# CARRIER-GAS ENHANCED ATMOSPHERIC PRESSURE DESALINATION

## Final Report

**Arizona State University**
**Tempe, Arizona**

**Cooperative Agreement No. 99-FC-81-0186**
**Desalination Research and Development Program Report No. 92**

**October 2002**

**U.S. Department of the Interior**
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The 1,000 gallon/day units have been developed costing less than $2,000 and operate from $3.70 to $1.70 per 1,000 gallons distillate for small facilities. The energy reduction effect of using liquid desiccant lithium bromide solutions was successfully investigated. The feasibility of desiccant heat pumping was confirmed at 180 ºF. Implementation of the desiccant technique with boiling regeneration should reduce the water cost from $3.50 to $2.70 per 1,000 gallons distillate. Using ambient dry desert air for regeneration would further reduce the water cost to $1.50 per 1,000 gallons for small seawater plants and to less than $0.80 for 100,000 gallon/day facilities. Such areas as Yuma, Arizona and the desert regions of California could produce low cost water from the sea by taking advantage of their dry year round environments. Other similar areas of the World would also benefit from this development. The applications for water reclamation were further extended from brackish and sea water to include RO plant effluent waters, evaporation pond waters (crystal deposition) and CMP (chemical mechanical planarization) slurries which contain sub-micron particulates. The Salt River Project and ASU are currently sponsoring the evaporation pond waters investigation.

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The principal investigator along with lab team 2002 (Dr. Bassem Hamieh, Dr. Michael Ybarra, Mr. Victor Banks, Mr. Joshua Brown, Mr. Andrew Davis, and Mr. Eric Segura) also wish to express their appreciation for funding from Salt River Project (Mr. Rick Schumm) and from ASU Office of Technology Collaborations and Licensing (Mr. Alan Poskanzer) for expanding the grass roots support of the Bureau of Reclamation. They have all helped take our primitive ideas to a demonstration reality—a reality that appears to be unbounded in its economically effective water reclamation applications.

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## Glossary

| | |
|---|---|
| A | Heat transfer area (ft$^2$) |
| $c_p$ | Heat capacity (BTU/lbmole °F) |
| B | 14 |
| F | Feed flow rate (lbmole/sec) |
| G | Carrier gas flow rate (lbmole/sec) |
| $\underline{h}$ | Molar enthalpy (BTU/lbmole) |
| h | Heat transfer coefficient (BTU/hr ft$^2$ °F) |
| k | Thermal conductivity (BTU/hr ft °F) |
| L | Liquid flow rate at any position in the tower (lbmole/sec) |
| M | Mass transfer factor |
| $\dot{n}$ | Molar flow rate (lbmole/sec) |
| $P_w$ | Vapor pressure of water (psia) |
| P | Total pressure (psia) |
| $P_f$ | Production density (lb/hr ft$^2$) |
| Q | Energy input at the top of the tower (BTU/sec) |
| q | Heat flux (BTU/hr ft$^2$) |
| R | Gas constant (BTU/lbmole °F) |
| RH | Relative humidity |
| S | Salinity at any position in the tower |
| T | Temperature (°F) |
| t | Thickness of heat transfer wall (ft) |
| U | Overall heat transfer coefficient (BTU/hr ft$^2$ °F) |
| V | Vapor loading (lbmoles of water vapor per lbmoles of carrier gas) |
| w | Width of the flow media (ft) |

## Subscripts

| | |
|---|---|
| B | Brine stream |
| D | Distillate stream |
| d | Dewformation side |
| e | Evaporation side |
| f | Liquid film |
| g | Gas |
| h | Top of the tower |
| 0 | Bottom of the tower |
| ref | Reference point |
| RH | Relative humidity |
| LM | Logarithmic mean |

## Greek

| | |
|---|---|
| $\lambda$ | Heat of vaporization of water (BTU/lbmole) |
| $\delta$ | Liquid film thickness (ft) |
| $\Gamma$ | Gamma (lb/hr ft) |
| $\rho$ | Density (lb/ft$^3$) |
| $\mu$ | Viscosity (lb/ft$^2$ sec) |

# 1. EXECUTIVE SUMMARY

Final double-helix NEWT[1] Towers have been built and operated at Arizona State University laboratories. The basic unit produces up to 150 gallons/day condensate with a gained output ratio of from 10 to 20. Eight of these units comprise a 1,000 gallon/day demonstration pilot plant of the Dewvaporation process. The 1,000 gallon/day desalination plant costs less than $2,000 and operates from $3.70 to $1.70 per 1,000 gallons distillate depending on fuel source.

Further energy reduction effects of using liquid desiccant lithium bromide solutions were also investigated. The feasibility of desiccant heat pumping was confirmed at 180 ºF. Implementation of the desiccant technique with boiling regeneration should reduce the water cost from $3.70 to $2.70 per 1,000 gallons distillate. Using ambient dry desert air for regeneration would further reduce the water cost to $1.70 per 1,000 gallons for small sea water plants and to less than $1.00 per 1,000 gallon/day for 1,000,000 gallon/day facilities. Such areas as Yuma, Arizona and the desert regions of California could produce low cost sea water by taking advantage of their dry year round environments. Other similar areas of the World would also benefit from this development.

A test unit was built to study the scaling phenomenon in the Dewvaporation process. No scaling was observed on the heat transfer walls wit evaporation pond waters from the SRP Coronado Generating Station. The solids formed and did not adhere to the plastic heat transfer walls but instead fell to the brine basin. The particles were extremely fine in the range of 50 microns and less.

The applications for water reclamation were further extended from brackish and sea water to include: Reverse Osmosis reject brine, evaporation pond waters (crystal deposition) and CMP (chemical mechanical planarization) slurries which contain gelatinous sub-micron particulates. Light stripping of volatile organic compounds from water was explored . The removal of 90 percent of VOC in parts per million would cost $0.19/1,000 gallons.

Dewvaporation technique is a specific process of humidification-dehumidification desalination, which uses air as a carrier-gas to evaporate water from saline feeds and dew form pure condensate at constant atmospheric pressure. The heat needed for evaporation is supplied by the heat released by dew fall condensation on opposite sides of a heat transfer wall. Since only a small amount of external heat is needed to establish temperature differences across the wall and since the temperature of the external heat is versatile, the external heat source can be from waste heat, from solar collectors or from fuel combustion. The unit is constructed out of thin water wettable plastics and operated at pressure drops of less than 8 cm of water.

The Salt River Project and the ASU Office of Technology Collaborations and Licensing are currently sponsoring the Dewvaporation pilot plant program as an extension of the grass roots support by the Bureau of Reclamation.

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[1] NEWT is used to describe air flow pattern through the tower, starting with the air flowing north and then in a zigzag pattern east and west.

# 2. BACKGROUND AND INTRODUCTION

The technology, Dewvaporation, investigated involves the desalination of seawater and brackish water, which may find immediate economic niche in small plant applications. Larger facilities will develop with time.

Many technologies have been used to perform the required desalination resulting in preferred technologies based on economics (Fosselgard and Wangnick, 1989). For example, in the desalination of mild brackish (less than 1,000 ppm TDS) water, Reverse Osmosis (RO) is superior to all desalination technologies. This is mainly a reflection of the fact that other technologies involve phase change (boiling) where as RO employs low-pressure pumps (less than 100 psia (6.90 bars)) to force water through semi-permeable membranes resulting in less energy consumption than that involved in a boiling process. One area where RO is ineffective in water purification is in the treatment of waters containing non-filterable suspended particulates. For example, the Colorado River contain silt in the 1 micron range which tend to foul RO membranes, thusly, increasing the maintenance and/or pretreatment costs of RO operation.

For the more TDS intense aqueous applications such as RO concentrates (Mickley, 2001), waste streams and seawater, other mechanical and thermal technologies economically compete with RO as seen by Larson *et al.*,1989a, 1989b. In the case of seawater desalination, the RO pump pressures increase to 1,000 psia (68.95 bar) and feed waters require expensive pre-treatments in order to protect and extend the life of the membranes.

The competitive technologies to RO for seawater desalination include Mechanical Vapor Compression (MVC), Multi-Stage Flash Distillation (MSF), and Multi-Effect Distillation (MED) with and without Thermal Vapor Compression. The MVC needs shaft power to drive its compressor. The motor can be either electrically or thermally driven. For electrically driven MVC, MVC plants consume more electricity than RO units in the same seawater service. The other processes dominantly use and reuse heat as the main driver to affect temperature-driving force between boiling and condensing at staged pressures. The thermally driven plants attempt to reuse the high temperature applied heat as many times as is economically possible to minimize operating costs. This energy reuse factor economically varies from 6 to 12. As the GOR increases so does the equipment capital cost. The optimum GOR value depends on factors such as plant capacity, cost of energy, cost of materials, interest and tax rates.

## 2.1 Dewvaporation Philosophy

The ASU patented technology, DEWVAPORATION, is extremely diverse in the desalination and water reclamation of seawater, brackish water, evaporation pond water, RO plant concentrates, Chemical Mechanical Planarization slurries from the semiconductor industries, volatile organic compounds (MTBE, TCE) contaminant removal from ground water all of which find an immediate economic niche in small plant applications. Larger plants will evolve in time.

The standard Dewvaporation Continuous Contacting Tower focuses on a relatively new non-traditional and innovative heat driven process using air as a carrier-gas and remaining at atmospheric pressure throughout the device. The heat source can be from low temperature solar (131 ºF, 55 ºC), waste heat, or combustible fuels (210.2 ºF, 90 ºC). Briefly, the process works for brackish desalination as viewed in Figure 1 ( Hamieh et al, 2000):

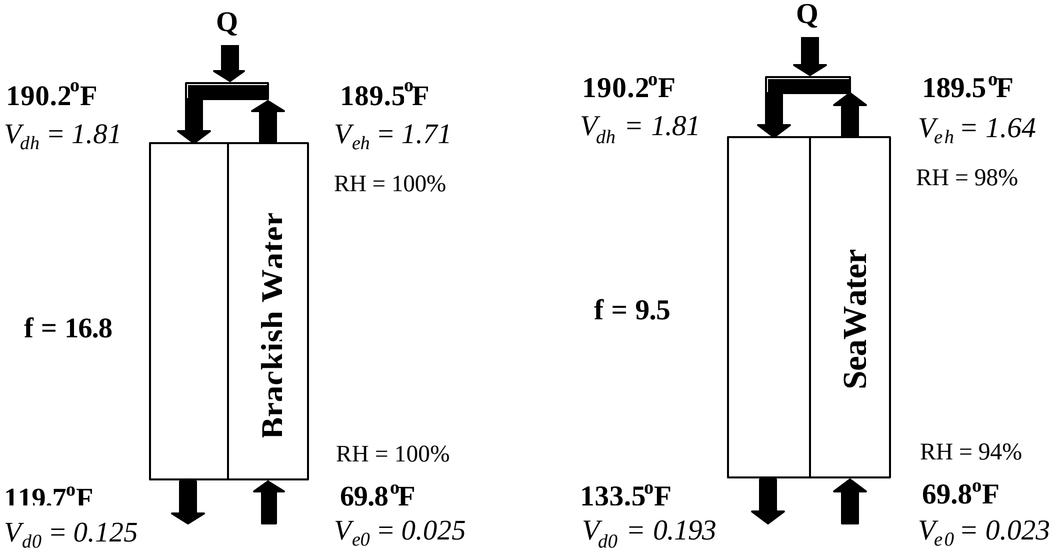
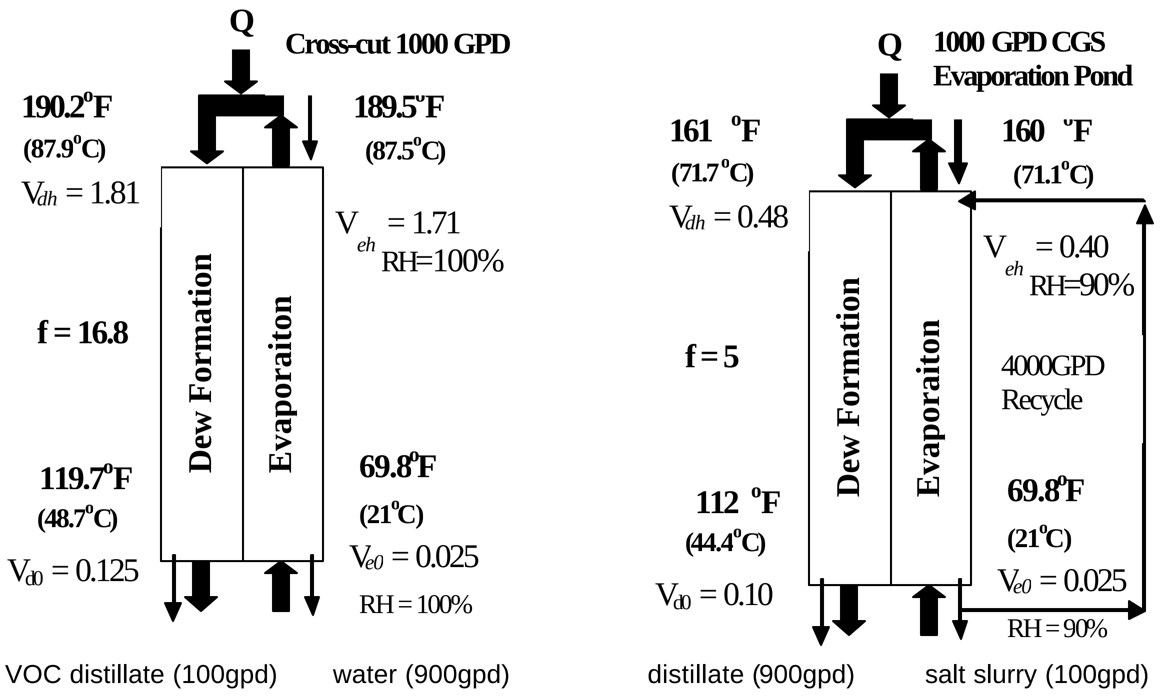


Figure 1.—Dewvaporation Continuous Contacting Tower Design Schematic for Desalination of Brackish Water and Seawater.

A carrier-gas such as air is brought into the bottom of the tower on the evaporation side of a heat transfer wall at a typical wet bulb temperature of 69.8 ºF (21 ºC), thereby containing about 0.025 moles of water vapor per mole of air. The wall is wetted by saline feed water, which is fed into the evaporation side at the top of the tower. As the air moves from the bottom to the top of the tower, heat is transferred into the evaporation side through the heat transfer wall allowing the air to rise in temperature and evaporate water from the wetting saline liquid which coats the heat transfer wall. Concentrated liquid leaves from the bottoms of the tower and hot saturated air leaves the tower from the top at 189.3 ºF (87.4 ºC) with a humidity of 1.71 moles of water vapor per mole of air. Heat is added to this hot air by an external heat source (in this investigation steam was used) increasing the air humidity and temperature to a V of 1.81 and 190.2 ºF (87.9 ºC) respectively. This hotter saturated air is sent back into the top of the tower on the dew formation side. The dew formation side of the tower, being slightly hotter than the evaporation side, allows the air to cool and transfer condensation heat from the dew formation side to the evaporation side. Finally, pure water condensate and saturated air leave the dew formation side of the tower at the bottom at 119.7 ºF (48.7 ºC). Total external heat needed is made up of the heat needed at the top to establish a heat transfer temperature difference and the heat needed to establish a temperature off-set between the saline feed stock and the pure water condensate. The detrimental effect of salt concentration on the energy reuse factor (or gain output ratio), f is explained in the theory section.



(2a) VOC Removal

(2b) Evaporation Pond Crystallization

Figure 2.—Dewvaporation Continuous Contacting Tower Design Schematic.

Figure 2a illustrates that VOC removal behaves ideally as the distillation of almost pure, brackish or sea water. The reclamation of evaporation pond waters that are saturated with salts (30 percent by weight) as in Figure 2b, is more difficult. The feed waters are processed to extinction by the recycle of bottoms brine back to the feed. The two products are distillate and wet salt solids.

Due to the slight desiccant effect of normal salts, the energy reuse factor decreases with increased salt concentrations. This suppressed vapor pressure of water reduces the relative humidity of saturated air causing the addition of more steam to make up the air dryness.

## 2.2 Predictive Model

From Figures 1 and 2 the mathematical definition of the energy reuse factor, f, is the ratio of the energy transferred through the heat transfer wall to the high temperature energy input as shown in equation 1 (Beckman, 1999):

$$f = \frac{V_{dh} - V_{d0}}{V_{dh} - V_{eh}} \qquad [1]$$

The definition of the molar production flux, $P_f$, is the gas traffic times the water vapor decrease of the dew formation side of the wall divided by the wall area as shown in equation 2:

$$P_f = \frac{G}{A} \cdot \left(V_{dh} - V_{d0}\right) \quad [2]$$

Typically, the feed/condensate temperature offset is kept to 10 ºF (5.6 ºC). This can be accomplished by either an internal or external feed heat exchanger. In this analysis, the energy reuse factor, f, was 16.8. By including the heat needed for the temperature offset, the factor reduces to about 13. Actually, the product of the factor and the molar production flux, $P_f$ , is a constant at parametric $V_{eh}$. The value of the constant is a function of the operating variables as shown in the following equations.

The amount of water vapor contained in the air carrier-gas is calculated by specifying the temperature, T, and calculating the vapor pressure, $P_w$ , from equation 3 (Smith and VanNess, 1987).

$$\ln P_w = B - \frac{\lambda}{R \cdot T} \quad [3]$$

where B and $\lambda$ are constants obtained by fitting a straight line to the $\ln(P_w)$ versus 1/T for the steam table. For temperature range of 32 - 212$^o$F (0 – 100$^o$C), B is 14 and $\lambda/R$ is 5209 K (Perry, Green, and Maloney, 1984). The moles of water vapor per mole of air is:

$$V = \frac{RH \cdot P_w}{P - RH \cdot P_w} \quad [4]$$

where the relative humidity (RH) is given as a function of salinity (S) by the following equation (Spiegler and Laird, 1980)

$$RH = 1 - 0.000538 \cdot S \quad [5]$$

The hottest temperature in the evaporating section is specified allowing the calculation of the largest value of the $V_{eh}$ in the evaporating section of the unit. Then the change in vapor content of the carrier-gas is specified across the top of the tower by:

$$\Delta V = V_{dh} - V_{eh} \quad [6]$$

From these specifications, the temperature difference across the heat transfer wall at any position can be described as:

$$\frac{1}{\Delta T_{LM}\big|_z} = \left[\frac{B^2 \cdot R}{\lambda}\right] \cdot \left[\frac{\left(1 + \Delta V + V_e\big|_z\right) \cdot V_e\big|_z}{\Delta V}\right] \quad [7]$$

In this process both the film heat and mass transfer coefficients are important in establishing the overall effective heat transfer coefficient, U. For simultaneous heat and mass transfer operations involving air and water, the Lewis Number is essentially unity (McCabe, Smith, and Harriott, 1993) allowing the coefficients to be related by similitude as $k_y = h_g/c_p$. The effect of the latent energy associated with the mass transfer of water vapor can be related to the sensible heat transfer associated with the air/vapor mixture by equation 9 after Werling, 1990.

$$h_f\big|_z = h_g\big|_z \cdot \left(1 + M\big|_z\right) \qquad [8]$$

where M is expressed as:

$$M = \left(\frac{\lambda}{RT}\right)^2 \cdot \left(\frac{R}{c_p}\right) \cdot V \qquad [9]$$

Taking into account both gas film heat transfer coefficients and the thermal resistance of the heat transfer wall, then the overall effective heat transfer coefficient, U, can be expressed as:

$$\frac{1}{U\big|_z} = \frac{1}{h_{fe}\big|_z} + \frac{1}{h_{fd}\big|_z} + \frac{t}{k} \qquad [10]$$

The heat transferred through the heat transfer wall, is essentially the latent heat needed to evaporate water as:

$$q\big|_z = G \cdot \lambda \cdot \left(V_e\big|_{z+\Delta z} - V_e\big|_z\right) \qquad [11]$$

The area needed for the heat transfer wall is obtained by an energy balance (Bird, Stewart, and Lightfoot, 1960).

$$\frac{A\big|_z}{q\big|_z} = \frac{1}{U\big|_z} \times \frac{1}{\Delta T_{LM}\big|_z} \qquad [12]$$

where

$$\Delta T_{LM} = T_{yd} - T_{ye} \qquad [13]$$

Upon integrating with respect to the overall area and assuming that t/k is small compared to the gas phase resistance, equation 14 then relates the total energy reuse factor, f, and the total production flux, $P_f$, as follows:

$$f \cdot P_f = \left\{\left[\frac{\lambda}{B \cdot R \cdot T}\right]^2 \cdot \left[\frac{h_g}{C_p}\right]\right\} \cdot \left(\frac{V_{eh}}{2 + V_{eh}}\right) \cdot (18) \cdot F_{RH} \qquad [14]$$

Where the detrimental effect, $F_{RH}$, of reduced relative humidity at the tower top exiting evaporation air stream, RH, is:

$$F_{RH} = 1 - (1 - RH) \cdot (1 + f) \cdot (1 + V_{eh}) \qquad [15]$$

Equation 14 shows that as the temperature increases, the product of energy reuse factor and molar production flux become greater. It is also apparent that the energy reuse factor, f, and the molar production flux, $P_f$, are related hyperbolically in an established unit. The detrimental effect of salt concentration is also included in this expression from Equation 15.

