TREATMENT OF CENTRAL ARIZONA PROJECT WATER: REVERSE OSMOSIS AND EVAPORATION POND BRINE DISPOSAL

Item Type	text; Electronic Thesis
Authors	MCCORKEL, MIA; Khatri, Chandra; Mohan, Ritika; Pedersen, Elizabeth
Citation	McCorkel, Mia, Khatri, Chandra, Mohan, Ritika, & Pedersen, Elizabeth. (2009). TREATMENT OF CENTRAL ARIZONA PROJECT WATER: REVERSE OSMOSIS AND EVAPORATION POND BRINE DISPOSAL (Bachelor's thesis, University of Arizona, Tucson, USA).
Publisher	The University of Arizona.
Rights	Copyright © is held by the author. Digital access to this material is made possible by the University Libraries, University of Arizona. Further transmission, reproduction or presentation (such as public display or performance) of protected items is prohibited except with permission of the author.
Download date	30/04/2022 20:21:52
Item License	http://rightsstatements.org/vocab/InC/1.0/
Link to Item	http://hdl.handle.net/10150/192552

TREATMENT OF CENTRAL ARIZONA PROJECT WATER:

REVERSE OSMOSIS AND EVAPORATION POND BRINE DISPOSAL

By

Mia McCorkel
Chandra Khatri
Ritika Mohan
Elizabeth Pedersen

A Thesis Submitted to The Honors College

In Partial Fulfillment of the Bachelor's degree
With Honors in

Chemical Engineering

THE UNIVERSITY OF ARIZONA

May 2009

Approved by:

____

Dr. Eduardo Saez
Chemical and Environmental Engineering

STATEMENT BY AUTHOR

SIGNED: _____________________________

Abstract

This project aims to design a reverse osmosis (RO) plant in Avra valley that will treat 1,969 L/s of Central Arizona Project (CAP) water with 80% recovery to supply drinking water for Tucson that meets the acceptable standard of 450 mg/L after CAP water and groundwater are blended. The RO unit, preceded by a pre-treatment process, consists of 624 pressure vessels in stage one, 360 in stage two, and six ESPA2+ spiral wound membranes per vessel. An optimized evaporation pond system treats the waste brine that is generated by RO. Evaporation ponds were determined to reduce the environmental impact of the RO process by preventing the brine from being injected back into the aquifer and further contaminating valuable groundwater. The pond system uses PVC-lined ponds, each with a filling time of 2.93 yrs and drying time of 2.87 years. The total capital investment for the plant and evaporation ponds is $99,200,000 with an annual operating cost of $68,800,000. In order to pay for annual costs, the Tucson water customers would have to pay 19% more for their water.

Roles and Responsibilities of Wilma Engineering Team Members

As a member of my senior design team Wilma Engineering, I actively participated in all aspects of the project. I concentrated on overseeing the entire process including leading the organization of the team, keeping track of deadlines, and meeting all requirements and due dates throughout the semester-long project timeline. With my global view of the project, I was able to assemble all of the pieces of our multiple aspect design into a coherent and connected project. I managed collecting all sections from my group members in a timely manner, helped them add any missing parts, and edited and completed each section. This included keeping track of all tables, figures, calculations, block flow diagrams, and process flow diagrams. In addition to my leadership role in the team, I contributed greatly to the environmental and safety statements of the report. Furthermore, I helped write the introduction, executive summary, and results and conclusions. Earlier in our work, I greatly contributed to the initial research, finding references, and defining our process. I also contacted companies for specifics, information, and quotes on equipment in our process.

The general breakdown of work in the group Wilma Engineering for the design report is as follows. The process rationale and equipment rationale were largely written by Ritika Mohan. A majority of the economic sections were written by Elizabeth Pedersen. The evaporation pond calculations and several of the statements throughout about the evaporation ponds were written by Chandra Khatri. Mia McCorkel wrote a majority of the environmental statement, added to many other sections, typed up and put together many of the references, and compiled and formatted the final report. Though these are the major contributions of the individual group members, all the members of Wilma Engineering helped with many different aspects of the report and put a lot of effort into creating the final product.

Treatment of Central Arizona Project Water:

Reverse Osmosis and Brine Disposal

Wilma Engineering

ChEE 443: Plant Design

Submitted May 1, 2009

Chandra Khatri, Senior Design Engineer

Mia McCorkel, Senior Design Engineer

Ritika Mohan, Senior Design Engineer

Elizabeth Pedersen, Senior Design Engineer

EXECUTIVE SUMMARY

The goal of this design project was to design a reverse osmosis (RO) plant to treat 1,969 L/s of Central Arizona Project (CAP) water for the city of Tucson with 80% recovery. The design also included safe disposal of the RO brine using evaporation ponds. Avra Valley was chosen as the building site due to its proximity to Tucson, availability of land to build the plant and ponds, and also an optimal climate for evaporation. With the increasing water demand from 125,000 acre-feet in 2000 to a predicted 250,000 acre-feet in 2050 (Tucson Water Plan, 2004) and raised standards for drinking water, it becomes necessary to design water treatment plants to alleviate these problems. Wilma Engineering will produce 7,196 L/s of treated water with an acceptable Total Dissolved Solids (TDS) of 450 mg/L, a sufficient amount to meet the Tucson water demands in the coming years.

With increasing environmental standards, the optimized configuration of two evaporation ponds ensures safe disposal of the concentrated brine with a TDS of 3,750 mg/L. The time period to fill a pond of dimensions $1600 \times 1600 \times 0.75$ m was determined to be 2.93 years, with 2.87 years required to dry the same pond. The scope of this study includes detailed calculations for analysis of the industrial reverse osmosis plant and optimization of evaporation ponds, while also addressing safety and environmental issues involved in each step of the process. Due to large feed water flow rate, a two-stage RO process, including approximately 5,900 ESPA2+ type RO membrane elements, is required for an 80% recovery. The overall process safety and environmental issues involved in disposal of the solids were also considered. The main safety hazards in the RO plant include the handling and storage of sulfuric acid used in the

pre-treatment of CAP water, and the high pressures up to 8.71 atm necessary for the reverse osmosis process. Leaking of the evaporation ponds is the main environmental hazard involved in the design.

A 30-year cost analysis was performed. The total capital investment was calculated to be $99,200,000 with annual operating cost of approximately $68,800,000. The total bare module cost of the equipment is about $43,000,000. Total annual sales are estimated to be $140,500,000 with the selling price of $1.753 per Ccf based on current prices for water (Tucson Water, 2009). The payback period was calculated to be 1.52 years, with an investor's rate of return (IRR) 39.3%, based on an analysis performed without accounting for the current operating costs of Tucson Water. The high initial costs are due to expensive PVC lining and cost of excavation to build the ponds and onsite landfill. When the current annual operating costs of Tucson Water were taken into account, the payback period was calculated to be 10.91 years with an IRR of 2.26%. In order to make the process profitable enough to be recommended, the selling cost of the water would have to be raised by 15% to $2.017 per Ccf. Another option would be to raise the selling cost of the water by 19% to $2.083 per Ccf in order to cover the annual operating costs of the RO plant and evaporation pond facility.

After an evaluation of this design, we have determined that it is economically feasible, while also incorporating an environmentally conscious solution for the RO brine disposal. The implementation of this plant in Avra Valley would be a viable solution to reduce the TDS of the water supplied to Tucson customers. However, at this time, the nearly-20% increase in water prices necessary to fund the project might impede public support for building the plant.

Table of Contents

1.0 INTRODUCTION

Maintaining the quality of water in Tucson has always been a difficult task. Groundwater demands are increasing due to increases in population from 486,699 in the year 2000 to a predicted 651,553 in 2020 (Pinkham and Davis, 2002). In order to alleviate the groundwater demands, Colorado River water is delivered to Tucson as part of the Central Arizona Project and is blended with native Avra Valley groundwater. Since an acceptable blend is considered to have a Total Dissolved Solids (TDS) concentration of 450 mg/L, a portion of the Colorado River water must be treated to reduce the average concentration from its current TDS level of 650 mg/L (Dittler, 2005)

1.1 OVERALL GOAL

The goal of this project is to design an industrial reverse osmosis (RO) plant in Avra valley that will treat 1,969 L/s of CAP water with 80% recovery. Care must also be taken to pre-treat the CAP water before it enters the RO unit. A proper pre-conditioning stage is required for reliable operation of RO membranes. The specifics for the choice can be found in Sections 2.7 and 3.1. This project focuses on treating the CAP water via reverse osmosis to meet the acceptable standards of 450 mg/L after CAP water and groundwater are blended. The system overview can be viewed in the block flow diagram (2.1) and process flow diagram (2.2).

In addition to designing the industrial sized reverse osmosis plant, our objective is also to focus on the environmental impacts of the wastes generated by this plant. Specifically, we propose an optimized evaporation pond system to treat the brine, or concentrate, generated by this plant. An efficient way to dispose of the toxic waste salts and other components is also discussed. Parameters considered for this design include the amount of land needed, the depth and configuration of the ponds, energy required, brine residence time, and method of solids disposal. Incorporation of evaporation ponds as the method of brine disposal reduces the environmental impact of the RO process by preventing the brine from being injected back into the aquifer and further contaminating valuable groundwater.

1.2 CURRENT MARKET INFORMATION

Water demand is increasing in Arizona every year due to increases in population. An estimation of population projection through 2050 can be seen in Figure 1.2 (Tucson Water plan, 2004).

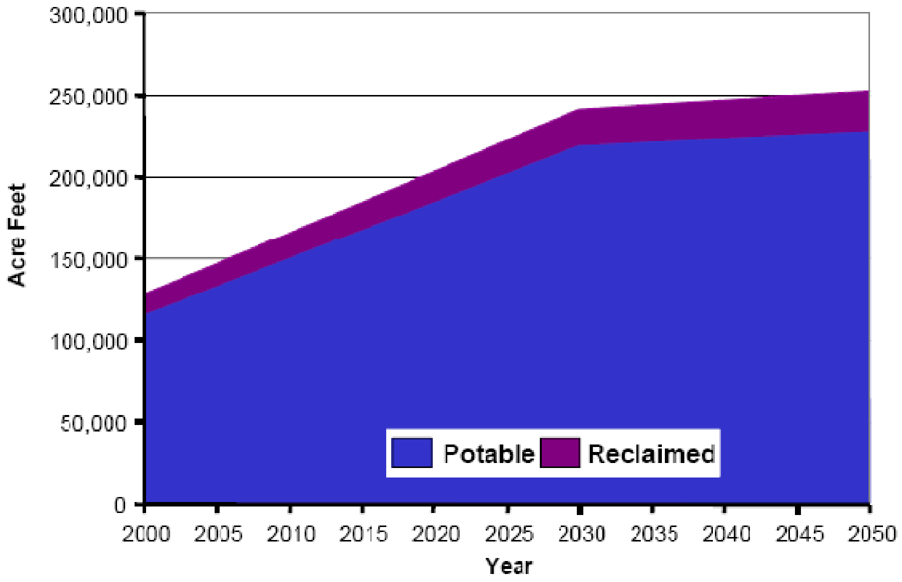


Figure 1.2: Projected annual water demand from 2000 to 2050.

Tucson Water hopes to meet these increasing water demands over the next 40 years in addition to meeting strict water quality targets, utilizing renewable resources, and achieving sustainable processes (Tucson Water Plan, 2004). In many parts of Arizona, the rate of groundwater pumping exceeds the rate at which the aquifer gets replenished by natural means. This leads to problems such as drying of aquifers and subsidence ("Groundwater", n.d.). Therefore, this problem will be alleviated if more CAP water is utilized instead.

To meet the current and future water demands, the Tucson Water Plan aims to implement enhanced treatment to reduce the TDS to 450 mg/L in CAP water (Tucson Water Plan, 2004). Our project has designed a plant to meet that goal.

With increased environmental concerns, it also becomes necessary to dispose of the brine in an environmentally conscious manner. Implementing residual management that uses evaporation ponds is considered in the Tucson Water Plan (2004), and as mentioned, has been incorporated into our design.

1.3 PROJECT PREMISES AND ASSUMPTIONS

Tucson Water introduced treated Colorado River water to the system via a CAP canal in 1992. However, this water has a low water quality due to high TDS of 650 mg/L, which is much higher than the acceptable TDS standard of 450 mg/L (Decision H2O, 2007). In addition, CAP water broke pipelines which were old and corroded, leading to "brown" water in thousands of Tucson homes. The CAP project was thus shut down in 1994, and only groundwater was used. PVC pipes are now used instead of steel pipes in new homes and other new pipes to avoid corrosion

(Basefsky, 2006). Around 1996, the decision was made to blend CAP water and ground water (Basefsky, 2006).

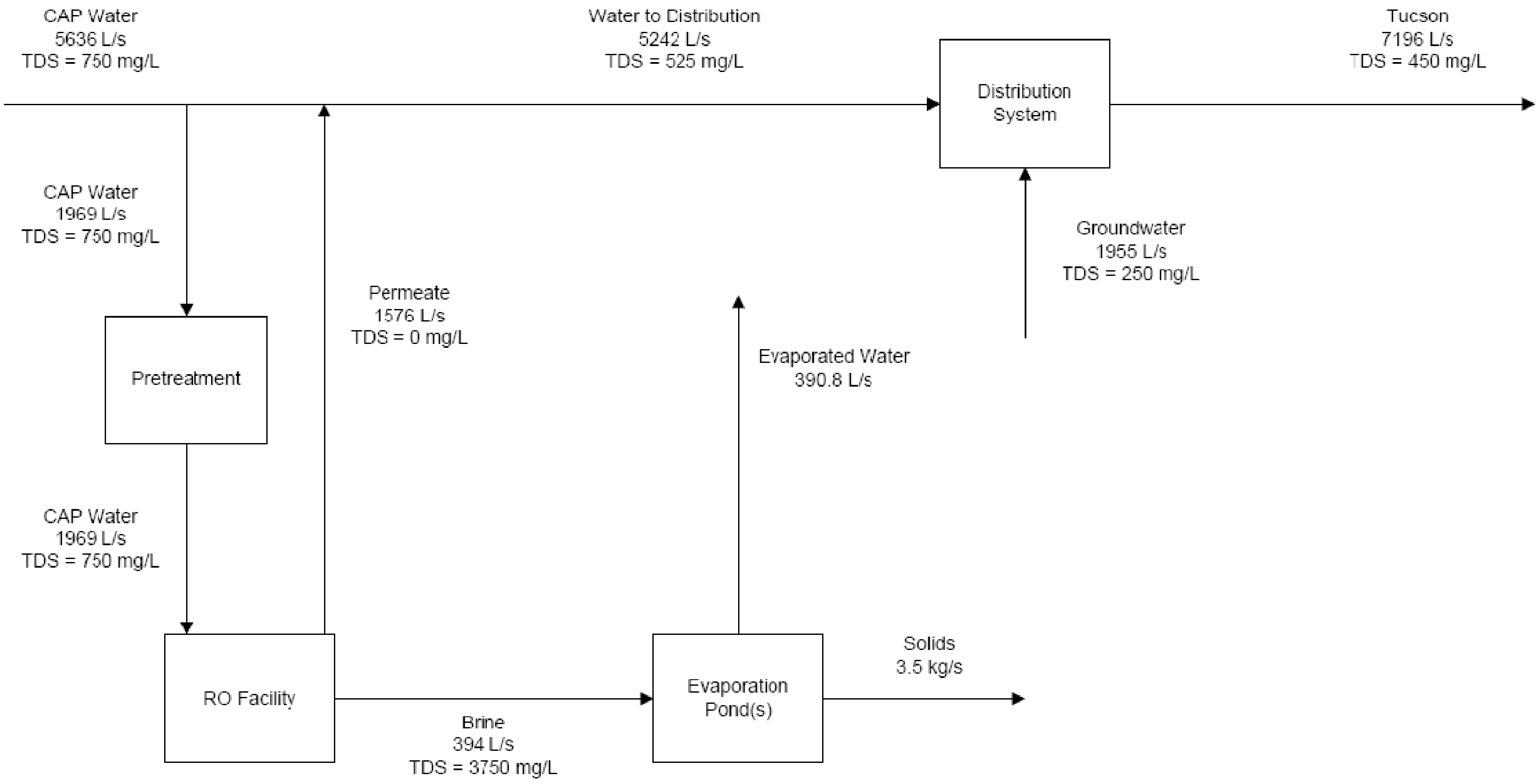
The design project aims to treat a large water flow rate of 1,969 L/s of CAP water, with component concentrations and TDS as shown in Section 5.2, obtained from University of Arizona PhD student Umur Yenal (personal communication, January 20, 2009). One significant assumption in our project lies in the validity of the data; however, a large flow rate with high TDS values is reasonable because the design allows for treatment of all the water for the city of Tucson. The data was also compared with the Tucson Water Plan, which had similar compositions and quality of CAP water (Tucson Water Plan, 2004).

A conventional pre-treatment is used before the RO plant due to large flow rates, and it is assumed that the pre-treatment will work acceptably well even though the latest technology such as ultra filtration is not used.

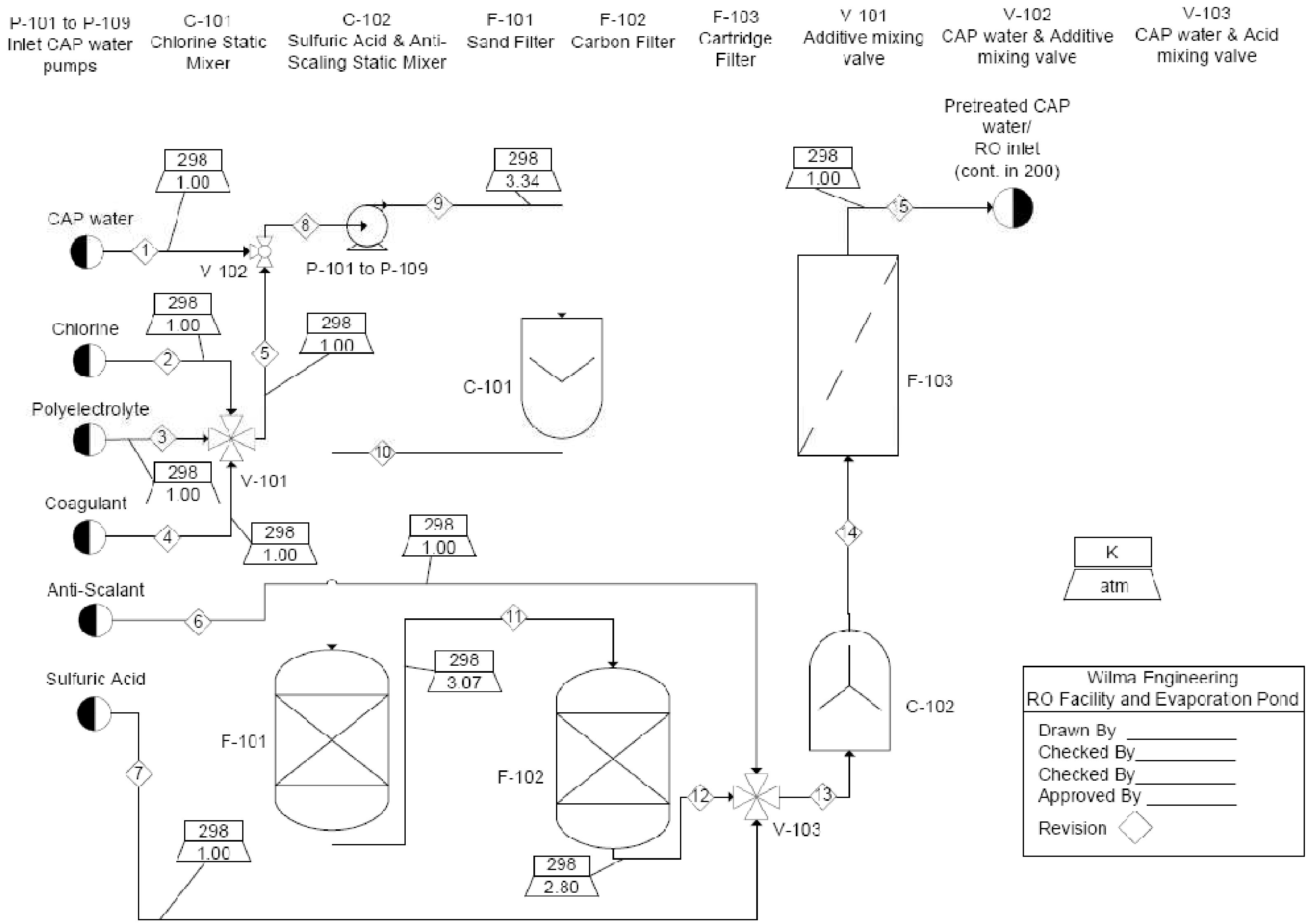
2.0 PROCESS DESCRIPTION, RATIONALE, AND OPTIMIZATION

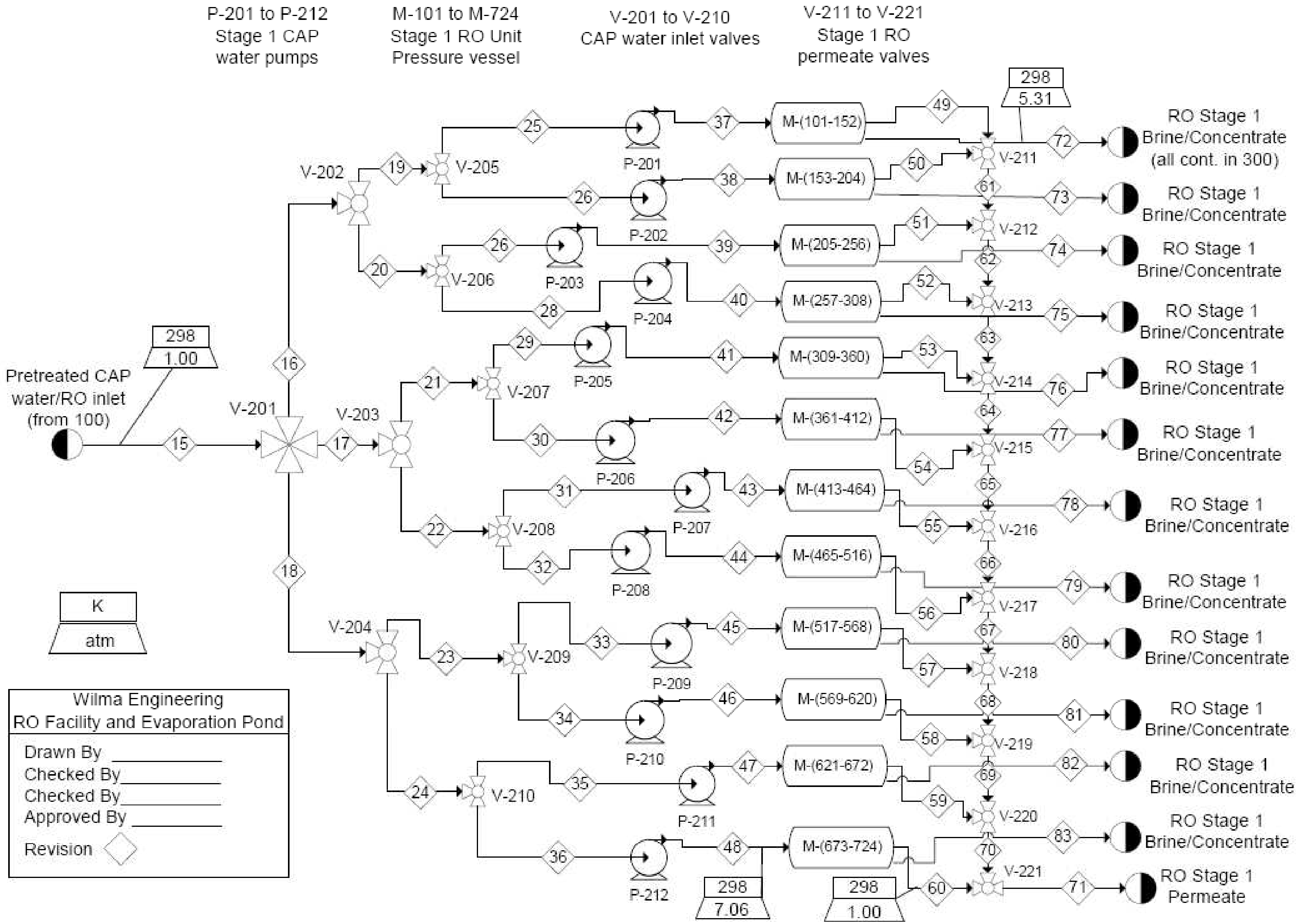
This section provides an overview for the entire plant, including pre-treatment, reverse osmosis, and brine management via evaporation ponds. Refer to the Block Flow Diagram in Section 2.1 for a general overview and the Process Flow Diagram in Section 2.2 for a more detailed view.

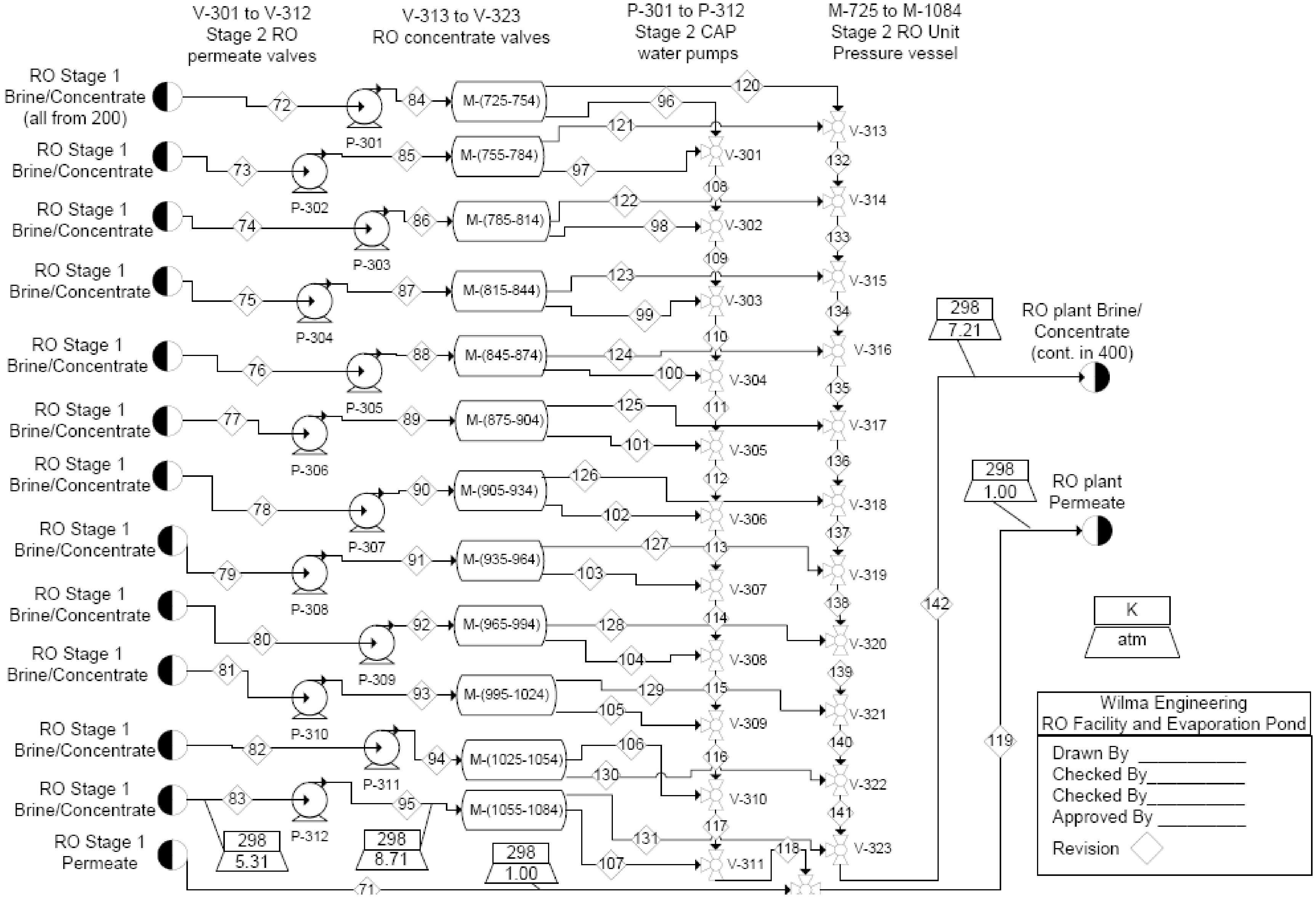
2.1 BLOCK FLOW DIAGRAM

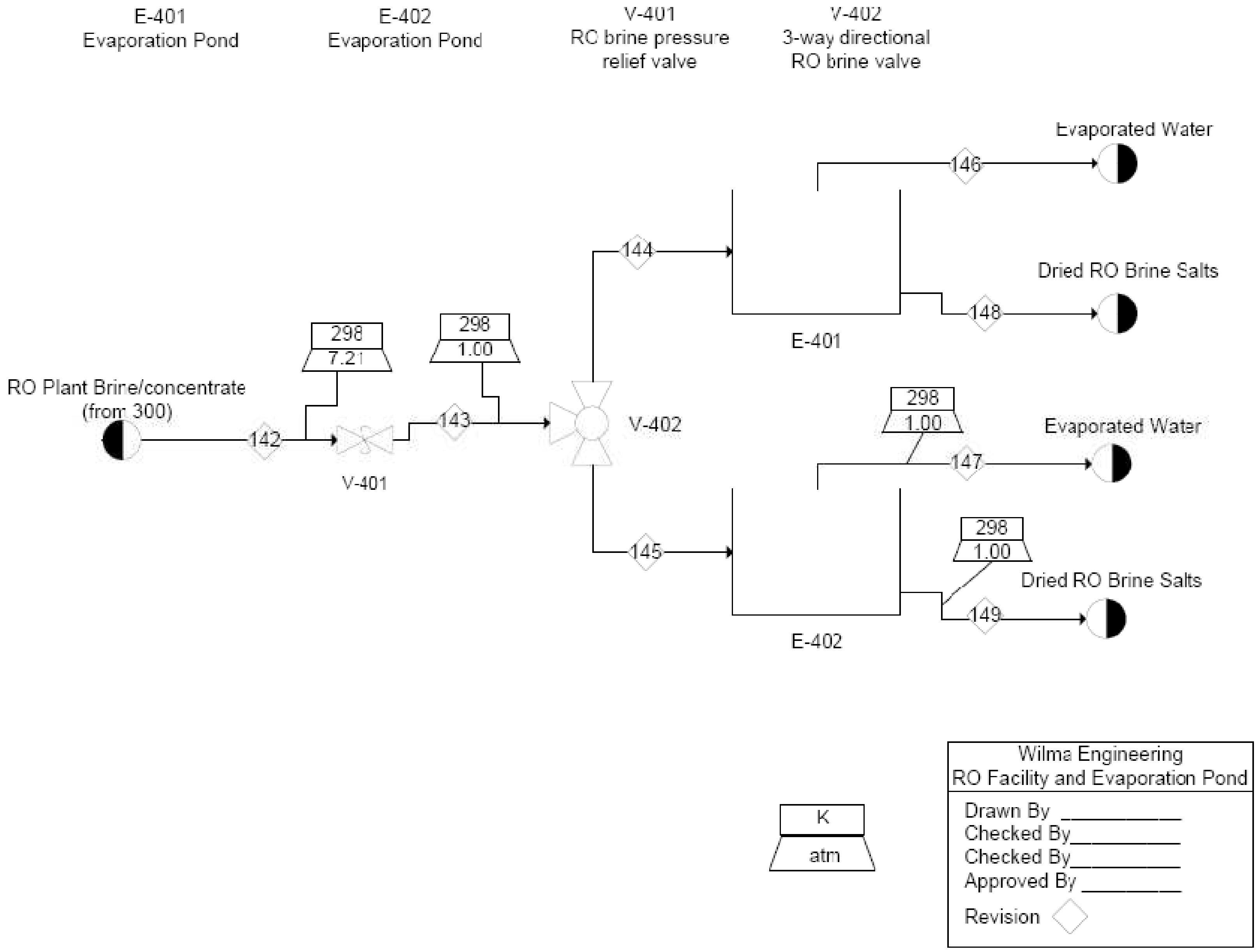


2.2 Process Flow Diagram




P-201 to P-212
Stage 1 CAP
water pumps
M-101 to M-724
Stage 1 RO Unit
Pressure vessel
V-201 to V-210
CAP water inlet valves
V-211 to V-221
Stage 1 RO
permeate valves
298
5.31
298
1.00
Pretreated CAP
water/RO inlet
(from 100)
15
V-201
16
17
18
V-202
V-203
V-204
19
20
21
22
23
24
V-205
V-206
V-207
V-208
V-209
V-210
25
26
26
28
29
30
31
32
33
34
35
36
P-201
P-202
P-203
P-204
P-205
P-206
P-207
P-208
P-209
P-210
P-211
P-212
37
38
39
40
41
42
43
44
45
46
47
48
M-(101-152)
M-(153-204)
M-(205-256)
M-(257-308)
M-(309-360)
M-(361-412)
M-(413-464)
M-(465-516)
M-(517-568)
M-(569-620)
M-(621-672)
M-(673-724)
49
50
51
52
53
54
55
56
57
58
59
60
V-211
V-212
V-213
V-214
V-215
V-216
V-217
V-218
V-219
V-220
V-221
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
RO Stage 1
Brine/Concentrate
(all cont. in 300)
RO Stage 1
Brine/Concentrate
RO Stage 1
Permeate
298
7.06
298
1.00
K
atm
Wilma Engineering
RO Facility and Evaporation Pond
Drawn By
Checked By
Checked By
Approved By
Revision


V-301 to V-312
Stage 2 RO
permeate valves
V-313 to V-323
RO concentrate valves
P-301 to P-312
Stage 2 CAP
water pumps
M-725 to M-1084
Stage 2 RO Unit
Pressure vessel
RO Stage 1
Brine/Concentrate
(all from 200)
RO Stage 1
Brine/Concentrate
RO Stage 1
Permeate
P-301
P-302
P-303
P-304
P-305
P-306
P-307
P-308
P-309
P-310
P-311
P-312
M-(725-754)
M-(755-784)
M-(785-814)
M-(815-844)
M-(845-874)
M-(875-904)
M-(905-934)
M-(935-964)
M-(965-994)
M-(995-1024)
M-(1025-1054)
M-(1055-1084)
V-301
V-302
V-303
V-304
V-305
V-306
V-307
V-308
V-309
V-310
V-311
V-313
V-314
V-315
V-316
V-317
V-318
V-319
V-320
V-321
V-322
V-323
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
298
5.31
298
8.71
298
1.00
298
7.21
RO plant Brine/
Concentrate
(cont. in 400)
298
1.00
RO plant
Permeate
K
atm
Wilma Engineering
RO Facility and Evaporation Pond
Drawn By ___________
Checked By___________
Checked By___________
Approved By __________
Revision


E-401
Evaporation Pond
E-402
Evaporation Pond
V-401
RO brine pressure relief valve
V-402
3-way directional RO brine valve
Evaporated Water
146
144
Dried RO Brine Salts
148
E-401
298
7.21
298
1.00
RO Plant Brine/concentrate (from 300)
142
V-401
143
V-402
298
1.00
Evaporated Water
147
298
1.00
Dried RO Brine Salts
145
149
E-402
K
atm
Wilma Engineering
RO Facility and Evaporation Pond
Drawn By ___________
Checked By___________
Checked By___________
Approved By _________
Revision

2.3 EQUIPMENT TABLES

All major equipment and relevant design parameters are listed in the following Tables 2.3.1-2.3.6. The equipment code number corresponds to the label on the Process Flow Diagram in Section 2.2.

