398	0.7163	0.99306	0.96541	-11.348	16.957	-13856.8	18673.4	4.99	413.4	0.1148	$0.028	-16.1%
0.7	0.21303	0.7098	0.99238	0.96386	-13.038	18.646	-13856.8	19092.1	5.44	431.2	0.1198	$0.029	-15.8%
0.8	0.31784	0.6831	0.98867	0.95870	-22.309	27.917	-13856.8	20884.8	7.38	512.2	0.1423	$0.034	-14.6%
0.9	0.63226	0.6472	0.97772	0.95354	-49.915	55.523	-13856.8	24025.3	10.86	669.6	0.1860	$0.045	-12.9%

Figure 12

Economic Analysis: RO systems

Diesel cost ($/gal)	Diesel fuel-to-electric conversion efficiency	Diesel heating value (MJ/gal)	Discount rate
$3.00	25%	135.5	10%

Recirculating Design

Operational hours	Generator energy (kWh/day)	permeate flow (m3/day)	Power per product (kWh/m3)	Recovery
12	96	30	1.02	80%

	Sales price
RO membranes	$ 638
pressure vessel	$ 1,500
prefilters/pumps	$ 2,800
tanks	$ 1,200
solar collector	$ 1,400
piping & structure	$ 1,000
generator/engine	$ 800

water price to break even ($/gal)	water price to break even ($/m3)
$0.002	$0.476

year	present value	acquisition price	salvage price	maintenance	annual cost of power used	price of water to break even ($/year)
0	1.0000	$9,338				
1	0.9091			$600	$2,793	$5,213
2	0.8264			$600	$2,793	$5,213
3	0.7513			$600	$2,793	$5,213
4	0.6830			$600	$2,793	$5,213
5	0.6209			$600	$2,793	$5,213
6	0.5645			$600	$2,793	$5,213
7	0.5132		$934	$600	$2,793	$5,213

Two Stage Design

Operational hours	Generator energy (kWh/day)	permeate flow (m3/day)	Power per product (kWh/m3)	Recovery
12	96	30	0.6	50%

	Sales price
RO membranes	$ 1,225
pressure vessels	$ 2,500
prefilters/pumps	$ 1,800
tanks	$ 1,200
solar collector	$ 1,400
piping & structure	$ 1,000
generator/engine	$ 800

water price to break even ($/gal)	water price to break even ($/m3)
$0.002	$0.505

year	present value	acquisition price	salvage price	maintenance	annual cost of power used	price of water to break even ($/year)
0	1.0000	$9,925				
1	0.9091			$800	$2,793	$5,527
2	0.8264			$800	$2,793	$5,527
3	0.7513			$800	$2,793	$5,527
4	0.6830			$800	$2,793	$5,527
5	0.6209			$800	$2,793	$5,527
6	0.5645			$800	$2,793	$5,527
7	0.5132		$993	$800	$2,793	$5,527

