



*Technical Overview of Aquaback's Water Distillation Process  
(Proprietary and Confidential)*

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**1 Executive Summary**

This document describes water distillation in general, Aquaback’s self-cleaning, thin-film vapor compression distillation, and some of the underlying physics and mathematical equations used by Aquaback’s equipment Configuration Engine.

**1.1 Conventions Used, plus Definitions & Symbols Table**

For clarity, certain terms specific to the Aquaback process will defined and capitalized. Also capitalized will be specific equipment designed and built by Aquaback, such as the Counter Flow Heat Exchanger. The following table describes both definition and symbols used in this Technical Overview:

Symbol	Defined Name and Description (if any)	Units	Value	Source
$inf$	Influent - water supplied by client to be cleaned	Gallons		
$dist$	Distillate - distilled water returned to client	Gallons		
$conc$	Concentrate - waste water including all cotaminants except vented Volatile Gasses	Gallons		
$vgas$	Volatile Gas	Gallons		
$evap$	Evaporation Water - mix of Influent and Distillate to be distilled	Gallons		
$\dot{V}_{inf}$	Influent Flow Rate	GPH	1.00	input
$\dot{V}_{dist}$	Distillate Flow Rate	GPH	0.90	calculated
$\dot{V}_{conc}$	Concentrate Flow Rate	GPH	0.10	input
$\dot{V}_{vgas}$	Volatile Gas Flow Rate (as if suspended or condensed into a liquid)	GPH	0.00	input
$\dot{V}_{comp}$	Compressor Steam Flow Rate	CFM		calculated
$Y_{inf}$	Influent Mass Fraction	PPM	2000	input
$Y_{dist}$	Distillate Mass Fraction	PPM	0.00	calculated
$Y_{conc}$	Concentrate Mass Fraction	PPM	20000	calculated
$Y_{vgas}$	Volatile Gas Mass Fraction	PPM	0	input
$Y_{evap}$	Evaporator Water Mass Fraction	PPM	11000	calculated
$Y_{ref}$	Reference Mass Fraction : sea water	PPM	35000	input
$\Delta T_{bp}$	Evaporator Water Boiling Point Rise @ atmospheric pressure for a given influent contamination level and targeted % of Distillate Recovery	°F	0.31	calculated
$\Delta T_{ref}$	Reference Water Boiling Point Rise @ atmospheric pressure for seawater (35,000 PPM salts)	°F	1.00	input
$\Delta T_{sat,ref}$	Reference Water Saturation Temperture Rise @ given Reference Saturation Pressure Rise for pure water	°F	3.33	input
$\Delta P_{sat,ref}$	Reference Saturation Pressure Rise for pure water	PSI	1.00	input
$\Delta P_{comp,bp}$	Pressure Rise Evaporator Boiling Point - the change in pressure to reach saturation point which corresponds to boiling point of Evaporation Water	PSI	0.09	calculated
$\Delta P_{comp,nom}$	Nominal Pressure Rise - pressure rise required of compressor to maintain cycle in absence of contamination	PSI	Proprietary	input
$\Delta P_{comp}$	Total Pressure Rise - to achieveditillation cycle at a given Influent Mass Fraction (contamination level)	PSI	Proprietary	calculated
$\rho_f$	Density of Water as a Fluid	%	100.0000	input
$\rho_g$	Density of Water as a Gas (steam)	%	0.0667	input
$\eta_{motor}$	Compressor Motor Efficiency	%	0.80	input
$\eta_{turbo}$	Compressor Turbo Efficiency	%	0.80	input
$\eta_{comp}$	Compressor Efficiency - total efficiency	%	0.64	calculated
$\dot{V}_{comp}$	Compressor Flow Rate (steam)	CFM	3.34	calculated
$\dot{E}_{comp}$	Motor power required - calculated	W	15.20	calculated
$e_{comp}$	Specific Energy Consumption - Compressor per gallon of Distillate - calculated	Whr/gal of Dist	16.89	calculated
$e_{pumps}$	Specific Energy Consumption - Pumps per gallon of Distillate	Whr/gal of Dist	5.00	input
$e$	Specific Energy Consumption - Total - calculated	Whr/gal of Dist	21.89	calculated