Mixer/Agitator	C-101	C-102
Type	Turbine	Tubine
Drive	Electric	Electric
Power [kW]	23	23
Inlet Temperature [K]	298	298
Outlet Temperature [K]	298	298
Residence time [min]	2	2
Volume [m^3]	63000*	63000*
Additives	Chlorine, Polyelectrolyte, Coagulant	Sulfuric Acid, Anti-Scalant
MOC	SS316	SS316

*Note: Mixers are assumed to handle the large flow rates and due to their large volume they will be built on-site.

Table 2.3.1: Significant design parameters of Mixers C-101 and C-102.

Filter	F-101	F-102	F-103
Type	Sand	Carbon	Cartridge
Pressure Drop [atm]	0.27	0.27	1.8
Number of Filters in Unit	21	13	38
Maximum Flowrate [gpm]	1500	2500	825
Maximum Pressure [psi]	75	90	150
Membrane type	N/A	Pentek DGD	Metal Fiber
Membrane Life [years]	5	5	5
MOC [housing]	SS316	Polypropylene	SS316

Table 2.3.2: Significant design parameters of Filters F-101 – F103.

Evaporation Pond	E-401*	E-402*
Width [m]	1600	1600
Length [m]	1600	1600
Depth [m]	0.75	0.75
Filling Time [days]	1070	1070
Drying Time [days]	1050	1050
MOC (lining)	PVC	PVC

Table 2.3.3: Design parameters for evaporation ponds E-401 and E-402. This evaporation pond schematic assumes that brine will be cycled between the two ponds.

Pump	P-101 through P-109	P-101/102 B	P-201 through P-212	P-201/202 B	P-301 through P-312	P-301/302 B
Mass Flow Rate [kg/s]	218.3	218.3	163.7	163.7	84	84
Volumetric Flow [L/s]	1969	218.8	164.1	164.1	84.2	84.2
Stages	1	1	1	1	1	1
Power [kW]	68	68	132	132	41	41
Efficiency	0.77	0.77	0.76	0.76	0.71	0.71
Driver Type	Electric	Electric	Electric	Electric	Electric	Electric
Suction Pressure [atm]	1.00	1.00	1.00	1.00	5.31	5.31
Discharge Pressure [atm]	3.34	3.34	7.21	7.21	8.71	8.71
Suction Temperature [K]	298	298	298	298	298	298
Discharge Temperature [K]	298	298	298	298	298	298
Type	Centrifugal	Centrifugal	Centrifugal	Centrifugal	Centrifugal	Centrifugal
MOC	SS316	SS316	SS316	SS316	SS316	SS316

Table 2.3.4: Design parameters for process pumps.

Membrane Unit	M-(101-152) through M-(673-724)	M-(725-754) through M-(1055-1084)
Transmembrane Pressure Drop [atm]	1.75	1.5
Feed Pressure [atm]	7.06	8.71
Concentrate Pressure [atm]	5.31	7.21
Membrane Type	Spiral Wound	Spiral Wound
Membrane MOC	*ESPA2+	ESPA2+
Specific Water Type	Surface/Brackish	Surface/Brackish
Membrane Radius [in]	8	8
Membrane Length [in]	40	40
Membrane Area [ft^2]	440	440
Membranes per unit	6	6
Recovery [%]	48.7	61
Stage	1	2
Salt Rejection [%]	99.6	99.6
Pressure Vessel MOC	SS316	SS316

*NOTE: ESPA2+ is Energy Saving PolyAmide from Hydronautics

Table 2.3.5: Design parameters for the membrane units.

Valve	V-101	V-102	V-103	V-201	V-202	V-203	V-204	V-205	V-206	V-207	V-208	V-209
Mass Flow Rate [kg/s]	1964.5	1964.5	1964.5	1964.5	654.8	654.8	654.8	327.4	327.4	327.4	327.4	327.4
Volumetric Flowrate (inlet) [L/s]	1969	1969	1969	1969	656.4	656.4	656.4	328.2	328.2	328.2	328.2	328.2
Design	4-way	3-way	4-way	4-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way
Type	Mixing	Mixing	Mixing	Splitting	Splitting	Splitting	Splitting	Splitting	Splitting	Splitting	Splitting	Splitting
Flow composition	Chlorine, etc.	Chlorine, etc.	Anti-scalant	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
MOC	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316

Valve	V-210	V-211	V-212	V-213	V-214	V-215	V-216	V-217	V-218	V-219	V-220	V-221
Mass Flow Rate [kg/s]	327.4	159.4	239.2	318.8	398.7	479.8	558.1	637.9	717.5	797.3	877.1	956.7
Volumetric Flowrate (inlet) [L/s]	328.2	159.9	239.9	319.8	399.9	478.4	559.8	639.8	719.7	799.7	879.7	959.6
Design	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way
Type	Splitting	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing
Flow composition	CAP water	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate
MOC	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316

Table 2.3.6: Design parameters for valves in process. Table continues on next page.

Valve	V-301	V-302	V-303	V-304	V-305	V-306	V-307	V-308	V-309	V-310	V-311	V-312
Mass Flow Rate [kg/s]	102.5	153.7	205	256.2	307.1	358.6	409.9	461.1	512.4	563.6	614.8	1571.2
Volumetric Flowrate (inlet) [L/s]	102.8	154.2	205.6	257	308	359.7	411.1	462.5	513.9	565.3	616.7	1576
Design	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way	3-way
Type	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing
Flow composition	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate	RO permeate
MOC	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316	SS316

Valve	V-313	V-314	V-315	V-316	V-317	V-318	V-319
Mass Flow Rate [kg/s]	65.6	98.4	131.2	164	196.8	229.6	262.4
Volumetric Flowrate (inlet) [L/s]	65.6	98.4	131.2	164	196.8	229.6	262.4
Design	3-way	3-way	3-way	3-way	3-way	3-way	3-way
Type	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing	Mixing
Flow Composition	RO brine	RO brine	RO brine	RO brine	RO brine	RO brine	RO brine
MOC	SS316	SS316	SS316	SS316	SS316	SS316	SS316

Valve	V-320	V-321	V-322	V-323	V-401	V-402
Mass Flow Rate [kg/s]	295.2	328	360.8	394	394	394
Volumetric Flowrate (inlet) [L/s]	295.2	328	360.8	394	394	394
Design	3-way	3-way	3-way	3-way	3-way	2-way
Type	Mixing	Mixing	Mixing	Mixing	Splitting	Pressure relief
Flow Composition	RO brine	RO brine	RO brine	RO brine	RO brine	RO brine
MOC	SS316	SS316	SS316	SS316	SS316	SS316

Table 2.3.6: Design parameters for valves in process. Continued from previous page.

2.4 STREAM TABLE

The following Table 2.4 contains flow rates, pressures, temperatures, phase, major component, and TDS concentration of each stream shown on the PDF in Section 2.2. Table 2.4 continues on the following pages.

Stream	1	2	3	4	5*	6	7	8**	9	10
Volumetric Flowrate [L/s]	1969	0.0019	0.0075	0.0007	0.01	0.0049	0.0011	1969	1969	1969
Mass Flowrate [kg/s]	1964.5	0.003	0.0098	0.002	0.0148	0.0059	0.002	1964.5	1964.5	1964.5
Pressure [atm]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	3.34	3.34
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	Solid	Solid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
Major Component	CAP water	Chlorine [100%]	Polyacrylamide [100%]	Iron Chloride [100%]	Pre-treatment chemicals	Vitech® 4000 [100%]	Sulfuric Acid [100%]	CAP water	CAP water	CAP water
TDS [mg/L]	750	0	0	0	0	0	0	750	750	750

*Note: Assumed volumes of streams 2,3, and 4 are additive since mixture information not available

**Note: Assumed that the volume and mass flow rates of the CAP water was not altered significantly with the addition of pre-treatment chemicals

Stream	11	12	13	14	15	16	17	18	19	20
Volumetric Flowrate [L/s]	1969	1969	1969	1969	1969	656.4	656.4	656.4	328.2	328.2
Mass Flowrate [kg/s]	1964.5	1964.5	1964.5	1964.5	1964.5	654.8	654.8	654.8	327.4	327.4
Pressure [atm]	3.07	2.80	2.80	2.80	1.00	1.00	1.00	1.00	1.00	1.00
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Lquid	Liquid	Liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	750	750	750	750	750	750	750	750	750	750

Table 2.4: Stream Table

Stream	21	22	23	24	25	26	27	28	29	30
Volumetric Flowrate [L/s]	328.2	328.2	328.2	328.2	164.1	164.1	164.1	164.1	164.1	164.1
Mass Flowrate [kg/s]	327.4	327.4	327.4	327.4	163.7	163.7	163.7	163.7	163.7	163.7
Pressure [atm]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	750	750	750	750	750	750	750	750	750	750

Stream	31	32	33	34	35	36	37	38	39	40
Volumetric Flowrate [L/s]	164.1	164.1	164.1	164.1	164.1	164.1	164.1	164.1	164.1	164.1
Mass Flowrate [kg/s]	163.7	163.7	163.7	163.7	163.7	163.7	163.7	163.7	163.7	163.7
Pressure [atm]	1.00	1.00	1.00	1.00	1.00	1.00	7.06	7.06	7.06	7.06
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	750	750	750	750	750	750	750	750	750	750

Stream	41	42	43	44	45	46	47	48	49	50
Volumetric Flowrate [L/s]	164.1	164.1	164.1	164.1	164.1	164.1	164.1	164.1	80	80
Mass Flowrate [kg/s]	163.7	163.7	163.7	163.7	163.7	163.7	163.7	163.7	79.8	79.8
Pressure [atm]	7.06	7.06	7.06	7.06	7.06	7.06	7.06	7.06	1.00	1.00
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	750	750	750	750	750	750	750	750	0	0

Table 2.4: Stream Table

Stream	51	52	53	54	55	56	57	58	59	60
Volumetric Flowrate [L/s]	80	80	80	80	80	80	80	80	80	80
Mass Flowrate [kg/s]	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8
Pressure [atm]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	0	0	0	0	0	0	0	0	0	0

Stream	61	62	63	64	65	66	67	68	69	70
Volumetric Flowrate [L/s]	159.9	239.9	319.8	399.9	479.8	559.8	639.8	719.7	799.7	879.7
Mass Flowrate [kg/s]	159.4	239.2	318.8	398.7	478.4	558.1	637.9	717.5	797.3	877.1
Pressure [atm]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	0	0	0	0	0	0	0	0	0	0

Stream	71	72	73	74	75	76	77	78	79	80
Volumetric Flowrate [L/s]	959.6	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2
Mass Flowrate [kg/s]	956.7	84	84	84	84	84	84	84	84	84
Pressure [atm]	1.00	5.31	5.31	5.31	5.31	5.31	5.31	5.31	5.31	5.31
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	0	1462	1462	1462	1462	1462	1462	1462	1462	1462

Table 2.4: Stream Table

Stream	81	82	83	84	85	86	87	88	89	90
Volumetric Flowrate [L/s]	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2
Mass Flowrate [kg/s]	84	84	84	84	84	84	84	84	84	84
Pressure [atm]	5.31	5.31	5.31	8.71	8.71	8.71	8.71	8.71	8.71	8.71
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	1462	1462	1462	1462	1462	1462	1462	1462	1462	1462

Stream	91	92	93	94	95	96	97	98	99	100
Volumetric Flowrate [L/s]	84.2	84.2	84.2	84.2	84.2	51.4	51.4	51.4	51.4	51.4
Mass Flowrate [kg/s]	84	84	84	84	84	51.2	51.2	51.2	51.2	51.2
Pressure [atm]	8.71	8.71	8.71	8.71	8.71	1.00	1.00	1.00	1.00	1.00
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	1462	1462	1462	1462	1462	0	0	0	0	0

Stream	101	102	103	104	105	106	107	108	109	110
Volumetric Flowrate [L/s]	51.4	51.4	51.4	51.4	51.4	51.4	51.4	102.8	154.2	205.6
Mass Flowrate [kg/s]	51.2	51.2	51.2	51.2	51.2	51.2	51.2	102.5	153.7	205
Pressure [atm]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	0	0	0	0	0	0	0	0	0	0

Table 2.4: Stream Table

Stream	111	112	113	114	115	116	117	118	119	120
Volumetric Flowrate [L/s]	257	308	359.7	411.1	462.5	513.9	565.3	616.7	1576	32.8
Mass Flowrate [kg/s]	256.2	307.1	358.6	409.9	461.1	512.4	563.6	614.8	1571.2	32.8
Pressure [atm]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	7.21
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	0	0	0	0	0	0	0	0	0	3750

Stream	121	122	123	124	125	126	127	128	129	130
Volumetric Flowrate [L/s]	32.8	32.8	32.8	32.8	32.8	32.8	32.8	32.8	32.8	32.8
Mass Flowrate [kg/s]	32.8	32.8	32.8	32.8	32.8	32.8	32.8	32.8	32.8	32.8
Pressure [atm]	7.21	7.21	7.21	7.21	7.21	7.21	7.21	7.21	7.21	7.21
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	3750	3750	3750	3750	3750	3750	3750	3750	3750	3750

Stream	131	132	133	134	135	136	137	138	139	140
Volumetric Flowrate [L/s]	32.8	65.6	98.4	131.2	164	196.8	229.6	262.4	295.2	328
Mass Flowrate [kg/s]	32.8	65.6	98.4	131.2	164	196.8	229.6	262.4	295.2	328
Pressure [atm]	7.21	7.21	7.21	7.21	7.21	7.21	7.21	7.21	7.21	7.21
Temperature [K]	298	298	298	298	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid	liquid
Major Component	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water	CAP water
TDS [mg/L]	3750	3750	3750	3750	3750	3750	3750	3750	3750	3750

Stream	141	142	143	144/145***	146/147***	148/149***
Volumetric Flowrate [L/s]	360.8	394	394	394	486300	3.0
Mass Flowrate [kg/s]	360.8	394	394	394	390.8	3.5
Pressure [atm]	7.21	7.21	1.00	1.00	1.00	1.00
Temperature [K]	298	298	298	298	298	298
Phase	liquid	liquid	liquid	liquid	vapor	solid
Major Component	CAP water	CAP water	CAP water	CAP water	Water	Brine Salts
TDS [mg/L]	3750	3750	3750	3750	0	[1:3 volume ratio of salt to water]

***Note: The given flow rates are averages between two streams that participate in a batch evaporation process in two evaporation ponds at different times For further reference on the drying and filling cycles see the Written Process Description in Section 2.6 or the material balances in Appendix D.

Table 2.4: Stream table. Contains flow rates, pressure, temperature, phase, major component, and TDS concentration of each stream. Stream numbers correspond to those on the PFD in Section 2.2.

2.5 UTILITY TABLES

The following Table 2.5.1 shows the electricity required by the process equipment, indicated by the PFD codes. The electricity in kilowatts is given, as well as the annual cost.

Utility	Equipment	Amount [per unit]	Annual Cost 2009 [per unit]
Electricity		[kW-h]	[$]
	P-101 to P-109	68	$60,000
	P-201 to P-212	132	$116,100
	P-301 to P-312	41	$35,900
	C-101	23	$20,500
	C-102	23	$20,500
Total Electricity		2743	**$2,404,800**

Table 2.5.1: Annual power use.

The following Table 2.5.2 shows the amount and annual cost of the raw materials needed for the process.

Raw Material	Amount	Annual Cost [$] 2009
CAP water	144,090 Acre-ft/yr	$20,605,100
Polyacrylamide [solid]	681,380 lb/yr	$10,220,100
Chlorine [100% liquid]	208,570 lb/yr	$27,200
Iron Chloride [solid]	139,050 lb/yr	$69,500
Sulfuric Acid [100% liquid]	139,050 lb/yr	$1,800
Vitech® 4000	410,190 lb/yr	$717,800
Well Water	49,980 Acre-ft/yr	$2,610,400
Total Raw Material Costs		**$34,251,930**

Table 2.5.2: Raw Materials.

2.6 WRITTEN PROCESS DESCRIPTION

Prior to being treated using reverse osmosis, the CAP water that comes from the Colorado River must be pre-treated in order to disinfect the water, protect the RO membranes, and increase the overall efficiency of the RO process. CAP water enters the pre-treatment facility as Stream 1 with a mass flow rate of 1964.5 kg/s and a TDS concentration of 750 mg/L (U. Yenal, personal communication, January 20, 2009). The temperature of the system remains at 298 K and the pressure is generally at 1.00 atm unless noted otherwise. More specific details about all of the streams can be found in the stream tables located in Section 2.4.

Liquid chlorine at a concentration of 100% enters in Stream 2 at around 0.003 kg/s, the polyelectrolyte polyacrylamide enters as a solid in Stream 3 at roughly 0.0098 kg/s, and a coagulant iron chloride enters as a solid in Stream 4 at 0.002 kg/s (Mike, personal communication, April 14, 2009). The chlorine is used as a disinfectant, and the coagulant and polyelectrolyte are used to increase the efficiency and ease of filtering. Streams 2, 3, and 4 then pass through a four-way valve V-101 where they are mixed together to form Stream 5, which has an overall mass flow rate of 0.0148 kg/s. Stream 5 then passes through three-way valve V-102 where it mixes with Stream 1 and then exits as Stream 8. The overall mass of Stream 1 is not affected a great deal by the addition of Stream 5, and therefore the mass flow rate of Stream 8 remains at around 1964.5 kg/s. The ending concentrations in the CAP water of Stream 8 of the components in Stream 5 are fairly small at 1 mg/L of the coagulant, 5 mg/L of the polyelectrolyte, and 1.5 mg/L of the chlorine (Mike, personal communication, April 14, 2009).

Stream 8 is assumed to be at atmospheric conditions when it enters pumps P-101 through P-109 in parallel. The CAP water then exits pumps P-101 through P-109 as Stream 9 at 3.34 atm. The purpose of pumps P-101 through P-109 is to raise the pressure of the stream before it enters the pre-treatment filtering system and to transport the liquid into the plant (S. Wolfson, personal communication, April 13, 2009). In order to mix in the chlorine, polyelectrolyte, and coagulant sufficiently, the water is passed through turbine mixer C-101, which has an assumed residence time of 2 minutes (Sieder, 2003). The thoroughly mixed CAP water then exits mixer C-101 as Stream 10 and enters the sand filter F-101, where it exits as Stream 11. After passing through the sand filter F-101, the CAP water of Stream 11 enters the carbon filter F-102 and exits as Stream 12.

The antiscalant Vitech® 4000 enters the system as a liquid with a concentration of 100% in Stream 6 at a mass flow rate 0.0059 kg/s and the sulfuric acid enters as a liquid at a concentration of 100% in Stream 7 (R. Goodlett, personal communication, April 14, 2009). The antiscalant is used to prevent the precipitation of components with low saturation values, or scaling, on the membranes in the RO units when the salt concentration in the solution is significantly increased. Sulfuric acid is used to regulate the pH of the water into the RO units in order to optimize the performance of the RO membranes and to also help prevent scaling. Streams 6 and 7 are then mixed with Stream 12 in four-way valve V-103 and exit as Stream 13. The final concentration of the antiscalant in the CAP water is around 1 mg/L and the final concentration of the sulfuric acid in the CAP water is around 1 mg/L.

Stream 13 then enters the turbine mixer C-102 where the CAP water, sulfuric acid, and antiscalant are thoroughly mixed. Stream 14 exits mixer C-102 and enters the cartridge filter unit F-103, which filters out more fine suspended solids and some of the chlorine to prevent damaging the membranes. The CAP water exits cartridge filter unit F-103 as Stream 15. Throughout the pre-treatment process, the TDS concentration remains at 750 mg/L due to the fact that it is largely the suspended solids, and not the dissolved solids that are filtered out during pre-treatment.

The pre-treated CAP water enters the RO facility as Stream 15 at 750 mg/L of TDS and 1969 L/s. The flow in Stream 15 is split using the four-way valve V-201 into Streams 16, 17, and 18, which are equal and each have a flow rate of 654.8 kg/s. Streams 16, 17, and 18 are then each split into two equal streams by using three three-way valves V-202, V-203, and V-204, respectively. The resulting streams from splitting Streams 16, 17 and 18 into equal parts are Streams 19 and 20, Streams 21 and 22, and Streams 23 and 24, respectively. Streams 19, 20, 21, 22, 23, and 24 are each split into two equal streams by valves V-205, V-206, V-207, V-208, V-209, and V-210, respectively. The streams resulting from the splitting of Streams 19, 20, 21, 22, 23, 24 are Streams 25 and 26, Streams 27 and 28, Streams 29 and 30, Streams 31 and 32, Streams 33 and 34, and Streams 35 and 36, respectively. Through the divergence of flow three separate times the TDS level is assumed to remain constant, and therefore the TDS level is equal at 750 mg/L for streams 25 through 36 (See Appendix D).

Streams 25 through 36 each pass through pumps P-201 A/B, P-202, P-203, P-204, P-205, P-206, P-207, P-208, P-209, P-210, P-211, and P-212, respectively and become streams 37 through 48, respectively. The purpose of the pumps is to raise the pressure to 7.06 atm prior to entering the membrane units (Hydranautics, 2009).

Stream 37 passes through membrane units M-101 to M-152 and is separated into permeate Stream 49 and concentrate Stream 72. Stream 38 passes through membrane units M-153 to M-204 and is separated into permeate Stream 50 and concentrate Stream 73. Stream 39 passes through membrane units M-205 to M-256 and is separated into permeate Stream 51 and concentrate Stream 74. Stream 40 passes through membrane units M-257 to M-308 and is separated into permeate Stream 52 and concentrate Stream 75. Stream 41 passes through membrane units M-309 to M-360 and is separated into permeate Stream 53 and concentrate Stream 76. Stream 42 passes through membrane units M-361 to M-412 and is separated into permeate Stream 54 and concentrate Stream 77. Stream 43 passes through membrane units M-413 to M-464 and is separated into permeate Stream 55 and concentrate Stream 78. Stream 44 passes through membranes M-465 to M-516 and is separated into permeate Stream 56 and concentrate Stream 79. Stream 45 passes through membrane units M-517 to M-568 and is separated into permeate Stream 57 and concentrate Stream 80. Stream 46 passes through membrane units M-569 to M-620 and is separated into permeate Stream 58 and concentrate Stream 81. Stream 47 passes through membrane units M-621 to M-672 and is separated into permeate Stream 59 and concentrate Stream 82. Stream 48 passes through membrane units M-673 to M-724 and is separated into permeate Stream 60 and concentrate Stream 83. Each concentrate stream exits its corresponding membrane unit in the first stage at 5.31 atm while the permeate streams are atmospheric conditions. Permeate streams 49 through 60 each have a mass flow rate of 79.8 kg/s and an assumed TDS concentration of 0 mg/L since the flux of salt through the membranes will be negligible. Concentrate streams 72 through 83 from the first membrane stage each have a mass flow rate of 84 kg/s and a TDS concentration of 1462 mg/L (See Appendix D).

The permeate streams from stage 1 are added together using several 3-way valves. Stream 49 is mixed with Stream 50 in valve V-211 and exits as Stream 61 at a flow rate of 159.4 kg/s. The mixed Stream 61 is then combined with permeate Stream 51 in valve V-212 and exits as Stream 62 at a flow rate of 239.2 kg/s. Stream 62 then enters valve V-213 where it is mixed with permeate Stream 52 and exits as Stream 63 at a flow rate of 318.8 kg/s. The mixed Stream 63 is then combined with permeate Stream 53 in valve V-214 where it exits as Stream 64 at a flow rate of 398.7 kg/s. Stream 64 then enters valve V-215 where it is mixed with permeate stream 54 and then exits as Stream 65 with a flow rate of 478.4 kg/s. The mixed Stream 65 is combined with permeate Stream 55 in valve V-216 where it then exits as Stream 66. Stream 66, with a flow rate of 558.1 kg/s, is then mixed with permeate Stream 56 in valve V-217. Stream 67 exits valve V-217 at a flow rate of 637.9 kg/s and then is mixed with permeate Stream 57 in valve V-218. Stream 68 exits valve V-218 at a flow rate of 717.5 kg/s. Then, Stream 68 is mixed with permeate Stream 58 in valve V-219, where it exits as Stream 69 with a flow rate of 797.3 kg/s. Stream 69 then enters valve V-220, where it is mixed with permeate Stream 59. Stream 70 exits valve V-220 at a flow rate of 877.1 kg/s and then enters valve V-221 where it is mixed with permeate Stream 60. Stream 71 exits valve V-221 at a flow rate of 956.7 kg/s. All of the permeate streams 49 through 71 have a TDS concentration of 0 mg/L (See Appendix D).

Concentrate streams 72 through 83 then pass through pumps P-301, P-302, P-303, P-304, P-305, P-306, P-307, P-308, P-309, P-310, P-311, and P-312, respectively. The concentrate Streams 72 through 83 exit pumps P-301 through P-312 as Streams 84 through 95, respectively. The purpose of pumps P-301 through P-312 is to raise the pressure of the stage 1 RO concentrate from 5.31 atm to 8.71 atm in order to enter the stage 2 RO membranes (Hydranautics, 2009).

Once Streams 84 through 95 have exited pumps P-301 through P-312 they enter in second stage membrane units M-(725-754), M-(755-784), M-(785-814), M-(815-844), M-(845-874), M-(875-904), M-(905-934), M-(935-964), M-(965-994), M-(995-1024), M-(1025-1054), and M-(1055-1084), respectively. Streams 84 through 95 exit their corresponding membrane unit with permeate streams 96 through 107, respectively and concentrate streams 120 through 131, respectively. The permeate streams 96 through 107 from the second stage of RO each have a flow rate of 51.2 kg/s, a TDS concentration of 0 mg/L. Concentrate streams 120 through 131 from the second stage of RO each have a flow rate of 32.8 kg/s, a TDS concentration of 3750 mg/L (See Appendix D). The concentrate streams exit the membrane units at a pressure of 7.21 atm while the permeate units are at atmospheric conditions (Hydranautics, 2009).