Additionally, higher values of $V_{eh}$, i.e. higher temperatures, improve both f and $P_f$ values, which is economically beneficial to the tower. However, higher temperatures are limited to the heat source temperature and the normal boiling point of water.

On the other hand, by taking into account the heat conduction resistance in the plastic heat transfer wall and the resistances due to the two liquid films on the wall, then equation 20 results. This expression resembles equation 16 but with an additional term F containing all of the plastic and liquid films resistances to heat transfer.

$$P_f \cdot f = \left(\frac{\lambda}{B \cdot R \cdot T}\right)^2 \cdot \left(\frac{h_g}{c_p}\right) \cdot \left(\frac{V_{eh}}{2 + V_{eh}}\right) \cdot F \qquad [16]$$

With:

$$F = \frac{1}{1 + F_{RH} + F_\varepsilon + F_{RH} \cdot F_\varepsilon \cdot \left(\frac{6 + 3 \cdot V_{eh}}{3 + 2 \cdot V_{eh}}\right)} \qquad [17]$$

Rearranging these equations into a form that would be linear in a data plot gives:

$$\frac{1}{(3 + 2 \cdot V_{eh}) P_{f\cdot} \cdot f} = \left[\left(\frac{c_p}{h_g}\right) \cdot \left(\frac{B \cdot R \cdot T}{l}\right)^2\right] \cdot \left(\frac{2 + V_{eh}}{3 \cdot V_{eh} + 2 \cdot V_{eh}^2}\right) + \frac{B^2 \cdot R}{6} \cdot \sum \frac{t}{k} \qquad [18]$$

Air Boundary Layer Wall & Liquids

Essentially, the manner in which Equation 18 is used is to determine the effective heat transfer area from the data obtained per run. All of the parameters on the right hand side of Equation 18 are known. Data from each run contain the temperature at the top of the tower, production rate and energy consumed. From the tower top temperature, the water vapor to air ratio and energy reuse ratio can be calculated. Therefore, the production density can be assessed on the left hand side of Equation 18. Since the production rate is data, then the effective heat transfer area in the tower can be identified. The effective area is a property of the tower mechanical design.

# 3. CONCLUSIONS AND RECOMMENDATIONS

From this investigation into the Dewvaporation process it can be concluded that:

- The Dewvaporation technique is capable of desalinating brackish water, seawater, evaporation pond water and RO concentrate waters.
- Capital costs for a 1,000 gallon/day unit vary from $1300 to $1800 depending on type of heat source.
- Water costs for a 1,000 gallon/day unit vary from $3.70/1,000 gallons to $1.70/1,000 gallons depending on heat source.
- The Dewvaporation technique can reclaim water from chemical mechanical planarization slurry without jell formation at the above costs.
- The Dewvaporation technique can remove 90 percent of volatile organic compound contamination from water for $0.19/1,000 gallons.

It is recommended that:

- The 1,000 gallon per day demonstration pilot plant be mobile so that brackish water, seawater and effluent waters from reverse osmosis water treatment plants can be treated on site. These operations will further demonstrate the versatility and economics of the Dewvaporation process.
- The liquid desiccant heat pumping feature be developed for the 1,000 gallon/day demonstration unit.
- Manufactures be invited to observer the performance of the demonstration unit for procurement of a manufacturing license from Arizona State University Office of Technology Collaborations and Licensing.

# 4. WORK PERFORMED

The initial work TASKS focused on the enhancement of energy efficiency by the use of lithium Bromide liquid desiccant heat pumping technique. The work TASKS were changed by agreement to switch the effort to design, build and operate units that would form a standard Dewvaporation 1,000 gallon/day demonstration pilot plant.

The initial investigation Objectives were based on the success of the phase 1 effort (98-FC-81-0049) and a follow on proposal entitled "Carrier-Gas Enhanced Atmospheric Pressure Desalination" that involved a lithium bromide liquid desiccant heat pumping feature. The TASKS in that original work schedule were:

1. Build Desiccant Regenerator
2. Build Desiccant Contact Heat Exchanger
3. Build Desiccant Liquid/Liquid Heat Exchanger
4. Develop Desiccant Process Mathematical Model
5. Join Desiccant Equipment with a Tower for System Implementation
6. Final Data Compilation and Final Report

At the completion of the Phase 1 effort (98-FC-81-0049), it was mutually agreed to change the continuing support from a focus on the desiccant heat pumping feature to the establishment of a sizable demonstration pilot plant. A 1,000 gallon/day design was selected as the target size.

The Revised Statement of Work shifted the focus of further development efforts in the Dewvaporation technique to a sizable demonstration of the standard steam addition method by specification of the following eight Objective TASKS:

1. Build a Water Boiler for the 1,000 GPD Pilot Plant
2. Build and Test a Desiccant Contact Heat Exchanger
3. Deleted (Build a Liquid/Liquid Heat Exchanger)
4. Develop Desiccant Process Mathematical Model
5. Build and Operate 1,000GPD Pilot Plant Towers
6. Final Data Compilation and Report
7. Technology Transfer
8. Build a Sub-module Pre-Pilot Plant Unit

The philosophy involved in each of these TASKS can be summarized as:

**TASK 1** (Build a water boiler for the 1,000GPD pilot plant) There were many pathways to achieving an efficient boiler many of which could have been complex and timely. The use of natural gas or propane instead of electricity poses more difficulty. However, it is felt by the research group, that a fuel boiler was first proposed but fuel supply to a mobile operation became difficult. An electrical unit using 110 volt supply was employed. Energy usage was calculated based on the use of natural gas at $0.35/therm.

**TASK 2** (Build and Test a Desiccant Contact Heat Exchanger) A small proof of concept test rig was proposed to observe the effect of 190 ºF humid air being dried by liquid desiccant giving the heat released to another humid air stream. Since the heat duty of this device was to be on the order 500 BTU/hr with a delta-temperature driving force of about $5^{o}$F , then the area required was about 1 square foot. It would be constructed similar to the main tower. Hot humid air will pass upward after being approximately divided 20 percent and 80 percent. The 20 percent stream will be contacted by desiccant flow on the heat transfer wall while the 80 percent stream will be contacted by water on the heat transfer wall.

**TASK 3** is DELETED. This task (Build Desiccant Liquid/Liquid Heat Exchanger) was considered unessential in the proof of concept of desiccant heat pumping phenomenon.

**TASK 4** (Development of a Desiccant Process Mathematical Model) A model would be needed to predict the production rate and energy reuse factors on desiccant system variables. Variables such as lithium bromide concentrations, desiccant flow rates and temperatures, tower top humid air split ratio, tower bottom temperature, outside ar relative humidity. In other words, the modeling of the regeneration/desiccant heat transfer train and incorporation with the main tower unit. The combined model would then aid in the final design of the system.

**TASK 5** (Build and Operate 1,000 GPD Pilot Plant Towers) Sub modules will be designed, built and operated to find the most promising tower design. The 1,000 gallon/day demonstration pilot plant will be comprised of multiple sub modules that together make up the capacity. The testing of one sub module will allow TASK 6, writing the Final Report, to start as one module will reflect the operation of the entire pilot unit.

**TASK 6** (final report) The Final Report will finish the project with a presentation to the Bureau of Reclamation in Denver.

**TASK 7** (Technology Transfer) involves the continual updating of brackish and seawater economics based on updated project completions along with continual seeking of industrial interest for technology transfer to manufacturing. To heighten interest in the developing desalination technology, the concept of heating sources will be broadened to lower temperature sources, such as solar, waste heat and others as they are identified. The fossil fuel combustion will also be broadened to include inexpensive materials such as bunker oils.

**TASK 8** (Design, construction and testing of sub modules which will comprise the pilot plant unit) This work began in October 1999 and ran continuously throughout the study. The pre-pilot units are actually sub-modules of the pilot plant tower. The size of the sub modules will be limited by ease of construction and physical transport. The capacities will range from 100 to 200 gallons/day thereby, requiring 10 to 5 sub modules to achieve the 1,000 gallon/day capacity.

## 4.1 Summary of TASK 1.0 (Build a Pilot Plant Boiler)

Initially, a combustible fuel boiler was planned. A propane hot water heater (GE Energy Miser 34,500 BTU/hr propane fuel) was purchased along with some external piping. The development to a boiler was postponed in January 2000, as all attention was place on TASK 8.0: the pre-pilot plant sub-module. A review of the proposed pilot plant locations reveled that there were electrical supplies available but liquid fuels were remote. This concern and others supported the development of an electric boiler.

The experimental plan for the 1,000 GPD pilot plant was to initially test sea and brackish waters at ASU, then move the unit to a designated Salt River Project (SRP) well site for demonstration. When the unit was to return to ASU, the unit was to be installed in the Chemical Engineering Unit Operations Laboratory. If that were the decision, then the boiler had to be electric and not gas fired. As a result, an electric boiler capable of at least 35 lb/hr of steam (10 kW) would be built and used at the SRP well site and at ASU Unit Operations Laboratory. The SRP well site and the evaporation pond at their Coronado Generation Station could reasonably facilitate 110 voltage 10kW electricity. A 55-gallon-metal-drum was modified with water heater electric heating rods for up to 35 lbs/hr atmospheric steam generation.

## 4.2 Summary of TASK 2.0(Build and Operate a Desiccant Contact Heat Exchanger)

The philosophy for using a liquid desiccant to enhance the energy reuse factor is based on the ability of strong salt solutions to absorb moisture from air thus drying the air and releasing the heat of vaporization. This heat can be released at higher temperatures than the original temperature of the air that was contacted by the desiccant and that heat can be reused to do an equal amount of water evaporation into another air stream.

Figure 3 shows that a slip stream of hot humid air at the top of the tower is contacted by a strong liquid desiccant stream (stream 2) in the desiccant contact heat exchanger (5). The remaining hot humid air is further humidified in (5) by evaporation of feed water to vapor by the energy furnished by the desiccant air drying. The now hotter humid air stream returns to the dewformation chamber while the dried air goes to the bottom of the evaporation chamber. The desiccant stream now diluted by the water vapor picked up in (5) returns to the boiler for regeneration. The steam released in the boiled from the boiling desiccant liquid is sent to the top of the dew formation chamber to further increase the temperature and humidity of the returning hot humid air. In this manner the boiling energy is essentially halved.

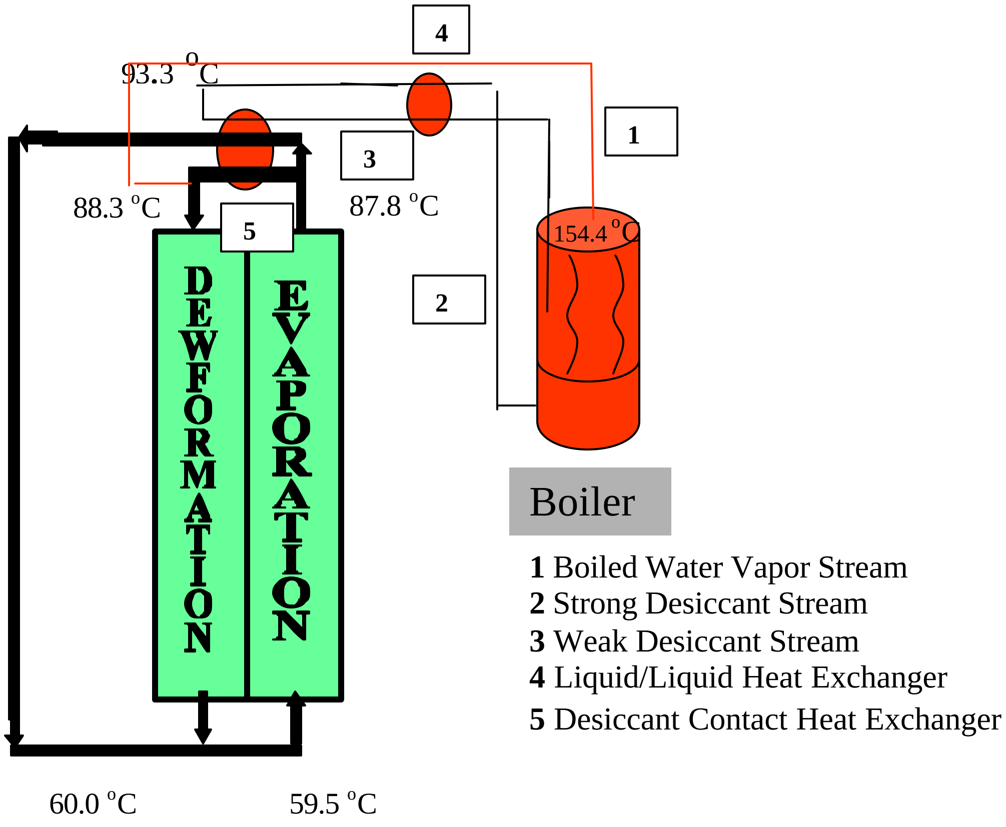


Figure 3.—Desiccant Heat Pumping with Boiler Regeneration.

The energy needs was reduced to half by this technique. If dry air were available, then the desiccant could be regenerated by

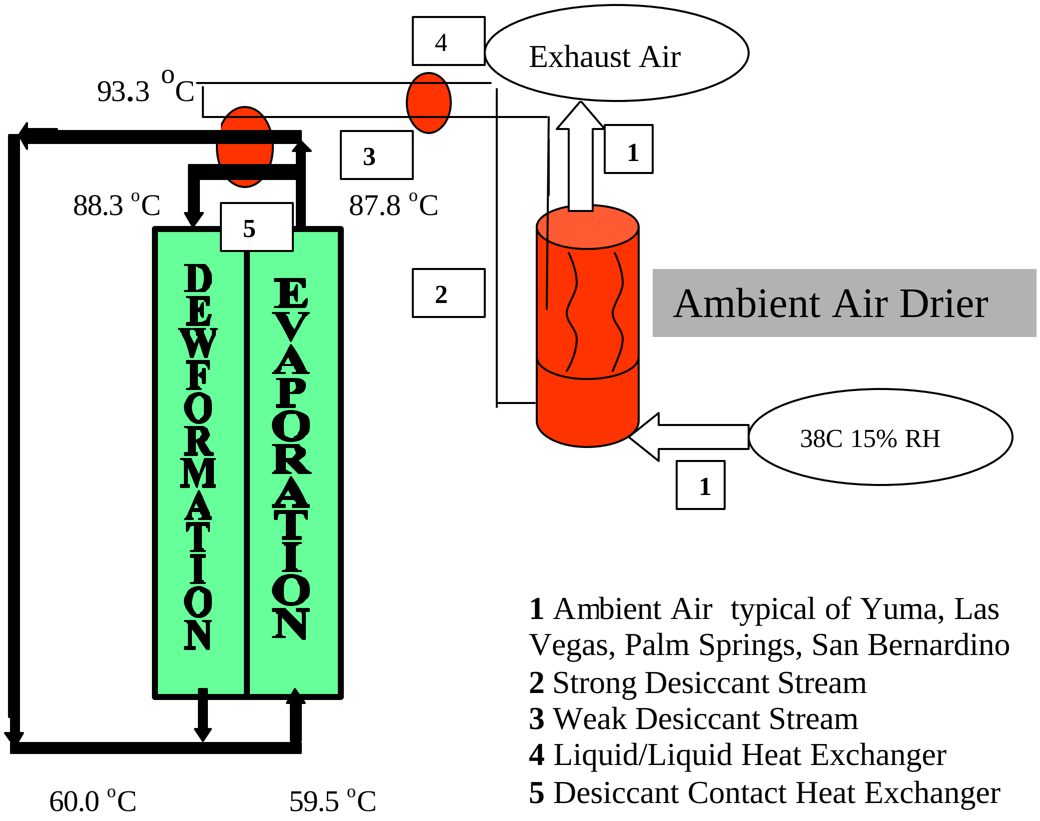


Figure 4.—Desiccant Heat Pumping with Ambient Air Drying.

In this technique of drying liquid desiccants to the original salt concentrations, dry air becomes more humid as the solution looses water. No energy is required other than a fan motor aided by natural wind.

Areas of the world where sea water exists with near by desert dry conditions are noted but not limited to the cities listed in Table 1 (www.bestplaces.net/html/climateus2).

The dry cities were cited as the most advantaged natural areas that could be advantaged for drying of desiccant liquids. However, more humid environment conditions do not preclude the advantaged use of ambient air regeneration techniques. Figure 5 shows how the fraction of water produced that would be given to the environment is a gradual loss as a function of environmental relative humidity.

The desiccant regeneration technique also works in environments more humid than desert regions. Figure 5 shows the effect of humidity on the water loss per 1,000 gallons/day (350 lbs/hr). The drier the environment, the less water is evaporated in the regenerator. The effect is linear so humid areas can utilized this ambient air desiccant drying technique but not as effectively as a desert region. Figure 6 shows the effect of ambient air relative humidity on the amount of condensate production per desiccant water evaporation to the atmosphere. This ratio would be the energy reuse factor except that no steam was inputted to the tower system. The ratio gives a sense of the operational characteristic f factor where bigger is better.

If the environment air is very humid, the ambient air regeneration technique can work if a solar collector is used to heat water, that can be stored, to heat humid air to a temperature to make that air about 20 percent relative humidity. For example, Houston, New Orleans or Miami, with air at 80 ºF and 80 percent relative humidity could be heated to 140 ºF with 150 ºF water to a condition of 20 percent relative humidity. Even cooler but humid regions such as San Francisco, California could use the desiccant ambient air regeneration by solar heating air to 125 ºF with 135 ºF hot water. These low water temperatures could be achieved in inexpensive single glazed flat plate solar collectors. A process to do that solar heating is shown in Figure 7.