## 2 Introduction of Water Distillation and Aquaback's Vapor Compression Distillation

### 2.1 Overview of Water Distillation

Cleaning contaminated water by distillation separates pure water (H<sub>2</sub>O) from the contamination by boiling dirty water to produce pure steam (H<sub>2</sub>O), and then condensing the steam into distilled water. When the pure water boils off, the contamination is left behind as “concentrated” dirty water. The boiling point of the contaminated water is directly related to how dirty the water is: higher contamination levels require higher boiling temperatures

There is a direct connection between the percentage of clean water which can be distilled out of given volume of contaminated water and the energy required. Extracting a higher percentage of clean water also means that all of the contamination has been concentrated into a smaller volume of “reject” water. In some situations, it is economical to repeat the distillation process by boiling the concentrated dirty water, making more clean water, and leaving behind a lesser volume of dirty water at a higher concentration of contaminants. In many cases the savings gained by disposing of less reject water more than offsets the cost of increased power consumed.

At some point, the concentration of a given contaminant becomes so high that the contaminant precipitates out of solution as a solid, thereby making the transition from a dissolved solid to a suspended solid. These solids may fall by gravity to the bottom of the concentrate sump, may float to the surface, or may stay suspended in the concentrate water. They can also build up on some protruding surface or feature of the system plumbing. The maximum concentration for a dissolved solid is approximately 320,000 parts per million (“PPM”) for many influents.

Three very common performance metrics for water purification methods, including distillation, are:

- The specific energy consumption (often measured in Watts per Hour per Gallon “Wh/G”) per gallon of source water treated;
- The percentage of “clean” water recovered to the amount of source treated, and;
- The amount of Total Dissolved Solids in the clean water.

It is important to that all three be considered in order to gauge a treatment method's effectiveness. For many water purification systems, energy consumption, including all required pretreatments, is the largest expense over the operating life of the equipment. Our goal is to minimize both the specific energy consumption and total cost per unit cleaned.

## 2.2 Introduction to Aquaback's Vapor Compression Water Distillation

Aquaback utilizes a patented self-cleaning, thin-film vapor-compression distillation process. This is a brief overview of Aquaback's process which has been verified by testing prototypes based upon patented technology

1. Incoming water (Influent) enters the system through custom heat exchangers which transfer heat to the Influent from the outgoing pure water (Distillate) and reject water (Concentrate or dirty water). Aquaback has optimized this preheating process to raise the water temperature entering the distiller close to 212°F (100°C).
2. The hot Influent is mixed with some of the collected Concentrate to create Evaporator Water
3. Evaporator Water is applied as a very thin film to the hot evaporator surface, causing the pure water (H<sub>2</sub>O) to boil out of the Evaporator Water, thereby turning to steam in the evaporator chamber.
4. The contaminants left behind on the evaporator surface are mechanically wiped off and collected as Concentrate which will exit the system though a heat exchanger, making the system self-cleaning.
5. The steam is drawn through the compressor increasing both the pressure and temperature of the steam, and sent to the condensing chamber. The condenser and evaporator surfaces are on opposite sides of the thin metal wall separating the evaporator and condenser.
6. The pressurized steam (215°F) feels the cooler (212°F) evaporator water and immediately condenses. Heat given off during the phase change from steam to water is quickly transferred through this wall to the cooler Evaporator Water.
7. Likewise the Evaporator Water absorbs the heat (215°F) given off by the condensing of the pressurized steam and boils

## 3 Aquaback's Configuration Engine

Aquaback has integrated the widely-known physics of compressed-vapor distillation and Aquaback's proprietary patented process into our Configuration Engine to:

- Prescribe the most efficient equipment package for a specific client need, and;
- Project both energy use and total operating costs for each client's specific deployment.

An Aquaback applications engineer works with each prospective customer to understand their water chemistry, volume, cost factors (capital, operating, energy, reject flow, disposal costs, etc.), current and potential future water regulations, operating environment, and overall objectives. Additional considerations may include multiple-stage distillation, a Zero-Liquid-Discharge (ZLD) capability, ammonia removal, flood-proofing, utilization of local waste heat, bypass flows, and electricity supply alternatives.