All the permeate streams from the second stage are combined together using 3-way valves and then added to the permeate exit Stream 71 from the first stage of membranes. Permeate Stream 96 is mixed with permeate Stream 97 in valve V-301 and then exits as Stream 108, which has a flow rate of 102.5 kg/s. The mixed Stream 108 is then combined with permeate Stream 98 in valve V-302. Stream 109 exits valve V-302 with a flow rate of 153.7 kg/s, and then mixes with Stream 99 in valve V-303. Stream 110 exits valve V-303 at a flow rate of 205 kg/s. Permeate stream 100 enters valve V-304 where it is combined with the mixed Stream 110. Stream 111 exits valve V-304 at a flow rate of 256.2 kg/s and then enters valve V-305 where it is mixed with permeate Stream 101. Then, Stream 112 exits valve V-305 at a flow rate of 307.1 kg/s before it enters valve V-306 where it is combined with permeate Stream 102. Stream 113 exits valve V-306 at a flow rate of 358.6 kg/s. Then Stream 113 enters valve V-307 where it is mixed with permeate Stream 103 and then exits as Stream 114 at a flow rate of 409.9 kg/s. Steam 114 then enters valve V-308 where it mixes with permeate stream 104 and exits as Stream 115 at a flow rate of 461.1 kg/s. Then Stream 115 enters valve V-309 where it mixes with permeate Stream 105 and exits as Stream 116 at a flow rate of 512.4 kg/s. Stream 116 enters valve V-310 where it mixes with permeate Stream 106 and exits as Stream 117 at a flow rate of 563.6 kg/s. After exiting valve V-310 permeate Stream 117 mixes with permeate Stream 107 in valve V-311. Stream 118 exits valve V-311 at a flow rate of 614.8 kg/s. The permeate Stream 118 from the second membrane stage combines with the permeate Stream 71 from the first membrane stage in valve V-312. Stream 119 exits valve V-312 at a flow rate of 1571.2 kg/s (See Appendix D).

The concentrate streams from Stage 2 are also added together using 3-way valves. Stream 120 is mixed with Stream 121 in valve V-313 and exits as Stream 132 with a flow rate of 65.6 kg/s. Stream 132 is then combined with concentrate Stream 122 in valve V-314 and exits as Stream 133, which has a flow rate of 98.4 kg/s. Then Stream 133 enters valve V-315 where it is mixed with concentrate Stream 123 and exits as Stream 134, which has a flow rate of 131.2 kg/s. The mixed Stream 134 is then combined with concentrate Stream 124 in valve V-316 where it exits as Stream 135 with a flow rate of 164 kg/s. Stream 135 then enters valve V-317 where it is mixed with concentrate stream 125 and then exits as Stream 136 with a flow rate of 196.8 kg/s. Stream 136 is combined with concentrate Stream 126 in valve V-318 where it then exits as Stream 137. Stream 137 has a flow rate of 229.6 kg/s and is mixed with concentrate Stream 127 in valve V-319. Stream 138 exits valve V-319 at a flow rate of 262.4 kg/s and then mixes with concentrate Stream 128 in valve V-320. Stream 139 exits valve V-320 at a flow rate of 295.2 kg/s. Then, Stream 139 is mixed with concentrate Stream 129 in valve V-321, where it exits as Stream 140 with a flow rate of 328 kg/s. Stream 140 then enters valve V-322, where it is mixed with concentrate Stream 130. Stream 141 exits valve V-322 at a flow rate of 360.8 kg/s and then enters valve V-323 where it is mixed with concentrate Stream 131. Stream 142 exits valve V-323 at a flow rate of 394 kg/s (See Appendix D). After exiting the RO facility the brine/concentrate Stream 142 is transported to an evaporation pond in order to dispose of the waste in a more environmentally benign manner.

The RO brine/concentrate from the RO plant, Stream 142, then is pumped to one of two evaporation ponds in parallel. The concentrate in Stream 142 enters pressure relief valve V-401 at a pressure of 7.21 atm and exits as Stream 143 at a pressure of 1.00 atm. Then, depending on which evaporation pond is in its drying stage and which is in its filling stage of the evaporation process, Stream 143 will exit the four-way valve V-402 as either stream 144 or 145. If evaporation pond E-401 is in its filling stage, then Stream 143 will exit valve V-402 as Stream 144 at a flow rate of 394 kg/s. In the case of filling evaporation pond E-101, valve V-402 would be closed off to Stream 145 and the flow rate of Stream 145 would therefore be 0 kg/s. The liquid present in evaporation pond E-102 would then have time to evaporate enough to remove and dispose of the salt slurry. If evaporation pond E-402 is in its filling stage, then Stream 143 will exit valve V-402 as Stream 145 at a flow rate of 394 kg/s. In the case of filling evaporation pond E-102, valve V-402 would be closed off to Stream 144 and the flow rate of Stream 144 would therefore be 0 kg/s. At this point the liquid in evaporation pond E-101 would be in its evaporation, or drying stage. On average the liquid water evaporates as Stream 146 or Stream 147 and as a vapor with a volumetric flow rate of 486,300 L/s at standard atmospheric conditions and a mass flow rate of 390.8 kg/s. Additionally, on average over time the salt slurry is removed as Stream 148 or Stream 149 at a rate of 3.5 kg/s. In Stream 149, 1.5 kg/s of the stream is salt and the rest consists of excess water/salt solution to form the salt slurry. In the chosen schematic, with the dimensions of the two alternated evaporation ponds E-101 and E-102 as 1600 x 1600 x 0.75 meters, the pond filling time is 1070 days and the drying time is 1050 days (See Appendix A). A slightly smaller time is allotted to the drying stage for completion of the salt removal process.

2.7 RATIONALE FOR PROCESS CHOICE

The RO plant is designed to be built in Avra Valley due to availability of land, which also gives an option to build large evaporation ponds for disposing the brine in an environmentally friendly way (U. Yenal, personal communication, January 20, 2009). The site gives the flexibility of meeting future capacity requirements, and it is compatible with the existing water supply network. In addition, the warm and dry climate in Arizona makes this option more feasible.

The treatment strategy chosen is reverse osmosis (RO), a treatment process that is commonly used in industry for purifying water (DecisionH20, 2000). The permeate obtained using reverse osmosis has an improved quality and can be used for a broad range of applications. Some applications of reverse osmosis include purifying water to use as drinking water or producing high purity water for use in power generation, pharmaceuticals, microelectronics, or food and beverage industries (Petrosepmembrane, 2001). Reverse osmosis can be used to remove many different contaminants ranging from salts to organic compounds to bacteria and viruses. Another reason for choosing an RO plant for water treatment over other methods such as ion exchange and flocculation is to meet the constraint of 450 mg/L TDS in the most economical way possible. Due to the large flow rate of water 1,969 L/s, an RO plant is the only viable option. An ion exchange method was not considered due to the cost associated with the regenerate chemicals, which was approximately the same as the RO plant for a feed water flow rate 42% lower than 1,969 L/s (Steyn and Schoeman, 2000). Ion exchange is not particularly good for this system because the focus is not to remove specific chemicals from the water but rather it is to reduce the overall TDS level to 450 mg/L in the most economical way possible (Kelly and Walker, 2003). Costs associated with regenerate chemicals are also a concern in an ion exchange method. About 20 ppm of 1 molar sodium hydroxide is required when a strong base anion resin is used (Polson, 2009) in contrast to 1 ppm of sulfuric acid required in the pre-treatment of the RO plant (R. Goodlett, personal communication, April, 14, 2009). The pressure drop across the ion exchange bed should not exceed 1 bar because the resins are likely to become deformed and flattened (Rohm and Haas, 2009). However, with large flow rates such as 1,969 L/s, a large ion exchange bed would be required, and the high pressures would damage the resins. Hence, ion exchange is not the most feasible option for this process. Flocculation alone is not the best option for treatment either, because of high flow rates involved and the constraint for achieving 450 mg/L. Therefore, flocculation is used only in the pre-treatment of the RO process to remove big particles. For more details on this process, refer to Section 3.1.1.

For high flow rates of water such as ours, reverse osmosis is done in 2 stages in order to decrease concentration polarization and make the system more efficient (Franks et. al, 2007). In terms of capital cost, a two stage design reduces the cost of piping and pressure vessels compared to a 3 stage design, in addition to achieving a better flux distribution throughout the system (Franks et. al, 2007). A 3 stage reverse osmosis can also achieve the required purity; however, it is not required for this design. A 2 stage RO process was determined to be the best for the flow rate in our system by the Hydranautics program IMSDesign™ (2009).

The RO process includes a pre-treatment system which removes coarse particles and particles which reduce the lifetime of the RO membranes due to fouling and scaling. The pre-treatment includes filtration (F-101, F-102, and F-103), mixers (C-101 and C-102), and addition of disinfectants such as chlorine. The specifics for pre-treatment can be found in Section 3.1. In pre-treatment, pH is adjusted to an appropriate level so that the Langlier index is correct (Siemens, 2006). Antiscalants are used on a volumetric basis to avoid scaling of the membranes (Siemens, 2006). A sand filter (F-101) is used to remove big flocculated particles formed by adding polyelectrolyte and coagulants. A carbon filter (F-102) is used to remove any traces of organic chemicals present in the incoming water such as pesticides, and chlorine (Siemens, 2006). A cartridge filter (F-103) at the end of pre-treatment ensures removal of any leftover particles which might contribute to the fouling of the membranes (Siemens, 2006).

Due to the large water flow rate of 1,969 L/s, 12 sets of 55 pressure vessels running in parallel are used. Each vessel has 6 membrane elements in series. These values are obtained by using a Hydranautics RO Projection Program IMSDesign™ for designing industrial sized RO plants (Hydranautics, 2009). Refer to Appendix B for program details.

Such a large feed water flow rate produces huge amounts of reject brine, and in order to dispose the brine, an evaporation pond system was designed. This system is used as a way to dispose of the concentrate stream because it was determined to be the most environmentally conscious method in Avra Valley. Multiple brine management methods for inland sites were considered, including surface water discharge, deep well injection, land application, wastewater discharge, solar ponds, and evaporation ponds (Mickley, 2001). The method chosen is largely based on the location of the site and state and local permitting. Wilma Engineering has chosen to implement an evaporation pond system due to the suitability of the region of Avra Valley. It has characteristic low rainfall and climatic conditions that are warm and dry: favorable for steady and relatively rapid evaporation rates.

There are, however, some disadvantages to evaporation ponds. They can require large areas of land, which can potentially limit their implementation or add significant cost. The situation in Avra Valley does not face this cost hazard though, as there is ample land available at a reasonable price.

Evaporation ponds are efficient because they help in safe disposal of water. Two evaporation ponds are used: the first pond is filled with concentrate, while the water in the second one is evaporating. This system was optimized so that enough time is available to clean each pond before reuse.

3.0 EQUIPMENT DESCRIPTION, RATIONALE, AND OPTIMIZATION

The following section describes and rationalizes each piece of equipment used in the water treatment plant. The specifications for all the equipment can be found in equipment tables in Section 2.3. Detailed process calculations and equipment calculations can be found in Appendix A. The material of construction used consists of stainless steel for mixers, filters, pumps, and pressure vessels. Stainless steel was chosen as the material of construction because small amounts of incompatible sulfuric acid (~1 ppm) are used in the pre-treatment process (Materials Compatibility, 2008). PVC liners are used for the evaporation ponds because they are strong, easily repaired, and economically feasible (Diebel, 2003), and plastic is used as the material of construction of some parts of filters because they are inexpensive (Plastic materials). Refer to the PFD in Section 2.2 as needed.

3.1 PRE-TREATMENT SYSTEM

The feed CAP water contains suspended solids which must be removed to avoid damaging the membranes of the RO process. The suspended solids may contain inorganic particles, colloids, microorganisms, and algae. High concentrations of suspended solids promote membrane fouling. Common indicators of suspended particles in RO industry are turbidity and Silt Density Index (SDI). For long term and reliable operation of RO units, the values of turbidity and SDI should not exceed 0.5 and 2.5 respectively (Hydranautics, 2009). A typical preconditioning package consists of the following steps:

- Large particle remover using coarse strainer.
- Use of chlorine to disinfect water.
- Clarification with or without flocculation.
- Lime treatment to reduce hardness.
- Media filtration.
- Adjustment of pH to reduce alkalinity
- Addition of antiscalants
- Using activated carbon filters to reduce chlorine
- UV radiation for sterilization
- Use of cartridge filters for removal of remaining suspended particles.

Figure 3.1 shows a typical pre-treatment system for CAP water (Hydranautics, 2009).

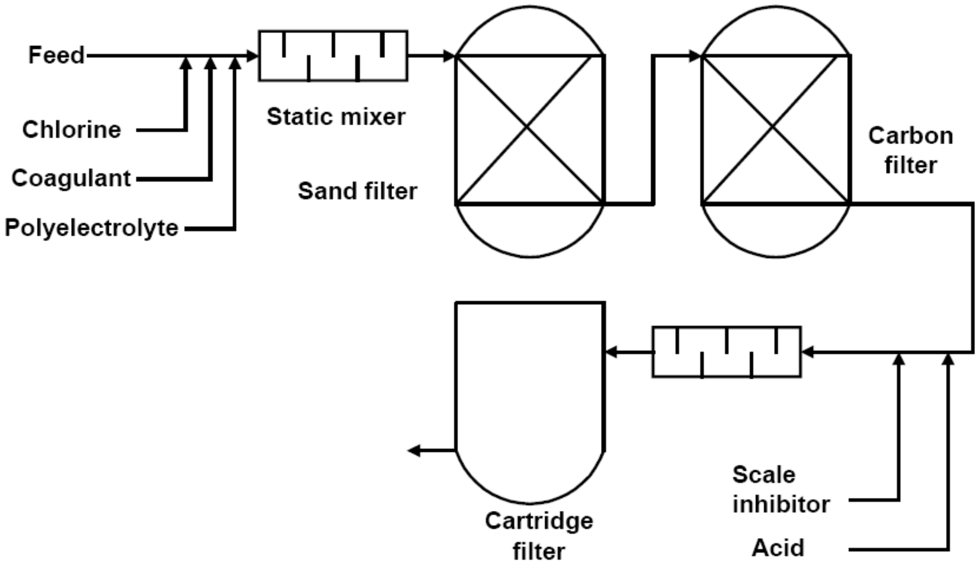


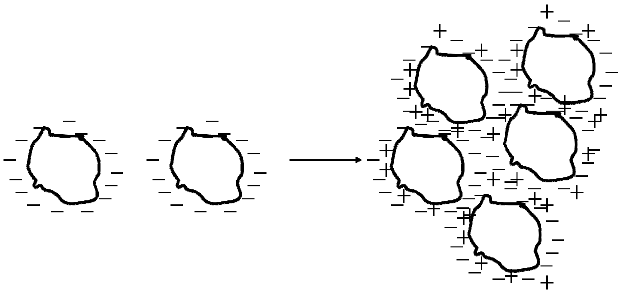
Figure 3.1: Pre-treatment of water prior to entering the RO unit (Hydranautics, 2009).

This a conventional type of filtration system utilizing media filters. It was chosen over new technologies such as ultra-filtration because of large flow rate of the feed, which makes it economically impractical to use ultra filtration (Charlie, personal communication, April 14, 2009).

The following section will describe specific equipment and important components of the pre-treatment system.

3.1.1 Addition of chlorine, coagulant, and polyelectrolyte

The surface feed water is disinfected by addition of chlorine to control the biological activity. The disinfection process is affected by pH, temperature, and contact time with water. Chlorine is extremely deleterious for the membranes, and therefore a very small amount (~1.5 ppm) of the chemical is added (Agriculture and Agrifood, 2009). In addition, large amounts of chlorine form disinfection byproducts such as dissolved organic carbon or tannins. Coagulant or flocculent, such as polyaluminum chloride (PAX) or iron chloride ($FeCl_3$), is added to promote coagulation by creating chemical attraction between particles due to presence of aluminum ions in water (Coagulation and Flocculation, 2008). Iron chloride is used because it is common and readily available (Coagulation and Flocculation, 2008). Suspended particles in the presence of PAX form large clusters of particles known as “flocs”, as illustrated in Figure 3.1.1.



Colloidal particles (0.001 – 1 µm) Floc (1-100 µm)

Figure 3.1.1: Illustration of floc formation (Coagulation and Flocculation, 2008).

Small amounts of polyelectrolytes such as polyacrylamide are added, which also serve as coagulants. Polyacrylamide is used because it is not only easily available but it is also the most common polyelectrolyte available for a cheaper price than other polyelectrolytes such as polyaniline and polyacrylonitrile (Goodlett, 2009). Some countries such as Japan do not permit polyelectrolytes because the presence of unreacted monomers in water may cause concern (Water Treatment Chemicals and Construction Materials). However, the US permits the use of polyelectrolytes, and hence, those concerns were ignored.

3.1.2 Static Mixer (C-101 and C-102)

As the name suggests, static mixers are used to mix all the added chemicals uniformly throughout the feed. According to Seider, the most widely used devices for agitation in vessels are propellers and turbines (2003, p. 537). Propellers are the cheaper option; however they are only rated for 1-8 Hp (2003, p. 553). Turbines are more versatile and have a higher range of 2-

60 Hp (2003, p. 553). Based on a calculated power requirement of 31.23 Hp (Appendix A), a turbine agitator was chosen. A closed vessel design was chosen to reduce contamination.

3.1.3 Sand Filters (F-101)

These filters are used to remove the flocculated particles while removing bacteria and most of the solids. Horizontal commercial sand filters are used to serve this purpose because these filters could withstand high flow rates up to 1500 gpm (Sand Filters, 2009). Since, 1500 gpm is still much lower than the feed water flow rate of 31,200 gpm, 21 sand filters in parallel are used to treat all the water. Each filter has 75 square feet of filtration area along with media drain. Sand filtration is based on two principles: mechanical straining and physical absorption. It is used for separating suspended and colloidal impurities from water by a passage through the sand (Schmidt and Shinault, 1998). The factor which has the largest effect in this process is the relative filter size of the filter medium (Schmidt and Shinault, 1998). Cleaning of sand filters will be done using back washing. Figure 3.1.3 shows an example of a sand filtration system.

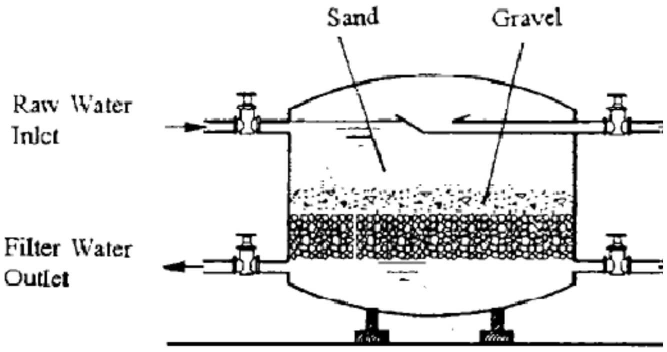


Figure 3.1.3: Illustration of a sand filtration process (Rapid Sand Filtration).

3.1.4 Carbon Filters (F-102)

This piece of equipment utilizes activated carbon to remove contaminants and impurities by chemical absorption. These filters also remove most of the chlorine added in the pre-treatment step (Dvorak and Skipton, 2008). This is important because chlorine affects the RO membranes negatively, and carbon filters help reduce the damage chlorine can possibly cause. The efficiency of this process is affected by carbon characteristics such as particle and pore size, surface area, and density (Dvorak and Skipton, 2008). An illustration which shows the process of carbon filtration can be seen in Figure 3.1.4.

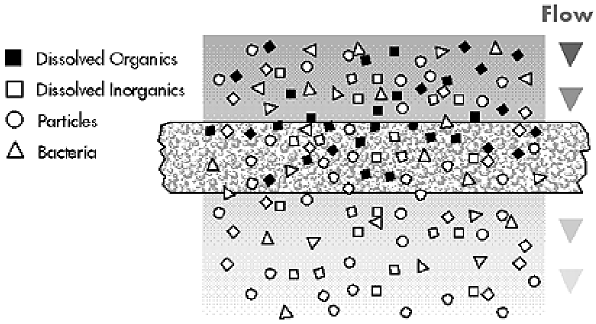


Figure 3.1.4: Illustration of carbon filtration (Reengineering, 2008).

3.1.5 Addition of antiscalants and sulfuric acid

Antiscalants are added to avoid scaling of RO membranes. In water treatment plants, only small amounts of antiscalants are added to avoid contamination. It was decided to add 3 ppm or 0.0059 kg/s of Vitech® 4000 as calculated using an antiscalant dosing program by Avistatech (R. Goodlett, personal communication, April 14, 2009). Vitech® 4000 is specifically used because of its versatile properties such as hardness inhibition ability, sulfate scale inhibition, dispersion, enhanced silica scale inhibition, and chlorine tolerance (R. Goodlett, personal communication, April 14, 2009).

3.1.6 Cartridge Filters

Cartridge filters act as the final barriers to the water-borne particles. The nominal rating in RO applications varies between 5-15 microns (Hydranautics, 2009). These types of filters are always used in reverse osmosis plants (Hydranautics, 2009). For high flow rate systems, such as 31,200 gpm, 38 cartridge filters in parallel are used. A maximum flow rate of 825 gpm can flow through each cartridge. For details and specifications, refer to Appendix F.

3.2 OVERALL RO SYSTEM

Commercial RO systems use spiral-wound membranes to treat water. The following section will explain how a spiral membrane works. The spiral-wound membrane RO unit is extremely effective because it allows for a large membrane area to be housed within a relatively small volume (Membrane Technology, 2008). Within the unit, the RO membrane is wrapped around a central axis, as shown in Figure 3.2a. Compared to the flat membrane RO system, this type of membrane handles larger flow rates of feed solution, producing permeate in larger quantities.

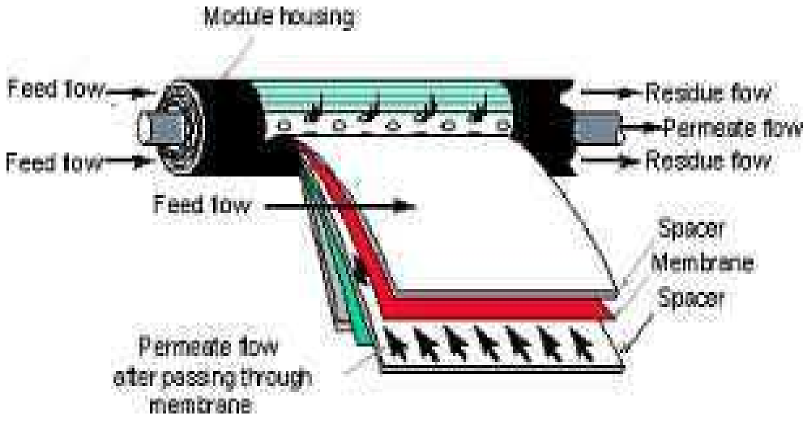


Figure 3.2a: Spiral membrane unit (Membrane Technology, 2008).

The system is divided into 2 groups of pressure vessels known as concentrate stages. Pressure vessels are connected in parallel with respect to feed flow in each stage. The number of pressure vessels in each subsequent stage decreases in the direction of feed flow usually in the ratio of 2:1 as shown in Figure 3.2b (Hydranautics, 2009).

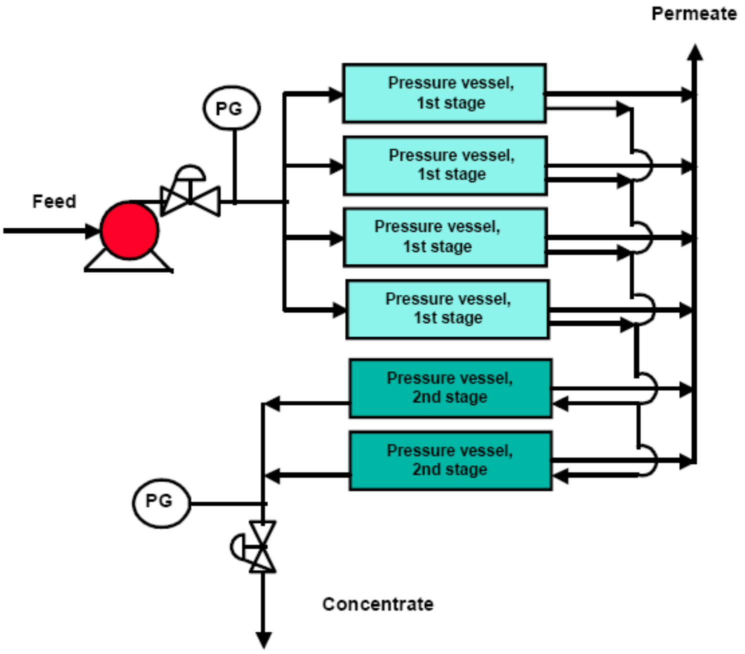


Figure 3.2b: Flow diagram for a 2 stage RO system (Membrane Technology, 2008).

3.2.1 RO membrane ESPA2+

Various membranes were investigated for use in the RO process. The particular type chosen was the Energy Saving Polyamide 2+ (ESPA2+) based on its high flow capacity and high rejection polyamide chemistry. This membrane has been tested and proven to achieve a 99.6% salt rejection at standard test conditions and has seen flow rates of 12,000 gpd (Franks, 2007). One advantage to this membrane is the reduced pressure drop as permeate travels through the spiral path to the element core. The surface area of the ESPA2+ is also large, at 440 ft^2, which is made possible by the method of manufacture (Franks, 2007). The higher surface area provides advantages such as a lower system flux and lower operating cost. The lower flux in turn reduces the cleaning chemical consumption, since fouling is decreased. Energy requirements are also reduced since the feed pressure is lower. In addition, the Hydranautics program for designing a reverse osmosis plant also recommended this type of membrane (2009). Therefore, ESPA2+ type membranes worked the best for our design. Since the feed water flow rate is extremely large (1,969 L/s), 5,904 total membranes were calculated for an 80% recovery. For details, refer to Appendix A, and refer to PFD in Section 2.2 to view the general parallel set up of the RO membranes.

3.3 PUMPS

Centrifugal pumps were selected instead of reciprocating, and various other types of pumps. Centrifugal pumps usually work the best and are easily available when the volumetric flow rate varies between 10 gpm to 5,000 gpm (Seider, 507). These types of pumps consist of an impeller with blades rotating inside a casing and require relatively low maintenance and also provide more steady fluid flow at the pump outlet (Centrifugal Pump Design, n.d.). In the pre-treatment process, 9 single stage 1,800 rpm VSC (Vertical Split Case) pumps (P-101 to P-109) with a flow rate of 3,500 gpm each are chosen over 7 single stage 1,800 rpm HSC (Horizontal Split Case) pumps with 5,000 gpm flow rate. This decision saved approximately $55,000. For more details on economic calculations, refer to Appendix A. The feed water flow rate in the design is 31,200 gpm, so it was decided to divide the flow rate into 12 streams, details of which can be viewed in PFD (Section 2.2). All of the pumps are driven by electric motors because they are more efficient (Seider, 509).

3.4 EVAPORATION PONDS (E-401 AND E-402)

The evaporation pond system is a semi-batch process and generally requires two time steps to operate. The first stage in extracting the solids from the water is to fill the pond. As the pond is filling, only a small portion of the water will evaporate. Once it is filled, the evaporation pond is allowed to stagnate until most of the water has evaporated and only salt slurry is left. While the water is evaporating, the RO brine is diverted to another pond. The slurry left from the RO brine after the water has evaporated would then be disposed of. Implementing an evaporation pond would prevent the RO brine from simply being injected back into the aquifer or contaminating the groundwater through other means. It takes 2.93 years to fill a pond of dimensions 1605 x 1605 x 0.75 m. The drying time for the evaporation ponds is 2.87 years. There are roughly 20 extra days in the drying time in order to account for the removal of the salts from the evaporation pond. The area of the evaporation pond was chosen in order to maximize the continuous evaporation during the filling process. Therefore, the optimal ratio between the drying time and filling time was 0.98. Higher drying to filling time ratios were disregarded because of the much larger areas that would be necessary for a successful evaporation pond system. Also, the depth of the evaporation pond was chosen to be 0.75 m in order to decrease the total time necessary for drying the RO brine. This was done to achieve reasonable times while still giving sufficient depth to the ponds. A benefit of installing an evaporation pond is that it greatly improves the environmental impact of the RO process by preventing the brine from becoming a large environmental and health hazard.

3.4.1 Use of PVC liners

Polyvinyl Chloride (PVC) was chosen as the most effective geomembrane liner material to line the evaporation ponds. Since evaporation of the RO brine in the ponds takes an extended period of time, it is important that the pond liners are resistant to leaks and easily repairable if damage occurs (Diebel, 2003). PVC is a durable membrane material with high chemical resistance to salts, a necessary property to withstand long-term exposure to pools of brine. In addition to its strength, it has a low coefficient of expansion, higher geomembrane interface strength, and the flexibility to resist wrinkling. PVC tends to drape around protrusions on the compacted layer underneath, so that the occurrence of small holes and brine loss is minimized. It can adapt and conform to rough sub grades better than most other geomembrane liner materials (Layfield, 2009) and easily lays flat after installing pre-fabricated large panels (Berube, 2006).

4.0 SAFETY ISSUES

4.1 SAFETY DISCUSSION

The design contains three main sections: pre-treatment, the RO plant, and the evaporation ponds used in conjunction with brine disposal. The greatest safety hazards can be found in the pre-treatment section. During the pre-treatment phase, small amounts of concentrated sulfuric acid, chlorine, coagulant, antiscalant, and polyelectrolyte are added to the water before entering the RO plant. Chlorine and sulfuric acid are highly corrosive and can cause severe burns through skin contact, eye contact, inhalation, and ingestion. Prolonged exposure to these chemicals can also lead to death. All personnel should wear a full protective suit, splash goggles, boots, and gloves when handling these substances in their concentrated forms (Sciencelab, 2008). These substances are contained in shielded storage areas. A detailed analysis of process hazards can be found in the following Process Hazard Analysis (Section 4.2).

Under normal circumstances, operation of the RO plant should not involve any specific safety considerations. None of the salts or chemicals in the water being treated are at high enough concentrations to pose a safety hazard should a release occur. The integrity of all the components becomes an issue since the system operates at high pressures up to 8.71 atm. Therefore, care must be taken to operate the plant in accordance with manufacturers' guidelines. In addition, the plant must be continuously monitored to record any deviations from normal behavior.

The following are some safety factors which must be taken into account when operating the RO plants (Panicker, 2008):

- Power system: It is important to have a reliable source of electricity when the plant is under operation. Power supply to the loads will be metered to check their performance and to keep values within the rating limits.
- Advanced Automation System: A conventional RO system has various automated system controls such as main power control, an emergency shutdown system, and a pressure monitoring system. However, additional controls that monitor critical parameters such as pressure or temperature can increase the safety of the plant. To manage the system Supervision Control and Data Acquisition (SCADA) along with controllers will be incorporated. The SCADA system allows a central station to send control information to, and receive feedback from remote stations. Flexibility is one of the main advantages of this device. The system can also be operated remotely.
- Operation of the Valves: The most critical points for the RO unit are the high pressure valve at the inlet and the permeate controlling valve at the exit. If the quality of the pre-treated water is not up to standard in terms of pH, turbidity, and chlorine content, it will be sent back for pre-treatment again before it enters the RO unit. Similarly, conductance of the permeate will be regularly checked to ensure sufficient water quality.

Safety issues are also present in the evaporation pond section. The following paragraph discusses the considerations for handling the brine from the RO unit.