Table 1.—Dry Cities in the World that are Capable of Economical Desiccant Regeneration

| **CITY** | **Relative Humidity** | |
|---|---|---|
| | **Jan** | **June** |
| **USA Yuma, AZ** | 26 | 15 |
| **USA Phoenix, AZ** | 34 | 12 |
| **USA Tucson, AZ** | 31 | 13 |
| **USA Las Vegas, NV** | 32 | 10 |
| **USA Barstow, CA** | 34 | 14 |
| **USA Palm Springs, CA** | 20 | 15 |
| **USA Ridgecrest, CA** | 34 | 14 |
| **USA San Bernardino, CA** | 36 | 15 |
| EGYPT Aswan | 29 | 11 |
| EGYPT Dakhla | 36 | 18 |
| EGYPT Kharga | 39 | 18 |
| EGYPT Luxor | 45 | 17 |
| ISRAEL Odva | 43 | 19 |
| ISRAEL Elat | 36 | 15 |
| SAUDI ARABIA Bishah | 29 | 9 |
| SAUDI ARABIA Medina | 28 | 7 |
| SAUDI ARABIA Riyadh | 32 | 8 |
| SAUDI ARABIA Tabuk | 32 | 12 |
| | **Mar** | **Sept** |
| AUSTRALIA Mount Isa | 32 | 19 |
| AUSTRALIA Tennant Creek | 34 | 16 |

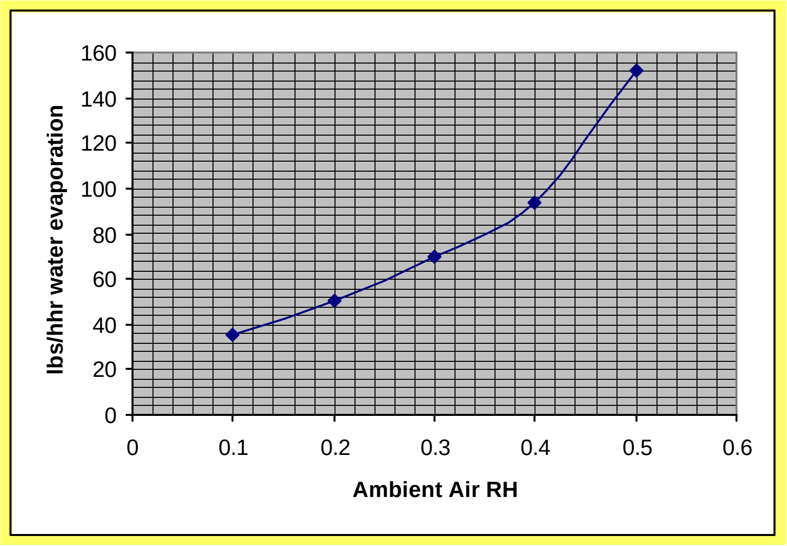


Figure 5.—Desalinated Water given to the Environment As a Function of Air Relative Humidity for a 1,000 Gallon/Day Plant (350 lbs/hr distillate).

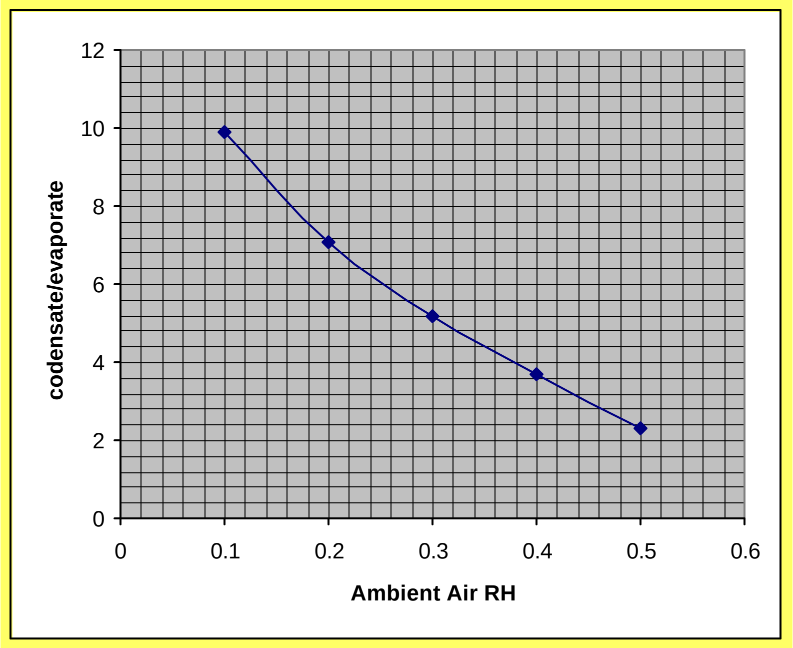


Figure 6.—Effective Energy Reuse factor for Ambient Air Drying of Desiccants.

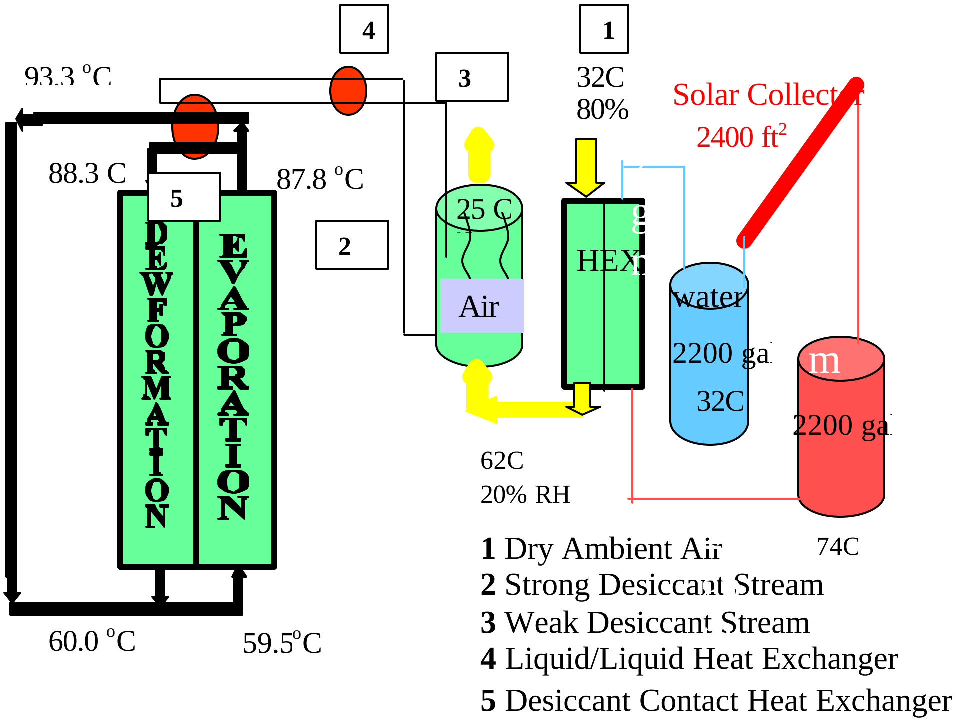


Figure 7.—Solar application to Ambient Regeneration of Liquid Desiccant.

The laboratory design and construction of the desiccant contact heat exchanger was completed in April 2000. Figure 8 shows the schematic of the desiccant contact heat exchanger with laboratory data results. The Laboratory unit is shown in Figure 9. The heat exchanger was 3 inches wide and 4 feet high. The desiccant was 55 wt% lithium bromide furnished by FMC Corporation. Steam saturated air was produced by boiling water at rates up to 3 lb/hr (at 180 °F air) in a 1 kW steam generator. Air was supplied from the wall source and split into two streams each of the streams was equipped with a rotameter to monitor air flow rates. Thermocouples were used to detect all wet and dry bulb air temperatures and liquid temperatures.

The exchanger was made up of four ¼ inch twin wall extruded polycarbonate sheets to withstand the projected temperatures of 280 °F (possible adiabatic operation). The sheets were sandwiched together using silicone sealant. In the very center of the sandwich was a REXAM polyester film acting as the heat transfer wall. Runs were made with varying air flow rate ratios and different desiccant flow rates. Figure 8 shows data of a balanced run.

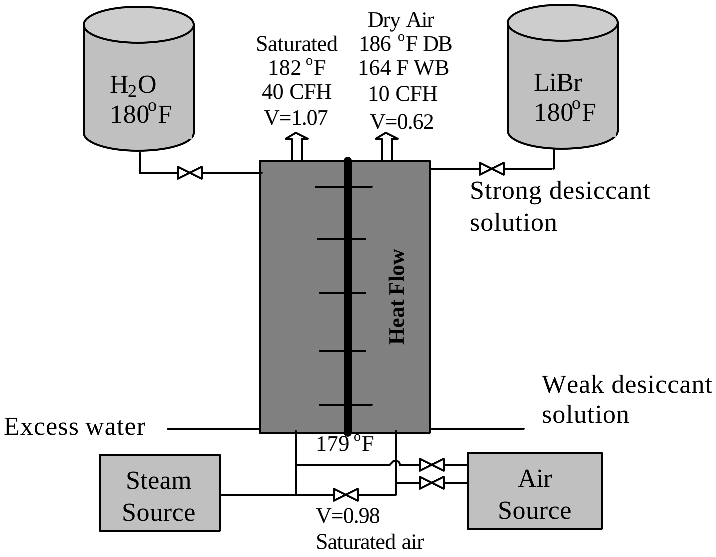


Figure 8.—Schematic of Laboratory Desiccant Contact Heat Exchanger.

This laboratory demonstration of Figure 9 was meant to establish a proof-of-concept that the desiccant heat pumping technique had merit. The 1,000 gallon/day process size contactor would transfer about 20 lbs/hr if a boiling regenerator were used with steam returned to the main tower. For dry air regeneration about 60 lbs/hr of water would be transferred by using 150 lbs/hr of 55 wt% lithium bromide solution.

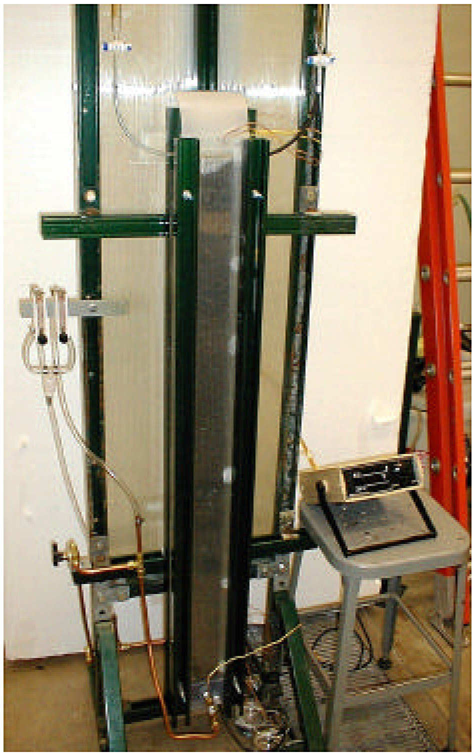


Figure 9.—Picture of Desiccant Heat Exchanger Laboratory Device.

## 4.3 Summary of TASK3.0 (Test Liquid/liquid Desiccant Heat Exchanger DELETED

The desiccant liquid/liquid heat exchanger transfers heat between two desiccant streams to preserve energy efficiency. The hot desiccant liquid from the desiccant boiler, which has a temperature of 310 ºF, cools to about 200 ºF before it enters the desiccant contactor. The heat loss is absorbed into the weak liquid desiccant leaving the desiccant contactor at 200 ºF and increases its temperature to about 260 ºF before it enters the 310 ºF desiccant boiler.

This piece of equipment was not needed for the desiccant heat pump technique proof of concept so it was deleted as being an unessential TASK for that purpose.

## 4.4 Summary of TASK 4.0 (Desiccant Process Mathematical Model)

The desiccant process modeling began with the Pressure-Concentration-Temperature (PxT) diagram of ASHRAE,1997. This diagram is the equilibrium relationship of vapor pressure, salt concentration and temperature of aqueous lithium bromide solutions. A spread sheet analysis was developed that established the process flow streams and energy needs of the desiccant system. Figure 10 shows an example output of the tower/ desiccant arrangement.

The model of Appendix A is set up with the basis of 1.0 lbmoles/hr of air passing through the Evaporation Chamber if the main desalination tower. The program user specifies:

- Tower Top Evaporation Temperature
- Tower Top Dew Formation Temperature
- Tower Bottom Dew Formation Temperature
- Ambient Air Dry Bulb Temperature
- Ambient Air relative humidity

Given these inputs, the model calculates:

- All process flow streams
- All resultant Temperatures
- All needed Heat Transfer Areas of contacting towers
- Effective Energy Reuse Factor
- Water vapor absorbed by the desiccant stream
- Condensate Production Rate
- Displays Results on a 1,000 gallon/day basis

This model was used to establish Figure 5 (Water evaporated from the liquid desiccant by ambient air vs ambient air relative humidity) and Figure 6 (effective energy reuse factor vs ambient air relative humidity.

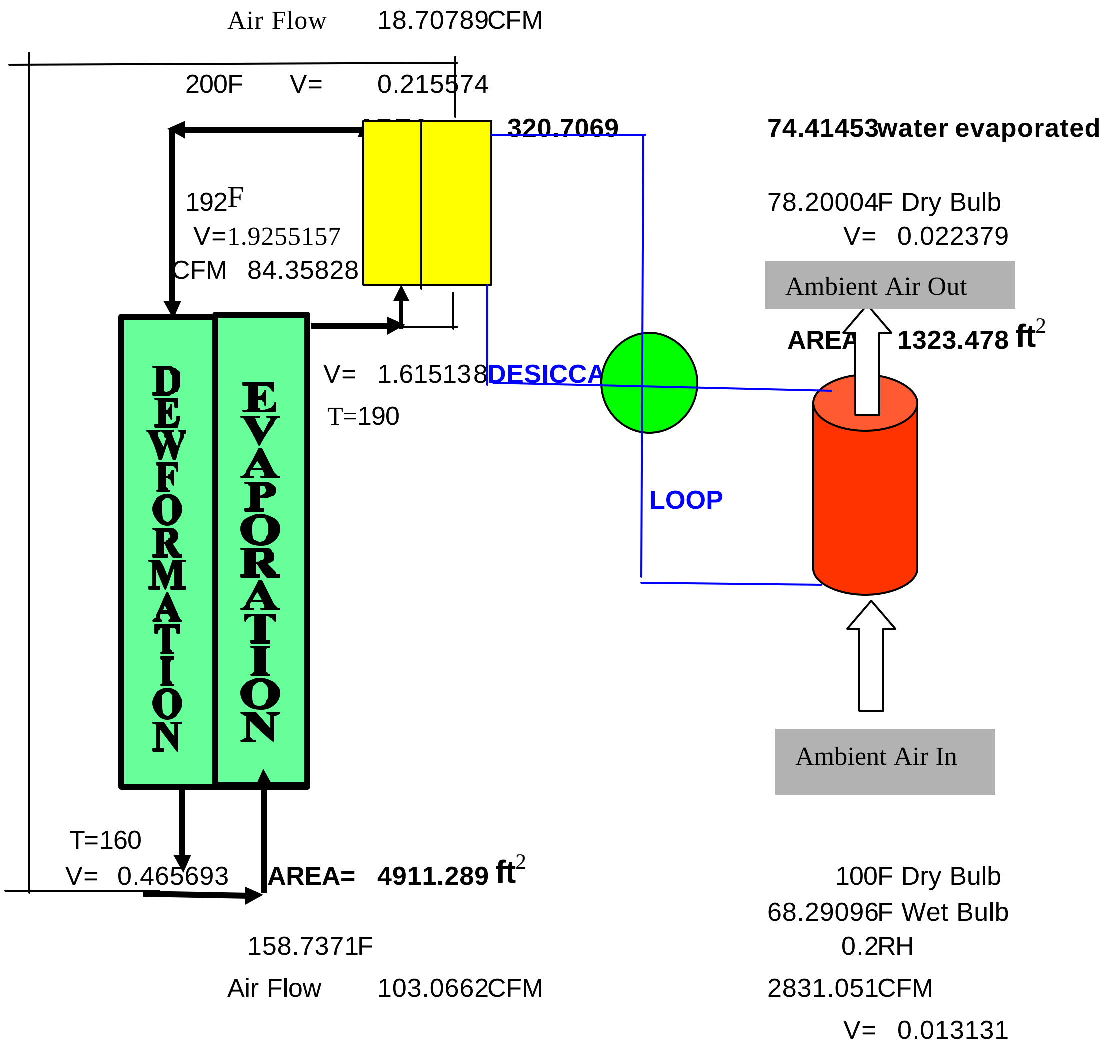


Figure 10.—Example Output of Modeling the Desiccant Heat Pumping Technique with Dry Ambient Air Regeneration.

The model was used to establish Figures 5 and 6.

## 4.5 Summary of TASK 5.0 (Build and Operate 1,000 GPD Pilot Plant Towers)

The 1,000 gallon/day pilot plant is an assemblage of 8 sub-modules that each produce 125 gallons/day of condensate. The final base tower is detailed in TASK 8 which is the development of a sub-modular dewvaporation towers The final design produces 125 gallons/day with an energy reuse factor in excess of 9 with a cost of LESS THAN $2000 and a water cost of less than $4/1,000 gallons for a 1,000 gallon/day desalination unit. Details of the economics are discussed in Section 5 of this report.

Since the 1,000 gallon/day unit is comprised of 8 sub-modules, the operational details of the entire pilot plant is reflected by the operational characteristics of a sub-module. The performance of the final module is detailed in TASK 4.8 (Build a Sub-module Pre-Pilot Plant Unit).

## 4.6 Summary of TASK 6.0 (Final Report)

The final report was prepared at a time when no new significant information could modify any of the major conclusions of this development investigation. The applications have become so very broad and the sub-modules have reached such an energy efficient stage and low unit cost of development that the time has come to inform the Bureau of Reclamation of the achievement level attained in the Dewvaporation desalination and reclamation technique.

## 4.7 Summary of TASK 7.0 (Technology Transfer)

Technology transfer was viewed as any event or action that would ease the market entry of the Dewvaporation technology for supply of desalination units to the satisfaction of public and private clean water needs. Events and actions included: peer publications, presentations to professional meetings, hosting industrial visitations, and maintaining low cost and non-complex designs.

Alternative fuels were also investigated as a technology transfer broadening impact. **Waste oil** combustion was identified and explored as an alternative inexpensive fuel source. Clean Burn Inc. of Lancaster, PA has developed a self cleaning burner for waste oil combustion. The Clean Burn hot water heater (200 ºF) costs $9000. This price is one at a time retail. The capacity would service a 10,000 GPD Dewvaporation desalination plant costing $10,000 without the boiler. Therefore, a 10,000 GPD combined unit would cost $19,000. The operating cost would be $1.40/1,000 gallons if the waste oil were free. In Arizona, the value of waste oil is $25/barrel to the receiver. This would actually produce water at no cost and a profit of $3.50/1,000 gallons. In addition, **Bunker oil** sells at $0.25/therm (www.bunkerworld.com) which would reduce the operating cost by $0.13/therm or $1.10/1,000 gallons as compared to natural gas usage.