The objective of this configuration process is to achieve the highest overall efficiency including specific energy consumption (Wh/G) based on influent, post-treatment TDS, and reject rate. Once the equipment and installation is priced, Aquaback can estimate the client's ROI for their proposed solution.

## 4 Mathematical Model Supporting the Configuration Engine

1. The waste water industry measures contamination in various ways. The following measurements are used in the Configuration Engine:
  - a. The preferred manner, and most accurate, is Mass. We also refer to “Mass Fraction” when dealing with waste water. It can be thought of as the ratio of the mass of the contamination to all other components of a given volume of water. Example: The Mass Fraction of Sodium in salt water equals the grams of Sodium per gram of solution. We indicate this with the variable “Y”.
  - b. “Total Dissolved Solids” (TDS) and “Total Suspended Solids” (TSS) are also measured as a Mass Fraction. Both TDS and TSS can be present in waste water simultaneously.
  - c. Aquaback has standardized on Parts per Million (PPM) to indicate the Mass Fraction of one or more contaminants.
2. All pressures are measured in Pounds per Square Inch (PSI).
3. We define Distillate Mass Fraction as EQUAL TO zero to imply that 100% of the contamination has been removed.

Figure 1 shows a simplified flow diagram of Aquaback’s Distillation Recycling Module (“DRM”). The graphic focuses on both boundary heat loss and mass flows. The input power is composed of a primary line to power the steam compressor, and a secondary line for all other requirements (pumps, controls, etc.). At steady state the input power is balanced by the insulation heat loss, the vent heat loss, and the net heat out flow via both the Distillate (aka: condensed water, distilled water) and Concentrate (aka: concentrated dirty water or Reject Water).

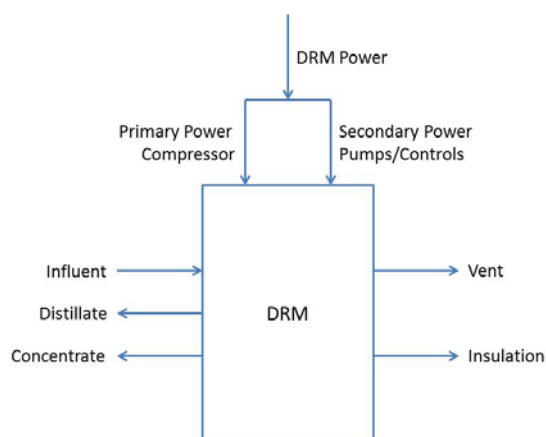


Figure 1. Flow diagram.

Conservation of Mass allows us to calculate the Distillate Flow Rate. The allowance for Volatile Gasses Flow Rate represents any element or compound which may evaporate and/or separate from the Influent at atmospheric pressure and at temperatures experienced in the Counter Flow Heat Exchanger. These gasses are separated from the Influent in the Volatile Gas Separator immediately after the Counter Flow Heat Exchanger. For the purposes of this discussion, the Volatile Gas Flow Rate and the Volatile Gas Mass Fraction are assumed to be zero. There are cases where the Volatile Gas is significant and should be accounted for.

$\dot{V}_{dist} = \dot{V}_{inf} - \dot{V}_{conc} - \dot{V}_{vgas}$	Distillate Flow Rate EQUALS Influent Flow Rate MINUS Concentrate Flow Rate MINUS Volatile Gas Flow Rate.
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The total mass of the contamination of the Concentrate is estimated using the “Conservation of Species” rule ( i.e., we can’t destroy any contamination).

$y_{conc} = y_{inf} - y_{dist} - y_{vgas}$	The Concentrate Mass Fraction is EQUAL TO the REMAINDER of the of the Influent Mass Fraction MINUS the Distillate Mass Fraction MINUS the Volatile Gas Mass Fraction
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In order to increase the percentage of Distillate produced from the Influent, the Concentrate percentage must be reduced.