The evaporation ponds, designed for safe waste disposal of the brine, do not pose specific risks as far as human safety is concerned. However, during the drying stage of the evaporation process, certain safety concerns due to presence of potentially toxic salts might arise. The brine from the RO plant consists of different amounts of salts which may be harmful for human and animal health. Various salts of magnesium, silicon, strontium, calcium, barium, potassium, sodium, bromide, chloride, fluoride, nitrite, phosphate, sulfate, and nitrate (See Table 5.2 in Section 5) are found in the CAP water treated at the RO plant. The brine as a whole consists of mainly sodium sulfate, calcium sulfate, and magnesium sulfate which are not dangerous as long as large quantities of the salts are not ingested. However, after the solution becomes more concentrated due to evaporation proper handling and disposal of the salts becomes a necessity. When handling the salts, protective equipment including gloves, safety glasses, and protective clothing must always be worn.

The following section contains the Process Hazard Analysis for the entire plant.

4.2 Process Hazard Analysis

Company: Wilma Engineering	**Plant:** University of Arizona- Spring 2009 Chemical Engineering Department	**Site:** Avra Valley	**Unit:**	**System:** Reverse osmosis desalination and evaporation pond brine disposal.

Method: What-if	**Type:** Line/Pipe	**Design Intent:** CAP water to pump before entering the RO unit.

Number: n/a

Team Members: Elizabeth Pedersen, Chandra Khatri, Ritika Mohan, Mia McCorkel

No.: 1	**Description:** Cap water lines

Item	What if...?	Root Causes/Related Questions	Responses	Safeguards	Action Items
1.1	What if the line leaked or ruptured?	Manufacturing defect Installation error Overpressure Gasket failure External impact	CAP water release causing potential seepage into underground aquifer	Monthly inspections Sealed dikes around pipes	1.11 Consider installing sensors to detect leak. 1.12 Install Over/Under pressure alarms
1.2	What if line is subjected to excessive pressure?	Failure of pump	Back up of water leading to pipe rupture (see above) High pressure downstream	Line pressure rating exceeds pressure sources. Operating pressure for the Pre-treatment system is 3.34 atm and there will be a safety factor of 25%. The pipes will be rated for 4.18 atm. Pressure relief valve (PRV) or rupture disk (RD) that releases to atmosphere at 4 atm.	1.21 Install valves to allow flow to be diverted to other pumps running in parallel.
1.3	What if the valve clogs?	Salt deposits and scaling.	Reduced flow	Flow meters and distributed control system (DCS).	1.31 Install antiscalants and flow meters.
1.4	What if the valve doesn't move to its design failure position (open, closed, or stationary)?	Maintenance or installation error. Software problem	Cap water leak.	Periodic valve testing. Alarm on DCS	1.41 Install alarms to detect failure.

Company: Wilma Engineering	**Plant:** University of Arizona- Spring 2009 Chemical Engineering Department	**Site:** Avra Valley	**Unit:**	**System:** Reverse osmosis desalination and evaporation pond brine disposal.
Method: What-if	**Type:** Pump	**Design Intent:** Pump CAP water into pre-treatment system.		
Number: P-101 – P-109				
Team Members: Elizabeth Pedersen, Chandra Khatri, Ritika Mohan, Mia McCorkel				
No.: 2	**Description:** High pressure cap water pump			

Item	What if…?	Root Causes/Related Questions	Responses	Safeguards	Action Items
2.1	What if the pump clogs?	Scaling and deposition.	Reduced flow, increased system pressure, increased concentration of pre-treatment chemicals.	Periodic pumps inspection.	2.11 Install pressure and/or concentration sensors and alarm systems.
2.2	What if the pump fails/breaks?	Extended use, installation or manufacturing defect.	No flow or back up of flow.	See above.	2.21 See above.

<table>
<tr><td colspan="2">Company: Wilma Engineering</td><td colspan="2">Plant: University of Arizona- Spring 2009 Chemical Engineering Department</td><td>Site: Avra Valley</td><td>Unit:</td><td>System: Reverse osmosis desalination and evaporation pond brine disposal.</td></tr>
<tr><td colspan="2">Method: What-if</td><td colspan="2">Type:</td><td colspan="3">Design Intent: Removes large particles, adjusts pH level, disinfects, and prevents scaling in membranes</td></tr>
<tr><td colspan="7">Number: C-101 – C-102, F-101 – F-103</td></tr>
<tr><td colspan="7">Team Members: Elizabeth Pedersen, Chandra Khatri, Ritika Mohan, Mia McCorkel</td></tr>
<tr><td>No.: 3</td><td colspan="6">Description: Pre-treatment system containing mixers, sand filters, carbon filters, cartridge filters, chlorine line, sulfuric acid line, antiscalant line, coagulant line, polyelectrolyte line</td></tr>
</table>

Item	What if…?	Root Causes/Related Questions	Responses	Safeguards	Action Items
3.1	What if the sulfuric acid line ruptures?	Manufacturing defect Installation error Overpressure Gasket failure External impact	Sulfuric acid release Incorrect pH of CAP water leading into RO Plant.	Monthly inspections Sealed dikes around pipes	See 1.11 and 1.12
3.2	What if the chlorine line ruptures?	See Above	Chlorine Release Water leading into RO Plant not disinfected.	See Above	See 1.11 and 1.12
3.3	What if antiscalant line ruptures?	See Above	Antiscalant Release Fouling of membranes	See Above	See 1.11 and 1.12
3.4	What if the coagulant line ruptures?	See Above	Coagulant Release Particles not filtered out before water enters RO – fouling of membranes.	See Above	See 1.11 and 1.12
3.5	What if the polyelectrolyte line ruptures?	See Above	Polyelectrolyte Release Particles not filtered out before water enters RO – fouling of membranes.	See Above	See 1.11 and 1.12
3.6	What if the flow into the pre-treatment system stops?	Pump failure Line rupture	Concentrated pre-treatment chemicals could cause corrosion or unsafe drinking water.	Under/over pressure alarms	
3.7	What if the mixer breaks?	See 3.1	CAP water release causing potential seepage into underground aquifer.	See 3.1	
3.8	What if the filters break/fail?	Manufacturing defect Installation error	Fouling of membranes Unsafe water	Monthly Inspections Water quality testing	

Company: Wilma Engineering	**Plant:** University of Arizona- Spring 2009 Chemical Engineering Department	**Site:** Avra Valley	**Unit:**	**System:** Reverse osmosis desalination and evaporation pond brine disposal.

Method: What-if	**Type:** Pumps	**Design Intent:** Increase pressure of CAP water flowing into RO unit.

Number: P-201 – P-212, P-301 – P-312

Team Members: Elizabeth Pedersen, Chandra Khatri, Ritika Mohan, Mia McCorkel

No.: 4	**Description:** Stage 1 and Stage 2 CAP water pumps

Item	What if...?	Root Causes/Related Questions	Responses	Safeguards	Action Items
4.1	What if the pump clogs?	Scaling and deposition.	Reduced flow, increased system pressure, and possible pressure vessel rupture.	Periodic pumps inspection.	4.11 Install pressure sensors and alarm systems.
4.2	What if the pump fails/breaks?	Extended use, installation or manufacturing defect.	No flow or back up of flow into pre-treatment system. Membrane could dry out.	See above.	4.21 See above.

Company: Wilma Engineering	**Plant:** University of Arizona- Spring 2009 Chemical Engineering Department	**Site:** Avra Valley	**Unit:**	**System:** Reverse osmosis desalination and evaporation pond brine disposal.
Method: What-if	**Type:** Pressure Vessel and membranes.	**Design Intent:** Water desalination: 750 mg/L TDS in; 0 mg/L TDS out		
Number: M-101 – M-724, M-725 – M-1084				
Team Members: Elizabeth Pedersen, Chandra Khatri, Ritika Mohan, Mia McCorkel				
No.: 5	**Description:** Pressure vessels containing 6 spiral RO membrane units each			

Item	What if…?	Root Causes/Related Questions	Responses	Safeguards	Action Items
5.1	What if the vessel over pressurized, leaked, or ruptured?	Pump clog or installation, manufacturing defect.	Membrane damage, cap water release.	Pressure sensors. Sealed dikes around pressure vessels	5.11 Install pressure relief system- pressure relief valves (PRV) and/or rupture disks (RD).
5.2	What if the membrane clogs?	Concentration polarization leading to scaling, and fouling.	Build up of pressure, low trans membrane flow.	Periodic inspection and cleaning.	5.21 Periodic membrane cleaning and replacement.
5.3	What if there is an external fire?	Lightning strike, electrical malfunction.	Possible boiling liquid, expanding vapor explosion (BLEVE) due to steam formation.	Steam release system	5.31 Install high pressure/temperature alert system.

Company: Wilma Engineering	**Plant:** University of Arizona- Spring 2009 Chemical Engineering Department	**Site:** Avra Valley	**Unit:**	**System:** Reverse osmosis desalination and evaporation pond brine disposal.
Method: What-if	**Type:** Open Vessel	**Design Intent:** Hold water during evaporation		
Number: E-401-402				
Team Members: Elizabeth Pedersen, Chandra Khatri, Ritika Mohan, Mia McCorkel				
No.: 6	**Description:** Evaporation ponds			

Item	What if…?	Root Causes/Related Questions	Responses	Safeguards	Action Items
6.1	What if vessel leaked or ruptured?	Installation or manufacturing defect	Brine release	Periodic checks	6.11 Consider replacing lining according to manufacturer's recommended product lifetime
6.2	What if the ponds overflow?	Upstream valve malfunction Above average rainfall	See above Disruption of set time schedule for pond rotation	Level alarms and automatic pump shutdown	6.21 Install flow meters
6.3	What if there is reduced flow to the designated pond?	Valve blockage due to scaling	Pressure build up in piping and insufficient flow to pond Disruption of set time schedule for pond rotation	Periodic checks / cleaning to remove scaling	6.31 Timely replacement of damaged equipment using spares

Company: Wilma Engineering	**Plant:** University of Arizona- Spring 2009 Chemical Engineering Department	**Site:** Avra Valley	**Unit:**	**System:** Reverse osmosis desalination and evaporation pond brine disposal.

Method: What-if	**Type:** Utilities	**Design Intent:** Provide electric power, control system, etc. to the facility

Number:

Team Members: Elizabeth Pedersen, Chandra Khatri, Ritika Mohan, Mia McCorkel

No.: 7	**Description:** Utilities and plant services

Item	What if...?	Root Causes/Related Questions	Responses	Safeguards	Action Items
7.1	What if electric power were lost momentarily or longer?	City-wide power outage due to storm Power line leading to plant down	Pumps quit Control systems down Plant shutdown- operability issue	Back up generator	
7.2	What if the control system (DCS, PLC, etc.) were lost?	Electric power lost Computer malfunction	Plant shutdown- operability issue Unit control lost	See above Periodic computer checks	7.21 Determine failure modes for pumps and valves.
7.3	What if there were inadequate drainage?	Water or brine release	Plant flood	Periodic drain checks and clearing of any blockages	
7.4	What if nighttime lighting were lost?	Loss of electric power Power surge	Hazard to operating and maintenance personnel	Flashlights Back up generator and lights connected to separate power source	7.41 Consider installing solar lighting 7.42 Put fence around the pond to prevent drowning
7.5	Plant people and contractors are not adequately trained?	Lack of adequate training programs	Potential incident	Specify safety and environmental training for employees Establish system to assure contractors provide training before coming on site Conduct initial contractor orientation Evaluate potential contractor's insurance coverage prior to letting contract	

5.0 ENVIRONMENTAL STATEMENT

A major priority of this project is to protect the environment. This section will provide an overview of the considerations made regarding the efforts to maximize the sustainability of the reverse osmosis process and the benefits of evaporation ponds for brine disposal. The environmental effects of potential contaminants in the CAP water will also be discussed.

A traditional Life Cycle Analysis (LCA) is difficult to perform on this process, since the only product made is drinking water for the city of Tucson. However, there are substantial environmental issues that can be discussed regarding the reverse osmosis and brine disposal process. These issues consist of (1) impacts due to taking water from the Colorado River and groundwater, (2) impacts from the management of waste products and brine from the RO process, and (3) impacts of greenhouse gas emissions from energy used in the processes.

5.1 WATER WITHDRAWAL

Withdrawing enough water to supply the city of Tucson has the potential to have negative consequences for the environment. Before the 1990s, groundwater was almost exclusively used to meet the demands of the Tucson community (Tucson Water Plan, 2004). An increased population following World War II led to an increased water demand, and groundwater withdrawals began to exceed natural recharge. Water demands continued to increase and water levels in the metropolitan and surrounding areas declined, causing measurable land subsidence and increased pumping posts.

When a water supply relies on an aquifer system, the sustainability and renewability of the aquifer must be considered in terms of water quantity and quality. Continued withdrawals that exceed the recharge capacity of the aquifer may deplete the resource (CADT, 2008). In terms of quality, a sustainable aquifer has a concentration that does not change significantly.

Land subsidence problems arise when withdrawals exceed recharge rates and the hydraulic head is gradually reduced. With less fluid pressure, the aquifer arrangement can shift, especially in unconsolidated rocks. It has been estimated that more than 80% of subsidence in the US is caused by overexploitation of groundwater resources (Galloway, 1999). Possible consequences of subsidence include damage to engineered structures such as buildings, roads, and utilities.

The Tucson Water Plan estimates that the volume of groundwater potentially available within the service area is 18.5 million acre-feet. However, this total volume is not legally available since it would violate the “safe yield” of the Arizona Groundwater Management Act of 1980 (2004). Another estimate uses a “sustainability model” to estimate the annually renewable groundwater. Aquifer depletion is not included in this estimate of 50,000 to 70,000 acre-feet per year (2004).

As an alternative to pumping groundwater, Colorado River water is the only renewable surface-water source available in Tucson, of which Arizona is entitled to 2.8 million acre-feet per year. Out of this, the city of Tucson is given an allocation of 144,172 acre-feet per year (Tucson Water Plan, 2004).

The entire city of Tucson could not be sustainable if it were to rely only on groundwater. The large allotment of CAP water available alleviates the stress of taking groundwater and increases groundwater sustainability. Utilizing the Colorado River Water more means that less water is taken out of precious Tucson groundwater.

5.2 BRINE MANAGEMENT

A major issue with reverse osmosis water treatment lies with the impacts of the waste products and potential environmental impacts from the concentrate management. By far the largest component of the waste generated from this facility is the concentrate produced. This brine consists of the constituents rejected from the river water in a much more concentrated form. Table 5.2 shows the estimated concentrations of the components in the CAP water entering the RO process. After reverse osmosis, the concentration of these components in the brine will be greatly increased to levels that are for the most part exceeding environmental limitations. Some of these constituents could cause adverse impacts if discharged into sensitive environments.

	Expected CAP Concentration (mg/L)
Sulfate	1600
Sodium	439.02
Chloride	402
Calcium	360.19
Magnesium	148.21
Silicon	30
Potassium	23
Strontium	5.75
Fluoride	0.945
Nitrate as N	0.795
Barium	0.52
Orthophosphate as P	0.2
Bromide	0.175
Nitrite as N	0.1
Trihalomethane	0.02345
Dibromomethane	0.0082
Dechloromethane	0.00755
Chloroform	0.0057
Bromoform	0.002

Table 5.2: Estimated CAP water concentrations (U. Yenal, personal communication, January 20, 2009).

As the water in the ponds evaporates, the concentrations of the brine components will increase and in many cases will exceed certain EPA limits, such as for drinking water, general exposure, or wildlife restrictions. This section will outline the contaminants that are present in the brine of the CAP water and their respective regulations. However, the final solid slurry is not intended to meet these limits since it will be disposed safely.

Calcium and Magnesium

Hardness in water results when there is high mineral content, particularly excessive amounts of calcium, magnesium, bicarbonate, and sulfate. Although water hardness is generally not harmful, these dissolved minerals affect the taste of water and at high concentrations can leave a white mineral deposit, or scale, on surfaces (Benjamin, 2002). Due to the fact that water hardness is considered only an aesthetic factor for water quality, there are no EPA standards for it. Additionally, there are not many known environmental hazards associated with aqueous calcium and magnesium. They are in fact a dietary mineral for many different organisms except for insects, and magnesium is a component of chlorophyll, which is an essential molecule for photosynthesis in plants ("Environmental Effects of Magnesium," 2008).

However, there could be indirect environmental effects from the presence of calcium, magnesium and other compounds that contribute to water hardness. Water softeners are used in order to combat water hardness, and these water softeners can contain chemicals such as phosphates, EDTA, NTA, and Zeolite A. Some of these softeners can cause eutrophication, act as mutagens, or increase the amount of sludge. Salts such as magnesium sulfate are not persistent in aquatic systems and do not contribute to the Biological Oxygen Demand (BOD), do not bio-accumulate in the food chain, and are not considered to be ecologically toxic ("Environmental Effects of Magnesium," 2008). Magnesium sulfate is not listed as a toxic chemical under SARA (Superfund Amendments and Reauthorization Act) Title III, it is not a CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act) hazardous substance and there is no CERCLA quantifiable limit for aqueous magnesium sulfate in the case of an accidental release (EPA, 2008).

Silicon

Silicon is naturally present in oceans, rivers, and other bodies of water. It is present in many minerals and can be released into water through weathering or other natural phenomena such as volcanic activity. Certain industrial processes, including the production of glass, porcelain, electronics, steel, and rubber or resin-like compounds also utilize silicon in some form. Silicon, specifically silicon dioxide, is a dietary requirement for many organisms. Diatoms and sea sponges use silicon for skeletal strengthening, larger animals such as chickens and rats require silicon for bone development, and it is most likely a dietary necessity for humans as well since it is present in the connective tissue and skin. It is an essential element for plant growth as well, with some species such as dandelions and bamboo containing silicon in the stems and leaves to increase stability. Extremely high concentrations of silicon may limit the growth of algae, but it is generally considered to be environmentally benign and naturally present in water in fairly large amounts (“Silicon and Water”, 2008).

Sodium Salts

Sodium dissolves in water from rocks and soils, and is naturally present in oceans, seas, lakes, and rivers. There are numerous industries that use sodium as well, from metallurgy to food. It is a dietary mineral for animals but not plants. In the case of the salt sodium sulfate, the fifty percent lethal concentration (LC50) value over 96 hours for many fish is greater than 100 mg/L, the LC50 value over 48 hours for daphnia is over 100 mg/L, and it does not significantly bio accumulate. However, concentrations above 100 mg/L are definitely achievable in the evaporation pond during the salt drying process, and it is therefore imperative that measures are taken to prevent any leakage in order to avoid any aquatic toxicity. Salts such as sodium chloride are classified as a water hazard class 1, which means that if the salt is present in concentrations about 3% it can pose a danger. Overall, though, a salt such as sodium chloride is not considered to be toxic to aquatic life. Sodium sulfate and other sodium salts can easily leach into ground water due to their solubility, and should therefore be disposed of properly to avoid groundwater contamination (Sodium Sulfate MSDS, 2006).

Bromide

Bromide salts are found naturally in sea water. The bromide ion itself is present in small amounts in many different organisms, and is therefore not expected to be extremely toxic at lower concentrations. At higher concentrations it has been used as a tranquilizer, and can therefore pose a small but reversible hazard. For specific bromide salts such as potassium bromide, which is an active ingredient in several pesticides, there is some ecotoxicological information available. This particular salt inhibits the growth of bacteria and algae, and has therefore been used as a liquid antimicrobial sanitizer (Chemical Properties of Bromine, 2008). Though potassium bromide is not particularly toxic to birds, as shown by several EPA studies, it is highly toxic to various aquatic animals such as the rainbow trout and daphnia magna. The EPA has not set limits on potassium bromide concentrations despite its toxicity to aquatic organisms because of its applications (EPA Pesticides and Toxic Substances, 1991). Bromine can also react with several organic compounds to form substances that are hazardous, as will be discussed in a later section about dibromomethanes and dichloromethanes (Ricca Chemical Company, 2006).

Fluoride

There are several sources of fluoride in drinking water. It is a water additive that is used to strengthen teeth, it can dissolve into water from natural deposits, and it is in discharge from fertilizer and aluminum factories. One of the main hazards associated with fluoride is that it can cause bone disease and tooth deformation at high concentrations. The EPA limit for fluoride in drinking water is 4 mg/L, because small concentrations are helpful in maintaining bone solidity. If fluorine is present in soils then it can accumulate in plants, and certain plants that are sensitive to fluorine can be adversely affected by its presence. Animals can accumulate large amounts of fluorine, especially in the bones. High concentrations of fluorine in animals can have several negative effects including dental decay, bone degradation, decrease of food uptake, and low birth weights (Chemical Properties of Fluorine, 2008).

Phosphorus as Organophosphates

Organophosphates are found in various applications including pesticides, herbicides, and nerve gases. They are therefore very toxic to many different organisms. A majority of organophosphates are extremely toxic to different types of wild birds. Organophosphates, depending on the specific type, range from being moderately to highly toxic to fish. For example, the fifty percent lethal concentration (LC50) over 96 hours is 0.003 mg/L for rainbow trout. Aquatic invertebrates are also adversely affected by organophosphates, with the LC50 as low as 0.015 µg/L for the organophosphate coumaphos in amphipods (Kamrin, 1997). Many of the organophosphates are regulated by the EPA as Restricted Use Pesticides (RUPs). The organophosphate azinphos-methyl, for example, has a class 1 toxicity rating and an imposed 24-hour reentry interval (Emedicine, 2008).

Nitrogen measured as Nitrate

Nitrates are usually present due to runoff from fertilizer usage, leaching from septic tanks, or from natural deposits. In high concentrations, nitrates can be toxic to people, especially infants. The EPA drinking water limit on nitrate is 10 mg/L (EPA, 2009). Nitrogen itself is a component of amino acids and therefore essential for all life. Once nitrogen is converted into nitrate it can be absorbed by plants, so therefore nitrate is an essential component of fertilizers. Large amounts of nitrates in water can cause eutrophication, which leads to a lack of oxygen in water and by proxy the death of fish. Direct exposure to nitrates can be harmful to aquatic invertebrates and fish, causing developmental problems in younger fish and amphibians, or even death at extremely high concentrations (Nitrogen and Water, 2008). Due to the fact that nitrate is extremely water soluble, it does not bind to the soil and very quickly gets into ground water when is released into the environment.

E. Coli, Coliform, and Heterotropic Plate Count

Coliform bacteria are not generally harmful because they are common in the environment. Both coliform bacteria and E. coli are found in the waste of humans and other animals, but coliform are also present in the soil and plants (Good Water Company, 2009). The EPA limits for drinking water are 500 bacterial colonies per millimeter, which is much greater than the concentration of coliform and E. coli in the RO concentrate. Also, the Heterotropic Plate Count (HPC) is a measure of the amount of bacteria in the water in general. The EPA limits on the HPC is 500 CPU/mL, and the HPC concentration of our brine is half of this number (EPA, 2008). The concentration could increase with evaporation to be greater than the limit for drinking water. However, these bacteria will most likely not have a significant environmental impact, especially since they occur naturally and will be in the presence of high concentrations of salts, some of which are commonly used as antimicrobial agents.

Dibromomethane and Dichloromethane

These organic halide compounds can be extremely toxic and are usually man-made, and enter water as effluent from chemical and drug companies. The current EPA maximum contaminant level (MCL) for dichloromethane is 0.005 mg/L, but the maximum contaminant level goal (MCLG) is zero mg/L (EPA, 2008). The concentration in the RO brine is higher than 0.005 mg/L. It is a carcinogen that can also cause liver problems. Organic bromine can have adverse effects on numerous organisms such as water fleas, fish, lobster, algae, and many others. It is also a mutagen and carcinogen, and can affect glands and the nervous system of humans and other animals (EPA, 2008). Overall these compounds are extremely toxic even in low concentrations, so care should be taken to avoid environmental exposure.

Trihalomethanes

Trihalomethanes are a byproduct of disinfecting drinking water. They can cause liver, kidney, or nervous system damage and are also carcinogenic. The EPA limit for drinking water is 0.08 mg/L, and though the RO brine has a lower concentration, evaporation of the brine may increase the concentration (EPA, 2008).

Chlorine

The EPA has established the environmental air limit for chlorine to be 0.2 ppm. Exposure to higher levels could result in discomfort and irritation. However, these effects may be reversible when exposure ends, depending on the concentration. There is also an EPA MCL and maximum residual disinfectant level (MRDL) for free chlorine (hypochlorous acid and hypochlorite) in drinking water of 4 mg/L (ATSDR, 2007).

Barium

The EPA has set the MCL for barium to 2 mg/L. Barium has been found to potentially cause gastrointestinal disturbances and muscular weakness from acute exposures to levels above the MCL. Chronic exposures have the potential to cause hypertension. However, in water, the more toxic soluble barium salts are likely to precipitate out as the less toxic insoluble sulfate or carbonate (EPA, 2008).

Sulfate

Sulfate in drinking water currently has a secondary maximum contaminant level (SMCL) of 250 mg/L, based on aesthetic effects. This regulation is not a federally enforced standard, but is provided as a guideline for states and public water systems. EPA estimates that about 3% of the public drinking water systems in the country may have sulfate levels of 250 mg/L or greater (EPA, 2008).

Sulfate occurs naturally in drinking water. Health concerns regarding sulfate in drinking water have been raised because of reports that diarrhea may be associated with the ingestion of water containing high levels of sulfate (EPA, 2008).

Pre-Treatment Chemicals

In addition to the natural components of the water, the brine can also contain chemicals used in the RO pre-treatment process.

Chlorine is added to minimize fouling in the process. However it is toxic to marine organisms if discharged to the environment directly. It is also possible that toxic organic compounds that are bioaccumulative and persistent can form with chlorine. However, although chlorine is added in the pre-treatment stage, the reverse osmosis membranes are sensitive to it, so minimal concentrations will be found in the brine (CADT, 2008).

Coagulants are also added during the pre-treatment process to remove suspended particles. They have a low toxicity but can form precipitates and increase turbidity (CADT, 2008).

Antiscalants are added to the water and may still be present in the brine. These are necessary to prevent the formation of scale precipitates and salt deposits (CADT, 2008).

Brine Disposal

One environmental risk of evaporation ponds is the potential leakage of the brine. Most states require impervious liners of clay or synthetic membranes to prevent seepage and resulting contamination of groundwater (Mickley, 2001). Our design includes this required liner, which is constructed of PVC, to best protect the environment from contamination. (See Section 3.4.1 on PVC rationalization.) Another consideration is the possibility of overflow due to larger than normal precipitation. Also, the increased concentrations in the ponds have the potential to introduce wildlife problems. For example, a case at the Kesterson National Wildlife Reserve had adverse affects on breeding and migrating birds due to high selenium levels (Hannam, 2003). Consideration for other options of brine management can be found in Section 3.4. Once the brine is transformed to a dense slurry, the design proposes to dispose of this waste in a landfill, also designed with PVC lining for optimal environmental protection.

The disposal of the solid waste accumulated in the ponds is regulated by organizations within the federal government such as the US EPA, Resource Conservation and Recovery Act (RCRA), and National Discharge Pollutant Elimination System (NPDES) as well as state and local regulations. Evaporation ponds specifically do not require permits according to the NPDES unless there is potential for leakage to either surface water or a drinking water aquifer and there is no required secondary containment method. Since it is difficult to prove if leakage will cause contamination, or where contamination originates from, it is safest to use a lined pond to avoid brine loss (CADT, 2008).

Federal regulations classify wastes as either industrial or municipal. Since municipal wastes are defined to originate from wastewater treatment plants, these are effluents that may contain bacteria and other microorganisms. In our case, the concentrate from the RO facility would be classified as an industrial waste. The federal regulations covering disposal of concentrate depend on the particular disposal method utilized. US EPA has not established any regulations that are specifically directed at disposal of water treatment plant residual; this regulation is primarily the responsibility of the states. Arizona does not have specific regulations (CADT, 2008).

5.3 ENERGY CONSIDERATIONS

Significant amounts of electrical energy are used in order to manage water resources. Reverse osmosis is an energy intensive process, and therefore has an environmental impact in terms of greenhouse gas emissions. According to the EPA, the annual output emission rates for greenhouse gases can be used as default factors for estimating emissions from electricity use. These estimates can be used as an indicator of a carbon footprint (EPA, 2008).

Subregion	Carbon dioxide, CO2 (lb/MWh)	Methane, CH4 (lb/GWh)	Nitrous oxide, N2O (lb/GWh)
Southwest (AZ and NM)	1,311.05	17.45	17.94

Table 5.3: Annual output emission rates in the southwest for carbon dioxide, methane, and nitrous oxide (EPA, 2008).

With these emission rates and the 2,743 kW-h of electricity used by the reverse osmosis process (see the Utility Table in section 2.5), the amount of greenhouse gas emissions is determined and shown in Table 5.4.

Carbon dioxide, CO2 (lbs)	Methane, CH4 (lbs)	Nitrous oxide, N2O (lbs)
31,524,400	419.59	431.37

Table 5.4: Estimation of amount (in pounds) of greenhouse gases emitted by reverse osmosis process, based on electricity used and emission rates in the southwest US.

In the United States in 2006, 5,825.5 metric tons of carbon dioxide was emitted due to energy use (Department of Energy, 2008). For a perspective of the extent that our RO process contributes to CO_2 emission, the 31.5 million pounds emitted by our RO process is a mere 0.00025% of this total. Methane and nitrous oxide contributions are even more insignificant.

6.0 ECONOMIC ANALYSIS

The overall objective of our reverse osmosis plant and evaporation pond design was to minimize the environmental impact of the brine while optimizing the costs in order to ensure that the process with the addition of the evaporation ponds would be economically feasible. All of the costs incurred with the implementation of the reverse osmosis plant and evaporation ponds are listed in Table 6.1. See Section 2.3 for the equipment cost table and Section 2.5 for the utilities and raw materials tables. Also refer to Appendix C for other costs and detailed calculations.

Item	Amount
Utilities	$2,400,000
Raw Materials	$35,700,000
Equipment	$43,000,000
Labor & Maintenance	$10,200,000
General Expenses	$13,400,000
Total water sales	$140,500,000
Measure of Profitability	**Value**
IRR	39.30%
Payback Period	1.52 years

Table 6.1: Estimated cost for proposed design and profitability measures.

The cost of utilities is $2,400,000 annually and includes the electricity costs for all of the pumps and mixers (Section 2.5). Additionally, the raw materials costs incurred per year are $35,700,000. The costs of the antiscalant, sulfuric acid, polyelectrolyte, coagulant, chlorine, CAP water, and Tucson aquifer water as well as the replacement costs of the sand filters, carbon filters, cartridge filters, and ESPA2+ RO membranes are included in the raw material costs and are calculated in detail in Appendix C. Tables outlining the specific calculations used in order to determine the Labor & Maintenance, and the General Expenses, can be found in Appendix C.

An itemized list of the costs for each piece of equipment necessary for the reverse osmosis plant and the evaporation ponds is shown in Table C2, and the detailed calculations for those costs are provided in Appendix C. The equipment costs include the cost of the pumps, sand filters, carbon filters, cartridge filters, mixers, pressure vessels, and reverse osmosis spiral wound membranes. The cost of the valves was considered to be negligible and therefore ignored. The total bare module cost for all of the equipment was calculated as $43,000,000.

The total water sales are $140,500,000 annually as calculated using the price of $1.753/Ccf that Tucson Water currently charges its customers (Tucson Water, 2009). Value would be added to the water as well after it has been treated using reverse osmosis, which would increase the overall selling price of the water. A study conducted by Tucson Water showed that taste was a very important factor for people when choosing their water. Overall 57% of people preferred 450 mg/L TDS water, 28% chose 650 mg/L TDS water, and the rest had no preference (Decision H2O, 2007).