**Solar heat** was also considered in the assistance of the desiccant dry air application in humid environments. Hot water is produced in a solar collector and stored for use. This stored hot water is used to heat ambient humid air to a temperature where the relativity has reduced to about 20 percent. The warm dry air is then used to dry liquid desiccant. In this manner, the solar collectors do not have to boil water but only heat it. In Miami, Florida 150 ºF water would be required and in San Francisco, California 125 ºF is needed. Collectors would be inexpensive flat plate single glaze design.

## 4.8 Summary of TASK 8.0 (Build a Sub-Module Pre-Pilot Plant Unit)

In this investigation of an economical and functional tower that would be inexpensive and easy to build, there were many designs, constructions and tests that culminated in one selected candidate: 900 ft$^2$ 125 gallons/day NEWT tower. Eight sub-modules will comprise the 1,000 gallon/day pilot plant.

### 4.8.1 Base Tower Design

The base tower design followed from the initial investigation of the Dewvaporation desalination process. The Tower was composed of framed REXAM heat transfer walls separated by internal and external horizontal sponge spacers. Figure 11 is a picture of the wall assembly.

Frame

REXAM covered Frame with spacers

Figure 11.—Frame Construction Involved in Base Design from Previous Work.

This design was successful in the phase I investigation (Beckman 1999). The REXAM polyester heat transfer wall was thin and stiff at 3 mills thickness and was water wetable. However, the wetable coating could scratch off and the sheet cost \$0.50/square foot. If the price were wholesale large volume at \$0.25/ square foot for a 7,000 ft$^2$ 1,000 gallon/day desalination unit, then the heat transfer wall alone would cost \$1,750. This was high compared to later findings.

### 4.8.2 Frameless Tower Design using 2 mil Polypropylene Sheet

A thin 2 mil thick polypropylene film costing $0.008/ square foot with a nylon cheese cloth for water wetting costing $0.025/ square foot led to the frameless design. That construction would reduce the heat transfer wall cost to $230 for a 1,000 gallon/day unit. The “frame-less” tower design was proposed and developed in detail in November 1999. This concept was implemented in the construction of the pre-pilot unit. It was decided to limit the assembly to 600 **f**$^2$ (ten condensate envelopes each with wall area of 60 ft$^2$). The pre-pilot unit construction was stopped at 100 GPD size in order to accelerate the testing program. Photographs of the construction of the pre-pilot plant reflect the concept of “simple is better.” Figure 12 shows the start of the unit assembly.

Figure 12.—Construction Start of the Heat Exchange Envelopes for the Pre-Pilot Unit.

A 4 foot by 8 foot plywood table was constructed to support the unit construction. First a 4 foot by 8 foot outer wall was placed on the table. This was followed be the alternate folding of polypropylene heat transfer walls from the 8 foot wide roll and water wettable nylon cheese cloth from the 4 foot wide roll. These rolls are shown in Figure 1. During the alternate foldings, the ¼ inch foam spacers were inserted between the heat transfer walls as shown in Figure 13. The horizontal spacers were held in place by plastic tape.

Figure 13.—Horizontal Foam Spacer Assembly.

Figure 14 shows the construction completion of the heat transfer envelopes. The ten-envelope package measured 5 inches thick.

Figure 14.—Completion of the Heat Transfer Envelopes of the Pre-Pilot Unit.

Figure 15 is an end view of the complete package and shows the imbedded nylon cords which were attached to each envelope. These cords act as top support for the envelopes when the unit is placed in the vertical position for operation.

Figure 15.—Side View of Completed Envelopes Showing Support Cords.

The problem with operations was the flexibility ease of the polypropylene film as compared to the more costly but stiffer REXAM sheet. The film tended to choke off the returning dew forming channels. To try to prevent the closure if the returning air slots, internal spacer designs were tried.

The second pre-pilot tower was built and tested in February 2000. The unit looked just like Figure 13 but without the vertical foam spacers plugs. The edges of the polypropylene heat transfer walls were attached to the edges of the out side shell to prevent vertical gas by-pass. The unit still had collapsed heat transfer walls due to the soft 2 mil polypropylene film. Operating pressures of 1.1 inches of water were measured at the intake air at the bottom of the saltwater side of the heat exchanger and 1.1 inches of water were measured at the top of the saltwater side of the heat exchanger. Therefore, the pure water side had sealed off entirely by 1.1 inches of water pressure. The horizontal spacers were placed 2 inches apart, which blocked off at least 25 percent of the wall area. There were two sets of ¼ inch spacers: one set installed on the saltwater side and the other set on the clean distillate side of the heat transfer wall as depicted in Figure 16a.

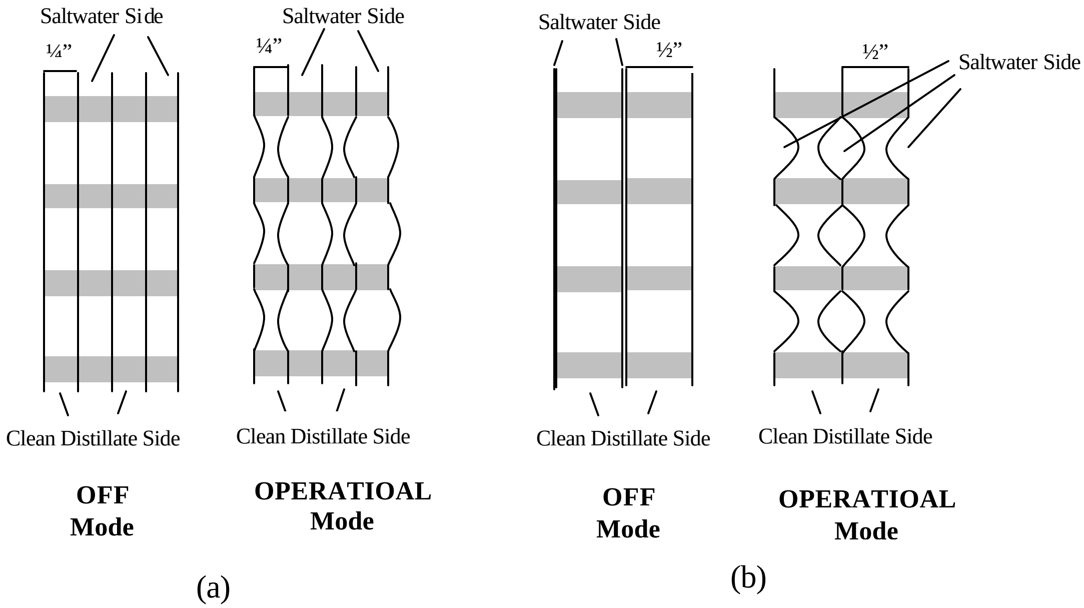


Figure 16.—Spacer Arrangement: (a) Second Unit (two sets of ¼ inch open cell foam) and (b) Third Unit (½ inch and 0 inch).

Closer spacing was deemed unreasonable as it would block off even more heat transfer wall thereby, rapidly increasing the construction complexity and cost of the unit.

The third pre-pilot tower used the same spacers as in unit two but both sets of spacers were installed on the clean distillate side. This arrangement, shown in Figure 16b, gave an average spacing of ¼ inches (½ inch dimension collapsing to zero inches). All of the spacers were taped directly to the inside walls of the pure condensate side of the heat transfer walls. This reduced the complexity of construction. There were no spacers located on the saltwater side. The third unit allowed air traffic through the tower but at a very reduced rate producing only 10 percent of the required distillate. At this point, the frameless design with horizontal spacers was abandoned.

### 4.8.3 Frameless Tower Design using Polypropylene Sheet with Reticulated Foam Fill

Materials for unit 4 were ready for assembly and operation in April 2000. This design featured continuous reticulated polyester foam sheet in the clean distillate side slot and was capable of remaining flat at essentially any air pressure drop through the tower. The foam increased the capital cost of the 1,000 GPD unit by about $600. Utilization of this concept was left until the exhaustion of the previously reported design attempts in order to avoid the cost increase. In addition, the pressure drop in the tower increased from 0.3 inches of water to 0.9 inches of water, which had a minor effect on capital and operation costs. The capital cost increased by $35 and the operating cost increased by $0.15/1,000 gallons. Reticulated foam is 95 percent void space and cut to 4 feet by 7 feet by ¼ inch. Figure 17 shows a sample of the reticulated foam that was used in unit 4. Reticulated foam is produced with various number of pores per inch (PPI).

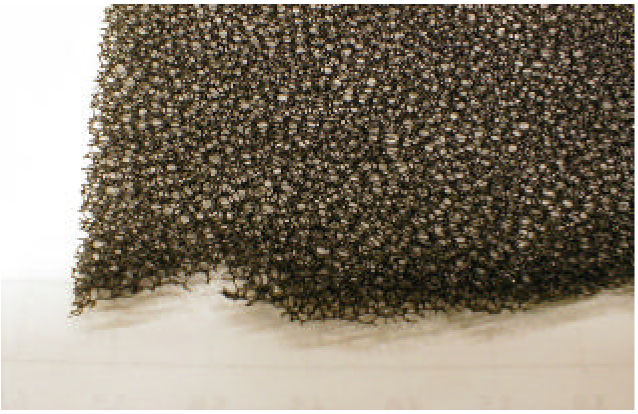


Figure 17.—Close-up of ¼ inch Thick Reticulated Foam Sheet.

A test unit was constructed, as shown in Figure 18, to test for pressure drop through the reticulated foam. Experiments were conducted at various velocities for 15, 20, and 30 PPI reticulated foams.

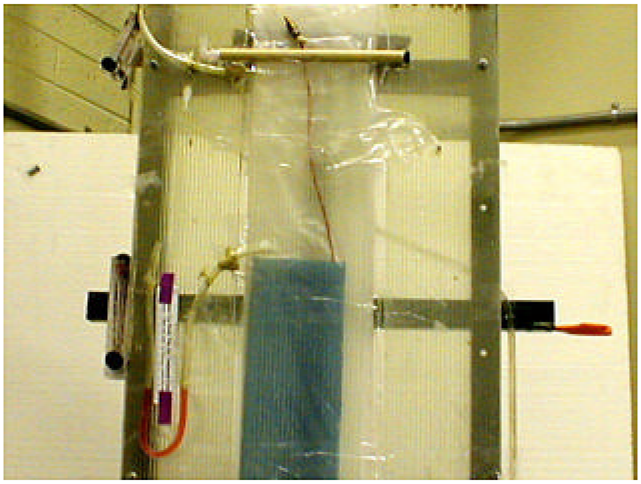


Figure 18.—Test Stand for Reticulated Foam Pressure Drop.

Initially, the foams were tested dry and then wet so as to best simulate the actual wet conditions in the tower during operation. Figures 19 and 20 show the pressure drop versus air velocity through the dry and wet reticulated sheet. Results show that they behave in a similar manner for the ¼ inch sheets tested. A 1/8 inch sheet was tested which increased the pressure drop by 33 percent over that of the ¼ inch sheets. The range of interest is in the zero to 2 ft/s velocity. At 1 ft/s average velocity and 6 horizontal passes, the pressure drop on the clean wet distillate side should be 0.7 inches of water. Data on the saltwater side shows 0.15 inches water giving a total pressure drop through the unit of less than 0.9 inches of water.

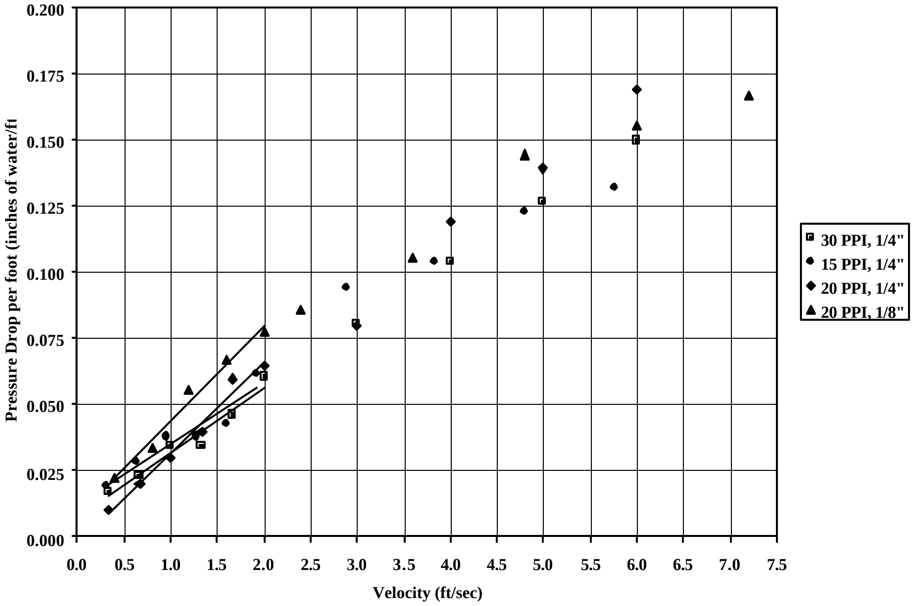


Figure 19.—Air Pressure Drop through Dry Reticulated Foam.

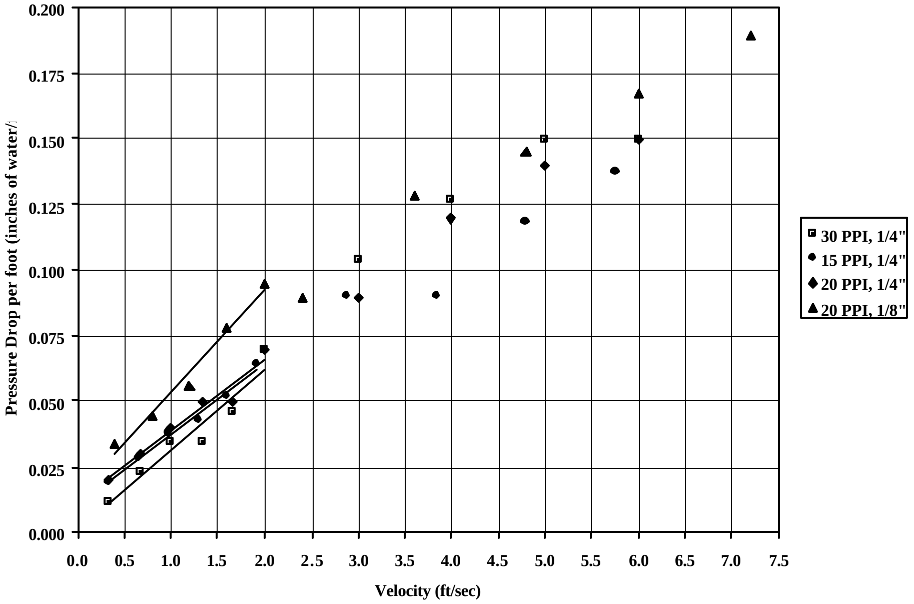


Figure 20.—Air Pressure Drop through Wet Reticulated Foam.

The reticulated foam was also tested for its resultant film heat transfer coefficient. The previous heat transfer coefficient test stand developed from Beckman,1999 was used. Results at a Reynolds number of 800 showed the film heat transfer coefficient for ¼ inch reticulated foam was 0.8 BTU/ft$^2$hr$^{o}$F. This is in the range of the coefficients found in by Beckman 1999 so there was no reduction of the heat transfer coefficient due to the foam. Figure 21 shows the reticulated foam placement in the polypropylene sheets.

The problem with the foam was that wherever the heat transfer was active, condensation would naturally form in the foam. When the condensate formed and wetted the foam, air on the dew side moved away from the wet zones to find lower pressure drop dry zones that were inactive for heat transfer. The reticulated foam investigations were abandoned in summer 2000.

Figure 21.—Polypropylene Bags with Reticulate Foam.

#### 4.8.4 Twin-Wall Extrusion Polypropylene Towers

Twin-wall extruded polypropylene heat transfer walls were applied to a new family of towers. The flow philosophy for these towers abandoned the total counter current serpentine flow patter to adopt the shell and tube heat exchanger philosophy of cross flow. In this manner airs on opposite sides of the heat transfer wall were forced to align thusly, making the area more effective. The choice of which side took on the cross (zigzag) flow pattern differentiated the two tower designs.

#### 4.8.4.1 WEST Tower with Twin-wall Extruded Polypropylene

The WEST Towers were first designed with a zigzag air flow pattern on the evaporation side of the heat transfer walls. The zigzag was located there since it was the most convenient side to construct the zigzag and desalination service envisioned no salt precipitation concerns. The plastic of choice was found to be twin-wall extruded polypropylene sheet. The acronym WEST refers to the air flow: first West and East in the upward travel on the evaporative side and then South on the dew formation side of the Tower.

The plastic heat transfer wall that best offered low cost economics, dimensional stability, free flow zones , manufacturability and availability was twin-wall extrusions found in Spring 2001. The twin-wall extruded plastics are available in many sizes (thickness) ranging from 2mm to 10mm. Coroplast Inc (1-800-666-2241) twin-wall 4mm polypropylene extruded sheet was purchased at $5.25 per 4 feet by 8 feet sheet from local suppliers. This price is for small quantity from a distributor. Projected price for bulk quantity direct from manufacturer is less than $2.50/sheet. Since both sides of the sheet can be used for heat transfer, the price for the heat transfer wall is $0.039/ft$^2$ Figure 22 shows an edge-on view of the twin-wall extruded plastic sheet.

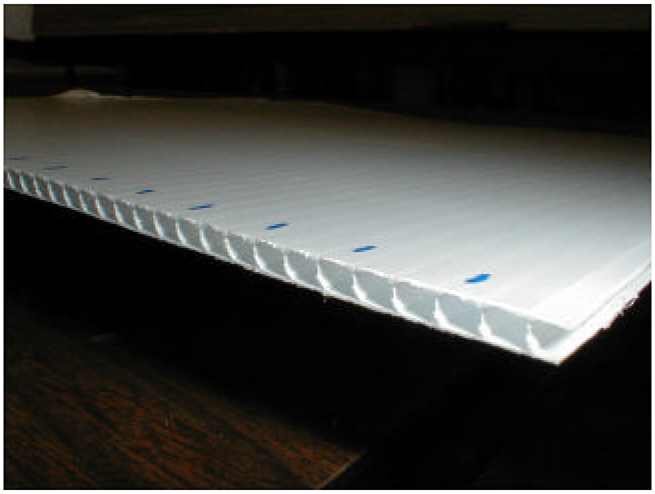


Figure 22.—Edge View of 4mm Twin-wall extruded polypropylene heat transfer wall sheet.

The first test units constructed with twin-wall heat exchanger sheets were built with 70 $ft^2$ of heat transfer wall to test various design features. These units produced about 3 lbs/hr of condensate. From those test units, three pre-pilot plant towers were constructed. Two have been operated and the third was abandened. Each of the WEST towers( 1 foot by 2 feet by 8 feet) contained 840 $ft^2$ of heat transfer wall projected to produce 36 lbs/hr condensate. The towers produce only 20 to 26 lbs/hr each.

Figure 23 shows details of the wall construction. The tower was piloted by towers made of 1 foot by 7 feet sheets so the design of the 840 $ft^2$ tower maintained these dimensions and essentially placed twelve piloted modules together in a 'twin" pattern. The evaporative side horizontal spacers were added to direct the upward moving air pattern in a zigzag manner. Figure 22 shows one layer of heat transfer wall. All together, there are 36 layers placed on top of each other. Of the 36 layers, 6 of them are feed liquid heat exchangers.