Example: Given that contamination has only two ways to get out of the system (either as a gas or in the Concentrate) and given that we have assumed the there are no Volatile Gasses in this example, if the Distillate Flow Rate is to be cut in half, the Concentration Mass Fraction has to double. The only means to increase the concentration of Concentrate is to further distill it. We have estimated that the Evaporation Water Mass Fraction, which represents a mixture of Influent and Concentrate waters, is lower than the Mass Fraction of the concentrate by a factor of two.

$y_{evap} \cong \frac{y_{inf} + y_{conc}}{2}$	The Evaporation Water Mass Fraction is EQUAL TO the SUM of the Influent Mass Fraction PLUS the Concentrate Mass Fraction DIVIDED BY two.
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Any change (indicated by  $\Delta$ ) to Evaporation Water Boiling Point Temperature ( $T_{bp}$ ) depends on the Evaporation Water Mass Fraction. A Mass Fraction of zero results in no change to the boiling point. The Mass Fraction is measured in Total Dissolved Solid (TDS). As a reference, we use a linear TDS / boiling point relationship where sea water was used for reference with a 1°F boiling point rise at 35,000 PPM ( $\Delta T_{ref} = 1$ ). The boiling characteristics of seawater are a well-known convention, and make a good reference point.

$\Delta T_{bp} \cong \Delta T_{ref} \left( \frac{y_{evap}}{y_{ref}} \right)$	The Evaporation Water Boiling Point Rise EQUALS the Reference Water Boiling Point Rise TIMES the ratio of Evaporation Water Mass Fraction to the Reference Mass Fraction (sea water at 35,000 PPM).
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Another factor in boiling point and condensation temperatures is pressure. The thickness of the water film applied to the vertical evaporator surface does not affect pressure, and all discussion of pressure will refer to the pressure of the steam in the evaporator and the condenser. After steam is produced in the evaporator at atmospheric pressure, it passes through a compressor increasing its pressure. Higher pressures increase the temperatures at which boiling and condensation occur (aka “saturation temperatures”). Conversely, cooks notice that water boils at a lower temperature at higher altitudes due to lower atmospheric pressure.

Water as gas (steam) occupies 1,667 times more volume than water as a liquid. When there is more pressure on the steam, the temperature at which the steam will condense rises. It is this higher condensing temperature that the Evaporator Water “feels” through the thin metal wall separating the evaporator from the condenser, and therefore the Evaporator Water boils.

The compressor pressure rise consists of two components:

1. The pressure change needed for the condensing temperature to be higher than the Evaporation Water Boiling Temperature, or the point at which the Evaporation Water will boiling and create steam via a “phase change”, and
2. The pressure change needed to attain the elevated boiling point due to contamination in the Evaporation Water.

The first pressure change, the Nominal Pressure Rise ( $\Delta P_{comp,nom}$ ), is proprietary

$\Delta P_{comp} = \Delta P_{comp,nom} + \Delta P_{comp,bp}$	Total Pressure Rise EQUALS the Nominal Pressure Rise PLUS the Pressure Rise Evaporator Boiling Point.
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As part of Aquaback’s proprietary process, we have determined the increase in pressure, Total Pressure Rise ( $\Delta P_{comp}$ ), required to achieve the steam temperature at which:

1. The compressed steam will immediately condense back into a liquid upon contact with the condensing wall, the temperature of which is below the “saturation reference temperature”;
2. The heat given off during this condensing process boils the Evaporator Water on the evaporation side of the condensing metal surface (which varies due to the contamination level);
3. The system may not need any additional heat beyond heat generated by the compressor.

We use a linear water saturation “curve” to estimate the pressure and temperature changes from the base boiling point of pure water at atmospheric pressure to estimate evaporation point where 1.0 PSI and 3.33 F were used for the saturation reference points. We indicate approximate value as the exact values are proprietary.