Figure 13

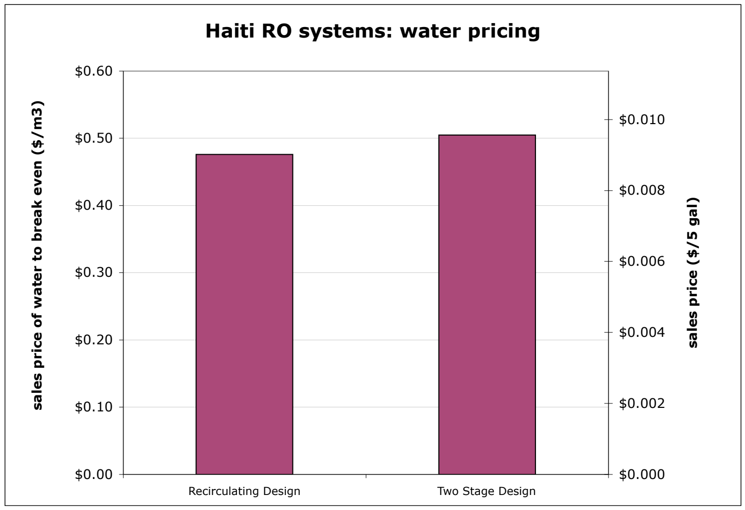


Figure 14

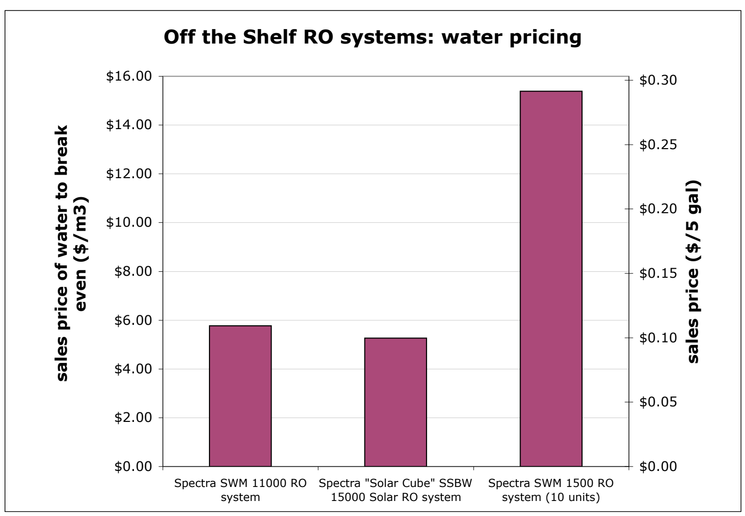


Figure 15

Reverse Osmosis System Analysis for FILMTEC™ Membranes — ROSA v6.1.5 ConfigDB U238786_55
Project: Haiti Desal_3 — Case: 2
Danny Codd, MIT — 5/12/2009

Project Information:

System Details

Feed Flow to Stage 1	40.00 m³/d	Pass 1 Permeate Flow	20.00 m³/d	Osmotic Pressure:	
Raw Water Flow to System	40.00 m³/d	Pass 1 Recovery	50.01 %	Feed	3.18 bar
Feed Pressure	8.61 bar	Feed Temperature	35.0 C	Concentrate	6.11 bar
Fouling Factor	0.85	Feed TDS	3860.03 mg/l	Average	4.65 bar
Chem. Dose	None	Number of Elements	5	Average NDP	3.48 bar
Total Active Area	36.23 M²	Average Pass 1 Flux	23.00 lmh	Power	0.50 kW
Water Classification: Surface Supply SDI < 5				Specific Energy	0.60 kWh/m³

Stage	Element	#PV	#Ele	Feed Flow (m³/d)	Feed Press (bar)	Recirc Flow (m³/d)	Conc Flow (m³/d)	Conc Press (bar)	Perm Flow (m³/d)	Avg Flux (lmh)	Perm Press (bar)	Boost Press (bar)	Perm TDS (mg/l)
1	LE-4040	1	3	40.00	8.27	0.00	25.03	8.00	14.97	28.70	0.00	0.00	161.94
2	LE-4040	1	2	25.03	7.65	0.00	20.00	7.55	5.03	14.47	0.00	0.00	397.35

Pass Streams (mg/l as Ion)							
Name	Feed	Adjusted Feed	Concentrate		Permeate		
			Stage 1	Stage 2	Stage 1	Stage 2	Total
NH4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	1518.44	1518.44	2388.61	2950.32	63.70	156.30	87.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HCO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl	2341.59	2341.59	3683.49	4549.70	98.24	241.04	134.16
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SiO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TDS	3860.03	3860.03	6072.10	7500.03	161.94	397.35	221.16
pH	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Figure 16

Operational point optimization: RO system

LE-4040 Elements: Stage 1-3 elements, Stage 2-2 elements
Pump efficiency: 80%

Variation with Feed Temperature

Permeate Flow (m3/day)	Recovery
20	50%

Temp (deg C)	Permeate concentration	Conc TDS	Feed Pressure (bar)	Power (kW)	Specific Energy (kWh/m3)	
20	94	7627	10.65	0.62	0.74	
25	126	7593	9.83	0.57	0.68	
30	168	7552	9.16	0.53	0.64	
35	221	7500	8.61	0.50	0.60	
40	286	7434	8.15	0.47	0.57	
45	366	7354	7.74	0.45	0.54	*too hot for membrane

Variation with Feed Pressure

Temp (deg C)	Feed flow (m3/day)
35	40

Feed Pressure (bar)	Perm TDS	Conc TDS	Recovery	Permeate flow (m3/day)	Power (kW)	Specific Energy (kWh/m3)	
6	288	5228	27.7%	11.1	0.35	0.75	
7	245	5989	37.1%	14.8	0.41	0.66	
8	226	6896	45.5%	18.2	0.46	0.61	
8.61	221	7496	50.0%	20.0	0.50	0.60	
9	219	7930	52.8%	21.1	0.52	0.59	
10	220	9067	58.9%	23.6	0.58	0.59	*too much recovery/element
11	225	10340	64.0%	25.6	0.64	0.60	*too much recovery/element
12	233	11716	68.4%	27.4	0.69	0.61	*too much recovery/element
13	244	13188	72.0%	28.8	0.75	0.63	*too much recovery/element

Figure 17

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Please see http://pumpagents.com/store/products/GouldsPumps/images/5GB.jpg

Figure 18: Multi-stage centrifugal vacuum pump (stainless steel body, cast iron ports).

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Please see http://www.codeline.com/files/Drawing_40A30.pdf

Figure 19: 8 in. RO fiberglass pressure vessel

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Please see http://www.sunraysolar.com/images/absorber.jpg

Figure 20: Off-the-shelf absorber plates

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Figure 21: Low-cost radiant floor heating absorber plates

Figure 22: Solar collector

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Figure 23: Freshwater tanks

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Please see http://www.hyundai-generators.co.uk/graphics/2500Ldualvoltagemed.jpg

Figure 24: Diesel generator

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