Figure 24 shows the 36 sheet composite stack of the 840 $ft^2$ tower. The small angled white pieces of twin-wall plastic sheet in the fore ground are the top feed liquid distributors that pour liquid evenly onto the top yellow sponges. The sponges help distribute the feed liquid more evenly onto the top of the entire structure. The installed steam lines are also shown that distribute steam to all twelve piloted sub units. Lexan twin-wall extruded clear polycarbonate forms the shell cover. The tower is complete when the top plate is installed and sealed.

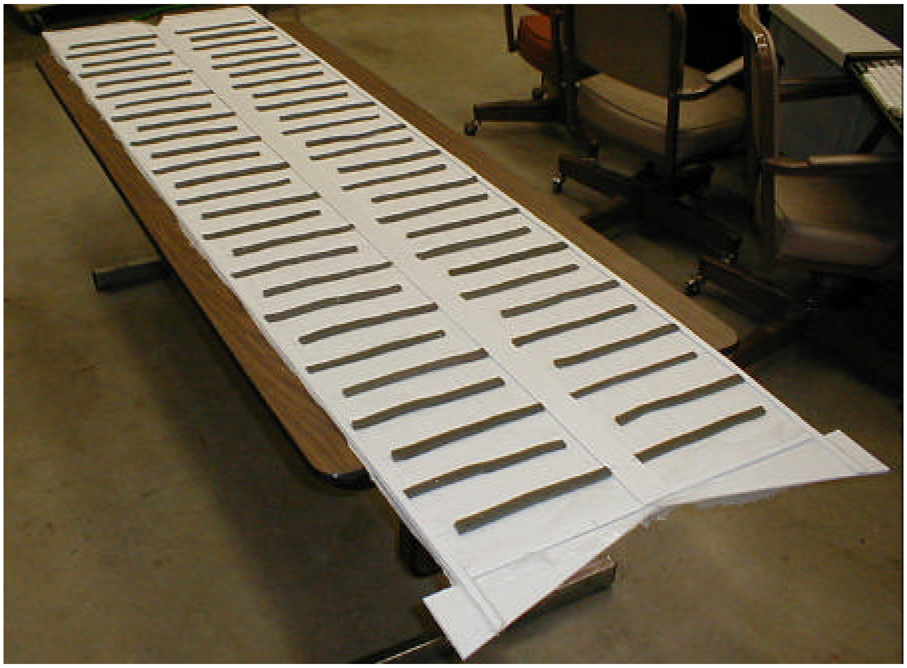


Figure 23.—Twin Construction of One Layer of the 840 $ft^2$ WEST Tower Showing the Spacer Zigzag Pattern on the Evaporation Chamber.

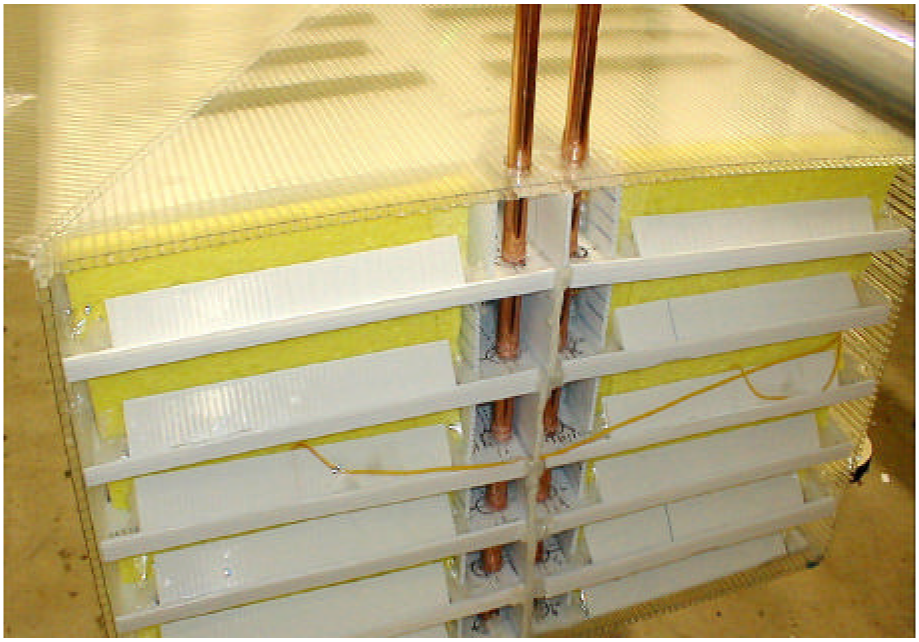


Figure 24.—Steam Line Placement in the Top Section of the 840 $ft^2$ Tower.

Figure 25 displays the 840 $ft^2$ tower in the testing rack. Styrofoam insulation, 3 inches thick, was wrapped around the tower and sealed to prevent any possible heat loss from thermal chimney effects.

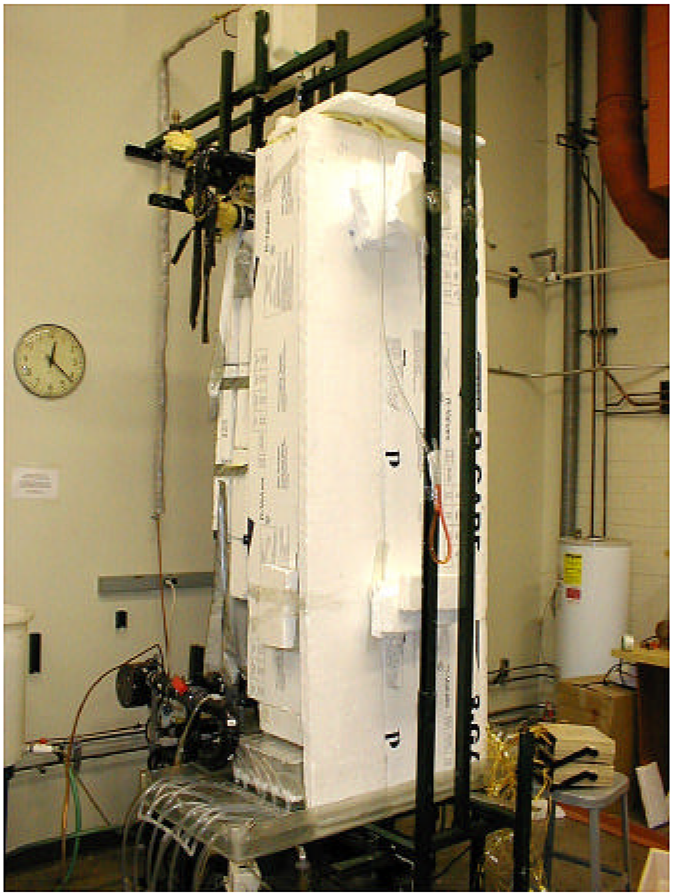


Figure 25.—WEST Tower Installed.

The main problem with performance from the WEST tower design was the streamline flow patterns of the air at the zigzag turn arounds.

All of the tower operations implied that airflow distribution has been the major problem in successful tower scale-up from bench to pilot plant size. To obtain a qualitative estimate of the airflow pattern and methods of its correction, water was used as flow in a shallow pan-type of apparatus to simulate the airflow in a tower. The same Reynolds Number (about 500) was used to link the experimental results. To observe the streamline flow patterns, food coloring (dye) was introduced at interesting points in the water flow field and its flow patters were observed. The same tower dimensions were used in the water flow experiments as existed in the towers. Since airflow in the actual towers was on the order of 2 ft/sec, water was flowed at about 6 ft/min to give the same Reynolds Number of about 500.

The serpentine or zigzag pattern was investigated, as it seemed to be the pattern of choice. Figures 26a and 26b show a time sequence of streamline flows that simulate the air mal-distribution problem.

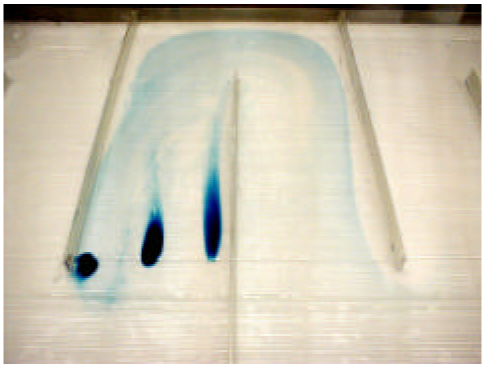


Figure 26a.—Flow Pattern at 30 Seconds

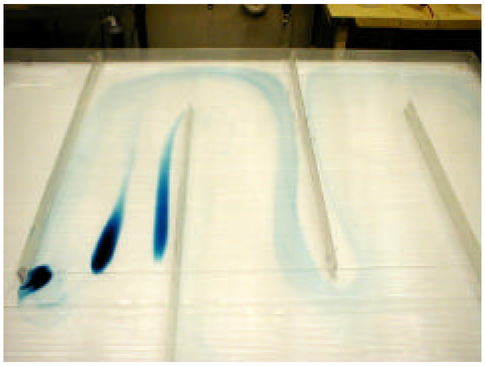


Figure 26b.—Flow Pattern at 2 Minutes

Figure 26 shows the start of the flow pattern after three blue drops of dye were injected into the water. The dye points were flowing in the northwest direction of this portion of the zigzag pattern. The fluid velocity (now viewed flowing in the northeast direction) is highest in the vicinity of the up stream partition wall. The fluid has passed the turn-around zone of a zigzag and is flowing in the vicinity of the new up stream partition wall. This pattern has totally missed about 3/4 of the available flow area for one zigzag pass. This could explain the low effective area calculated at about 20 percent to 25 percent.

#### 4.8.4.2 NEWT Tower with Twin-wall Extruded Polypropylene

In another attempt to improve the heat transfer wall efficiency, a design was proposed that possessed the features of no horizontal spacers on the evaporative side and allowed generated solids on the evaporation side to wash out of the unit. This design was designated as a N.E.W.T tower (air flows North first then zigzags from East to West composing the Tower). The research of this design was supported by the Salt River Project located in Phoenix, Arizona. As has been evidenced by past results, solids formation in the tower evaporative chambers do not adhere to the heat transfer walls. SRP has evaporation ponds that have salt concentrations approaching ocean conditions. The waters in these ponds are not reclaimed but evaporate instead for Zero Discharge compliance. A standard WEST tower had horizontal spacers on the evaporative side which directed air to zigzag up the evaporative passage. The NEWT tower directs air to flow straight up the evaporative side so that when solids form, their fall out of the tower will not be hindered by horizontal spacers. The necessary zigzag flow pattern was designed into the dew formation side of the tower. The dew formation liquids are pure distillate so no flow problems were anticipated. A 350 $ft^2$ NEWT Tower was built by repeating a single sheet design as shown in Figure 27.

Figure 27.—Basic Heat Transfer Wall of a NEWT Tower Design.

The dimensions of the sheet are about 1 foot wide and 4 ¼ feet high. Two of these sheets are connected together to form a double helical pattern for the dewformation sideways from of air and condensate.

The key to operation with a zigzag air flow pattern down the dew formation chamber (inside the twin wall extrusion sheet) was to pitch the flow lines downward by at least a 7 degree angle so that condensate produced could flow down and exit the chamber at the bottom. With an angle less than 7degree pitch, water did not flow due to surface tension effects. To keep the pitch always directed downward, the sheets were paired and connected together along their vertical edges. This double helix pattern worked very well in allowing condensate to always flow down hill and exit at the tower bottom. The first tower contained 350 $ft^2$ of gross heat transfer wall and measured 12 inch by 16 inch by 5 foot high as shown in Figure 28. Water production was from 9 lbs/hr (26 gallons/day) to 24 lbs/hr (70 gallons/day) by varying the steam rate. Energy reuse factor varied from 22 to 10 respectively.

Figure 28.—Internal Heat Transfer Wall Stacking for a 350 $ft^2$ NEWT Tower.

Data from the two runs that were made with the 350 $ft^2$ NEWT tower are listed in Table 2:

Table 2.—NEWT Tower Runs on December 21, 2001

| Run | Max Temperature, F | Condensate, lbs/hr | Energy Factor, f |
|---|---|---|---|
| 12211 | 206 | 24 | 10 |
| 12212 | 192 | 9 | 21 |

Based on the 350 $ft^2$ gross (1 foot wide) NEWT tower, a 700 $ft^2$ NEWT tower (two feet wide) was designed and built. This tower produced a maximum 40 to 50 lbs/hr condensate with energy reuse factors of 9 to 14 and represent the final design such that all future construction will be redundant to this 700 $ft^2$ NEWT tower. The tower measures 1 ½ feet by 2 feet by 5 feet high as shown in Figure 29.

Figure 29.—700 $ft^2$ NEWT tower Final Sub-Module Produces 125 GPD at f=10
(Note: Eight of these Sub-Modules Comprises 1,000 GPD Demonstration Pilot Plant)

Operation of the 125 gallon/day (43 lbs/hr) 700 $ft^2$ NEWT tower occurred in July 2002. The run analysis is shown in Table 3.

TABLE 3.—NEWT 700 $ft^2$ Run Data and Analysis July 2002

| Run Number | Air Rate,CFM | $V_H$ | $T_{HOT}$, F | C, lbs/hr | f | $F_{max}$ | TDS |
|---|---|---|---|---|---|---|---|
| 7123 | 4.4 | 3.46 | 200 | 42.7 | 8.1 | 12.7 | 30 |
| 7124 | 3.6 | 4.1 | 201 | 41.8 | 9.1 | 12.2 | 30 |
| 7125 | 5.4 | 3.2 | 199 | 49.1 | 6.4 | 8.7 | 30 |
| 7162 | 3.6 | 4.38 | 202 | 42.5 | 6.8 | 14.5 | 60 |
| 7164 | 6.2 | 2.37 | 193 | 35 | 11.8 | 15 | 65 |
| 7166 | 4.8 | 2.37 | 195 | 31 | 12.1 | 16.6 | 70 |
| 7168 | 3.1 | 3.59 | 200 | 30.6 | 11 | 16.6 | 68 |
| 7183 | 4.6 | 2.91 | 198 | 38 | 8.7 | 10.4 | 72 |
| 7185 | 4.8 | 4.08 | 201 | 51.9 | 7.9 | 9.8 | 71 |

The data suggests that production rates f distillate varies from 30 lbs/hr to over 50 lbs/hr with energy reuse factors from 7 to 12. The fmax was calculated by extending the data to change the recovery to 50 percent and adjusting the feed temperature to be 10 °F cooler than the effluent distillate and brine liquids. This would emulate a feed/effluent heat exchanger that will be in place for pilot plant operation.

The selected standard operating conditions for future performance to produce 43 lbs/hr (125 gallons/day) will be 3.6 CFM air rate with 202 °F top temperature. This should give a pressure drop of 70 mm water, and energy reuse factor of 14. An f = 14 is achievable with controlled feed rate to give a 50 percent to 70 percent water recovery along with a feed/effluent external heat exchanger.

Analysis of variable effects reveled the obvious relationship between pressure drop rise with increase in distillate rate as shown in Figure 30. The effective heat transfer area, as calculated from Equation 18, was found to correlate with tower top temperature (expressed as Vmax). The effective heat transfer area increased with increase in Vmax as shown in Figure 31. Effective area was found not to correlate with distillate rate, water feed rate, brine rate, nor pressure drop.

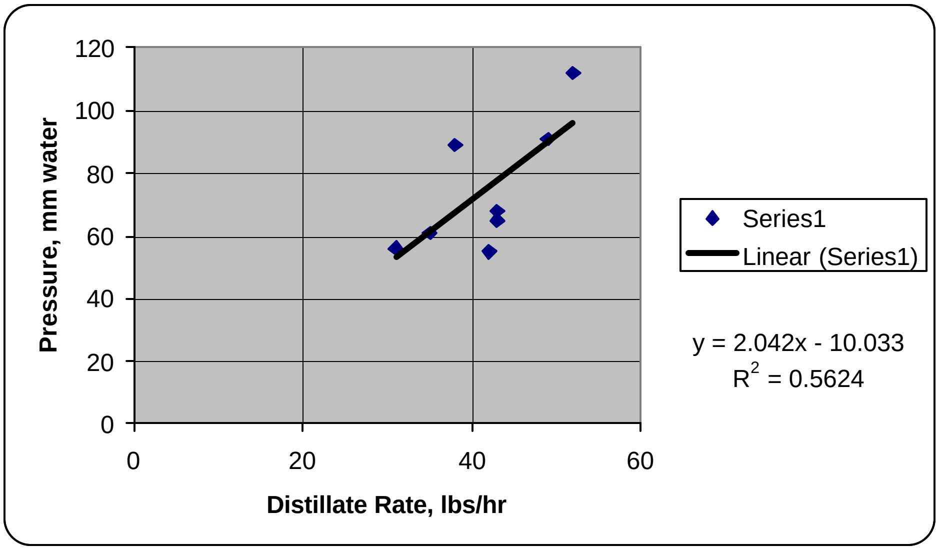


Figure 30.—NEWT Tower Pressure Drop vs Distillate Rate.

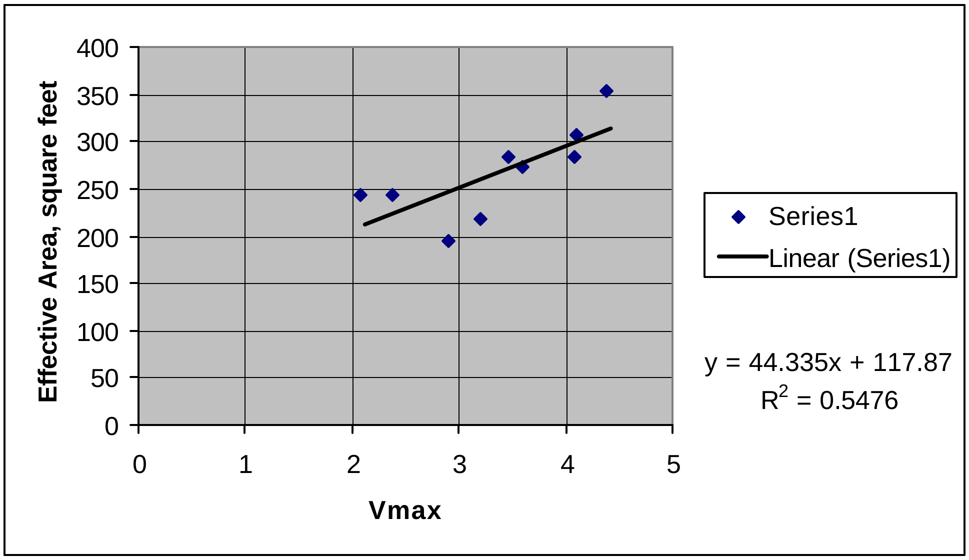


Figure 31.—Effective Area Calculated from Equation 18.

From Figure 31 operations at 202F relates to an Vmax of 4.4 and an effective heat transfer wall area of 315 $ft^2$. The effective production density would then be 0.136 lbs/$ft^2$ hr. This value along with a factor of 9 to 14 is superior to all other previous tower designs.

### 4.8.5 Extended Applications

Applications of the Dewvaporation technique was broadened from seawater and brackish water reclamation to include reclamation of evaporation pond water, removal of trace volatile organics from contaminated water, and reclamation of Chemical Mechanical Planarization slurries from the semiconductor industry.