Also, for people who chose the 450 mg/L TDS, cost was only important to 9% of the survey participants but taste was important to 68% of the participants. Even for those who preferred the 650 mg/L TDS water, taste was important to 48% while cost was important to 37% or less (Decision H2O, 2007). The aforementioned study proves that people would be willing to pay slightly more in order to obtain cleaner, better tasting water. The demand for water is inelastic;

even if the cost increases, the demand will not decrease significantly. The price of the raw materials could vary over time, but the total raw materials cost is most sensitive to the price of the CAP water and polyelectrolyte due to the fact that they contribute the most to raw materials costs.

When optimizing the evaporation ponds, the overall area and volume were chosen in order to minimize the overall evaporation cycle time along with the total implementation cost. The cost of the evaporation ponds depends on both the area and the depth. The cost of excavation of the evaporation pond and the cost of the PVC lining were by far the largest expenses incurred by investing in an evaporation pond, with the excavation cost equaling $11,700,000 and the cost of the PVC lining equaling $19,500,000 as outlined in Appendix C. Therefore, by minimizing the total area and depth the initial cost of the ponds could be decreased greatly. The evaporation pond configuration and cost optimization was achieved by using a drying to filling time ratio of 0.98, which would then only require two ponds to be excavated, and using a slightly larger area of 1600 x 1600 square meters but a smaller depth of only 0.75 m. (Refer to Appendix A for evaporation pond calculations.) A higher drying to filling time ratio would require more evaporation ponds and the total area would increase dramatically, which would in turn have a large effect on the cost to implement the evaporation ponds.

In order for a process to be recommended, the investor’s rate of return (IRR) is typically around 15% and the payback period should be no greater than 4 years (Sieder, 2003). An IRR of between 15-30% and a payback period of less than 4 years are good indicators that the chosen design will be profitable and should therefore be considered. For this particular design of the

RO plant and evaporation ponds the IRR, not taking into account the expenses paid by Tucson Water, was 39.3% and the payback period was 1.52 years (Appendix C). Therefore, the proposed design is economically feasible and profitable. It is financially attractive and recommended by the Wilma Engineering design team on an economic basis.

There are other costs incurred for the overall maintenance and operation of the water system in Tucson that Tucson Water currently pays. These annual costs include items such as installing new water laterals to homes, checking water meters, business staff, community relations, and consultant fees, among other costs. The fixed annual costs for Tucson Water, not including the cost of the CAP water and Tucson aquifer water and assuming a 5% increase in costs from the fiscal year 2006, is around $68,300,000 (City of Tucson Water Department, 2006).

When taking this operating cost into account without increasing the cost of the water, the payback period increases to 10.91 years and the IRR decreases to 2.26%. Therefore, the cost of the water should be increased in order for the process to be profitable enough to be recommended. An analysis was done using Solver in Microsoft Excel in order to gauge how much the water price would have to increase in order to make the process more profitable. When the price of the water was increased by 15% to $2.017/Ccf the payback period was 4.00 years and the IRR was 15.09%. A screenshot of this Excel work can be seen in Appendix E.

Practically, the capital investment could be borrowed with public bonds, since Tucson Water is a utility company, and then the only increase in the water price would be that necessary for the operation and maintenance of the RO and evaporation pond facility. The increase in the water price for the consumers in this situation would 19% or be \$0.33/Ccf. The calculation for the new price of water was performed by taking into account the raw materials, utilities, operation, maintenance, and overhead costs necessary to run the reverse osmosis and evaporation pond facility. The general expenses necessary for selling the product and research were assumed to be covered already by Tucson Water. The increase in the selling price of water is fairly steep and may not be accepted by the general consumer, making installing the plant not practically feasible. The value added to the water and how well the public response would be to such an increase needs to be accounted for before making a final recommendation on whether or not the plant should be implemented.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Wilma Engineering has determined that the proposed RO plant and evaporation pond design is a viable solution for treating CAP water. A two-stage RO process was chosen to handle the large flow rate into the plant. The IMSDesign™ program was used to determine an optimal number of 624 pressure vessels for the first stage and 360 pressure vessels for the second stage, with six ESPA2+ spiral wound membranes per vessel. This configuration met the project goal of 80% recovery.

Evaporation ponds are recommended to reduce the environmental impact of the highly concentrated brine from the plant. The implementation of the evaporation ponds would include the cost of land, excavation, and PVC lining for a total of about $31,900,000. An optimal arrangement of two ponds in parallel was chosen, each with dimensions of 1600 x 1600 x 0.75 m. The filling time was determined to be 2.93 years and the drying time was determined to be 2.87 years. Twenty days were left between drying and filling for removal of the salt slurry. A PVC-lined onsite landfill was chosen for slurry disposal to prevent leakage into the underground aquifer.

The total capital investment for the plant and evaporation ponds was determined to be $99,200,000 and the annual operating cost was found to be $68,800,000. The project would most likely be funded using bonds to cover the capital investment and increasing the price of water to cover the annual costs. Water prices would have to be increased 19% to $2.017 per Ccf to cover the annual costs.

Wilma Engineering recommends the use of this RO facility with evaporation ponds, but acknowledges that the increase in water price may decrease public support for the project. Tucson Water is currently able to supply acceptable quality water without an RO treatment facility. If water quality standards increase or public opinion shifts toward cleaner water, the design provided by Wilma Engineering will offer an affordable and environmentally conscious solution.

8.0 FUTURE WORK

There are various aspects of this project that could be assessed for improvement in a future design or analysis. In regard to the evaporation ponds, one area of investigation would be the implementation of a solar pond in series with the evaporation ponds. The solar pond would generate solar energy by trapping the heat generated by the sun in a higher salt concentration portion of the gradient pond. Any energy that is generated by the solar pond could be used to power the RO plant, or sold for profit if there is an excess. The design methodology and procedure for the solar gradient pond and evaporation pond system are outlined in a paper by Agha et. al (2002). Another option that should be considered when reevaluating the evaporation ponds is to have several evaporation ponds in series instead of in parallel. The technique of having evaporation ponds in series was recommended by Mehrotra in his discussion on evaporation pond optimization (1976). Additionally, the calculations for the evaporation pond were performed by assuming constant evaporation and rainfall rates, but a more accurate result could be obtained if a seasonal model was adopted for calculating the evaporation pond parameters.

Consideration of methods to increase evaporation rates of the ponds may also be worthwhile. The use of extended surfaces provides capillary action, which in turn increases the evaporation rate of the water (Gilron, 2003). Evaporation rates can be increased further by use of a “Wind-Aided Intensification of eVaporation” (WAIV) system by providing a higher wind velocity and by proxy a higher mass transfer rate between the pond or extended surfaces and the surrounding air (Gilron, 2003). A complete cost analysis would have to be performed in order to determine if the benefits in evaporation rate and pond size would outweigh the cost to run the equipment. Several small scale tests were conducted in order to gauge the effectiveness of the WAIV systems and different types of extended surfaces such as sheets and cylinders along with different materials for the extended surfaces such as nonwoven geotextiles or woven netting (Gilron, 2003). Including extended surfaces and a high velocity wind source greatly increased the evaporation rate in the study by Gilron, and could be implemented in an evaporation pond system to decrease the total amount of area necessary and in turn greatly decrease the cost expenditure on the pond. A large cost incurred from the installation of the evaporation pond was from the PVC lining. Although PVC lining is a very good option and fairly inexpensive, other options for lining could be considered in order to reduce the implementation costs of the evaporation pond.

For the RO system, several variables could be looked at. For future designs, several different RO modeling programs could be used in order to visualize different discrepancies and find the optimal solution. A different type or size of membrane could be considered to gauge cost effectiveness of using a particular membrane. Due to the fact that the RO plant would be located in Avra Valley near Tucson, solar cells could be installed in order to provide energy for the operation of the facility. Using solar cells could greatly reduce the cost of utilities. The majority of the annual costs for the running of the RO plant were for the pre-treatment, especially the cost of the polyelectrolyte and antiscalant. Therefore it may be beneficial to find a new method of pre-treatment for a more cost effective way to prepare the water for reverse osmosis.

9.0 REFERENCES

Agency for Toxic Substances and Disease Registry (ATSDR). (2007). Retrieved from http://www.atsdr.cdc.gov/csem/nitrate/no3standards_regulations.html.

Agha, K.R., Abughres, S.M., & Ramadan, A.M. (2002). Design Methodology for a Salt Gradient Solar Pond Coupled with an Evaporation Pond. *Solar Energy*, 72(5), 447-454.

Agriculture and Agro Food. (2009). Retrieved April 2009, from www4.agr.gc: http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1236097753569&lang=eng.

Basefsky, M. (2006, April). *Issues of Aging infrastructure.* Retrieved April 2009, from www.swhydro.arizona.edu: http://www.swhydro.arizona.edu/archive/V5_N2/feature4.pdf.

Benjamin, Mark. (2002). *Water Chemistry.* New York: McGraw-Hill.

Berube, D., Diebel, P., Rollin, A., and Stark, T. (2006). *PVC Geomembranes for Large Evaporation Ponds*. Retrieved from HYPERLINK http://pgi-tp.cee.uiuc.edu/forWeb/Technical_Files/Technical_Root/Ponds/Evaporation/PVC%20Geomembranes%20For%20Large%20Evaporation%20Ponds.pdf.

Central Arizona Project. (2009). Water and Replenishment Component. Retrieved April 8, 2009 from http://www.cap-az.com/operations/recharge/more%2Dinfo/rates/.

Centrifugal Pump Design. (n.d.). Retrieved April 2009, from www.energymanagertraining.com: www.energymanagertraining.com/equipment_all/fans_pumps/pdf/Centrifugal_Pump_Design.pdf.

Chemical Engineering. (2009). Chemical Engineering Plant Cost Index. Retrieved April 7, 2009, from http://che.com/pci/.

Chemical Properties of Bromine. (2008). Lenntech Water Treatment. Retrieved from http://www.lenntech.com/Periodic-chart-elements/Br-en.htm.

Chemical Properties of Fluorine. (2008). Lenntech Water Treatment. Retrieved from http://www.lenntech.com/periodic-chart-elements/F-en.htm.

The City of Tucson Water Department. (2006). Annual Fiscal Report. Retrieved from http://www.ci.tucson.az.us/water/docs/ar2006.pdf.

Cityrating.com. (2002). *Average Humidity: Tucson, AZ.* http://www.cityrating.com/relativehumidity.asp.

Committee on Advancing Desalination Technology, National Research Council. (2008). Desalination: A National Perspective. Retrieved from HYPERLINK "http://books.nap.edu/openbook.php?record_id=12184&page=108" http://books.nap.edu/openbook.php?record_id=12184&page=108.

Crites, J.W. (1998-2009). Northern Arizona Land. Retrieved April 2, 2009 from http://www.landandfarm.com/lf/s/63/northern_arizona_land.asp.

CSG Network. (1973-2009). Water Density Calculator. Retrieved March 23, 2009, from www.csgnetwork.com/h2odenscalc.html.

Decision H2O. (2007). Tucson Water. Retrieved from http://www.decisionh2o.com/weeklyresults.htm.

Department of Energy. (2008). *Greenhouse Gases, Climate Change, and Energy.* Retrieved from http://www.epa.gov/solar/documents/egridzips/eGRID2007V1_1_year05_GHGOutputRates.pdf.

Diebel, P. (2003). Lining Evaporation Beds. *GFR Engineering Solutions.* Retrieved from HYPERLINK "http://www.geomembrane.com/TechPapers/0403_GFR_pg31_web.pdf" http://www.geomembrane.com/TechPapers/0403_GFR_pg31_web.pdf.

Dittler, R., Diabueno, R., Gressley, K., & Glenn, B. (2005). *The Tucson Basin Desalinization Project.* Retrieved April 2009, from www.ag.arizona.edu: http://ag.arizona.edu/swes/tucwater1/For%20Website%20Fall05/Final%20Draft%20Group%203%20Paper.htm.

Dvorak, B., & Skipton, S. (2008). Drinking Water Treatment: Activated Carbon Filtration. *NebGuide*, 1-4.

Emedicine. *(2008). Organophosphate Toxicity.* Retrieved from http://emedicine.medscape.com/article/167726-overview.

"Environmental Effects of Magnesium." (2008). Lenntech Water Treatment. Retrieved from HYPERLINK "http://www.lenntech.com/elements-and-water/magnesium-and-water.htm" http://www.lenntech.com/elements-and-water/magnesium-and-water.htm.

EPA. (2008). *Year 2005 GHG Annual Output Emission Rates*. Retrieved from http://www.eia.doe.gov/oiaf/1605/pdf/EFactors1998-2000.pdf.

EPA. (2009). *Drinking Water Contaminants.* Retrieved from http://www.epa.gov/safewater/contaminants/index.html#listmcl.

EPA Pesticides and Toxic Substances. (1991). *Potassium Bromide.* Retrieved from http://www.epa.gov/oppsrrd1/REDs/factsheets/0342fact.pdf.

Forsythe, W. (2003). Smithsonian Physical Tables. 9th Ed. Norwich, NY: Knovel.

Franks, B. R., Andes, C. R., & Patel, M. (2007). Implementing Energy Saving RO Technology in Large Scale Waste Water Treatment Plants. 1-25.

Galloway, Devin, David R. Jones, and S.E. Ingebritsen, eds, 1999, *Land Subsidence in the United States,* Washington, D.C., United States Geological Survey, Circular 1182, 177 pp. Retrieved from HYPERLINK "http://pubs.usgs.gov/circ/circ1182/" http://pubs.usgs.gov/circ/circ1182/.

Gilron, J., Folkman, Y., Savliev, R., Waisman, M., & Kedem, O. (2003). WAIV – Wind Aided Intensified Evaporation for Reduction of Desalination Brine Volume. *Desalination*, 158, 205-214.

Goodlett, Robert. "Rgoodlett@avistatech.com." E-mail to the author. 14 Apr. 2009.

Good Water Company. (2009). *Water Contaminants.* Retrieved from HYPERLINK "http://goodwatercompany.com/Common_Contaminants/Most_Common_Concerns___Wells__Private_and_Public/index.html" \l "sec29" http://goodwatercompany.com/Common_Contaminants/Most_Common_Concerns___Wells__Private_and_Public/index.html#sec29.

Groundwater. (n.d.). Retrieved from www.ag.arizona.edu: http://ag.arizona.edu/AZWATER/azmap/ground.html BIBLIOGRAPHY \l 1033.

Haas, R. a. (2009). *Ion Exchange Resins*. Retrieved April 2009, from www.amberlyst.com: http://www.amberlyst.com/faq_general.htm.

Horizontal Commercial Sand Filters. (2009). Retrieved April 2009, from www.astralpoolusa.com: http://www.astralpoolusa.com/index.php?page=shop.product_details&flypage=shop.flypage&product_id=22&category_id=8&manufacturer_id=0&option=com_virtuemart&Itemid=314.

Hydranautics. (2009). *Membranes*. Retrieved from membranes.com: http://membranes.com/index.php?pagename=imsdesign.

ICIS. (2009). Indicative Chemical Prices A-Z. Retrieved April 23, 2009 from http://www.icis.com/StaticPages/a-e.htm#C.

InflationData.com. (2003-2009). Historical US Inflation Rate 1914-Present. Retrieved April 2, 2009 from http://inflationdata.com/inflation/Inflation_Rate/HistoricalInflation.aspx.

Ion Exchange or Reverse Osmosis? (2003). Retrieved April 2009, from www.dow.com: http://www.dow.com/liquidseps/design/ix_ro.htm.

Kelly, T., & Walker, T. (2003). Solids, Organic loads, and nutrient concentration reductions in swine waste slurry using polyacrylamide aided solids flocculation treatment. *Bioresource technology , 90* (2), 151-158.

Kamrin, Michael. (1997). Pesticide Profiles: Toxicity, Environmental Impact, and Fate. Retrieved from http*://books.google.com/books?id=8IM_A0aTM6UC&pg=PA135&lpg=PA135&dq=organophosphates+environmental+impact&source=bl&ots=VwK1fva0Ya&sig=kPo5FhjWEw7idzVDbkKSyPbbOv8#PPA136,M.*

Layfield Group. (2009). *PVC Liner*. Retrieved from layfieldgroup.com/index_resources.cfm?copyID=17&ID=cor&type=case

Materials Compatibility. (n.d.). Retrieved April 2009, from www.flw.com: http://www.flw.com/material/index.html.

Mehrotra, Subhash. (1976). "Optimization of Evaporation Pond Cost." *Journal of the Environmental Engineering Division.* pp. 165-173.

Membrane Technology. (2008). Retrieved April 2009, from www.lenntech.com: http://www.lenntech.com/plate-and-frame-membranes.htm.

Mickley, Michael. Desalination and Water Purification Research and Development Program Report No. 69. (2001). Bureau of Reclamation Technical Service Center. Retrieved from http://www.usbr.gov/pmts/water/publications/reportpdfs/report069.pdf.

National Guidelines and Standards. (2004). *Nitrate.* Retrieved from http://www.ec.gc.ca/ceqg-rcqe/English/Html/GAAG_Nitrate_WQG.cfm.

National Weather Service. (2009). *Tucson Arizona Climate.* Retrieved from http://www.wrh.noaa.gov/twc/climate/tus.php.

Nitrogen and Water. (2008). Lenntech Water Treatment. Retrieved from http://www.lenntech.com/elements-and-water/nitrogen-and-water.htm.

Okorafor, Ogbonnaya. (1999). *Solubility and Density Isotherms for the Sodium Sulfate-Water-Methanol System.* Journal of Chemical and Engineering Data. 44 (3), 488-490.

Panicker, S., Tewari, P.K. (2008). Safety and reliability aspects of seawater reverse osmosis desalination plant of nuclear desalination demonstration project. *International Journal of Nuclear Desalination.*

Perry, R.H., Green, D.W. (1997). Perry's Chemical Engineers Handbook. 7th Ed. McGraw-Hill.

Plastic Materials. (n.d.). Retrieved April 2009, from www.industrial101.com: http://www.industrial101.com/equipment/plastic-materials.aspx.

Rapid Sand Filtration. (n.d.). Retrieved April 2009, from www.who.int: http://www.who.int/water_sanitation_health/hygiene/emergencies/fs2_14.pdf.

Reverse Osmosis and Mineral Removal. (2000). Retrieved April 2009, from www.decisionh20.com: http://www.decisionh2o.com/reverseosmosis.htm.

Reverse Osmosis Pretreatment System. (2006). Retrieved April 2009, from www.water.siemens.com: http://www.water.siemens.com/SiteCollectionDocuments/Product_Lines/Industrial_Wastewater_Systems/Brochures/EPWP-ROP-IUE-DS-1206.pdf.

Ricca Chemical Company. (2006). *Potassium Bromide MSDS.* Retrieved from http://www.vwrsp.com/msds/10/RC5/RC5879.5-1.pdf.

Richard, P., & Davis, B. (2002). *Northern Central Arizona Water Demand Study.* Technical Report.

roengineering. (n.d.). Retrieved April 2009, from www.google.com: http://www.google.com/imgres?imgurl=http://www.roengineering.com.hk/Eng/Picture/TechE2.gif&imgrefurl=http://www.roengineering.com.hk/Eng/tech.htm&h=264&w=480&sz=44&tbnid=0eQGJvnwEvo9yM::&tbnh=71&tbnw=129&prev=/images%3Fq%3Dcarbon%2Bfilteration%2Bprocess%2.

ROwaterSystems, Inc. (2009). HYDRANAUTICS - ESPA2+ 8 in. X 40 in. 12,000 GPD Reverse Osmosis Membrane. Retrieved April 9, 2009 from http://www.rosystems.com/reverse-osmosis/water-treatment-products/ESPA2-Plus.html.

Schmidt, D., & Shinault, C. (1998). *Rapid Sand Filtration*. Retrieved April 2009, from www.ce.vt.edu: http://www.cee.vt.edu/ewr/environmental/teach/wtprimer/rapid/rapid.html.

Sciencelab.com. (2008). Sulfuric Acid MSDS. Retrieved from HYPERLINK "http://www.sciencelab.com/xMSDS-Sulfuric_acid-9925146" http://www.sciencelab.com/xMSDS-Sulfuric_acid-9925146.

Seider, W.D., Seader, J.D., Lewin, D.R. (2003). *Product and Process Design Principles: Synthesis, Analysis, and Evaluation.*

"Silicon and Water." Lenntech Water Treatment. (2008). Retrieved from HYPERLINK "http://www.lenntech.com/elements-and-water/silicon-and-water.htm" http://www.lenntech.com/elements-and-water/silicon-and-water.htm.

Sodium Sulfate MSDS. (2006). J.T. Baker. Retrieved from HYPERLINK "http://www.jtbaker.com/msds/englishhtml/s5022.htm" http://www.jtbaker.com/msds/englishhtml/s5022.htm.

Steyn, A., & Schoeman, J. (2000). Investgation into alternative water treatment technologies for treatment of underground mine water discharged by Grootvlei proprietary mines Ltd into the Blesbokspruit in South Africa. *Desalination , 133*, 13-30.

Tucson Water. (2009). Current Water Rate Schedules. Retrieved April 9, 2009 from http://www.ci.tucson.az.us/water/rates.htm.

Tucson Water Plan: 2000-2050. Nov 2004. City of Tucson Water Department.

Water Resources Research Center. (1995). Water in the Tucson Area: Seeking Sustainability. Retrieved April 6, 2009 from http://ag.arizona.edu/AZWATER/publications/sustainability/report_html/chap5_09.htm

Water Treatment Chemicals and Construction Chemicals. (n.d.). Retrieved April 2009, from www.who.int: http://www.who.int/water_sanitation_health/dwq/S14.pdf.

Water Treatment: Coagulation and Flocculation. (2003). Retrieved April 2009, from www.engr.msu.edu: www.egr.msu.edu/classes/ce280/voice/powerpoint/fall2003/lecture25.ppt.

Western Regional Climate Center. (n.d.) *Historical Climate Information.* Retrieved from www.wrcc.dri.edu.

What is Reverse Osmosis. (2001, April). Retrieved from www.petrosepmembrane.com: http://www.petrosepmembrane.com/mtech/w_is_ro.htm.

10.0 NOMENCLATURE

Symbols	Definition	Units
A	Area of evaporation pond	m^2
B	Overall theoretical inlet volumetric flow rate	m^3
C	Molar concentration of salt	mol/m^3
C	Cost of production	dollar
Ccf	Volume	100 cubic feet
C_B	Base purchase cost	dollar
$C_{buildings}$	Cost of buildings	dollar
C_{BM}	Bare module cost	dollar
C_P	Purchase cost	dollar
$C_{offsite}$	Cost of offsite facilities	dollar
C_{site}	Cost of site	dollar
C_{TBM}	Total bare module cost	dollar
C_{TDC}	Total depreciable cost	dollar
C_{WC}	Working capital	dollar
COM	Cost of manufacture	dollar
D	Depreciation	dollar

DW&B	Direct wages and benefits	dollar
E	Evaporation rate	m/min
E_o	Fresh water evaporation	m/min
F	Future value	dollar
F_{BM}	Bare module factor	Unit less
F_M	Material factor	Unit less
F_T	Pump type factor	Unit less
GE	General expenses	dollar
H	Pressure head	feet
IRR	Investor's rate of return	percent
i	Average inflation value	Unit less
k_p	Mass transfer coefficient	inches/mm Hg
M	Maintenance	dollar
N	Net earnings or profit	dollar
NPV	Net present value	dollar
n	Time (in cost calculations)	years
O	Labor related operations	dollars
P	Pressure	atm

P	Present value	dollar
P_B	Break power	hp
P_c	Power consumption	hp
P_v	Vapor pressure of water and salt	mm Hg
P_∞	Vapor pressure of water at T_∞	mm Hg
PBP	Pay back period	years
Q	Volumetric flow	gpm or L/s
R	Rainfall	m/min
S	Size factor	unit less
S	Sales	dollar
s	Amount of salt	moles
S_{equip}	Salvage cost of the equipment	dollar
t	Time	sec or min
t	Tax rate	percent
T	Absolute temperature	K
V	Volume	m^3 or gal

Greek	**Definition**	**Units**
α	A positive constant	m^3/mol

ρ	Density	lb/ft^3
η	Efficiency	Unit less
τ	Residence time	min

APPENDICES

APPENDIX A – EVAPORATION POND CALCULATIONS

In order to calculate the optimal area and depth for the evaporation ponds, several calculations needed to be done in order to take into account the evaporation rate, rainfall, and salt concentration along with many other factors.

Evaporation pond governing equations

A paper discussing the theory behind the optimization of evaporation ponds by Mehrotra proposes an equation showing the behavior of the pond during its filling stage (1976). Several calculations were used in order to model the evaporation pond filling process. First, the concentration in the pond is given as (Mehrotra, 1976):

$$C(t) = \frac{s(t)}{V(t)} \ ; V > 0 \tag{A1}$$

where V(t) is the volume (m^3) the liquid in the pond as a function of time and s(t) is the amount of salt in the pond as a function of time in moles, given by the equation:

$$s(t) = C_0 q_0 t \tag{A2}$$

where C_0 is the concentration of the inlet stream (mol/m^3), q_0 is the flow rate of the inlet stream (m^3/min), and t is the total time (min) that liquid has been entering into the pond. The total volume of liquid in the pond changes according to the following equation:

$$V(t) = ARt + q_0 t - A\int_0^t E[C(t)]dt \tag{A3}$$

where A is the area of the pond (m^2), R is the rainfall (m/min), and E is the evaporation rate of the water (m/min). The evaporation rate of the water is dependent on the salt concentration, which varies as the pond fills. This is the reason why the evaporation rate is expressed in the previous equation as a function of concentration, which in turn is expressed as a function of time. For simplification of the overall calculations a linear relationship was assumed in the paper between salt concentration and evaporation rate. The equation for evaporation rate as a function of time then becomes:

$$E = E_0(1 - \alpha C) \tag{A4}$$

where E_0 is the evaporation rate of freshwater (m/min) and α is a positive constant (m^3/mol). Later calculations using the vapor pressure as a function of concentration were performed in order to support this assumption. All of the previous equations were combined and differentiated with respect to time, t, in order to obtain the following equation:

$$\frac{-C_0 q_0 dC}{AE_0\alpha C^3 + BC^2 - C_0 q_0 C} = \frac{dt}{t} \tag{A5}$$

where C is the concentration (mol/m^3) at time t in the evaporation pond and B is given by the equation:

$$B = q_0 - A(E_0 - R) \tag{A6}$$

The constant B represents the overall theoretical inlet volumetric flow rate due to the fact that it subtracts the amount of water evaporated at any particular time from the flow rate of the RO brine. When Equation A5 is integrated it yields the following equation:

$$\ln(t) = \left[- C_0 q_0 \frac{1}{2E_0 \alpha A} \ln \frac{C^2}{AE_0 \alpha C^2 + BC - C_0 q_0} + \frac{B}{E_0 \alpha \sqrt{4AE_0 \alpha C_0 q_0 + B^2}} \tanh^{-1}\left(\frac{B - 2C_0 q_0 C}{\sqrt{4AE_0 \alpha C_0 q_0 + B^2}} \right) \right] \quad \text{(A7)}$$

The behavior of the integrated equation as time approaches zero is studied in order to prove that the constant of integration is zero. When dC/dt is set equal to zero, Equation A5 is reduced to an equation expressing the equilibrium concentration, which is the concentration that the pond reaches at infinite time. The equilibrium concentration is shown by the following equation:

$$C_e = \frac{- B + \sqrt{B^2 + 4AE_0 \alpha C_0 q_0}}{2AE_0 \alpha} \quad \text{(A8)}$$

where C_e is the equilibrium concentration (mol/m^3). The time necessary for the pond to reach the equilibrium concentration is assumed to be negligible in several of the calculations. Prior to completing the calculations for the filling time and drying time some of the equation parameters needed to be ascertained.

Calculation of alpha, evaporation rate, and rainfall rate

Pan evaporation rates are measurements which combine several factors such as wind speed, humidity, and solar radiation.

The pan evaporation rates for Arizona were found from the Western Regional Climate Center (n.d.). By using the average monthly values and Penman's equation (Linecre, 1997), the mass transfer coefficient can be calculated.

Table A1 shows average monthly pan evaporation rates in Tucson, Arizona in the years 1982 – 2005.

Months	E_0(inches)	Avg Temp (°F)	Pv^0 (mm Hg)	Avg RelativeHumidity	P_∞ (mm Hg)	$P_V^0 - P_\infty$ (mm Hg)
January	3.94	51.3	9.844	30.572	4.62668	5.21732
February	4.68	54.4	10.87	32.635	4.6741	6.1959
March	7.53	58.7	12.78	35.74	4.8564	7.9236
April	10.57	65.8	16	40.9	4.64	11.36
May	14.14	74	21.5	47.75	5.16	16.34
June	16.51	83.8	29.1	56.45	6.5475	22.5525
July	14.61	86.6	32.1	59.35	13.482	18.618
August	12.17	84.5	30.043	57.2715	14.72107	15.32193
September	10.71	80.4	26.73	53.565	11.09295	15.63705
October	8.05	70.4	18.7	44.55	7.1995	11.5005
November	4.93	59.2	12.78	35.99	5.2398	7.5402
December	3.23	52	9.9	30.95	4.7025	5.1975

Table A1: Average monthly pan evaporation rates in Tucson, AZ (1982-2005). (Western Regional Climate Center, n.d.)

Calculation of mass transfer coefficient

Using Penman's equation (Linecre, 1997)

$$E = k_p \left(P_v - P_\infty\right) \qquad \text{(A9)}$$

where k_p is the mass transfer coefficient. P_v is the vapor pressure of the water and salt. $P_\infty = \Phi$ P_v^o (Φ is the average relative humidity and P_v^o is the vapor pressure of water at T_∞).

Average relative humidity and average temperature data is obtained from Cityrating.com (2002). P_v^o data is obtained from steam tables. Pan evaporation data for Tucson is obtained from Western Regional Climate Center (n.d.).

Using the above Equation A9, E vs. (Pv - P∞) is plotted on Excel and the following graph is shown in Figure A1:

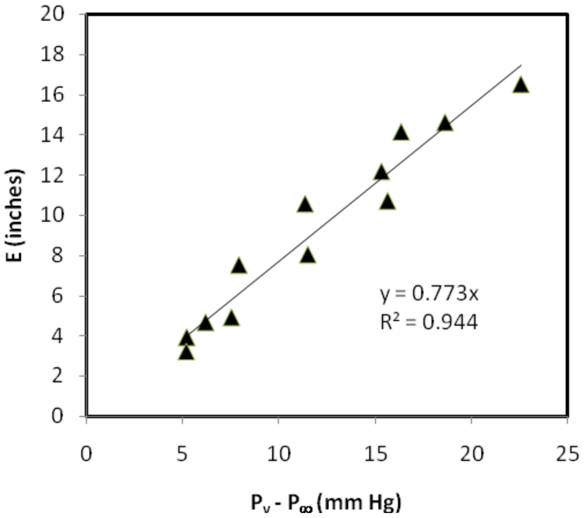


Figure A1: Pan Evaporation vs. pressure change in Arizona.