$\Delta P_{comp,bp} \cong \Delta P_{sat,ref} \left( \frac{\Delta T_{bp}}{\Delta T_{sat,ref}} \right)$	The Pressure Rise Evaporator Boiling Point induced by the compressor is approximately EQUAL to the PRODUCT OF the Reference Saturation Pressure Rise TIMES the Evaporator Boiling Point Rise DIVIDED by Reference Water Saturation Temperature Rise.
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The Compressor Steam Flow Rate is determined by Conservation of Mass rule and measured in Cubic Feet per Minute (CFM). We DIVIDE the Distillate Flow Rate (measured in Density of Water as Liquid where density is represented by the Greek letter Rho “ρ”, times volume of Distillate Flow) BY the density of water as steam. As a reference point, at atmospheric pressure, steam occupies 1,667 (1,000/0.6) times more volume than an equal mass of water as a liquid, so the ratio of density of steam to pure water is 1,667 to 1.

$\dot{V}_{comp} = \frac{\rho_f \dot{V}_{dist}}{\rho_g}$	Compressor Steam Flow Rate is EQUAL TO the Density of Water as a Liquid TIMES the Distillate Flow Rate DIVIDED by the Density of Water as a Gas
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In order to estimate the Motor Power Required ( $\dot{E}_{comp}$ ) to drive the compressor (measured in Watts “W”), we need to know how efficient the motor/turbo combination (which makes up the compressor) is and what volume of steam requires the change in Steam Pressure ( $\Delta P_{comp}$ ). An incompressible flow approximation is used to calculate the total motor and compressor power where  $\eta_{comp}$  and  $\eta_{motor}$  are the Compressor Turbo Efficiency and the Compressor Motor Efficiency (including bearings), respectively. The efficiency is taken from the input table, and which is generally set at 64% as most motors and turbo components can run optimally at 80% efficiency. (80% X 80% = 64%).

$\dot{E}_{comp} \cong \frac{\dot{V}_{comp} \Delta P_{comp}}{\eta_{turbo} \eta_{motor}}$	The Motor Power Required is EQUAL TO the Compressor Steam Flow Rate TIMES the Total Pressure Rise DIVIDED by the PRODUCT of The Compressor Turbo Efficiency TIMES the Compressor Motor Efficiency.
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The primary specific energy consumption of the compressor ( $e_{comp}$ ) is measured in Watt Hours (Whs) per gallon of Distillate, and calculated as follows

$e_{comp} = \frac{\dot{E}_{comp}}{\dot{V}_{dist}}$	The Specific Energy Consumption – Compressor EQUALS Motor Power Required DIVIDED by the Distillate Flow Rate.
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The total specific energy consumption (Whs per Gallon of Distillate) includes the secondary term from the data input table. We have estimated this power to be approximated at 5 Whs per gallon of distillate

$e = e_{comp} + e_{pumps}$	Specific Energy Consumption -Total EQUALS the SUM of the Specific Energy Consumption – Compressor PLUS the Specific Energy Consumption - Pumps.
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## 5 Inputs and Results

- The influent mass fraction range was constrained by a maximum concentrate mass fraction of 32%, or 320,000 PPM, which approximates the solubility limit, beyond which TSS precipitate out of solution.

Results are shown in Figures, 2, 3 and 4. Keep in mind that we cannot pinpoint an optimal reject rate, only a reject rate curve. The optimum reject rate is customer dependent via the ROI sensitivity to power vs reject water costs. For instance, some customers pay to haul away concentrate and are therefore very sensitive to concentrate volume, while others reject the concentrate essentially for free and are therefore more sensitive to electrical power.

Figure 2 shows the first of three “Total Dissolved Solids maps” and focusses on low Distillate reject water rates of 5%, 10%, 15% and 20%, which are consistent with most waste water of less than 20,000 PPM. The next two figures focus on Distillate reject water rates of 10 to 40% and 20 to 80% respectively.