#### 4.8.5.1 Evaporation Pond Water Reclamation

Reclamation of salty water was accomplished by processing a 5 gallon sample of SRP Coronado Generating Station evaporation pond water located in St. Johns, Arizona. The solids formed and did not adhere to the plastic heat transfer walls but instead fell to the brine basin. The particles were extremely fine in the range of 50 microns and less.

Analyses of the CGS circulating cooling water and evaporation pond water is located in Appendix C. The pond water seems to have about twice the concentration of salts compared to the circulating cooling water that feeds the pond. Magnesium and pH are about four times higher probably due to the high solubility of which reduces its tendency to precipitate. This effect was also observed in the NGS Crystallizer System.

Operational data from the 350 $ft^2$ tower suggests an over all wall area efficiency of 75 percent after taking into account of all the noted efficiency reductions. The previous

WEST towers were 20-25 percent efficient after taking into account its efficiency reductions. A value of 75 percent suggests that there are diminishing returns in further attempts to increase the over all wall efficiency. The final 700 $ft^2$ NEWT tower produced a maximum of 60lbs/hr and will be used as a basic design of the future pilot plant construction and demonstration programs.

This data allows a projection of the water reclamation steam needs. The feed water to the evaporation pond is the cooling water circulation stream of 300gpm with a salt content of 1.2 percent (Appendix C). The desalination effort starts fairly easily by removing water from the solution and concentrating the salt to seawater conditions of 3.6 percent. At that point, 67 percent of the water has been removed. Continued reclamation removes another 28 percent of the water as the solution becomes saturated with its salts. Therefore, 95 percent of the total water is reclaimed to get the salt solution to saturation. The final crystallizer tower removes the final 5 percent of the water and leaves wet salt to be disposed of on CGS property. Essentially, the 300gpm (18,000 gallons/hr) of feed to condensate produced requires 18,000 lbs/hr of atmospheric steam or equivalent heat from some other 200F source. About 1,800 lbs/hr of solid salts would be produced for disposal.

Based on the data collected in this initial investigation of water reclamation from evaporation ponds at CGS, the following utility and equipment costs were projected for processing the 300 gpm of cooling water system blow down which feeds the current CGS evaporation pond.

At 300 gpm the daily water production would be 432,000 gal/day. A Dewvaporation facility would cost about $500,000. The process plant would serve as both concentrating evaporators and final crystallizer.

Figure 32 is the process flow diagram of 300 gpm blow down water feed to the evaporation pond. Basically, the blow down contains 1.2 percent dissolved salts as reported by CGS in Appendix C. The reclamation of 50 percent of the water concentrates the brine to 2.4 percent. Removal of a total 67 percent of the blow down concentrates the waters to 3.6 percent that is essentially equivalent to seawater salt content. Continued water removal to achieve salt saturation requires a total of 95 percent of the feed. In other words, 95 percent of the cooling water blow down occurs without precipitation of crystals. Therefore, a Dewvaporation tower that forms the solids removes the final 5 percent of the waters. As more of the waters are reclaimed, the energy reuse factor, f, would decrease from 11.1 to 5. These numbers are based on the reclamation of brackish waters by Dewvaporation towers having a f = 15 as typically experienced in the ASU laboratory. The total amount of steam needed by the process is 6,760 + 2,870 + 6,900 + 1,340 = 17,870 lbs/hr. The total amount of condensate is (150 gpm + 50 gpm + 85.6 gpm + 13.4 gpm) 60 min/hr 8.34 lbs/gal = 149,600 lbs/hr. The overall average f for the process shown in Figure 16 is 149,600 lbs/hr /17,870 lbs/hr = 8.4.

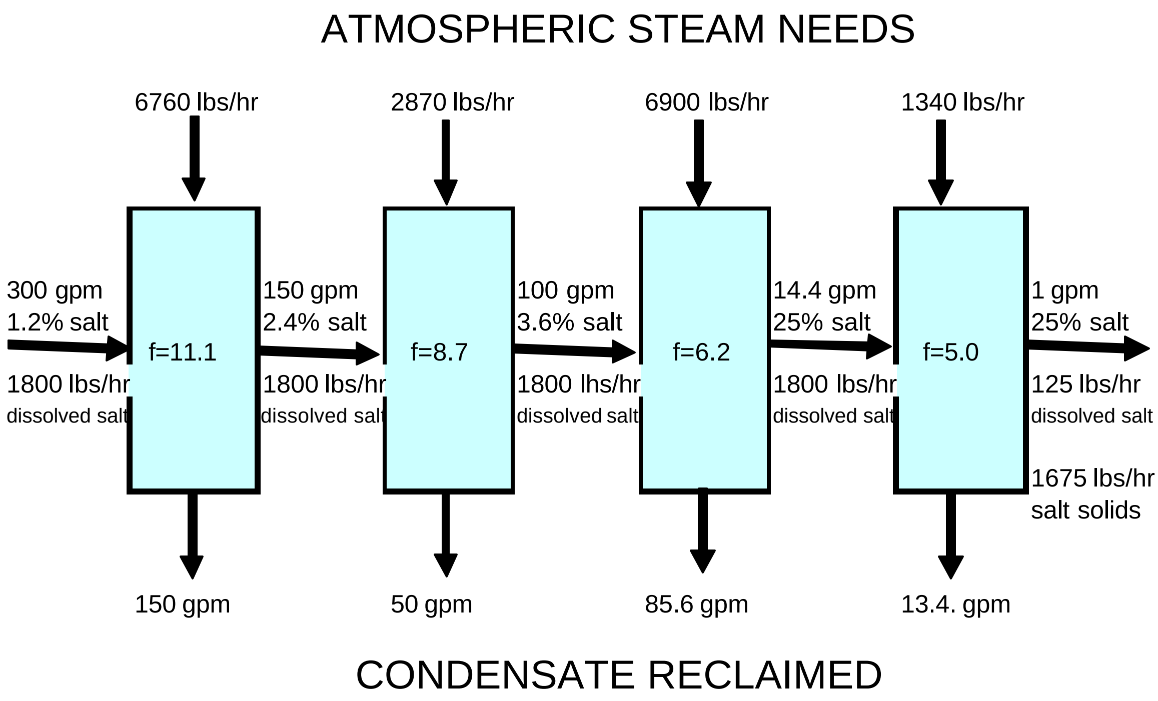


Figure 32.—CGS Circulation Cooling Water Blow Down Water Reclamation.

The electrical needs for operating a fan with 31,000 CFM at 3 inches of water pressure drop with a 30 percent efficient fan/motor would be 36kW. The feed pump would require 300gpm with a 5 feet head. At 20 percent efficiency the power would be 1.4kW (2 hp).

Students investigated different wetting gauzes for the heat transfer walls, liquid feed rates needed to flush the solids from the heat transfer walls, and removal of volatile organic compounds from water. The graduate students advanced the mathematical analysis of the technology by modeling the heat transfer resistance contribution of the 9-thousandth-of-an-inch-thick-plastic walls to the overall heat transfer efficiency.

Of the five plastic gauzes tested, two were found to be better than the gauze currently in use. If was recommended that costs be obtained for the better wetting weaves from the supply company, Clothcrafters, Inc of Elkhart Lake, Wisconsin. Costs received resulted in a $0.10/ft$^2$ increase. This would increase the total cost of a 1,000 gallon/day desalination plant from $1,500 to $3,300. It was decided to stay with the current gauzes.

Also the feed sweep rate needed to flush crystals down the heat transfer walls was investigated. Sweep rates ranged from 20 lbs/hr ft to 5 lbs/hr ft. The sweep rate was defined to be the lbs/hr of feed liquid flow rate divided by the width of the sheet it flowed down in feet. It was found that 5 lbs/hr ft worked very well which was higher than the standard sweep rate of 1 lb/hr ft as used in desalination for the past three years. The towers were then designed for this new higher sweep rate. The design involved increasing the feed heat exchanger area in the tower as more feed liquid has to be heated up when distributed to the top of the tower.

The goal of the research was to determine a minimum gamma needed for washing crystals off of nylon gauze and observing the wet ability of several other gauzes.

The design of the experiment consisted of a heated plate measuring 9 inches wide and 1-1/2 feet high. One sheet of twin wall extruded polypropylene was placed flush with the hot plate. The channels in the plastic sheet were positioned vertically and sealed at the bottom. The channels were filled with water to provide for conduction heat transfer. The test gauze was laid on the outside face of the plastic. Spacers were placed on top of the gauze and a clear sheet of thin wall extruded polycarbonate was secured against the spacers. The water traveled down the inside of the formed space created between the polycarbonate and polypropylene sheets.

The air traveled up by natural convection through the space between the plastic sheets. Air was heated by the hot plate to approximately 130 ºF to better simulate the tower environment. As the water evaporated into the heated air, salt crystals were left on the gauze. The flushing rate of the feed water washed the crystals down the gauze.

The water delivery system consisted of a reservoir of saturated liquid that was elevated higher then the hot plate set up previously described. Water flowed by gravity through a clamped plastic tube into a copper pipe with several small holes drilled into it. The copper pipe was secured above the space between the two plastic sheets. This arrangement adequately distributed the water in an even flow.

The hot plate temperature was maintained at 200 ºF. This provided a temperature between the plastic sheets of roughly 130 ºF. When the hot plate temperature was increased to try to increase the temperature between the plates to better simulate the top of the tower, the polypropylene sheet in direct contact with the top of the hot plate began to melt and warp. For this reason, all tests were run with a temperature between the plastic sheets of 130 ºF.

Run one used cotton gauze with a temperature between the plastic sheets of 130 ºF. The SRP Coronado Generating Station evaporation pond water was run through the system. Since the feed solution was not saturated with salt, roughly 26 hours were required to generate crystals when one gallon of liquid was used. The gamma for this run was 30 lb/hr ft. The run resulted in no crystals adhering to the gauze and the crystals were given to SRP for testing. The gamma used was higher than what was typically used in tower operation so lower values were investigated.

The Run 2 used saturated salt water at a flow rate of 1 $cm^3/s$. The run was conducted with cotton gauze and a temperature between the plastic sheets of 130 ºF. The run resulted in no crystals adhering to the gauze surface and 90 percent of the cotton was adequately wetted. The gamma calculated was 10.3 lb/hr ft.

The Run 3 used the same temperature and flow rate as the previous run. This flow rate was 1 $cm^3/s$. The SRP evaporation pond water was run through the set up. The concentration of the evaporation pond water was 20,000 ppm. This was determined through the use of the TDS meter. The CGS water was first boiled so that it was saturated before being run through the experiment. In this manner solids would immediately start forming and falling out. The experiment was allowed to run for 2.5 hours. When the gauze was examined, it was noted that the top corners were not wet. Since they were not being wet, crystals had formed in the dry areas. The loss of area was taken into consideration when calculating the gamma for this run. It was assumed that approximately 90 percent of the surface area was actually being used. This in turn increased gamma to nearly 9.52 lb/hr ft.

The next several runs considered different gauzes. The new gauzes were first tested to see if they could withstand the temperatures inside of the tower. The gauzes were boiled in 200 °F water for 15 minutes and then examined. They were also sprayed with water to see if they wetted well. Table 1 shows the results and whether or not the gauze was recommended for further investigation.

Table 4.—Wetting Results of Different Tested Gauzes

| **Material** | **Shrinking** | **Observations** | **Wetting** |
|---|---|---|---|
| Leno Weave | NO | Large Weave | Good |
| Cheese Cloth | NO | Same as Cotton, No need to investigate further | No Good |
| T-504 | NO | Fine Weave | Excellent |
| Smooth Weave | NO | Fine Weave | Excellent |
| #007 Disposable | NO | Since is is disposable, will degrade in tower. | No Good |

The gauzes that were not ruled out on the basis of wetting or deforming were examined. The first material examined was the Leno Weave. Saturated salt water was run on the gauze. The temperature between the plastic sheets remained 130 °F. The Leno Weave had crystals adhere to the surface at a flow rate of 1 $cm^3$/s. The material also did not wet as well as the others. The gamma calculated was 12.1 lb/hr ft.

The next gauze considered was the smooth weave. Saturated salt water was used in the run. The temperature was once again 130 °F between the plates. The flow rate remained 1 $cm^3$/s. The gauze wetting was similar to the cotton gauze. The only areas where crystals did adhere were found to be dry when removing the gauze. Approximately 10 percent of the gauze did not wet similar to the cotton. This gave a gamma of approximately 11.4 lb/hr ft.

The last gauze examined was the T-504. This gauze wet well. Similarly to the cotton and the smooth weave gauzes, the only salt crystals found were where the gauzes had dried out. This area that dried was less than 5 percent of the total area. This was less than that of the other two comparable weaves which were cotton and smooth weave that had approximately 20 percent dry. The temperature between the plastic sheets remained unchanged at 130 °F. The flow rate was 1 $cm^3$/s. The gamma calculated was found to be 10.8 lb/hr ft.

Of the three gauzes smooth weave, T-504, and the cotton gauze, the T-504 gauze performed the best with the most area wetted with the same flow rates. The gauze had the fewest crystals adhere to it for this reason. The gauze was almost completely wet with a gamma of 10.8 lbs/hr ft.

The conclusions drawn from these runs were that the critical gamma is dependent upon the necessary flow rate to wet the material and not the flow rate required to flush the crystals off of the gauze as previously thought. In order to closely investigate this gamma, Nylon was reviewed since it is presently in the tower.

The first run completed using the nylon gauze used saturated salt water with at temperature between the plastic sheets of 130 ºF. The flow rate was 1 $cm^3$/s. The gauze behaved similarly to the cotton and resulted in crystals along the sides where the gauze dried. Approximately 15 percent of the area was dry reducing the width of the gauze to .65 feet. This increased the value of gamma to just over 12.1 lbs/hr ft.

The next run maintained a temperature between the plastic sheets of 130 ºF. Saturated salt water was used. The flow rate was reduced to .5 $cm^3$/s thus reducing the mass flow rate to 3.96 lb/hr. The resulting gamma was calculated to be 6.0 lbs/hr ft. The area that remained wet did not significantly decrease from the run when the gamma was 10 lbs/hr ft.

The next run once again had a temperature between the plastic sheets of 130 ºF. Saturated salt water was run through the experiment. The flow rate was reduced to .26 $cm^3$/s. The mass flow rate was therefore reduced to 2.1 lb/hr. Approximately 20 percent of the gauze was covered in crystals. Again this was a result of the area becoming dry. Taking into account the decrease in wetted width to be .61 foot, the calculated gamma was 3.4 lb/hr ft. Figure 7 shows the crystals left on the gauze.

The investigation into the different gauzes revealed that the T-504 gauze out performed all of the others including the cotton. The gauze wetted very well and had very little dry spots at a gamma of 10 lbs/hr ft.

#### 4.8.5.2 Trace Volatile Organic Compound Removal

Removal of volatile organic compounds in the parts per million range was investigated. Volatile organics that have seeped into ground waters include such chemicals as trichloroethylene, TCE, from the semiconductor industry and Methyl Tertiary Butyl Ether, MTBE, from gasoline. Ethanol was used in the ASU laboratory investigation to emulate those hazardous materials. Ethanol has a similar vapor pressure to those organics but is environmentally friendly in the parts per million levels. Air was used to evaporate water that contained 1,300 ppm ethanol. The amount of water evaporated and remaining ethanol concentration were monitored. When the ethanol concentration reduced by 90 percent, about 80 percent of the water remained. This ethanol reduction agreed with theory and is shown in Figure 33.

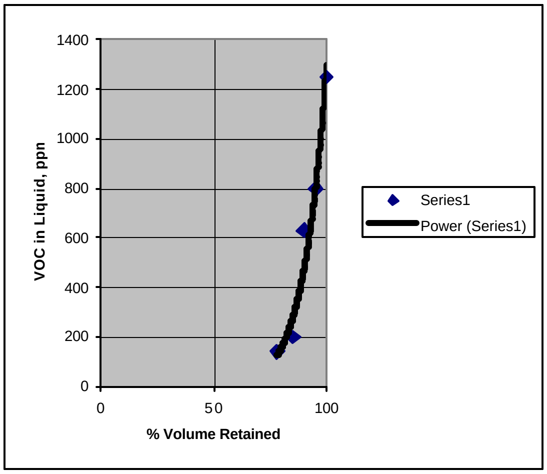


Figure 33.—Laboratory Data of 1,300 ppm Ethanol Stripping from Water Using Air.

A mathematical model of the Dewvaporation tower was built to simulate the VOC stripping in a Dewvaporation tower.

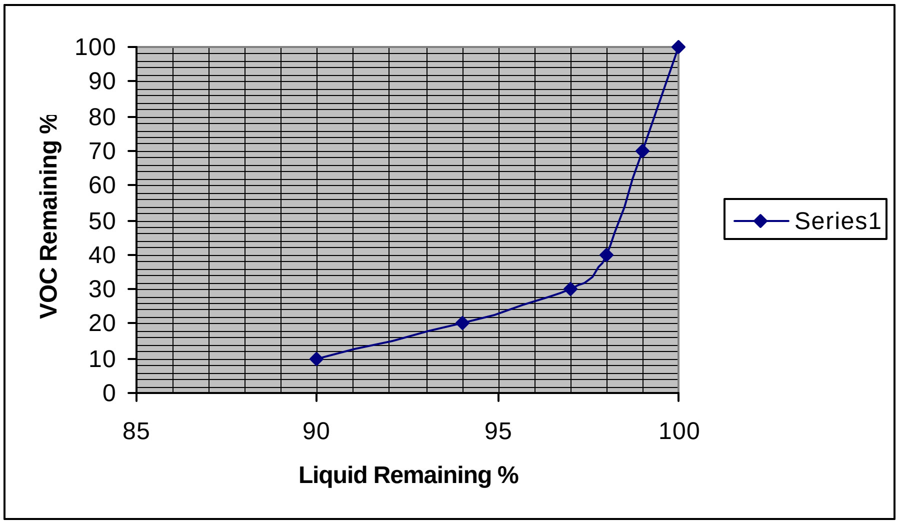


Figure 34.—VOC Simulated Stripping from Water in a Dewvaporation Tower.

In this mathematical simulation of Ethanol/MTBE/TCE removal from contaminated water, VOC at 100ppm was reduced to 10 ppm by evaporation of 10 percent of the feed water as shown in Figure 34. For a 1,000 gallon/day water production, a 500 $ft^2$ Dewvaporation tower would be needed costing \$900. Operating cost would be (1,000 gallons 8.34 lbs/gallon by 0.10 by \$0.35 /therm by 1,000 BTU/lb)/(1,000,000 BTU/therm by 15 factor) = \$0.19/1,000 gallons.

#### 4.8.5.3 Chemical Mechanical Planarization (CMP) Slurry Reclamation

Chemical mechanical polishing (CMP) has emerged as a preferred technology used to planarize semiconductor materials. In the manufacturing of multilevel integrated circuits, CMP is used to planarize both dielectric and metal films. Dielectric films such as $SiO_2$ are typically planarized using highly alkaline, silica-based slurries. These slurries contain approximately 10-12 percent solids by weight and are characterized by a pH in the vicinity of 11. Acidic, alumina-based slurries are used for planarizing metal films such as W, Al, and Cu. Alumina slurries used for metal CMP contain roughly 3 to 5wt% solids and chemicals such as complexants, corrosion inhibitors, and oxidants. The alumina or silica particles in the slurry are submicron in size and hence may be considered to be in the colloidal regime.