Using the Figure A1, k_p = 0.7735 inches/mm Hg.

Once the mass transfer coefficient k_p is calculated, the value of alpha for our particular system can be calculated. Even though the CAP water system is very complex and has many different ions, the most prevalent cation was sodium, and the most common anion was sulfate. Therefore, physical data for the salt sodium sulfate was used in order to calculate alpha, and from alpha the evaporation rate. Using sodium sulfate gave a good approximation because it was the most common salt and it had a higher saturation concentration than many of the other salts. Due to the larger saturation concentration, sodium sulfate would theoretically precipitate out after many other salts, which would give a more conservative estimate of evaporation times because the salt would be present longer and therefore affecting the evaporation rate for a larger period of time. Other salts in the solution, such as barium sulfate, would actually precipitate out sooner because they are already almost at saturation or super-saturated at the inlet.

In order to calculate the overall molar concentration all of the salts in the CAP water were taken into account. The molar concentration of ions in the incoming CAP water, taking into account all of the different components, was 63.98 mol/m^3. Therefore the molar concentration of Na_2SO_4, or C_0, would be 28.35 mol/m^3. Also the inlet volumetric flow rate, or q_0, was calculated using unit conversions to be 23.64 m^3/min. The various components and their corresponding molar concentrations are shown in Table A2.

	Mg	Si	Sr	Ca	Ba	K	Na	Br	Cl	F	SO_4	NO_3
Concentration [mg/L]	148.2	30	5.8	360.2	0.5	23	439	0.2	402	0.95	1600	0.795
Molecular Weight [g/mol]	24.3	28.1	87.6	40.1	137.3	39	23	79.9	35.4	18.9	96	62
Concentration [mol/m^3]	6.10	1.07	0.07	8.98	0.00	0.59	19.09	0.00	11.36	0.05	16.67	0.01
Total ion concentration	**63.98**											

Table A2: Molar concentrations of the different ions present in CAP water.

In order to calculate the evaporation rate of the sodium sulfate solution, the change in the vapor pressure as a function of salt concentration, at the boiling point of water, was found in the Smithsonian Physical Tables (Forsythe, 2003). When calculating how the vapor pressure, and therefore the evaporation rate, of the sodium sulfate solution at the desired conditions changed, it was assumed that the addition of sodium sulfate had the same ratio effect compared to the pure water vapor pressure even at different temperatures. The assumption can also be written as follows:

$$\frac{P_{water,T1} - P_{solution,T1}}{P_{water,T1}} = \frac{P_{water,T2} - P_{solution,T2}}{P_{water,T2}} \tag{A10}$$

where P_{water} is the vapor pressure of water (mm Hg) at its corresponding temperature T1 or T2, and $P_{solution}$ is the vapor pressure of the salt solution (mm Hg) at its corresponding temperature T1 or T2.

The theory that the assumption was based on is that for a given salt concentration the ratio between the pressure affect and pure water vapor pressure will remain constant. In order to verify this assumption, vapor pressure data for sodium carbonate salt solutions at varying temperatures was found in Perry's Handbook and then analyzed (1997). The results of the analysis are graphed in Figure A2, showing that the temperature appears to have a negligible effect on the vapor pressure ratio at a specific salt concentration.

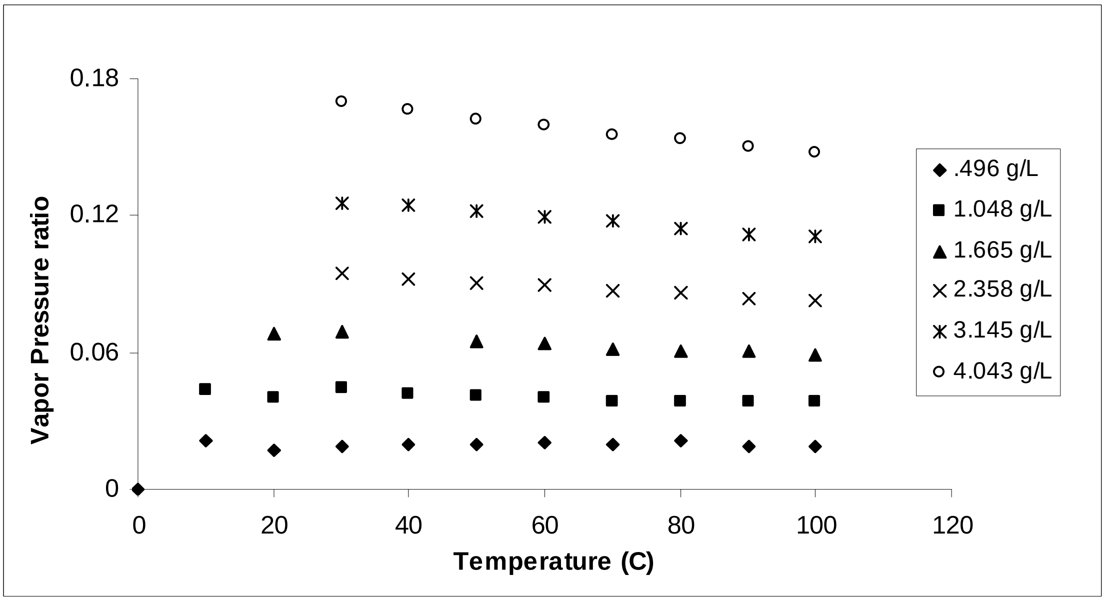


Figure A2: Temperature vs. the Vapor pressure ratio at different sodium carbonate concentrations.

To ensure that the data between the two sources that were used, the Smithsonian Physical Tables and Perry's Chemical Engineering Handbook, was similar enough in order to make a comparison data for sodium carbonate concentration versus solution vapor pressure from both sources was graphed together. The two data sets were in agreement, as shown in Figure A3. Therefore, the data from the Smithsonian Physical tables relating to the vapor pressure of the sodium sulfate solutions was used.

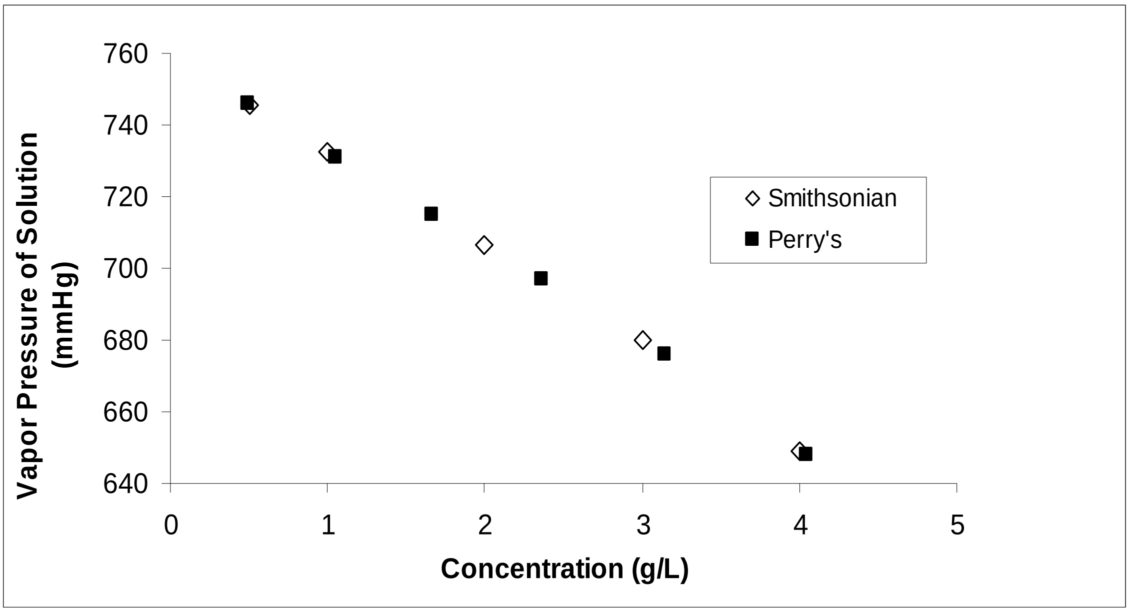


Figure A3: Concentration vs. Vapor pressure of solution for sodium carbonate.

The vapor pressure data for sodium sulfate was used in order to calculate alpha. Extrapolations of the ratio between the vapor pressure change due to the presence of the salt and the vapor pressure of pure water were used in order to obtain the vapor pressures of sodium sulfate solutions at various temperatures. The vapor pressures as temperature and concentration are varied are shown in Table A3. The average vapor pressures between 293 K and 303 K were calculated in order to determine the vapor pressure at the pond's typical operating temperature of 298 K.

Temperature [°C]	Concentration [mol/m^3] 0	500	1000	2000	3000
10	9.2000	9.0475	8.8974	N/A	N/A
20	17.5000	17.2099	16.9243	16.3740	15.7914
30	31.8000	31.2728	30.7539	29.7539	28.6953
40	55.3000	54.3832	53.4809	51.7419	49.9010
50	92.5000	90.9664	89.4572	86.5484	83.4691
60	149.5000	147.0214	144.5822	139.8809	134.9041
70	239.8000	235.8244	231.9118	224.3708	216.3879
80	355.5000	349.6062	343.8059	332.6264	320.7920
90	526.0000	517.2795	508.6974	492.1561	474.6458
100	760.0000	747.4000	735.0000	711.1000	685.8000
Ratio	N/A	0.0166	0.0329	0.0643	0.0976

Table A3: Vapor Pressure of Na_2SO_4 solutions [mm Hg] at varying temperatures and concentrations.

As shown previously, the evaporation rate of a solution is obtained from the vapor pressure by using Penman's equation, Equation A9. An average value found from the gathered relative humidity data of 7.25 mm Hg was used for the vapor pressure of water in the air, P_∞. Additionally, the previously solved for value of k_p was used along with the vapor pressures of the salt solution at different concentrations calculated at 298 K from the values listed in Table A3. The resulting evaporation rate was then graphed against the concentration, as shown in Figure A4.

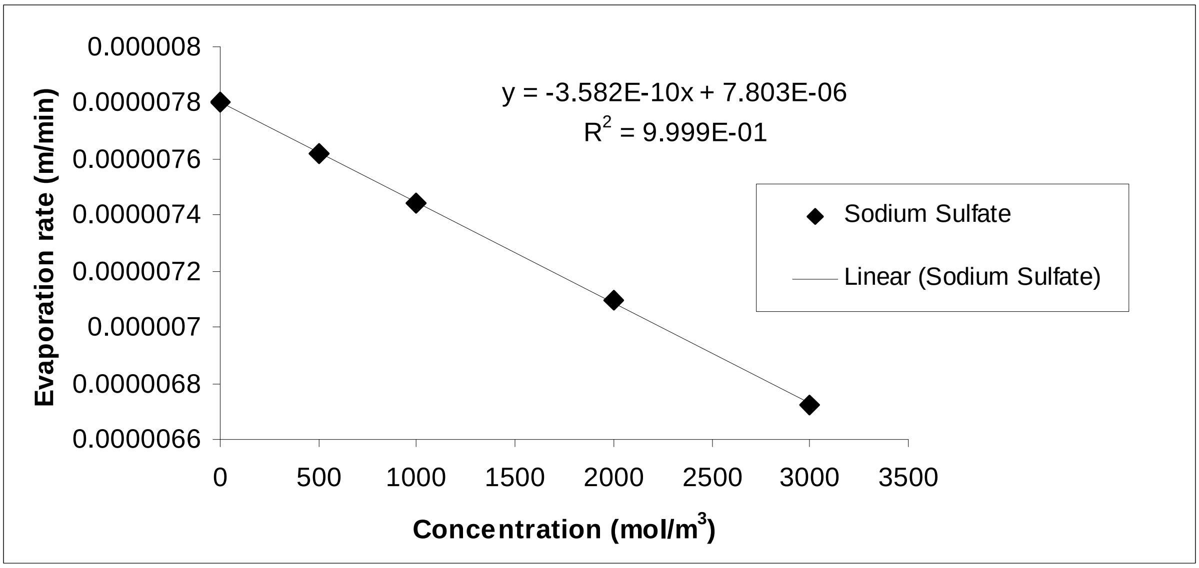


Figure A4: Concentration versus evaporation rate for sodium sulfate

The slope of this line, as shown by Equation A11, is equal to:

$$slope = -\alpha E_0 \tag{A11}$$

Therefore, for the sodium sulfate system alpha was calculated to equal 4.589 x 10^{-5} m^3/mol.

The average annual rainfall in Tucson is very low. However, when doing a sensitivity analysis it was obvious that this term in the equation could not be ignored or considered to be negligible. Even small changes in the rate of rainfall many times had a very significant effect on the equilibrium concentration, which in turn vastly affected the results. For example, for a pond with an area of 2,250,000 m^2 the equilibrium concentration changed from 132 mol/m^3 when the rainfall was taken into account, to 195 mol/m^3 when the rainfall was considered to be zero, which is an almost 50% increase. Therefore, the average rainfall was taken into account. The average rate of rainfall in Tucson (R) was found to be 5.80 x 10^{-7} m/min (National Weather Service, 2009). An overall average value for the rainfall in Tucson was used even though the rainfall in Tucson actually varies a great deal from month to month. For example, during the months of August and September, during the monsoon season, the rainfall is much greater. However, due to the fact that the evaporation ponds have both a filling time and a long drying time of around 2.93 years each it was assumed that the rainfall would average out over the evaporation cycle and that the ponds would not overflow. Additionally, during the summer months right before the monsoon season the rainfall is much lower but the evaporation rate is somewhat greater. Therefore, the extra evaporation during the summer is assumed to counterbalance the excess rainfall during the monsoon season. The average annual pan evaporation rate (E_0) in Tucson was determined to be 9.44 x 10^{-6} m/min (Western Regional Climate Center, n.d.). Assuming an average evaporation rate and average rainfall rate could be a possible source of error in the calculations. If the rainfall rate was higher than expected or if the evaporation rate was lower than expected, then the drying and filling times would increase. Conversely, if the rainfall rate was lower than expected or if the evaporation rate was much higher than expected then the drying and filling times would decrease. One possible method of dealing with the discrepancies in the data would be to calculate everything on a seasonal basis. The seasonal method could be accomplished by separating the different seasons and calculating how much the water level in the pond changes depending on the evaporation and rainfall rates in the different seasons. Performing the calculations separately for the different seasons is one way of dealing with the change in the evaporation and rainfall rates with the season. The values of alpha, evaporation rate, and rainfall rate, were then used in the calculations for the filling and drying times.

Calculation of Filling Time

Several approaches were taken in order to calculate the filling time. Due to the sensitivity and inherent instability of Equation A7, a more straightforward approach to calculating the filling time was taken. First, the equilibrium concentration of the pond was calculated using Equation A8. Then, several feasible pond dimensions were assumed and a theoretical pond volume could then be calculated. Also, assuming the pond reaches the equilibrium concentration fairly quickly it can be said that the pond will be at the equilibrium concentration once it is completely filled. Therefore, the total amount, in moles, of salt in the pond will be equal to:

$$s = V_t C_e \tag{A12}$$

where V_t is the theoretical pond volume and C_e is the equilibrium concentration. The total amount of salt that enters into the pond, taking into account the inlet concentration of the brine and the volumetric flow rate of the brine, was given previously in Equation A2. Theoretically, according to the law of conservation and assuming that none of the salt diffuses into the surrounding air, the total amount of salt that enters the pond should equal the total amount of salt that is in the pond once the pond is completely filled and at its equilibrium concentration. For this reason Equation A12 and Equation A2 are set equal to each other and then solved to give a filling time according to the following equation:

$$t_f = \frac{V_t C_e}{C_0 q_0} \tag{A13}$$

As shown by the above equation, the more similar the values of C_e and C_0 are, the more closely t_f approaches the time to simply fill the evaporation pond without any continuous evaporation. The value of C_e is only affected by changes in the area, and not the depth. For this reason, larger areas allow for a greater amount of continuous evaporation, according to the governing equations. The fact that larger areas allow for continuous evaporation is used in the optimization of the evaporation ponds because continuous evaporation is more efficient and therefore more desirable in the design of an evaporation pond.

Drying Time

The amount of time that the liquid in the evaporation pond takes to evaporate was divided into two parts. First the time necessary for the pond to reach the saturation concentration of the characteristic salt sodium sulfate was calculated. It was assumed that after the pond reaches saturation the salt continually precipitates out and the liquid in the pond remains at the saturation concentration of sodium sulfate.

A differential equation describing the behavior of the pond during the drying process was used from the beginning of the drying stage until the pond reaches saturation:

$$\frac{dV}{dt} = -EA + RA \tag{A14}$$

where, as outlined previously, E is the evaporation rate of the salt solution (m/min), R is the average rainfall rate in Tucson (m/min), and A is the area of the evaporation pond (m^2). This equation shows that the change in the volume of liquid in the evaporation pond is a function of both the amount of water evaporated and the amount of water added due to rainfall.

At the very start of the drying process the evaporation pond is at the equilibrium concentration C_e. The concentration in the evaporation pond as a function of volume is given by the following equation:

$$C = \frac{C_e V_0}{V} \tag{A15}$$

where V_0 (m^3) is the volume of the liquid in the pond when it is full at the beginning of the drying stage, and V (m^3) is the volume of the pond at any specific time t (min). When Equation A4 for the evaporation rate and Equation A15 for the concentration as a function of volume are substituted in to the differential Equation A14, the resulting equation is:

$$\frac{dV}{dt} = -AE_0(1 - \alpha \frac{C_e V_0}{V}) + RA \tag{A16}$$

Then, after rearranging Equation A16 and integrating, the result is an equation of the following form:

$$\int_{V_0}^{V_s} \frac{dV}{\frac{a}{V} + b} = \int_0^{t_1} dt \tag{A17}$$

where V_s (m^3) is the volume of the pond when it first reaches saturation, t_1 (min) is the drying time necessary for the pond to reach saturation, and the constants a and b are defined as follows:

$$a = AE_0 \alpha C_e V_0 \tag{A18}$$

$$b = AR - AE_0 \tag{A19}$$

The solution of the integration of Equation A17 is given by the following equation:

$$t_1 = \left[\frac{-(a + bV_s)}{b} + \frac{a}{b}\ln[-(a + bV_s)]\right] - \left[\frac{-(a + bV_0)}{b} + \frac{a}{b}\ln[-(a + bV_0)]\right] \tag{A20}$$

Once the time necessary to reach the saturation volume is calculated, the amount of drying time after that must be determined.

After the pond has reached its saturation point the concentration is assumed to remain constant, so a slightly different equation is used to determine the time after saturation:

$$V_{end} = V_s + ARt_s - AE_0(1 - \alpha C_{sat})t_s \tag{A21}$$

where V_{end} (m^3) is the volume of material in the pond at the end of the drying process, t_s (min) is the time to dry the pond after saturation, and C_{sat}(mol/m^3) is the saturation concentration. From Equation A21, t_s can be calculated explicitly:

$$t_s = \frac{V_{end} - V_0}{AR - AE_0(1 - \alpha C_{sat})} \tag{A22}$$

At the end of the drying process, some water is left in the solid, creating a salt slurry.

Although the evaporation rate can be greatly affected by the presence of a solid or a super-saturated solution, in this particular case the presence of the solid was considered to be insignificant. Some future work could take into account more factors near the end of evaporation such as the porosity of the solid, super-saturation, and other things that could affect the evaporation rate near the end of evaporation and drying of the salts. In this instance it was assumed that there would be enough water remaining at the end of the drying process that the drying stage model at the saturation point, and by proxy Equation A22, would still be valid for the system from the saturation point until the end of drying. Also, it was assumed that there would be enough nucleation points for crystallization of the salts, preventing the super-saturation of the solution.

The volume at saturation, V_s, is calculated using the saturation data for sodium sulfate. In a paper by Okorafor the solubility isotherms for sodium sulfate are experimentally found. At 298 K the solubility of sodium sulfate in water is 224.1 g/L (Okorafor, 1999).

Through unit conversions, this value of C_{sat} is found to be 1578.2 mol/m^3. The volume at saturation is then found using an overall mole balance and the following equation:

$$V_s = \frac{C_e V_0}{C_{sat}} \tag{A23}$$

The volume at the end of the drying process, V_{end}, is calculated using the density data for sodium sulfate. The density of anhydrous sodium sulfate is 2.68 g/cm^3 (Sodium Sulfate MSDS, 2006), and the molecular weight of sodium sulfate is 142 g/mol. After unit conversions, the density of anhydrous sodium sulfate is found to be 18,873 mol/m^3. The total amount of salt in the pond is found using Equation A24, and then the volume of the dry salt is calculated using the following equation:

$$V_{salt} = 18873 \cdot s \tag{A24}$$

where s is the total amount of salt (moles). The ending volume is assumed to be three times that of the volume of the salt. At the end of the drying process, the volume not taken up by the salt is made up of the excess water that is left at the end of the evaporation process. This is shown by Equation A25.

$$V_{end} = 3V_{salt} \tag{A25}$$

Overall Calculations

Various areas and depths were input into the previous equations in order to obtain the overall filling and drying times, and from there determine the optimal design for the evaporation pond system. The results of such exploratory calculations are shown in Table A4.

Pond Dimensions	Area [m^2]	Depth [m]	Filling Time [days]	Drying Time [days]	Ratio
400 x 400	160000	1	5	111	22.20
400 x 400	160000	2	10	221.9	22.19
400 x 400	160000	3	15	332.9	22.19
400 x 400	160000	4	20	443.8	22.19
800 x 800	640000	1	24.7	440.2	17.82
800 x 800	640000	2	49.5	880.4	17.79
800 x 800	640000	3	74.2	1320.5	17.80
800 x 800	640000	4	98.9	1760.7	17.80
1600 x 1600	2560000	0.5	654	711	1.09
1600 x 1600	2560000	1	1308	1423	1.09
1600 x 1600	2560000	2	2616	2846	1.09

Table A4: Results of Evaporation Pond calculations calculated using specific dimensions

The slightly larger pond areas seemed to give a more reasonable ratio between the drying time and evaporation time. The decrease in area for the smaller ponds did not seem to make up for the increase in the ratio between drying and filling time. The higher the ratio between the drying and the filling time is, the more ponds would have to be installed in order to handle the inlet flow rate. For example, for a drying time that is twice the filling time, three ponds would have to be excavated. After the preliminary calculations showed that larger areas were more favorable, the area was varied using the Solver function in Microsoft Excel in order to give the exact ratio that was desired.

It was discovered that the smaller ratios of around one were better because even though they had slightly longer times for the total evaporation cycle, the total area for all of the ponds that would be necessary was significantly smaller. Additionally, the recommended depth would be 1 m or below in order to avoid inordinately large filling and drying times. The filling and drying times both scale directly with the depth, so if the depth is doubled, the times will also double and are therefore very sensitive to changes in the depth.

Wilma Engineering concluded that the optimal ratio for successful operation of the evaporation pond system was around 0.98 with a depth of 0.75 m. A drying time to filling time ratio of 0.98 would leave some extra time during the drying cycle in order to account for the time necessary for the removal of the dried brine salts. Additionally, the chosen ratio and depth were favorable because of the smaller total areas and feasible drying and filling times. The total equipment that would be necessary for this system would be two evaporation ponds with dimensions 1605 x 1605 x 0.75 cubic meters. The filling time would be, as shown in Table A5, 1070.7 days and the drying time would be 1049.2 days, for a total evaporation cycle time of 2141.4 days or 5.86 years.

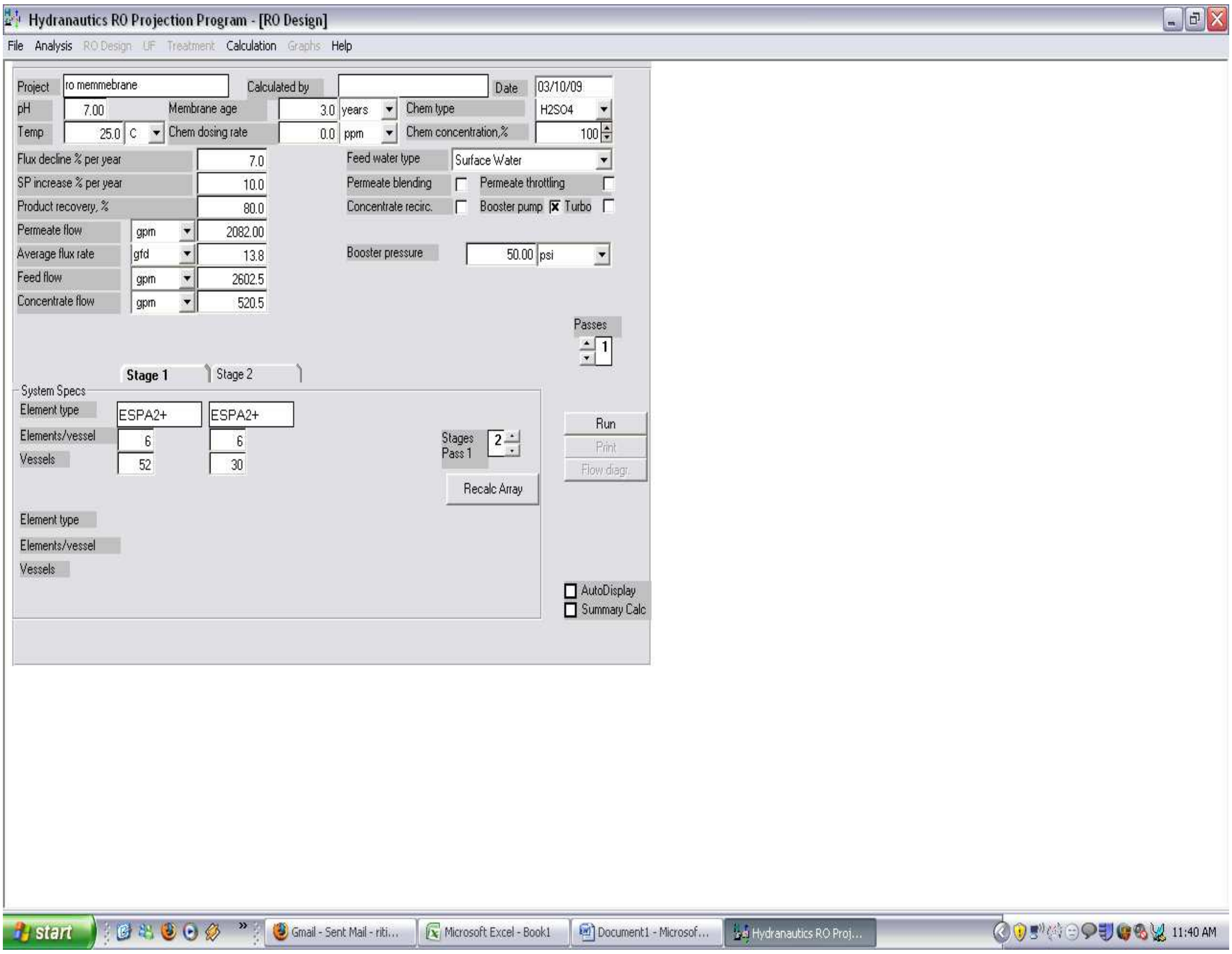
Ratio	Depth [m]	Area [m^2]	Filling Time [days]	Drying Time [days]
1	0.25	2573102	351	351
1	0.5	2573102	701	701
1	1	2573102	1403.9	1403.9
2	0.25	2438754	187.5	375
2	0.5	2438754	375	750
2	1	2438754	750	1500
3	0.5	2317995	247.8	743.4
3	1	2317995	495.6	1486.7
4	0.5	2201207	180.2	720.9
4	1	2201207	360.5	1441.8
0.98	0.5	2576153	713.8	699.5
0.98	0.75	2576153	1070.7	1049.2
0.98	1	2576153	1427.5	1399

Table A5: Results of Evaporation pond calculations calculated with specific drying and filling time ratios.

APPENDIX B – REVERSE OSMOSIS PROCESS PROGRAM

The design of the RO process was assisted by a program called IMSDesign™ (Hydranuatics, 2009). This section explains how it was used.

Permeate flow, recovery, pH, type of water, booster pressure, element type based on flow rate and temperature are input. The rest of the information is automatically calculated by the program. The TDS is also entered in the beginning. The feed water flow rate shown is less by a factor of 12 than the actual feed water flow rate of 1969 L/s in the following figure. 1969 L/s is a huge flow rate which cannot be handled by one pump alone in an optimal way; hence, it was decided to split the main feed water flow rate stream into 12 equal streams.