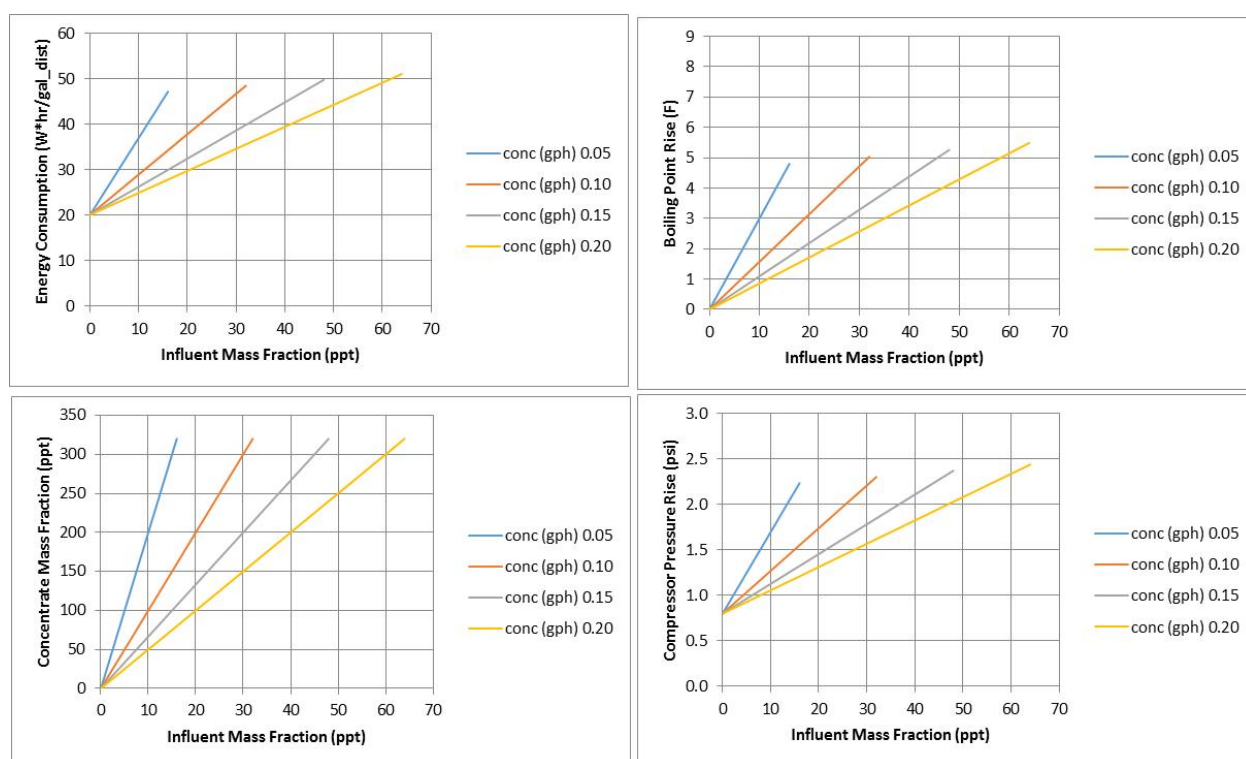


Figure 2. TDS map, 5 to 20% reject rate.

- The graphs show the relative relationship between Influent TDS and 1) specific energy consumption and 2) concentrate mass fraction.
- We see that the energy consumption increases as
  - the Influent mass fraction increases and/or
  - as the reject rate decreases.

- Both increase the boiling point rise in the evaporator, which increases the required compression.
- As a practical consideration, at 10,000 PPM Influent, the energy consumption drops by 15% as the reject rate is increased from 10% to 20%.

Figure 3 shows the TDS map for intermediate reject rates of 10, 20, 30, 40%. In addition to points 1 & 2 above:

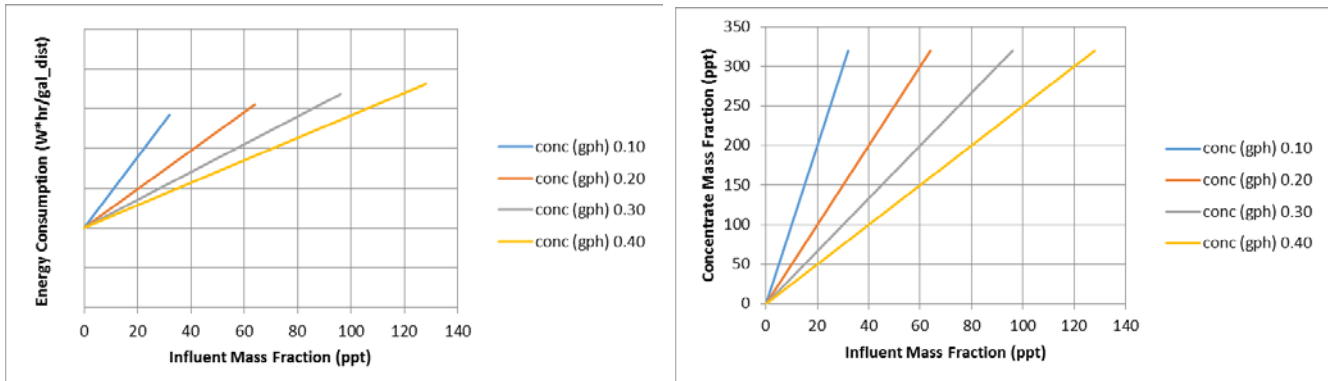
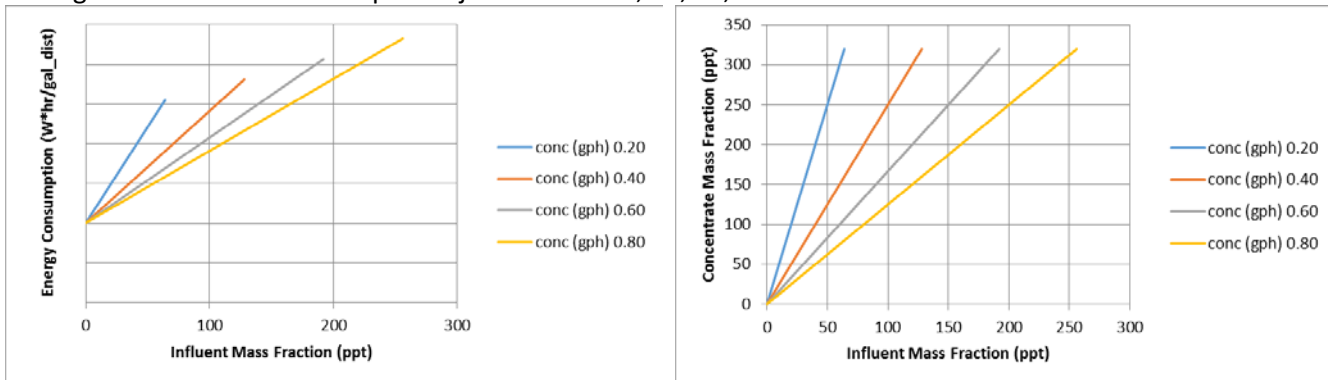


Figure 3. TDS map, 10 to 40% reject rate.

- Here the influent mass fraction range increases by a factor of 2. The power consumption rise is similar linear with the smaller increments shown in Figure 2.

Figure 4 shows the TDS map for reject rates of 20, 40, 60, 80%.



• Figure 4. TDS map, 20 to 80% reject rate.

- The influent mass fraction range increases by a factor of 4X to a maximum of 260,000 PPM. The linear climb of the power consumption and compressor pressure slows at the higher reject rates.
- The large reject rates of 60 to 80% theoretically show the practical limits of single stage distillation. At a reject rate of 50%, the maximum influent mass fraction is 150,000 to 160,000 PPM because we have constrained the output to the 320,000 PPM.
- We do not yet know how specific contaminant precipitation will affect the maximum mass fraction that a single stage distiller can handle.

Source: TDS map single stage e 04 Aug 2015 V2.1xlsx

## 6 Conclusion

A number of plots were generated showing the trade-offs with respect to influent TDS and reject rate. The model was formatted in a spreadsheet to become a user-friendly tool.

## 7 References

1. Aquaback Engineering Memorandum: Specific Energy Consumption Based on Influent TDS and Reject Rate, David Dussault, EM2015-018. 28 July 2015
2. MS Excel File: TDS\_map\_single\_stage 04Aug2015 V1.2.xlsx
3. MS Excel File : Technical Paper Symbols and Definitions Table - 10 Aug 2015.xlsx