A key consumable in the CMP process is the polishing/planarization slurry. The major waste stream from a CMP tool is the polishing slurry in a very diluted form. The typical waste from a dielectric planarization step is a suspension of silica particles at a concentration of 0.05 to 0.2 wt%. Available information indicates that approximately 30 to 50 L of waste slurry may be generated per 200 mm wafer for each level of planarization. Waste slurries may also undergo further dilution if mixed with post-CMP clean rinse water. With increased implementation of the CMP technique in fabrication areas, the problem of slurry waste treatment is attracting increasing attention. To comply with environmental regulations and to allow for recycling of deionized water, these dilute slurries have to be treated to separate solids from the liquid dispersion medium. After consuming an estimated 108 billion gallons of water in 1999, semiconductor produces expect to us more than 138 billion gallons in 2000. Water and waste resource issues constrain the expansion of fabs and the overall growth industry. The 1999 International Technology Roadmap for Semiconductors (ITRS) specifies that the net feed water use be reduced from its current 13 gal/in$^2$ to 5 gal/in$^2$ by 2005, with a 2008 and beyond long-term goal of 2 gal/in$^2$, and a proportional decrease in ultrapure water (UPW). These goals are complicated by the industry's emerging transition to 300 mm wafers. The ITRS recognizes that part of the industry's water use must be controlled through better effluent management.

CMP is an extremely precise and repetitive process using slurry as the chemical component. Separating each cycle of planarization are the much longer steps of pad conditioning, wafer buffing, rinse, wafer handling, and idle periods. Each of these steps consumes a constant flow of UHP, creating a unique high-volume waste stream that is intermittently concentrated, but extremely dilute overall. For example, assuming an average UPW use of 5.1 gal/min on a continuous basis (7days/week, 24 hours/day), 10 commercially available CMP tolls will consume approximately 86,400 gallons of UPW daily. This generates an equal amount of CMP wastewater. This calculates to an annual consumption of 31.5 million gallons of UPW requiring approximately 52.57 million gallons of feed water.

Despite its volume, the nonslurry process steps dilute the waste stream so significantly that approximately 70 percent of this effluent is actually "clear" water. "Clear" water is defined as having a turbidity level of 0.75 nephelometric turbidity units (NTU), the average standard for United States drinking water. By comparison, DI water should be approximately 0.5 NTU. In practice, CMP slurry solids may be as high as 30 percent during the actual CMP step, but the high volumes of UPW water surrounding the process dilute the collected waste stream to an average of 0.02 percent

Through CMP produces high volumes of extremely dilute waste, the suspended solids in the waste do pose serious challenges for disposal. Slurry solids readily clog municipal waste systems. Within many fab waste systems, mixed oxide and metal slurries agglomerate into a viscous mass, and slurry solidifying in discharge lines is a chronic problem that requires frequent attention. Increasingly, local jurisdictions are restricting the release of suspended solids into municipal waste systems.

To reduce the amount of slurry waste stream volume for treatment and to provide a means to recover a substantial amount of “clear” water, a method for separating “clear” water from slurry needs to be implemented. Dewvaporation is an innovative technique that has shown promise in the desalination of sea water and the purification of brackish water. This technique has not been attempted with CMP. The focus of this investigation to establish Dewvaporation as a viable means of separating CMP slurry into a purified water stream and a concentrated CMP slurry waste stream.

The dimensions of the Dewvaporation tower used in this study were 82 inches high, 16 inches wide (minus 2-½-inch spacers), and five modules (approximately 2.25 inches deep). This provides a total effective heat transfer area of 85 $ft^2$.

This consists of one heat exchanger; five modules with five dew sides and six evaporative sides. Thermocouples are placed at the top of the tower. Two thermocouples are placed on the dew formation side. Each is in a separate module. While two thermocouples are placed on the evaporative side of two modules. Another thermocouple is placed at the top of the tower in the heat exchanger, in order to obtain the heated feed temperature that will run down the evaporative sides of the tower. A sixth thermocouple is placed at the bottom of the tower to record the bottoms temperature. A seventh thermocouple is placed in the feed line to the tower after the feed heating tank. This allows the temperature of the feed stock to be recorded. A separate handheld thermocouple device is used to determine ambient air temperature, distillate temperature, and exit air temperature.

Fifteen gallons of a feed stock solution of 1wt% solids CMP slurry was prepared and placed in the tower feed tank. Air, as the carrier-gas, was introduced into the bottom of the column at a velocity of 0.1 m/s. The feed valve on the feed tank was opened to allow feed to be pumped into the internal heat exchanger in the tower. Three different feed rates were used for this particular experiment. The feed rates were 8.0 $lb_m$/hr, 6.0 $lb_m$/hr, and 4.0 $lb_m$/hr. It takes approximately 15 minutes before the heat exchange fills with feed and begins wetting the tower evaporative walls. Prior to the feed being introduced into the tower, it is heat to approximately 105-110 °F. External heat is introduced to the top of the tower via a boiler apparatus. The boiler is fed with a direct utility steam line.

Condensate is captured in a distillate container, which is fed to a collection container. Concentrated bottoms are caught in a small funnel that leads to a collection port. The majority of the bottoms stream drains into the tower's catch basin. The bottoms samples are collected by suction or gravity feed into a collection vial through the collection port. Condensate volume and bottoms samples are collected for 6 minutes per run. Temperatures are taken at this time of all thermocouples on the tower, distillate temperature, exit air temperature. Total dissolved solids (TDS) measurements are taken on both distillate and bottoms samples. These samples are collected and set aside for further analysis to determine weight percent of solids in each.

From the running this column at three different feed rates, a material balance was taken around the entire column. Assuming a negligible about of material accumulated in the tower, the results of these mass balances are as follows:

Table 5.—CMP Water Reclamation Data in a Dewvaporation Tower

| Run | Feed Flow Rate ($lb_m$/hr) | Distillate Flow Rate ($lb_m$/hr) | Bottoms Flow Rate ($lb_m$/hr) | Percent Fresh Water Reclaimed |
|---|---|---|---|---|
| 1 | 8.0 | 3.30 | 4.70 | 41.25% |
| 2 | 8.0 | 3.63 | 4.37 | 45.38% |
| 3 | 6.0 | 3.30 | 2.70 | 55.00% |
| 4 | 4.0 | 3.52 | 0.48 | 88.00% |
| 5 | 4.0 | 2.53 | 1.47 | 63.25% |

The distillate recovered visually appears like DI water while the bottoms is cloudy and non-transparent. The bottoms samples appear to be more opaque than the feed solution and approach that of the original 15wt% CMP slurry. As Table 5 indicates, the highest water reclamation achieved was 88 percent, with an average of 59 percent of reclaimed "clear" water over all the runs. These few pieces of evidence indicate that proof-of-concept that Dewvaporation can, indeed, reclaim water from CMP slurry. These same indicators also point to observation that the bottoms stream of the tower produced a more concentrated CMP solids waste stream.

When determining the efficiency of each separation run of the tower, the energy balance needs to be determined. One quantitative measure to determine the Dewvaporation effectiveness is the energy reuse factor as shown in Table 6.

Table 6.—CMP Water Reclamation Energy Reuse Factor

| Run | Feed Flow Rate (lbm/hr) | Energy Reuse Factor, f |
|---|---|---|
| 1 | 8.0 | 20+ |
| 2 | 8.0 | 14.1 |
| 3 | 6.0 | 20.8 |
| 4 | 4.0 | 7.3 |
| 5 | 4.0 | 6.1 |

This shows the energy reuse factor to be relatively high on runs 2 and 3 and then dropping on runs 4 and 5. The runs on 4 and 5 had lower feed rates and relatively high exit air temperatures (147 ºF and 148 ºF, respectively). This is likely the result of incomplete wetting of the tower walls.

A second experiment was run that tested the anti-gel capability of polyvinyl alcohol (PVA).The primary objectives of this investigation are to: (1) determine if CMP can be processed in a NEWT tower; (2) inhibit CMP gel formation at possible operating tower conditions, and (3) determine the amount of water reclaimed from this process.

Approximately 10 gallons of standard 1 wt% CMP solids solution was prepared from at 15 wt% CMP solids stock solution. To this solution polyvinyl alcohol (PVA) was added. PVA acts as a gel inhibitor, thus allowing higher tower operating temperatures without gel formation and subsequent tower plugging as seen by Sparke, 2000. From previous experimentation with CMP slurry processing, it was determined that adding 1g/L of PVA would increase the gelling temperature from 158 ºF to 183.2 ºF at 10wt% CMP. Thus, with 10 gallons (approximately 40 L) of 1 wt% CMP slurry feed and the possibility of increasing the CMP slurry concentration up to 10 wt%, 8 grams for PVA was added to the slurry feed tank. This would provide protection against gel formation up to approximately boiling, 212 ºF, for a 1 wt% solution and 194 ºF for a 10 wt% solution.

The NEWT tower was then run over several hours. The beginning feed rate was 8 lb/hr (60 ml/min). As runs continued at this feed rate, the amount of distillate produced was in the range of 2.5 to 4.5 lb/hr. The feed rate was then decreased to 6 lb/hr and then further to 4 lb/hr. The reduction in feed rate was attempting to concentrate the bottoms stream with CMP solids while continuing to produce a consistent amount of distillate at a rate of approximately 3.5 to 4.0 lb/hr.

Compressed air was delivered to the tower through a rotameter at 32.6 ft$^3$/hr. This would provide the tower with an air velocity equivalent to 0.1 m/s exit air velocity that was used with the WEST tower runs in a previous study. In order to provide energy to the upward flowing air stream, steam was delivered to the top of the tower. Wall steam was used to heat a 55-gallon boiler. This heating in turn created steam within the drum and that steam was fed directly to the top of the tower. A thermocouples was placed at the bottom and top of the tower to monitor the temperature of the incoming liquid feed as it entered the tower and just prior to it leaving the vertical heat exchanger at the top of the tower. Additional thermocouples were placed at the top of the tower on the evaporative side and dew formation side to monitor those temperatures. A thermocouple attached to a catch basin at the bottom of the tower monitored the bottoms stream temperature. Exit air and distillate temperatures were monitored by a portable handheld thermocouple. Liquid manometers were placed at the top and bottom of the tower to measure the pressure drop across the tower.

Upon running the NEWT tower, a relatively consistent amount of distillate was collected. The feed rate was lowered as explained previously until the feed rate approached the distillate production rate. Theoretically this would allow for a maximum distillate production rate and a concentrated waste bottoms stream. As seen in Table 7, as the 1wt% CMP slurry feed rate was decreased from 60 mL/min (8lb/hr) to 30 mL/min (4 lb/hr) the amount of water that was reclaimed was 89 percent when averaging Trials 7–9.

Table 7.—CMP High Temperature Run with PVA Gel Prevention

| Trial Number | Date of Run | Feed Flowrate (mL/min) | Distillate Volume (mL/6min) | Distillate Volume (mL/min) | Bottoms* Volume (mL/min) | Percent Distillate Recovery |
|---|---|---|---|---|---|---|
| 1 | 1/24/02 | 60 | 112 | 18.67 | 41.33 | 31.1 |
| 2 | 1/24/02 | 60 | 155 | 25.83 | 34.17 | 43.1 |
| 3 | 1/24/02 | 60 | 210 | 35.00 | 25.00 | 58.3 |
| 4 | 1/24/02 | 45 | 160 | 26.67 | 18.33 | 59.3 |
| 5 | 1/24/02 | 45 | 185 | 30.83 | 14.17 | 68.5 |
| 6 | 1/24/02 | 45 | 185 | 30.83 | 14.17 | 68.5 |
| 7 | 1/24/02 | 30 | 165 | 27.50 | 2.50 | 91.7 |
| 8 | 1/24/02 | 30 | 160 | 26.67 | 3.33 | 88.9 |
| 9 | 1/24/02 | 30 | 155 | 25.83 | 4.17 | 86.1 |

* Note: The bottoms volume is calculated from feed rate minus distillate rate.

These results were consistent with previous data from the WEST tower that showed 88 percent reclaimed waters. However, the NEWT tower was purposely run much hotter than the WEST tower. Running a hotter tower would promote the gelling affect of the CMP. As the temperature increases, the 1 wt% CMP feed is more prone to gelling. The evaporative temperatures at the top of the tower approached 199 ºF. As the feed rate diminished and the production of distillate staying constant, the bottoms concentration of weight percent CMP will increase. As the concentration increases the gelling temperature decreases. Thus, running a very hot tower with a concentrated CMP stream being produced in the tower provided excellent opportunity of gel formation. From the data in Table 7, the distillate production rate stayed relatively constant. This indicates that there was no plugging of the tower on the dew formation side of the tower from CMP gel forming.

### 4.8.6 Tower Inherent Inefficiencies

Advances in the modeling the heat transfer characteristics involving thicker plastic heat transfer walls, laminar flow patterns and cross-flow efficiencies were accomplished by help of all of the graduate students. All of these detrimental effects will be used to mathematically reduce the actual heat transfer wall area to an “effective” wall area.

***Effect 1: Efficiency reduction due to parabolic air velocity patterns***

This effect reflects the fact the center core of the moving air, a parabolic profile, moves more rapidly in the provided slots bounded by the heat transfer walls. Since the center air is moving more rapidly there is less time for heat conduction and water vapor diffusion from the walls to effectively get to the center line air. Therefore, air trying to heat up does not get as hot nor as humid in any specific height location in the tower as previously modeled. The three partial differential equations involving air velocity, temperatures and humidity in two dimensions were solved via parametric perturbation techniques (Finlayson 1980). This effect reduced the effective wall area by 20 percent as reported by Ybarra, 2001.

Laminar slot flow is parabolic in its shape as illustrated in Figure 35. As the air moves either up or down the tower, the air is either heating and humidifying or cooling and de-humidifying. The heat and humidity must diffuse into the center line of the air from the wet heat transfer walls.

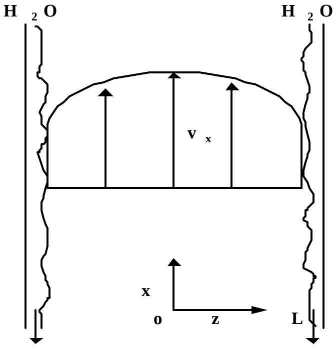


Figure 35.—Air Parabolic Flow Between Two Flat Wet Heat Transfer Walls.

Briefly, the momentum equation, equation 19, establishes the flow regime. It relates the air velocity momentum in the x direction with momentum to the side walls (the z direction) of the slot.

$$r n_x \frac{\partial n_x}{\partial x} = \frac{\partial P}{\partial x} + m \frac{\partial n_x}{\partial z^2} \qquad [19]$$

Equation 20 is the heat transfer equation that relates heat moving up or down the tower to the heat conducting into the centerline of flow from the slot walls.

$$\frac{\partial r C_p n_x T}{\partial x} = k \frac{\partial^2 T}{\partial z^2} \qquad [20]$$

The mass diffusion equation, equation 21, relates the water vapor concentration in the air stream, $C_A$ , in the dominant flow with the water vapor either evaporating from or condensing on the slot heat transfer walls.

$$\frac{\partial C_A n_x}{\partial x} = D \frac{\partial}{\partial z} \left[ \frac{1}{1 - C_A / C} \frac{\partial C_A}{\partial z} \right] \qquad [21]$$

Using the parametric perturbation technique, the solution to these equations can be summarized as the reduction in theoretical energy reuse factor, equation 22, by the parameters involved in the problem, equation 19.

$$f_{act}/f_{theo} = 1/(1+\text{epsilon}(1+V)^2/3V\text{delta}V) \tag{22}$$
$$= 1/(1+.1) = .9$$

$$\text{epsilon} = L^2 v_{xo}/\text{height}*\text{diffusivity} \tag{23}$$

The typical reduction in the energy reuse factor is about 10 percent in each flow direction. Overall, there is a 20 percent reduction in f that can be viewed as a 20 percent reduction in effective heat transfer wall area.

### *Effect 2: Number of cross flow stages (number of zigzags)*

This effect is caused by the lower efficiency of cross current flow in view of perfect counter current flow patterns as shown in Figure 36**.** The cross flow is required so that airs on opposite sides of the heat transfer walls have a chance to exchange heat. The designs have 16 passes that reduces the wall efficiency by 10 percent compared to infinite passes. More passes would improve this effect but would increase air pressure drop due to increases in air velocity and air flow path length.

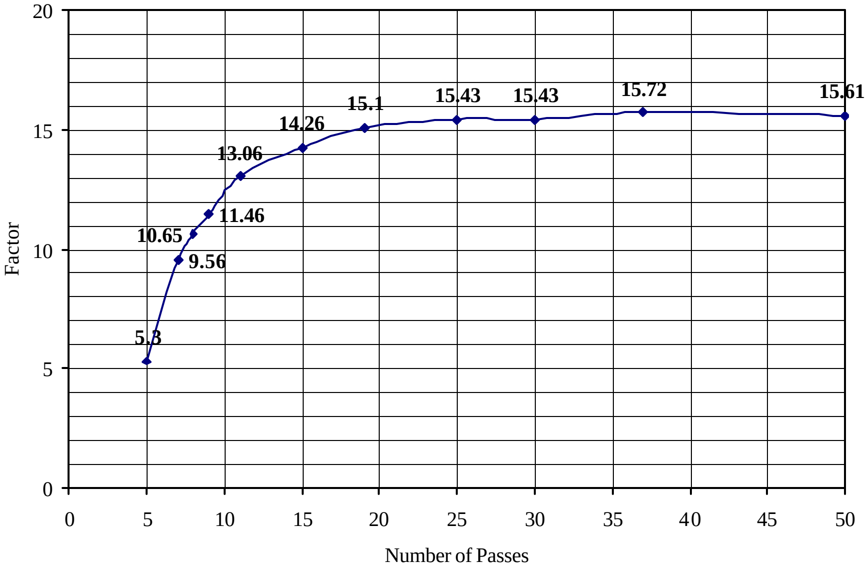


Figure 36.—Effect of Number of Zigzag Cross Flow Passes on Area Efficiency.

### *Effect 3: Plastic Heat Transfer Wall Thickness*

A mathematical model of heat transfer was solved that related the importance of plastic wall heat conduction to the overall heat conduction involving air boundary layers and liquid boundary layers. This expression was used to assess the effective wall area based on operations data of the top temperature, condensate production rate and energy reuse factor (number of multi-effects).

By taking into account the heat conduction resistance in the plastic heat transfer wall and the resistance due to the two liquid films on the wall, then equation 20 results. This expression resembles equation 14 but with an additional term F.

Figure 37 is a plot of the ratio of wall heat transfer resistance to total heat transfer resistance as a function of the maximum tower temperature. The V in the air boundary resistance term is a function of the water vapor pressure that is a function of temperature. Figure 37 shows that the plastic resistance becomes more important as temperature increases.

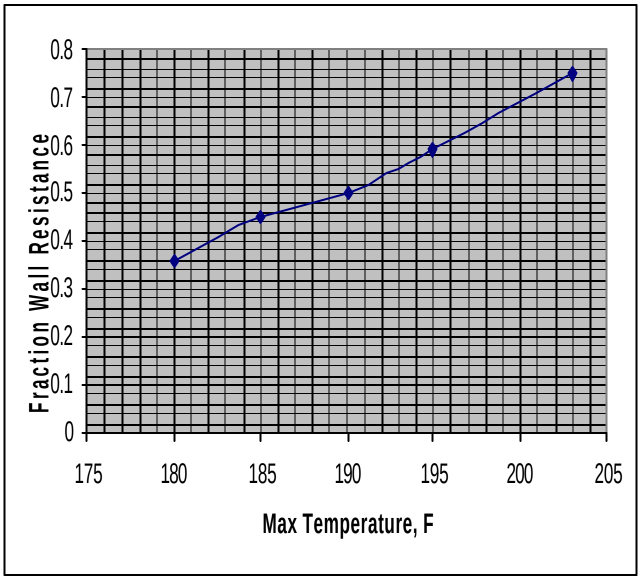


Figure 37.—Plastic wall heat transfer resistance compared to over all resistance.