Project: ro memmebrane
Calculated by:
Date: 03/10/09
pH: 7.00
Membrane age: 3.0 years
Chem type: H2SO4
Temp: 25.0 C
Chem dosing rate: 0.0 ppm
Chem concentration,%: 100
Flux decline % per year: 7.0
SP increase % per year: 10.0
Product recovery, %: 80.0
Permeate flow: gpm 2082.00
Average flux rate: gfd 13.8
Feed flow: gpm 2602.5
Concentrate flow: gpm 520.5
Feed water type: Surface Water
Permeate blending ☐
Permeate throttling ☐
Concentrate recirc. ☐
Booster pump ☒
Turbo ☐
Booster pressure: 50.00 psi
Passes: 1

System Specs

	Stage 1	Stage 2
Element type	ESPA2+	ESPA2+
Elements/vessel	6	6
Vessels	52	30

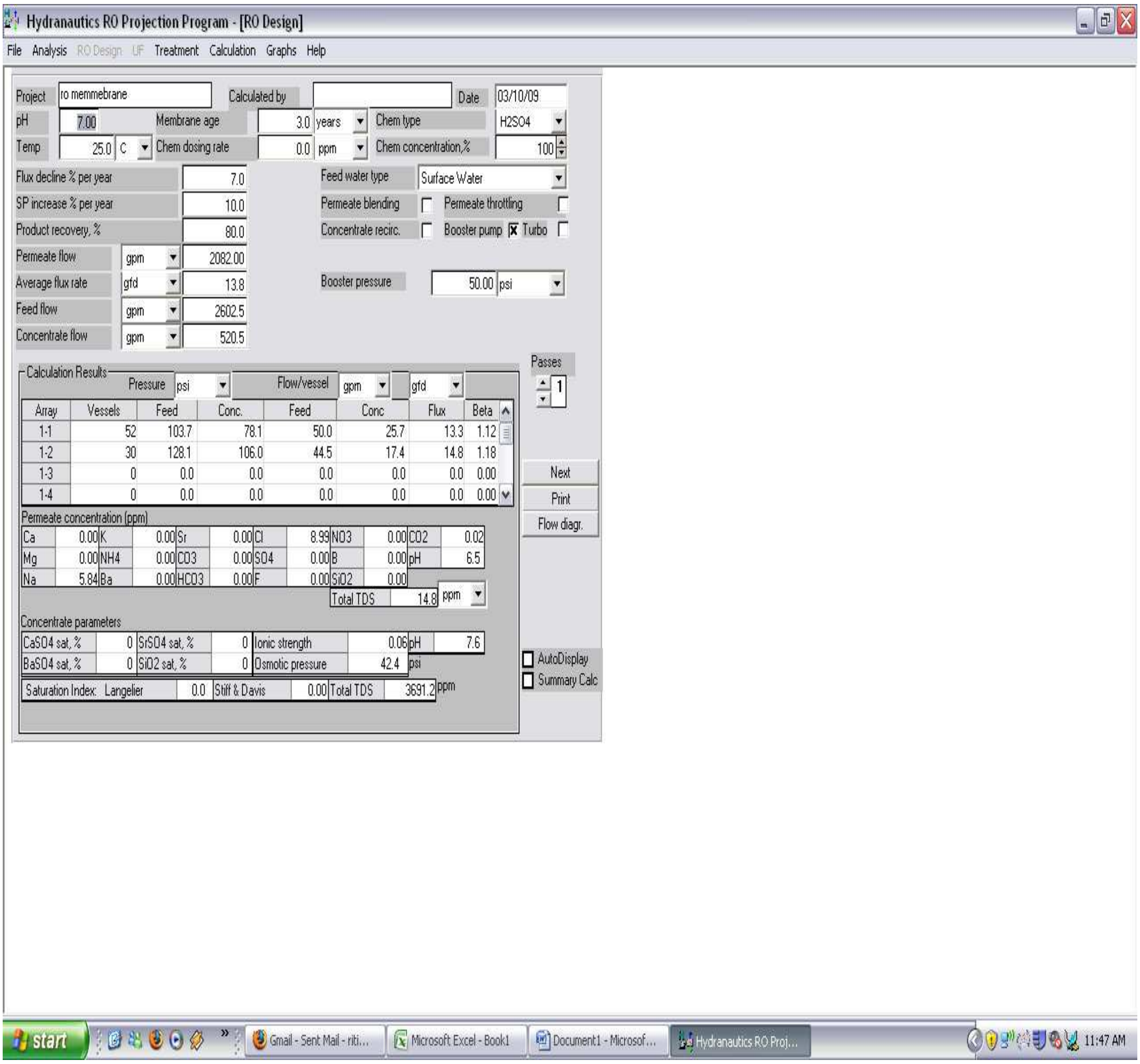
Stages Pass 1: 2

Element type
Elements/vessel
Vessels

☐ AutoDisplay
☐ Summary Calc

The "run" button is hit for the program to execute. The next window is the following:

The concentrate pressure and the intermediate pressures between stages are obtained using the following information:



Project: ro memmebrane
Calculated by:
Date: 03/10/09
pH: 7.00
Membrane age: 3.0 years
Chem type: H2SO4
Temp: 25.0 C
Chem dosing rate: 0.0 ppm
Chem concentration,%: 100
Flux decline % per year: 7.0
SP increase % per year: 10.0
Product recovery, %: 80.0
Permeate flow: gpm 2082.00
Average flux rate: gfd 13.8
Feed flow: gpm 2602.5
Concentrate flow: gpm 520.5
Feed water type: Surface Water
Permeate blending ☐ Permeate throttling ☐
Concentrate recirc. ☐ Booster pump ☒ Turbo ☐
Booster pressure: 50.00 psi
Passes: 1

Calculation Results — Pressure: psi; Flow/vessel: gpm; gfd

Array	Vessels	Feed	Conc.	Feed	Conc	Flux	Beta
1-1	52	103.7	78.1	50.0	25.7	13.3	1.12
1-2	30	128.1	106.0	44.5	17.4	14.8	1.18
1-3	0	0.0	0.0	0.0	0.0	0.0	0.00
1-4	0	0.0	0.0	0.0	0.0	0.0	0.00

Permeate concentration (ppm)

Ca	0.00	K	0.00	Sr	0.00	Cl	8.99	NO3	0.00	CO2	0.02
Mg	0.00	NH4	0.00	CO3	0.00	SO4	0.00	B	0.00	pH	6.5
Na	5.84	Ba	0.00	HCO3	0.00	F	0.00	SiO2	0.00		

Total TDS: 14.8 ppm

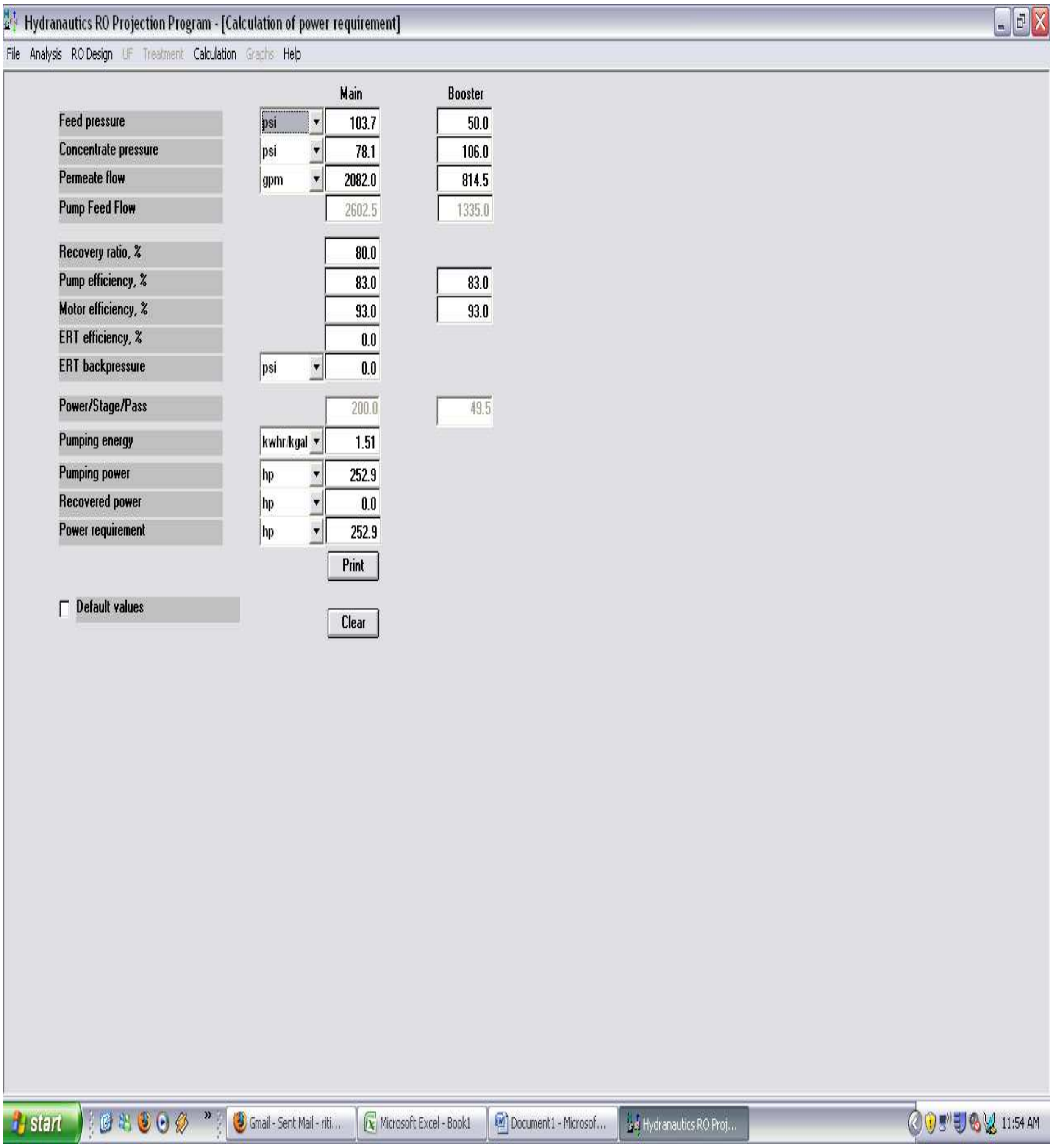
Concentrate parameters

CaSO4 sat, %	0	SrSO4 sat, %	0	Ionic strength	0.06	pH	7.6
BaSO4 sat, %	0	SiO2 sat, %	0	Osmotic pressure	42.4	psi	

Saturation Index: Langelier 0.0 Stiff & Davis 0.00 Total TDS 3691.2 ppm

☐ AutoDisplay
☐ Summary Calc

Power requirements of the pumps are also calculated by the program with a predicted efficiency. The following figure provides that information. Hit the "Calculation" key to get to the following screen:



Hydranautics RO Projection Program - [Calculation of power requirement]

		Main	Booster
Feed pressure	psi	103.7	50.0
Concentrate pressure	psi	78.1	106.0
Permeate flow	gpm	2082.0	814.5
Pump Feed Flow		2602.5	1335.0
Recovery ratio, %		80.0	
Pump efficiency, %		83.0	83.0
Motor efficiency, %		93.0	93.0
ERT efficiency, %		0.0	
ERT backpressure	psi	0.0	
Power/Stage/Pass		200.0	49.5
Pumping energy	kwhr/kgal	1.51	
Pumping power	hp	252.9	
Recovered power	hp	0.0	
Power requirement	hp	252.9	

☐ Default values

The rest of cost calculations are done on excel using Seider and price quotes from different companies. Refer to Appendix C for detailed economic calculations and Appendix E for prices via phone and email.

APPENDIX C – DETAILED ECONOMIC CALCULATIONS

Equipment Costs

Pumps P-101 – P-109

The function of these pumps is to supply CAP water to the pre-treatment process. First, the pressure head across the pump is calculated (Seider, 2003). The density, ρ, was found using an online density calculator (CSG Network, 1973-2009).

$$H = \frac{\Delta P}{\rho} \tag{C1}$$

$$H = \frac{34.4\,psi(144)}{62.278\frac{lb}{ft^3}} = 79.5\,ft$$

Using the pressure head, the size factor for the pump is calculated, which is used to calculate the base purchase cost for the pump (Seider, 2003).

$$S = Q \times H^{\frac{1}{2}} \tag{C2}$$

$$S = 3500\,gpm \times 79.5^{\frac{1}{2}} = 31{,}215\,gpm * ft^{.5}$$

$$C_B = e^{(9.2951-0.6019 lnS+0.0519(lnS)^2)} \tag{C3}$$

$$C_B = \$5{,}566.13$$

Next, the base purchase cost for the pump is calculated. Based on the flow rate and pump head, a one stage, 1800 rpm, VSC orientation, with pump-type factor F_T = 1.5, and a material factor F_M = 2 for stainless steel will be used (Seider, 2003).

$$C_P = F_T F_M C_B \tag{C4}$$

$$C_P = 1.5 \times 2.0 \times 5{,}566.13 = \$16{,}698$$

To cost the electric motor required to power the pump, the governing equation for the purchase cost of a motor is (Seider, 2003):

$$C_P = F_T C_B \tag{C5}$$

In order to solve for the base purchase cost of the motor, C_B, first calculate the power consumption using the following relationship (Seider,2003):

$$P_c = \frac{P_B}{\eta_M} = \frac{Q \times H \times \rho}{33{,}000 \times \eta_P \times \eta_M} \tag{C6}$$

Where η_M has a relationship with the flow rate (Q) and η_P has the following relationship (Seider, 2003):

$$\eta_P = -0.316 + 0.24015 lnQ - 0.01199 lnQ^2 \tag{C7}$$

$$\eta_P = 0.845$$

$$\eta_M = 0.80 + 0.0319 lnP_B - 0.00182 lnP_B^2 \tag{C8}$$

The pump brake horsepower, P_B, is found by rearranging the power consumption relationship.

$$P_B = \frac{Q \times H \times \rho}{33{,}000 \times \eta_P} \tag{C9}$$

$$P_B = 83.084\ hp$$

Next, calculate the power consumption and use the resulting value to calculate η_M from equation C8:

$$\eta_M = 0.80 + 0.0319 lnP_B - 0.00182 lnP_B^2 = 0.905$$

The power consumption can now be calculated from equation C6 and plugged in to find the base purchase cost of the electric motor (Seider, 2003).

$$P_c = \frac{P_B}{\eta_M} = \frac{83.084}{0.905} = 91.761\ hp$$

$$C_B = e^{\left(5.4866 + 0.13141 lnP_c + 0.053255 lnP_c^2 + 0.028628 lnP_c^3 - 0.0035549 lnP_c^4\right)} \tag{C10}$$

$$C_B = \$4{,}136.44$$

A totally enclosed, fan-cooled, 1800 rpm motor with a motor-type factor, F_T =1.3 is used (Seider, 2003). This will keep the cost for the electric motor as low as possible. Using equation C5:

$$C_P = F_T C_B \tag{C11}$$

$$C_P = \$5{,}377$$

The total cost of the pump includes the pump purchase cost and the motor purchase cost, as follows.

$$C_{Ptotal} = C_{Ppump} + C_{Pmotor} = 16{,}698 + 5{,}377 = \$22{,}076$$

This value is the purchase cost for the total pump using the mid-2000 cost index of 394 (Seider, 2003). To calculate the 2009 purchase cost, the 2009 cost index of 539.7 is used (Chemical Engineering, 2009) and the following equation:

$$\frac{\quad}{\quad} \tag{C12}$$

$$C_{P2009} = \frac{539.7}{394} \times 22{,}076 = \$30{,}239$$

The process uses nine of these pumps, so the total cost of the pumps is:

$$C_{P2009} * 9 = \$30{,}239 * 9 = \$272{,}154$$

These calculated values are shown in the following Table C1. The cost of the remaining pumps in the RO process, including P-201 – P-212 and P-301 – P-312, were calculated in a similar manner. Intermediate and final values for these calculations are also shown.

Parameter	CAP to Pre-Treatment (P-101 – P-109)	Stage 1 CAP Pumps (P-201 - P-212)	Stage 2 CAP Pumps (P-301 – P-312)
PUMP			
ΔP (psi)	34.4	89	50
H (ft)	79.54	205.79	115.61
Q (gpm)	3500	2601	1335
S (gpm*ft$^{.5}$)	31214.85	37312.06	14354.24
C_B (\$)	5566.13	6065.51	3979.37
C_P (\$)	16,698	18,197	11,938
ELECTRIC MOTOR			
η_P	0.85	0.83	0.79
P_B	83.08	162.48	49.21
η_M	0.91	0.92	0.90
P_C	91.76	177.53	54.88
C_B (\$)	4136.44	8225.79	2420.31
C_P (2000) (\$)	5,377	10,694	3,146
Total C_P (2000) (\$)	22,076	28,890	15,085
C_P 2009 per pump (\$)	30,239	39,574	20,663
Number of pumps needed	9	12	12
Total C_P 2009 (\$)	\$272,154	\$474,882	\$247,953

Table C1: Calculated costs for plant pumps.

Pressure Vessels (M-101 – M-1084)

The Stage 1 and Stage 2 pressure vessels will be 8” RO pressure vessels designed to hold 6 40” elements with end ports included. These vessels will be purchased from Weatherford A&M Composites for $2,237 per vessel (D. Geffert, personal communication, April 14, 2009). The RO plant requires 984 pressure vessels for a total uninstalled cost of $2,201,208.

Mixers (C-101, C-102)

The mixer will be a stainless steel turbine agitator handling a flow rate, Q, of 118.4 m^3/min (Appendix C). In order to calculate the volume, V, of the mixer, a residence time, τ, of 2 minutes will be assumed. Volume can be calculated as follows:

$$V = Q \times \tau$$

$$Q = 118.4 \frac{m^3}{\min}, \tau = 2\ min$$

$$V = 236.4\ m^3 = 236\ m^3 \times 264.17 \frac{gal}{m^3} = 62556\ gal$$

Due to the large mixer volume, it will have to be constructed onsite. According to Seider, the power required for a mixer that blends miscible liquids is 0.5 hp for every 1000 gallons (2003). Therefore the power required for the mixer is

$$P = \frac{0.5}{1000} \times 62556 = 31.27\ hp$$

C_B is then calculated, which includes the motor and shaft along with speed reducer (Seider, 2003).

$$C_B = 2850 \times P(in\ hP)^{0.57} = \$\ 20{,}283$$

For a stainless steel material of construction, F_M = 2, and C_P is calculated as follows (Seider, 2003):

$$C_p\,(2000) = C_B \times F_M = \$\,40{,}566$$

Using the CE Index, the cost in 2009 is:

$$C_p\,(2009) = \frac{539.7}{394} \times 40566 = \$\,55{,}568$$

Similarly, C_p for the 2nd mixer (C-102) = $ 55,568

Bare Module Cost of all Equipment

The bare module cost of the pumps, mixers, pressure vessels and other equipment can be calculated using the respective F_{BM} factor, as shown in Table C2 below. It was assumed that the F_{BM} for a mixer was the same as the F_{BM} for a horizontal pressure vessel. C_{BM} is calculated using the following equation (Seider, 2003).

$$C_{BM} = F_{BM} C_{P2009}\,.$$

Equipment	**Total C_P 2009**	**F_{BM}**	**C_{BM}**
Pump (CAP Water to pretreatment)	$272,154	3.3	$898,107
Mixer (C-101)	$55,567	3.05	$169,479
Mixer (C-102)	$55,567	3.05	$169,479
Stage 1 CAP Water Pumps (P-201 - P-212)	$474,882	3.3	$1,567,111
Stage 1 Pressure Vessels (M-101 - M-676)	$1,395,888	3.05	$4,257,458
Stage 2 CAP Water Pumps (P-301 - P-312)	$247,953	3.3	$818,243
Stage 2 Pressure Vessels (M-677 - M-976)	$805,320	3.05	$2,456,226
Total	**$3,307,330**		**$10,336,105**

Table C2: Bare Module cost of equipment.

Cost of Spares

The cost of spare equipment was calculated based on the number of spares needed to be purchased, as shown below in Table C3. Two spare pumps for each pump section were accounted for. Only one spare mixer was purchased, since C-101 and C-102 are identical. Spares for 1% of the pressure vessels were purchased.

Equipment	**Spares purchased**	**Cost of spares ($)**
Pump (CAP Water to pretreatment)	2	$199,579
Mixer (C-101)/Mixer (C-102)	1	$169,479
Stage 1 CAP Water Pumps (P-201 - P-212)	2	$261,185
Stage 1 Pressure Vessels (M-101 - M-676)	7	$40,937
Stage 2 CAP Water Pumps (P-301 - P-312)	2	$136,374
Stage 2 Pressure Vessels (M-677 - M-976)	4	$27,291
Total		**$834,846**

Table C3: Cost of spare equipment.

One-Time Costs

Cost of Excavation

The cost of excavation will include the cost of excavating the two ponds and the onsite landfill. In order to determine the cost of excavation for the landfill, the landfill volume must be found. The landfill will be designed to fit the amount of salt slurry produced over the 30-year life of the plant. Each cycle of filling then drying takes 2.93 years (Appendix A) and leaves 123,671 m^3 of salt slurry in the pond. The total life of 30 years can be divided by the cycle length to get a total of 11 cycles over the 30-year lifetime. The number of cycles can be multiplied by the volume of salts produced per cycle to get a total volume of 1,360,400 m^3. Assuming a depth of 20 m and a square pond gives a length of 261 m and a width of 261 m. Adding the volume of the landfill to the total volume of both ponds, 3,864,000 m^3, gives a total excavation volume of 5,224,400 m^3. A quote was received from Catclaw Contractors stating an excavation cost of \$2.23/m^3 (K. Robertson, personal communication, April 16, 2009). Refer to Appendix G for Phone Log with price quote. Multiplying the volume by the cost gives a total cost of excavation of \$11,650,500.

Cost of Land

Land will be purchased on which to build two 1605 m x 1605 m x 0.75 m evaporation ponds and a 261 m x 261 m x 20 m onsite landfill. The width of each item can be multiplied by its length to get the total area of land needed for that item. Using this calculation, the area of land needed for one pond was determined to be 2,576,025 m^2 and the area needed for the landfill was determined to be 68,121 m^2. Adding the areas for all three items and converting to acres gives a total land area of 1,290 acres. The price of undeveloped land in Coconino County was found to be \$563/acre (Crites, 1998-2009) and it will be assumed that that price is valid for Avra Valley. Multiplying the cost by the total area gives a total land cost of \$726,200.

Cost of PVC lining

PVC will be used to line the two 1605 m x 1605 m x 0.75 m evaporation and the 261 m x 261 m x 20 m onsite landfill. The total area of PVC lining needed can be determined as follows:

$$Surface\ Area = (2 * Width * Depth) + (2 * Length * Depth) + (Length * Width)$$

Using this equation, the total surface of PVC needed for one pond was found to be 2,580,840 m^2 and the total surface area needed for the landfill was determined to be 89,001 m^2. Adding all of the areas and converting to square feet gives a total PVC area of 56,497,328 ft^2. Using this area and a PVC cost, including installation, of \$0.345/ft^2 (M. Winterbourne, personal communication, April 14, 2009), the total PVC cost was determined to be \$19,491,600.

Annual Costs

Salt Removal

Once the drying phase has been completed, the salt slurry must be removed from the evaporation pond. Outside excavators will be hired to excavate, load, and haul the salt to the onsite landfill. At the end of each cycle, 123,671 m^3 of salt will need to be removed (Calculation shown in Appendix C). An estimate of \$2.23/m^3 for excavation, loading, and hauling was given by Catclaw Contractors and can be used to determine the cost of salt removal (K. Robertson, personal communication, April 16, 2009). Multiplying the cost of excavation by the salt volume yields a total salt removal cost of \$275,786 per cycle. For costing purposes, an annual removal value will be determined assuming a fixed amount of money will be set aside for removal per year. Dividing the total removal cost per cycle by the cycle length of 2.93 years (Appendix A) gives an annual cost of \$94,125 for salt removal.

CAP Water

The total amount of CAP water needed per year can be calculated from the CAP water flow rate of 5636 L/s into the plant (Appendix C). After unit conversions, this flow rate can be expressed as 144,092 acre-ft/yr. The Central Arizona Project lists a CAP water cost of $143 per acre-ft (Central Arizona Project, 2009). Multiplying the cost by the total flow gives an annual CAP water cost of $20,605,000.

Chlorine

The amount of chlorine needed per year was determined to be 208,573 lbs based on the flow rate of chlorine into the pre-treatment system. An average price of $0.13/lb for chlorine in 2008 was found (ICIS, 2009). Multiplying these values gives a total annual cost of $27,114 for chlorine in 2008. From this present value, P, an average inflation value, i, (InflationData.com, 2003-2009) and the number of years, n, a future value, F, for 2009 could be determined as follows:

$$F = P(1+i)^n \tag{C13}$$

$$F = \$27{,}114(1+.03)^1 = \$27{,}928$$

Based on these calculations, the annual cost for chlorine in 2009 will be $28,000.

Coagulant

Using the feed flow rate into the pre-treatment system, the amount of coagulant needed per year was determined to be 139,049 lbs with the help of Robert Goodlett of Avistatech. The cost of coagulant was found to be $0.50/lb (personal communication, April 14, 2009). Multiplying these values gave a total annual coagulant cost of $69,500.

Polyelectrolyte

Using the flow rate of polyelectrolyte into the pre-treatment system, the amount of polyelectrolyte needed per year was determined to be 6,813,378 lbs (Mike, personal communication, April 14, 2009). The cost of polyelectrolyte was found to be $1.50/lb (Rob Goodlett, Personal Communication, 4/14/09). Multiplying these values gave a total annual polyelectrolyte cost of $10,220,000.

Sulfuric Acid

The amount of sulfuric acid needed per year was determined to be 139,049 lb based on the flow rate of sulfuric acid into the pre-treatment system. A typical price of $0.04/lb for sulfuric acid in 2006 was found (ICIS, 2009). Multiplying these values gives a total annual cost of $5,562 for chlorine in 2006. From this present value, P, an average inflation value, i, (InflationData.com, 2003-2009) and the number of years, n, a future value, F, for 2009 can be determined as follows:

$$F = P(1+i)^n \qquad \text{(C13)}$$

$$F = \$5{,}562(1+.03)^3 = \$6{,}078$$

Based on these calculations, the annual cost for sulfuric acid in 2009 will be $6,000.

Antiscalant

Using the flow rate of the antiscalant into the pre-treatment system, the total amount of antiscalant needed per year was determined to be 410,193 lbs. The cost of the antiscalant was found to be $1.75/lb (Rob Goodlett, Personal Communication, 4/14/09). Multiplying the cost of antiscalant by the amount needed gives a total annual cost of $717,800 for antiscalant.

Cartridge Filters

Overall there are 38 cartridge filters and one spare. It is assumed that all of the cartridge filters have the same lifetime as the sand filters and are good for 5 years. A quote was obtained estimating the cost of each filter to be $27,000 (Mike, personal communication, April 14, 2009). Taking into account the price of each filter, the cost to replace all 39 (including a spare) cartridge filters would be $1,053,000. Since all of the cartridge filters must be replaced every 5 years, the annual cost in 2009 incurred by the cartridge filters would be $210,600.

Carbon Filters

Overall 13 carbon filters are needed to handle the incoming flow rate of 31,209 gpm. It is assumed that all of the carbon filters have the same lifetime as the sand filters and must be replaced every 5 years. An estimate of $20,000 per filter was received from Alar Engineering

(Mike, personal communication, April 14, 2009). Taking into account the price per filter, the cost to replace all 13 carbon filters plus one spare would be $280,000. Due to the fact that all of the carbon filters are replaced every 5 years, the annual cost incurred from replacing the carbon filters would be $56,000.

Sand Filters

Overall 21 sand filters are needed to successfully treat the desired flow rate of CAP water. It is assumed that all of the filters are replaced every 5 years (Steve Wolfson, Personal Communication, April 13, 2009). The current cost of each sand filter is $22,000 (Steve Wolfson, Personal Communication, April 13, 2009). Taking into account the price of each filter, the cost to replace all 21 sand filters plus one spare would be $484,000. Since all of the filters are replaced every 5 years, the annual cost incurred by continued use and replacement of the sand filters would be $96,800.

Well Water

In order to lower the TDS concentration of the CAP water and meet the water usage demand for the city of Tucson, the CAP water is mixed with well water whose source is an aquifer below Tucson. It is estimated that 49,982 acre-ft/year of well water is mixed with the CAP water before the water is distributed to the city of Tucson (Water Resources Research Center, 1995). The cost of the well water, including the maintenance, operation, and repair costs of the well, was $40/acre-ft in 1995 (Water Resources Research Center, 1995). After multiplying the water cost by the water usage, the total annual cost for the well water in 1995 was calculated to be $1,999,283. Using equation C13, the cost of well water in 2009 was found to be $2,532,600.

Membranes

In the designed RO facility there are total 5,904 membranes, as calculated from the Hydranautic RO design program (2009). Assuming that the number of spares is 1% the total number of membranes, there would be 60 spares and 5,964 membranes total. Each RO membrane costs $583 (ROwaterSystems, Inc., 2009). Therefore, the cost to replace all 5,964 membranes would be $3,478,500. The ESPA2+ membranes that were chosen were assumed to have an average membrane lifetime of 3 years under continuous usage. Taking the lifetime of the membranes into account, the annual cost to replace the RO membranes would be $1,159,500.

Water Selling Price

The total amount of water sold is the total amount of water that is allocated to Tucson and sold to the residents. Each year the people of the city of Tucson use 80,169,800 Ccf, where 1 Ccf is equal to 100 cubic feet. The cost of water in Tucson is listed by Tucson water as $1.753 per Ccf (Tucson Water, 2009). After multiplying the water usage by the cost of water the total amount earned for selling the water is found to be $140,537,600 per year.

Operating Costs and IRR

The total depreciable capital (C_{TDC}) for the reverse osmosis plant along with the evaporation ponds was calculated using the Guthrie method, as shown in the following equation (Seider, 2003):

$$C_{TDC} = 1.18(C_{TBM} + C_{site} + C_{buildings} + C_{offsite}) \tag{C14}$$

where $C_{offsite}$ is the cost of offsite facilities, $C_{buildings}$ is the cost of the buildings, and C_{site} is the cost of the site. These values are calculated as shown in Table C4.

Cost	Method of Calculating
C_{site}	**15% of C_{TBM}**
$C_{buildings}$	**30% of C_{TBM}**
$C_{offsite}$	**5% of C_{TBM}**

Table C4: Method of calculating certain building costs.

The total operation and maintenance costs were calculated as shown in Table C5 (Seider, 2003).

Cost	Method of Calculating	Total
Feedstocks (raw materials)		$35,702,000
Utilities		$2,404,800
Operations [labor related] [O]		$2,810,100
Direct wages and Benefits [DW&B]	$30/operator-hr	$1,872,000
Direct salaries and benefits	15% of DW&B	$280,800
Operating supplies and services	6% of DW&B	$112,300
Technical assistance to manufacturing	$52,000/(operator/shift)-yr	$260,000
Control Laboratory	$57,000/(operator/shift)-yr	$285,000
Maintenance [M]		$6,132,400
Wages and benefits [MW&B]	3.5% of C_{TDC}	$2,666,300
Salaries and benefits	25% of MW&B	$666,600
Materials and services	100% of MW&B	$2,666,300
Maintenance overhead	5% of MW&B	$133,300
Operating overhead		$1,250,700
General plant overhead	7.1% of M&O-SW&B	$389,500
Mechanical department services	2.4% of M&O-SW&B	$131,700
Employee relations department	5.9% of M&O-SW&B	$323,700
Business services	7.4% of M&O-SW&B	$405,900
Property taxes and insurance	2% of C_{TDC}	$1,523,600
Depreciation [D]	8% of (C_{TDC}-1.18C_{alloc})	$3,555,000
Cost of manufacture [COM]	Sum of above	$53,378,700
General expenses [GE]		$13,421,300
Selling expense	1% of sales	$1,405,400
Direct research	4.8% of sales	$6,745,800
Allocated research	0.5% of sales	$702,700
Administrative expense	2.0% of sales	$2,810,800
Management incentive compensation	1.25% of sales	$1,756,700
Sales		$140,573,600
Tap Water	$1.753/100 ft^3 [2009]	$140,573,600
Total Production Cost [C]	**COM+GE**	**$66,800,100**

Table C5: Overall costs for the operation of the RO facility.

The feedstocks (raw materials) include CAP water, Well Water from the Tucson aquifer, polyelectrolyte, chlorine, antiscalant, sulfuric acid, and coagulant. Additionally, the annual costs incurred from the replacement of the sand filters, carbon filters, cartridge filters, and RO membranes are also included in the cost of the feedstocks. The utility cost is the cost for electricity necessary for the initial CAP water pump, the Stage 1 RO pumps, and the inter-stage RO pumps. In order to find the operating costs, it was assumed that there were three sections to the plant: one section for the pre-treatment of the CAP water, and one for each membrane stage with the evaporation ponds included in the last RO plant section since they do not require as much maintenance. Fluids processing requires two operators per section in this situation due to the extremely high flow rate of liquid and the higher operating pressures. Therefore, assuming five shifts, there would be a total of 30 shift-operators at the plant. One labor year for technical assistance and control laboratory was assumed with five shifts per day. Overall, the plant was assumed to run 365 days out of the year. All of the costs were normalized to 2009.

$$DW\&B = (operators/shift)(5shifts)(2{,}080hr/yr - operator)(\$/hr) \tag{C15}$$

where operators/shift is the number of operators needed per shift, and \$/hr is the hourly wage of the operators, assumed to be \$30/hr (Seider, 2003).