At the standard operating temperature of 190 ºF, the wall represents about 50 percent of the total resistance. In other words, if metal having excellent thermal conductivity were to replace the plastic wall having low thermal conductivity, then the needed heat transfer area would be halved. However, cost would increase. Typically, thin stainless steel costs about $1/ft^2$ were as this polypropylene sheet costs $0.03/ft^2$. In a projected 1,000 gallon/day desalination tower, about 7,000 ft$^2$ of plastic heat transfer wall would be required at a material cost of $210. A stainless steel tower would require 3,500 ft$^2$ at a material cost of $3,500.

Also the model predicted a maximum temperature range in which a maximum Pf product could be expected. Figure 38 shows the results for brackish and sea water operation. The preferred temperature operation range is from 185 ºF to 195 ºF. The maximum temperatures normally set in the laboratories usually falls within this range. For operation with saturated salt solutions, the optimum max temperature is about 160 ºF due to the reduction in air relative humidity at the top of the evaporation chamber.

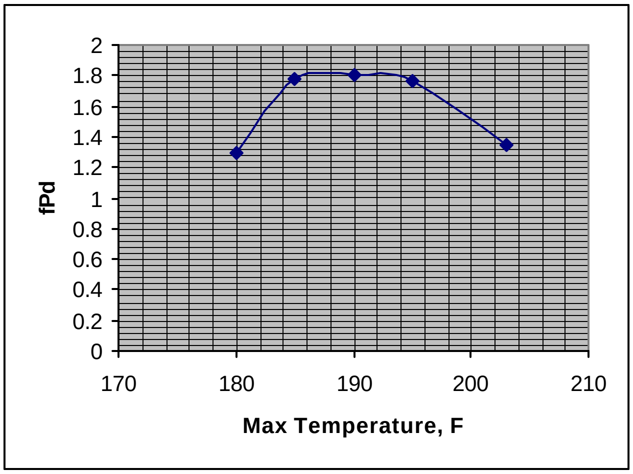


Figure 38.—Optimum Max Temperatures for Seawater in a Dewvaporation Tower.

### *Effect 4: NEWT water flow return channels*

During the operation of the NEWT towers, it was observed that the 3 lower channels out of 18 were filled with condensate flowing down the dewformation side. This resulted in an area reduction of 1-3/18 = .83 or 83 percent reduction.

Data from the two runs that were made with the 350 $ft^2$ NEWT tower are listed in Table 2. The effective heat transfer area involved in the 350 $ft^2$ gross tower was calculated by taking into account the geometry of the walls with spacers and liquid heat transfer walls that block water evaporation. The walls were 12 inches wide with a 1½-inch–wide liquid heat transfer wall and two ¾-inch-side-spacers. So the wall effective area reduced to 350 $ft^2$ (1-3/12) = 262 $ft^2$. Taking into account the efficiency reductions of Effects 1, 2, and 4 gives: 262 $ft^2$ .8 .9 .83 = 156 $ft^2$.

The data-based effective area was calculated for each run by the use of equation 18. The production density is the condensate rate divided by the effective area. From Run 1 and Run 2 the effective area was estimated from equation 18 to be 133 $ft^2$ and 101 $ft^2$ respectively. Using the average effective area of (133+101)/2 = 117 $ft^2$, then the fraction of the area realized from the collected data was 117/156 = 0.75 or 75 percent.

Operational data from the 350 $ft^2$ tower suggests an over all wall area efficiency of 75 percent after taking into account of all the noted efficiency reductions. The previous WEST towers were 20 percent to 25 percent efficient after taking into account its efficiency reductions. A value of 75 percent suggests that there are diminishing returns in further attempts to increase the over all wall efficiency. The final 700 $ft^2$ NEWT tower produced a maximum of 60 lbs/hr and will be used as a basic design of the future pilot plant construction and demonstration programs.

# 5. ECONOMICS

Based on the data as presented in Appendix B, a nominal NEWT 1,000 gallon per day desalination facility was designed and priced for seawater desalination. The tower consists of 8 sub-modules with a total dimension of 6 feet by 4 feet by 5 feet high. The cases considered were: Case 1 standard operation with natural gas combustion boiling; Case 2 standard operation with waste heat boiling at $1/1,000 lbs atmospheric steam; Case 3 liquid desiccant heat pumping with boil-back regeneration; and Case 4 liquid desiccant heat pumping with dry air regeneration. The energy reuse factor of 10 was assumed for sea water from 700 $ft^2$ NEWT tower operation with higher f values for brackish water which ranged from 15 to 20. (Appendix B). Tables 8 and 9 summarize capital and total water costs for a 1,000 gallon (3.79 $m^3$) per day unit.

Table 8.—Capital cost of NEWT 1,000 gallon/day plant

| | Standard Operation | | Desiccant-Assisted Operation | |
|---|---|---|---|---|
| | Case 1 | Case 2 | Case 3 | Case 4 |
| Components | Natural gas | Waste heat | Desiccant/boil | Desiccant/air |
| Heat transfer wall/gauze | $313 | $313 | $376 | $376 |
| Feed hex | 66 | 66 | 80 | 100 |
| Cover | 30 | 30 | 40 | 50 |
| Heater/boiler/regenerator | 105 | 0 | 120 | 90 |
| Pumps | 42 | 42 | 80 | 80 |
| Fans | 50 | 50 | 50 | 110 |
| Feed/effluent hex | 35 | 35 | 42 | 50 |
| Contingency (20%) | 128 | 107 | 158 | 171 |
| Total parts cost | $769 | $643 | $946 | $1,027 |
| Assembly (20%) | 154 | 128 | 190 | 205 |
| Total construction cost | $923 | $771 | $1,136 | $1,232 |
| Gross margin (50%) | 462 | 386 | 568 | 616 |
| **Total Unit Cost** | **$1,385** | **$1,157** | **$1,704** | **$1,848** |

The capital costs are dominated by the heat transfer wall size and material cost. The wall with gauze is about half of the total parts cost.

Table 9.—Water cost per 1,000 gallons from NEWT 1,000 gallon/day plant

| | Standard Operation | | Desiccant-Assisted Operation | |
|---|---|---|---|---|
| | Case 1 | Case 2 | Case 3 | Case 4 |
| Components | Natural gas F=10 | Waste heat F=10 | Desiccant/boil | Desiccant/air |
| Fuel | $2.94 | $0.84 | $1.96 | $0.42 |
| Capital charge | 0.40 | 0.34 | 0.50 | 0.54 |
| O&M | 0.33 | 0.33 | 0.33 | 0.33 |
| Electricity | 0.05 | 0.05 | 0.07 | 0.30 |
| Chemicals | 0.05 | 0.05 | 0.05 | 0.15 |
| **Total** | **$3.77** | **$1.61** | **$2.91** | **$1.74** |

The operating costs in Table 9 are dominated by the natural gas fuel cost ($0.35/therm) which represents about 75 percent of the total cost. Fuel costs can be reduced by less expensive fuels, higher GOR values and by the use of waste heat (case 2) or desiccant heat pumping (cases 3 and 4). As an example, atmospheric steam that is usually generated from waste heat recovery processes associated in chemical plants and petroleum refineries, costs about $1/1,000lb ($2.20/1,000 kg). This steam could be used at a cost of $0.84 per day. This would reduce the operating cost from $3.77 to $1.61 per 1,000 gallons (3.79 $m^3$) of distillate.

The desiccant heat pumping applications can have significant cost reductions Case 3 shows the reduction in fuel needs by essentially increasing the energy reuse factor from 10 to 15. Case 4 uses dry ambient air to regenerate the liquid desiccant solution back to full strength for reuse. This case should not need any fuel but a fuel charge was added to accommodate the heat loss due to the distillate and brine effluents being 5 ºF warmer than the feed stock. Actually, the additional heat of dilution associated with the strong desiccant picking up moisture in the tower should eliminate the fuel change resulting in a water cost of $1.32/1,000 gallons.

Cost projections to a 1,000,000 gallon/day facility are summarized in Table 10. The costing factors that contributed to a reduction in capital cost was a:

- Plastic cost reduction from $2.50 to $2.00 per standard sheet due to volume increase

- Cost reduction in ancillary boilers, pumps and fans due to size

- Reduction if contingency cost from 20 percent to 10 percent

The operating costs in Table 10 are reduced from the 1,000 gallon/day facilities by:

- Reduced capital costs per 1,000 gallons/day
- Reduced O&M charge by operator consolidation
- Reduced electrical charge from $0.08/kWh to $0.05/kWh commercial rate
- Elimination of extra fuel charge for case 4 (desiccant air regeneration)

Table 10.—Capital and water costs for a 1,000,000 gallon/day NEWT plant

| Design heat source | Capital cost | Water cost (per 1,000 gallons) |
|---|---|---|
| Natural gas @ $0.35/therm | $780,000 | $3.44 |
| Desiccant enhanced/boiler | $990,000 | $2.54 |
| Waste heat @ $1/1,000 lb steam | $720,000 | $1.33 |
| Desiccant enhanced dry air regen | $1,100,000 | $0.91 |

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# APPENDIX A

## Model for Desiccant Heat Pumping with Ambient Air Regeneration

## INPUTS

| | |
|---|---|
| Set Top Tower Evap Temp THE = | 190 |
| Set Top Tower Dew Temp THD = | 192 |
| Set Bottom Tower Dew Temp TCD = | 160 |
| Set Ambient Air Dry Bulb Temp TDW | 100 |
| Set Ambient Air Relative Humidity RH | 0.2 |

## CALCULATIONS -Main Desalination Tower

| | |
|---|---|
| Vapor Pressure PHE= | 9.264166 |
| Vapor Pressure PHD= | 9.675245 |
| Vapor Pressure PCD= | 4.670613 |
| Desiccant Temp Tdes= | 200 |
| Vapor Pressute Strong Desic at Tdes Pdes1= | 2.606952 |
| Vdes= | 0.215574 |
| V hot evap channel Seawater= VHE | 1.615138 |
| V hot DEW channel = VHD | 1.925516 |
| VCD= | 0.465693 |
| slip stream of air, X, =(VHD-VHE)/(VHD-Vdes) | 0.181513 |
| Delta Water Picked-up | 0.25404 |
| **Condensate Production, lbmoles/hr** | 1.194846 |
| **f =** | 4.703383 |
| Utop= | 54.6596 |
| Ubot= | 26.29617 |
| VCE= | 0.420293 |
| PCE= | 4.531273 |
| TCE= | 158.7371 |
| qtop= | 109.3192 |
| qbot= | 33.20957 |
| **Pd=** | 0.003959 |
| **Heat Transfer Area =** | 301.7948 |

## CALCULATIONS -Desiccant Contact Heat Exchanger

| | |
|---|---|
| **Water Absotbed by desiccant** | 0.25404 |
| Udes= | 23.20328 |
| **Heat Transfer Area of Desiccant Contactot** | 19.70718 |

## CALCULATIONS -Ambient Air Regenerator

| | |
|---|---|
| Air Analysis | |
| Tambient= | 100 |
| RHambient= | 0.2 |
| Pambient= | 0.190518 |
| Vambient= | 0.013131 |
| Twetbulb= | 68.29096 |
| Vwetbulb | 0.025462 |
| Texhaust= | 78.20004 |
| Vexhaust= | 0.022379 |
| **Air Rate=** | 27.46829 |
| Delta Temp Ln Mean= | 18.74216 |
| **Wall Area=** | 81.32667 |

## INPUTS

| | |
|---|---|
| Set Top Tower Evap Temp THE = | 190 |
| Set Top Tower Dew Temp THD = | 192 |
| Set Bottom Tower Dew Temp TCD = | 160 |
| Set Ambient Air Dry Bulb Temp TDW | 100 |
| Set Ambient Air Relative Humidity RH | 0.2 |

## CALCULATIONS-Main Desalination Tower

| | |
|---|---|
| Vapor Pressure PHE= | =EXP(16.38-9200/(460+B5)) |
| Vapor Pressure PHD= | =EXP(16.38-9200/(460+B6)) |
| Vapor Pressure PCD= | =EXP(16.38-9200/(460+B7)) |
| Desiccant Temp Tdes= | =B5+10 |
| Vapor Pressute Strong Desic at Tdes Pdes1= | =EXP(17.14-10680/(460+B14)) |
| Vdes= | =B15/(14.7-B15) |
| V hot evap channel Seawater= VHE | =0.98*B11/(14.7-0.98*B11) |
| V hot DEW channel = VHD | =B12/(14.7-B12) |
| VCD= | =B13/(14.7-B13) |
| slip stream of air, X, =(VHD-VHE)/(VHD-Vdes) | =(B18-B17)/(B18-B16) |
| Delta Water Picked-up | =B20*(B17-B16) |
| **Condensate Production, lbmoles/hr** | =(1-B20)*(B18-B19) |
| **f =** | =B22/B21 |
| Utop= | =1/(1/100+1/500+2/(3*55*B18)) |
| Ubot= | =1/(1/100+1/500+1/(3*55*B19)+1/(3*55*B19)) |
| VCE= | =B20*B16+(1-B20)*B19 |
| PCE= | =14.7*B26/(1+B26)/0.96 |
| TCE= | =-460+9200/(16.38-LN(B27)) |
| qtop= | =B24*(B6-B5) |
| qbot= | =B25*(B7-B28) |
| **Pd=** | =(B29+B30)/36000 |
| **Heat Transfer Area =** | =B22/B31 |

## CALCULATIONS-Desiccant Contact Heat Exchanger

| | |
|---|---|
| **Water Absotbed by desiccant** | =B20*(B17-B16) |
| Udes= | =1/(1/100+1/500+1/(3*55*B17)+1/(3*55*B16+1)) |
| **Heat Transfer Area of Desiccant Contactot** | =18000*B34/(B35*10) |

## CALCULATIONS-Ambient Air Regenerator

| | |
|---|---|
| Air Analysis | |
| Tambient= | =B8 |
| RHambient= | =B9 |
| Pambient= | =B40*EXP(16.38-9200/(460+B39)) |
| Vambient= | =B41/(14.7-B41) |
| Twetbulb= | =(7*B39+18000*(B42+0.036))/(7+18000*0.0009) |
| Vwetbulb | =0.0009*B43-0.036 |
| Texhaust= | =B39-(0.75-B40)*(B39-B43)/(1-B40) |
| Vexhaust= | =B42+0.75*(B44-B42) |
| **Air Rate=** | =B34/(B46-B42) |
| Delta Temp Ln Mean= | =((B39-B43)-(B45-B43))/LN((B39-B43)/(B45-B43)) |
| **Wall Area=** | =18000*B34/(3*B48) |

# APPENDIX B

## Operational Data 700 FT$^2$ NEWT Tower

## NEWT Tower Data for 700 $ft^2$ Sub-Module

| RUN | 7123 | 7124 | 7125 | 7162 | 7164 | 7166 | 7168 | 7183 | 7185 |
|---|---|---|---|---|---|---|---|---|---|
| Air Flow Rate, CFM | 4.4 | 3.6 | 5.4 | 3.6 | 6.2 | 4.8 | 3.1 | 4.6 | 4.8 |
| Feed Flow Rate, ml/min | 1,000 | 1,000 | 1,000 | 1,000 | 700 | 400 | 400 | 900 | 700 |
| Condensate Rate,ml/min | 323 | 317 | 372 | 322 | 265 | 235 | 232 | 288 | 394 |
| Feed Temp, F | 107 | 111 | 112 | 107 | 102 | 91 | 101 | 121 | 110 |
| Hex Temp, F | 199/199 | 201/201 | 201/200 | 203/200 | 197/196 | 199/198 | 204/201 | 197/199 | 203/201 |
| Evap Temp , F | 198/199 | 199/200 | 198/199 | 201/202 | 194/196 | 197/198 | 201/202 | 195/200 | 198/201 |
| Dew Temp, F | 202/200 | 203/201 | 202/202 | 201/203 | 195/196 | 199/198 | 203/201 | 199/200 | 201/201 |
| Exhaust Air Temp, F | 135/135 | 143/143 | 158/160 | 141/136 | 112/108 | 108/105 | 113/113 | 134/139 | 145/146 |
| Brine Temp, F | 114 | 116 | 120 | 134 | 116 | 112 | 113 | 130 | 124 |
| Condensate Temp, F | 135/136 | 140/140 | 149/150 | 138/140 | 130/120 | 115/110 | 130/120 | 127/131 | 144/145 |
| TDS Condensate | 30 | 30 | 30 | 60 | 65 | 70 | 68 | 72 | 71 |
| Pressure Drop, mm H2O | 65 | 55 | 91 | 68 | 61 | 56 | 46 | 89 | 122 |
| | | | | | | | | | |

# APPENDIX C

## Evaporation Pond Water Analysis

# SALT RIVER PROJECT
## Coronado Generating Station

## Water Analysis
01-24-02

| | CGS U2 Circ Cooling Water | CGS Evap Pond |
|---|---|---|
| pH | 7.64 | 8.23 |
| Turbidity | 12 NTU | 6.5 NTU |
| Conductivity | 21,920 us/cm | 51,270 us/cm |
| TDS (Factor 0.57) | 12,494 mg/L | 29,224 mg/L |
| Total Hardness (as CaCO3) | 2325 ppm | 8210 ppm |
| Calcium (as CaCO3) | 725 ppm | 1400 ppm |
| Magnesium (as CaCO3) | 1600 ppm | 6810 ppm |
| P Alkalinity | 0 ppm | 0 ppm |
| M Alkalinity | 60 ppm | 224 ppm |
| Chloride ( as Cl) | 3467 ppm | 7937 ppm |
| Sulfate (as SO4) | 7682 ppm | 18,721 ppm |
| Silica (SiO2) | 85 ppm | 10.8 ppm |

# APPENDIX D

## SI Metric Conversion

SI Metric Conversion

| From | To | Multiply by |
|---|---|---|
| inch | cm | 2.54 |
| inch | mm | 25.4 |
| ft | m | 0.3048 |
| ft$^2$ | m$^2$ | 0.0929 |
| $^o$F | $^o$C | $^oC = (^oF-32)/1.8$ |
| psia | bar | 0.06895 |
| lbmole/sec | gmole/sec | 453.59 |
| BTU/lbmole $^o$F | J/gmole K | 4.184 |
| BTU/lbmole | J/gmole | 2.326 |
| BTU/hr ft$^2$ $^o$F | W/m$^2$ K | 5.6783 |
| BTU/hr ft $^o$F | W/m K | 1.73073 |
| BTU/hr | W | 0.29307 |
| BTU/hr ft$^2$ | W/m$^2$ | 3.1546 |
| lb | kg | 0.45359 |
| lb | g | 453.59 |
| lb/hr | g/hr | 453.59 |
| lb/hr ft | kg/hr m | 1.488 |
| lb/hr ft$^2$ | kg/hr m$^2$ | 4.8826 |
| lb/ft$^3$ | g/mL | 0.016 |
| gal | m$^3$ | 0.003785 |