The cost of manufacture (COM) is the sum of the operations costs, maintenance costs, operating overhead, property taxes and insurance, and depreciation. The total annual cost of production (C) is the COM plus the general expenses (GE), but minus the depreciation (Seider, 2003). The total annual cost of production excluding depreciation ($C_{excel\ dep}$) is the cost of production minus the depreciation. The annual constant value for the depreciation used in calculating the COM and payback period (PBP) was calculated as a straight-line depreciation. The tax rate is assumed to be at 37% (Seider, 2003). As mentioned, Table C5 shows all of these calculations and their resulting values for the designed RO plant and evaporation ponds.

The net earnings or profit was calculated using Equation C16 (Seider, 2003).

$$\mathrm{N} = (1 - t)(\mathrm{S} - \mathrm{C}) \tag{C16}$$

where t is the tax rate, 0.37, S is the total sales, and C is the total cost of production.

The payback period was calculated as 1.52 years using Equation C17 (Seider, 2003).

$$\mathrm{PBP} = \frac{\mathrm{C}_{\mathrm{TDC}}}{\text{net earnings} + \text{annual depreciation}} = \frac{\mathrm{C}_{\mathrm{TDC}}}{(1 - t)(\mathrm{S} - \mathrm{C}) + \mathrm{D}} \tag{C17}$$

In order to calculate the working capital, an equation from Seider that takes into account the current assets minus the current liabilities.

$$\mathrm{C}_{\mathrm{WC}} = \text{cash reserves} + \text{inventory} + \text{accounts receivable} - \text{accounts payable} \tag{C18}$$

where cash reserves, inventory, accounts receivable, and accounts payable are calculated as shown in Table C6.

Asset/Liability	Method of Calculating
Cash reserves	8.33% of COM
Inventory	1.92% of main product sales
Accounts receivable	8.33% of total sales
Accounts payable	8.33% of the cost of feedstock

Table C6: Method of calculating values necessary to find the working capital.

The overall working capital was calculated to be \$15,877,576. The Investor's Rate of Return (IRR) is the interest rate that will give a net present value of zero at the end of the plant lifetime. The Net Present Value (NPV) is first calculated from Equation C19. The NPV is the sum net present value from the previous year along with the present worth of the current year's cash flow. The cash flow is the net earnings plus the depreciation.

$$NPV^{r} = NPV^{r-1} + \frac{Cashflow}{(1+i)^{r-1}} \tag{C19}$$

where NPV^r is the net present value of the current year, NPV^{r-1} is the net present value of the previous year, *i* is the interest rate, r is the current year that the calculations are being performed at (Seider, 2003). In order to obtain a more accurate value for the IRR, the net earnings and the cash flow are both calculated using a depreciation that is found using the sum-of-the-years-digits method (SYD) as shown in Equation C20 (Seider, 2003).

$$SUM = \sum_{j=1}^{n} j = \frac{n(n+1)}{2} \tag{C20}$$

where n is the total number of years. For a 30 year lifetime *SUM* is equal to 465. The annual depreciation during any given year is given in Equation C21 (Seider, 2003).

$$D_t = \frac{\text{depreciable years remaining}}{\text{SUM}}(C_{TBM} - S_{equip}) \qquad \text{(C21)}$$

where S_{equip} is the salvage cost of the equipment which is assumed to be 8% of the total bare module cost, and C_{TBM} is the total bare module cost of the equipment. Once the NPV for all the years has been calculated solver is used in order to find an interest rate *i* that gives a NPV of zero at the end of the RO plant and evaporation pond life. In this case the plant life was assumed to be 30 years from the start of treating the CAP water in the RO plant along with an initial 3 years in order to build the plant. When calculated using solver, the IRR was found to be an astounding 39.3%. Refer to Appendix E to see the Excel spreadsheet used to calculate these discussed values.

APPENDIX D – OVERALL MASS AND ENERGY BALANCES

Refer to the Figure D1 for stream numbers reflecting overall process and not the actual PFD. Our target is to calculate Total Dissolved Solids (TDS) in stream 2, and the unknown flow rates around the system. Again, the following calculations only reflect overall material balances as shown in Figure D2.

Please note that the calculations for material balances reflecting specific stream numbers in PFD (Section 2.2) and stream Table (Section 2.4) be shown later after overall material balances have been calculated.

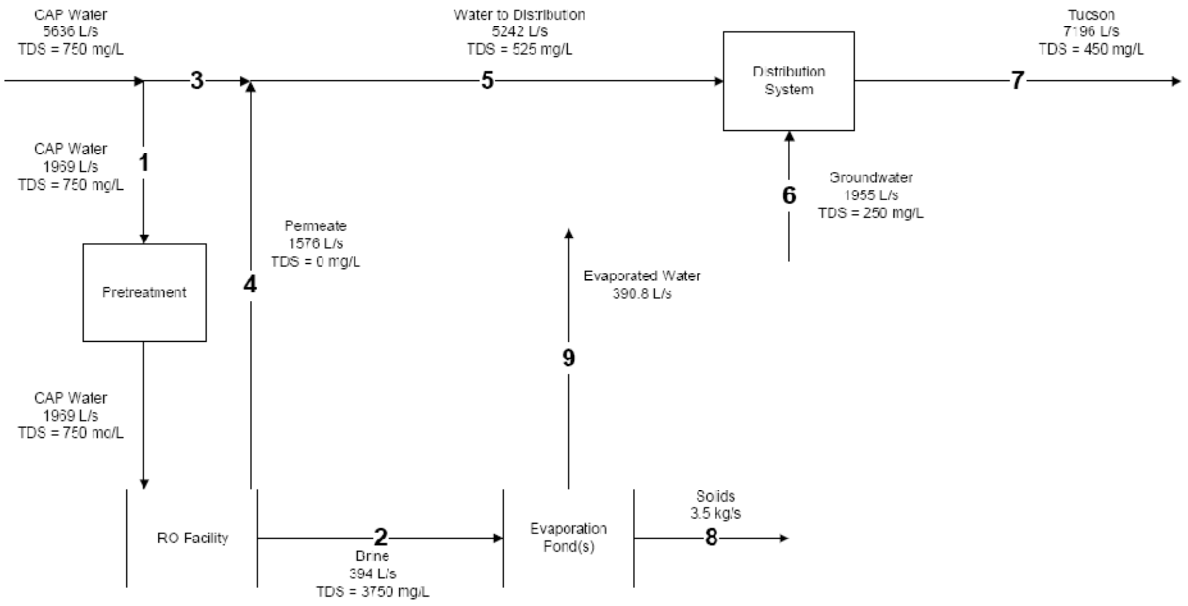


Figure D1: An Illustration showing overall material balances around the system. This figure does not reflect the stream numbers in Stream Table 2.4.

The following conversion will be used in our calculations:

$$1 \text{ AFY (Acre X Ft / Yr)} = 43560 \text{ ft}^3 / \text{yr} = 1.23348 \text{ X } 10^6 \text{ L / yr} \qquad \text{(D1)}$$

The following are the known flow rates:

Stream 1 (From D1 conversion and CAP water data):

$$Q_1 = 144{,}172 \text{ AFY} = (144172 \text{ X } 1.23348 \text{ X } 10^6) / (365 \text{ X } 24 \text{ X } 3600) \text{ L/s}$$

$$= 5635.7 \text{ L/s}$$

$$TDS_1 = 750 \text{ mg/L}$$

Stream 6 (From C1 and Tucson aquifer water data):

$$Q_6 = 50{,}000 \text{ AFY} = (50000 \text{ X } 1.23348 \text{ X } 10^6) / (365 \text{ X } 24 \text{ X } 3600) \text{ L/s}$$

$$= 1954.5 \text{ L/s}$$

$$TDS_6 = 250 \text{ mg/L}$$

According to the requirements given by Tucson water management stream 7 cannot have more than 450 mg/L of TDS. We calculated the flow rates that are required around the system and the RO plant to achieve the minimum limit set by the government.

If there were no RO plant, stream 7 would have approximately 620 mg/L of TDS which is much higher than the limit set by the government. TDS in stream 7 is calculated as the following (assuming streams 2 and 3 are absent).

$$TDS_7 = (Q_1 \text{ X } TDS_1 + Q_6 \text{ X } TDS_6) / (Q_1 + Q_6) \sim 620 \text{ mg/L} \qquad \text{(D2)}$$

Therefore, the RO plant facility is set up to meet the requirements for Tucson water. The above equation changes to the following:

$$TDS_7 = (Q_5 \text{ X } TDS_5 + Q_6 \text{ X } TDS_6) / (Q_5 + Q_6) \qquad \text{(D3)}$$

Where

$$Q_5 = Q_4 + Q_3 \qquad \text{(D2)}$$

$$Q_4 = Q_1 - Q_2 \qquad \text{(D3)}$$

$$Q_7 = Q_5 + Q_6 \qquad \text{(D4)}$$

Assuming the RO plant has a rejection coefficient of 0.8,

$$Q_3 = 0.8 \text{ X } Q_2 \qquad \text{(D5)}$$

We will use solver in excel to determine flow rate of stream 2. Assume any flow rate for Q_2, and set the value of TDS_7 to 450 by changing Q_2. Doing that gives us the following result:

Stream 2:

$$Q_2 = 1969.4 \text{ L/s}$$

$$TDS_2 = 750 \text{ mg/L}$$

TDS_2 is the same as TDS_1, because composition does not change when a stream splits.

Stream 3 (From D7):

$$Q_3 = 0.8 \text{ X } Q_2 = 1575.5 \text{ L/s}$$

$$TDS_3 = 0$$

(TDS_3 is zero since the permeate from the RO facility does not contain any solids)

Stream 4 (From D5):

$$Q_4 = Q_1 - Q_2 = (5635.7 - 1969.4) \text{ L/s} = 3666.2 \text{ L/s}$$

$$TDS_4 = 750 \text{ mg/L}$$

(TDS_4 is the same as TDS_1, because composition does not change when a stream splits)

Stream 5 (From D4):

$$Q_5 = Q_4 + Q_3 = (3666.2 + 1575.5) \text{ L/s} = 5241.8 \text{ L/s}$$

$$TDS_5 = (Q_3 \text{ X } TDS_3 + Q_4 \text{ X } TDS_4) / (Q_3 + Q_4) = 524.5 \text{ mg/L} \qquad \text{(D8)}$$

So stream 7 is (From C6):

$$Q_7 = Q_5 + Q_6 = 7196.3 \text{ mg/L}$$

We will be designing a system for treating stream 8 which is also called the brine or concentrate. This stream contains large amounts of TDS, and an efficient method is needed to avoid this TDS to seep through the ground and contaminate the ground water.

$$Q_8 = Q_2 - Q_3 = 393.\ 88 \text{ L/s} \tag{D9}$$

$$TDS_8 = (Q_2 \text{ X } TDS_2) / (Q_8) = 3750 \text{ mg/L} \tag{D10}$$

The following material balances are PFD stream specific. Please refer to the PFD in Section 2.2 for more details.

Stream 1 in Figure D1 is the same as stream 1 in the PFD. Therefore,

$$Q_1 = 1969 \text{ L/s at } P_1 = 1 \text{ atm and } T_1 = 298 \text{ K.}$$

Q_1 is the feed stream and undergoes pre-treatment process before it enters the RO plant. Chlorine, polyelectrolyte, coagulant are added together in streams 2, 3, and 4 respectively. They are mixed in stream 5.

Mass flow rates of 0.003 kg/s chlorine, 0.098 kg/s polyelectrolyte, 0.002 coagulant are added in streams 2, 3, and 4 respectively (Goodlett, 2008). Therefore, the mass flow rate of stream 5 is (0.003 + 0.098 + 0.002) kg/s = 0.0148 kg/s.

Since negligible amounts of chemicals are added, the following flow rates result

$$Q_8 = Q_9 = Q_{10} = Q_{11} = Q_{12} = Q_{13} = Q_{14} = Q_{15} = 1969 \text{ L/s}$$

All these streams go through a series of filters (F-101, F-102, and F-103) for removal big particles such as dirt to avoid any damage to the RO membranes.

The change in pressure between stream 8 and stream 9 is 2.24 atm (Hydranautics, 2009). So,

$$P_9 = 3.34 \text{ atm}$$

Q_{15} enters the RO plant after getting pre-treated and splits into 3 streams (16, 17, and 18). This gives,

$$Q_{16} = Q_{17} = Q_{18} = 1969/3 = 656.4 \text{ L/s.}$$

Streams 16, 17, and 18 split further into 2 streams each. So,

$$Q_{19} = Q_{20} = Q_{21} = Q_{22} = Q_{23} = Q_{24} = 656.4/2 = 328.2 \text{ L/s}$$

Similarly, streams 19, 20, 21, 22, 23, and 24 further split into 2 other streams. This gives,

$$Q_{25} = Q_{26} = Q_{27} = Q_{28} = Q_{29} = Q_{30} = Q_{31} = Q_{32} = Q_{33} = Q_{34} = Q_{35} = Q_{36} = 328.2/2 = 164.1 \text{ L/s}$$

All these streams are pumped to a pressure of 7.06 atm. (As calculated by the Hydranautics program IMSDesign™ for designing RO plant.) See Appendix B for screen shots of the program.

Since only the pressure is changed and the streams are only liquid, streams 37-48 have the same flow rate as streams 25 to 36. In other words,

$$Q_{25-36} = Q_{37-48} = 164.1 \text{ L/s}$$

Streams 37-48 enter the RO membranes ESPA2+ selected from the Hydranautics program IMSDesign™ (2009). Note that the feed has been split into 12 equal streams because 1969 L/s is a large flow rate and it is therefore more efficient to divide huge flow rate into smaller flow rates.

The whole calculation for the RO plant was done using Hydranautics program (See Appendix B). Each stream (37-48) enters 55 pressure vessels, each containing 6 membrane elements in stage 1 of the RO plant. Refer to PFD (Section 2.2) for details.

Total Vessels in stage 1 = $12 \times 52 = 624$

Total membrane elements in stage 1 (assuming 6 elements per vessel) = $624 \times 6 = 3744$

When an 80% recovery and a feed water flow rate of 164.1 L/s was entered into the Hydranautics program IMSDesign™, the concentrate and permeate recovery was calculated. (See Appendix B.)

Streams 49-60 are the individual permeate streams, and streams 72-83 are the concentrate flow rates calculated by the program for stage 1.

$$Q_{49\text{-}60} = 80 \text{ L/s}$$

$$Q_{72\text{-}83} = 84.2 \text{ L/s}$$

These concentrate streams leave at a pressure of 5.31 atm (Hydranautics, 2009).

$$Q_{61} = Q_{49} + Q_{50} = 159.9 \text{ L/s}$$

$$Q_{62} = Q_{51}+Q_{61} = 239.9 \text{ L/s}$$

$$Q_{63} = Q_{52} + Q_{62} = 319.8 \text{ L/s}$$

$$Q_{64} = Q_{53} + Q_{63} = 399.9 \text{ L/s}$$

$$Q_{65} = Q_{54} + Q_{64} = 479.8 \text{ L/s}$$

$$Q_{66} = Q_{55} + Q_{65} = 559.8 \text{ L/s}$$

$$Q_{67} = Q_{56} + Q_{66} = 639.8 \text{ L/s}$$

$$Q_{68} = Q_{57} + Q_{67} = 719.7 \text{ L/s}$$

$$Q_{69} = Q_{58} + Q_{68} = 799.7 \text{ L/s}$$

$$Q_{70} = Q_{69} + Q_{59} = 879.7 \text{ L/s}$$

$$Q_{71} = Q_{70} + Q_{60} = 959.6 \text{ L/s}$$

Streams 71 to 83 now enter stage of the RO plant. Refer to PFD (Section 2.2) for details. These streams again pass through centrifugal pumps P-301 to P-312 in parallel. Streams 71 to 83 are increased to a pressure of 8.71 atm and they exit the pumps as streams 84 to 95. Therefore,

$$Q_{84\text{-}95} = 84.2 \text{ L/s.}$$

The Hydranautics program IMSDesign™ calculated 30 pressure vessels each containing 6 membrane vessels (See Appendix B).

So, total pressure vessels in stage 2 = $12 \times 30 = 360$

Total membranes in stage 2 (6 elements per vessel) = $360 \times 6 = 2160$

Similarly, as shown in stage 1 calculations, stage 2 concentrate and permeate streams were calculated using the Hydranautics program IMSDesign™ (2009) (See Appendix B).

$$Q_{120\text{-}131} = 32.8 \text{ L/s}$$

Similarly, $Q_{96\text{-}107} = 51.4$ L/s

$$Q_{108} = Q_{96} + Q_{97} = 102.8$$

$$Q_{109} = Q_{98} + Q_{108} = 154.2 \text{ L/s}$$

$$Q_{110} = Q_{109} + Q_{99} = 205.6 \text{ L/s}$$

$$Q_{111} = Q_{110} + Q_{100} = 257 \text{ L/s}$$

$$Q_{112} = Q_{111} + Q_{101} = 308 \text{ L/s}$$

$$Q_{113} = Q_{112} + Q_{102} = 359.7 \text{ L/s}$$

$$Q_{114} = Q_{113} + Q_{103} = 411.1 \text{ L/s}$$

$$Q_{115} = Q_{114} + Q_{104} = 462.5 \text{ L/s}$$

$$Q_{116} = Q_{115} + Q_{105} = 513.9 \text{ L/s}$$

$$Q_{117} = Q_{116} + Q_{106} = 565.3 \text{ L/s}$$

$$Q_{118} = Q_{117} + Q_{107} = 616.7 \text{ L/s}$$

The total permeate out of the RO plant = $Q_{71} + Q_{118} = 1576$ L/s

Check: $= 0.8 \times 1969 \sim 1576 \frac{L}{s}$

Similarly for the total concentrate (streams 132-142):

$$Q_{132} = Q_{120} + Q_{121} = 65.6 \text{ L/s}$$

$$Q_{133} = Q_{132} + Q_{122} = 98.4 \text{ L/s}$$

$$Q_{134} = Q_{133} + Q_{123} = 131.2 \text{ L/s}$$

$$Q_{135} = Q_{134} + Q_{124} = 164 \text{ L/s}$$

$$Q_{136} = Q_{135} + Q_{125} = 196.8 \text{ L/s}$$

$$Q_{137} = Q_{136} + Q_{126} = 229.6 \text{ L/s}$$

$$Q_{138} = Q_{137} + Q_{127} = 262.4 \text{ L/s}$$

$$Q_{139} = Q_{138} + Q_{128} = 295.2 \text{ L/s}$$

$$Q_{140} = Q_{139} + Q_{129} = 328 \text{ L/s}$$

$$Q_{141} = Q_{140} + Q_{130} = 360.8 \text{ L/s}$$

$$Q_{142} = Q_{141} + Q_{131} = 394 \text{ L/s}$$

The concentrate exits at 7.21 atm and then goes to the evaporation ponds for safe disposal.

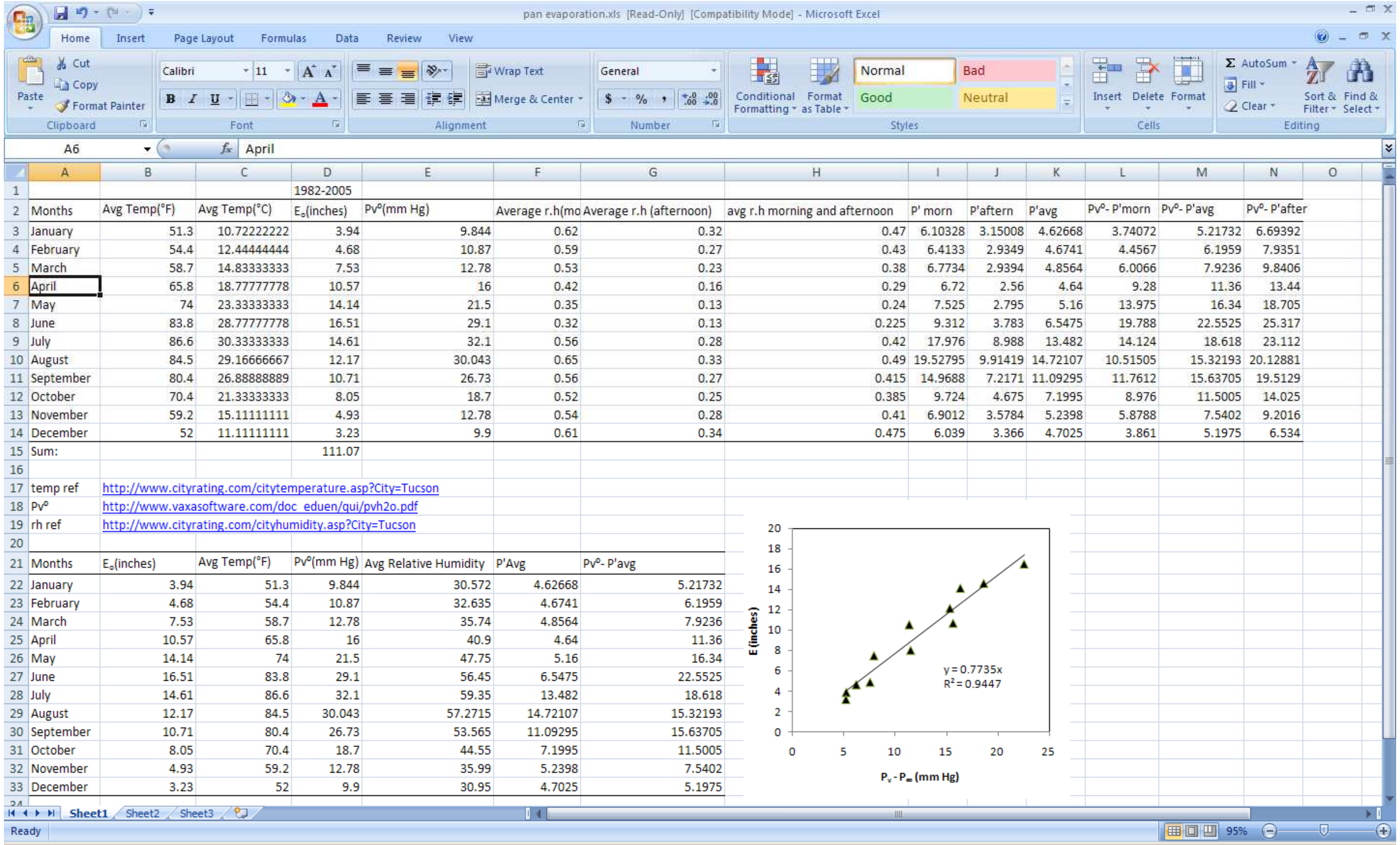
Therefore,

$$Q_{142} = Q_{143} = 394 \text{ L/s}$$

If evaporation pond E-401 is in its filling stage, then Stream 143 will exit valve V-402 as Stream 144 at a flow rate of 394 L/s or 394 kg/s and the flow rate of Stream 145 would then be 0 L/s. If evaporation pond E-402 is in its filling stage, then Stream 143 will exit valve V-402 as Stream 145 at a flow rate of 394 L/s or 394 kg/s and the flow rate of Stream 144 would then be 0 L/s. The overall evaporation rate of liquid water is 392.9 L/s, which equals a vapor volumetric flow rate of 487,449 L/s. Some of the liquid water that enters into the ponds remains with the salts when the water has been mostly evaporated. The volume of the water left in the pond is twice the volume of the salt that has precipitated. The volume of the salt was assumed to equal the volume which was calculated by using the density of the most common salt, sodium sulfate. The density of sodium sulfate is 2.68 g/cm^3 (Sodium Sulfate MSDS, 2006). The total mass flow rate of the pure salt is 1.5 kg/s, which yields a solid volumetric flow rate 0.6 L/s and a total slurry flow rate of 1.7 L/s. The mass flow rate of the added saturated salt solution is 1.2 kg/s. Therefore, the overall average flow rate of the brine salts is 2.7 kg/s or 1.7 L/s. Practically, during the drying stage of the evaporation cycle all of the salt slurry will be removed at once from one pond within the extra allotted time. Also, the water will be evaporating at different rates during the year and from each pond as the ponds are filling and once they are filled.

Appendix E – Excel Spreadsheets

Spreadsheet for the calculation of mass transfer coefficient:

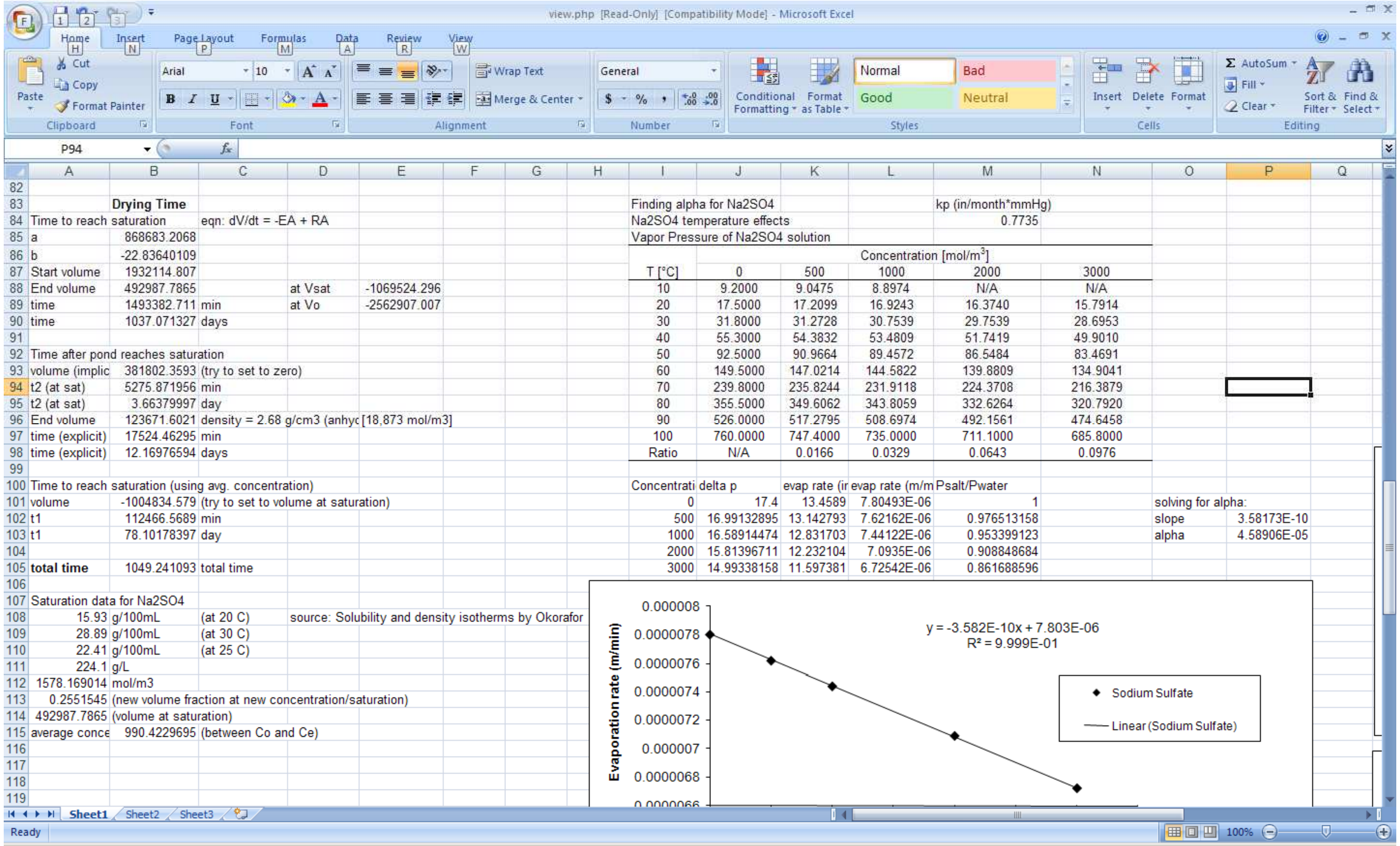


A6 April

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1				1982-2005										
2	Months	Avg Temp(°F)	Avg Temp(°C)	E_o(inches)	Pv°(mm Hg)	Average r.h(mo	Average r.h (afternoon)	avg r.h morning and afternoon	P' morn	P'aftern	P'avg	Pv°- P'morn	Pv°- P'avg	Pv°- P'after
3	January	51.3	10.72222222	3.94	9.844	0.62	0.32	0.47	6.10328	3.15008	4.62668	3.74072	5.21732	6.69392
4	February	54.4	12.44444444	4.68	10.87	0.59	0.27	0.43	6.4133	2.9349	4.6741	4.4567	6.1959	7.9351
5	March	58.7	14.83333333	7.53	12.78	0.53	0.23	0.38	6.7734	2.9394	4.8564	6.0066	7.9236	9.8406
6	April	65.8	18.77777778	10.57	16	0.42	0.16	0.29	6.72	2.56	4.64	9.28	11.36	13.44
7	May	74	23.33333333	14.14	21.5	0.35	0.13	0.24	7.525	2.795	5.16	13.975	16.34	18.705
8	June	83.8	28.77777778	16.51	29.1	0.32	0.13	0.225	9.312	3.783	6.5475	19.788	22.5525	25.317
9	July	86.6	30.33333333	14.61	32.1	0.56	0.28	0.42	17.976	8.988	13.482	14.124	18.618	23.112
10	August	84.5	29.16666667	12.17	30.043	0.65	0.33	0.49	19.52795	9.91419	14.72107	10.51505	15.32193	20.12881
11	September	80.4	26.88888889	10.71	26.73	0.56	0.27	0.415	14.9688	7.2171	11.09295	11.7612	15.63705	19.5129
12	October	70.4	21.33333333	8.05	18.7	0.52	0.25	0.385	9.724	4.675	7.1995	8.976	11.5005	14.025
13	November	59.2	15.11111111	4.93	12.78	0.54	0.28	0.41	6.9012	3.5784	5.2398	5.8788	7.5402	9.2016
14	December	52	11.11111111	3.23	9.9	0.61	0.34	0.475	6.039	3.366	4.7025	3.861	5.1975	6.534
15	Sum:			111.07										
16														
17	temp ref	http://www.cityrating.com/citytemperature.asp?City=Tucson												
18	Pv°	http://www.vaxasoftware.com/doc_eduen/qui/pvh2o.pdf												
19	rh ref	http://www.cityrating.com/cityhumidity.asp?City=Tucson												
20														

	A	B	C	D	E	F	G
21	Months	E_o(inches)	Avg Temp(°F)	Pv°(mm Hg)	Avg Relative Humidity	P'Avg	Pv°- P'avg
22	January	3.94	51.3	9.844	30.572	4.62668	5.21732
23	February	4.68	54.4	10.87	32.635	4.6741	6.1959
24	March	7.53	58.7	12.78	35.74	4.8564	7.9236
25	April	10.57	65.8	16	40.9	4.64	11.36
26	May	14.14	74	21.5	47.75	5.16	16.34
27	June	16.51	83.8	29.1	56.45	6.5475	22.5525
28	July	14.61	86.6	32.1	59.35	13.482	18.618
29	August	12.17	84.5	30.043	57.2715	14.72107	15.32193
30	September	10.71	80.4	26.73	53.565	11.09295	15.63705
31	October	8.05	70.4	18.7	44.55	7.1995	11.5005
32	November	4.93	59.2	12.78	35.99	5.2398	7.5402
33	December	3.23	52	9.9	30.95	4.7025	5.1975

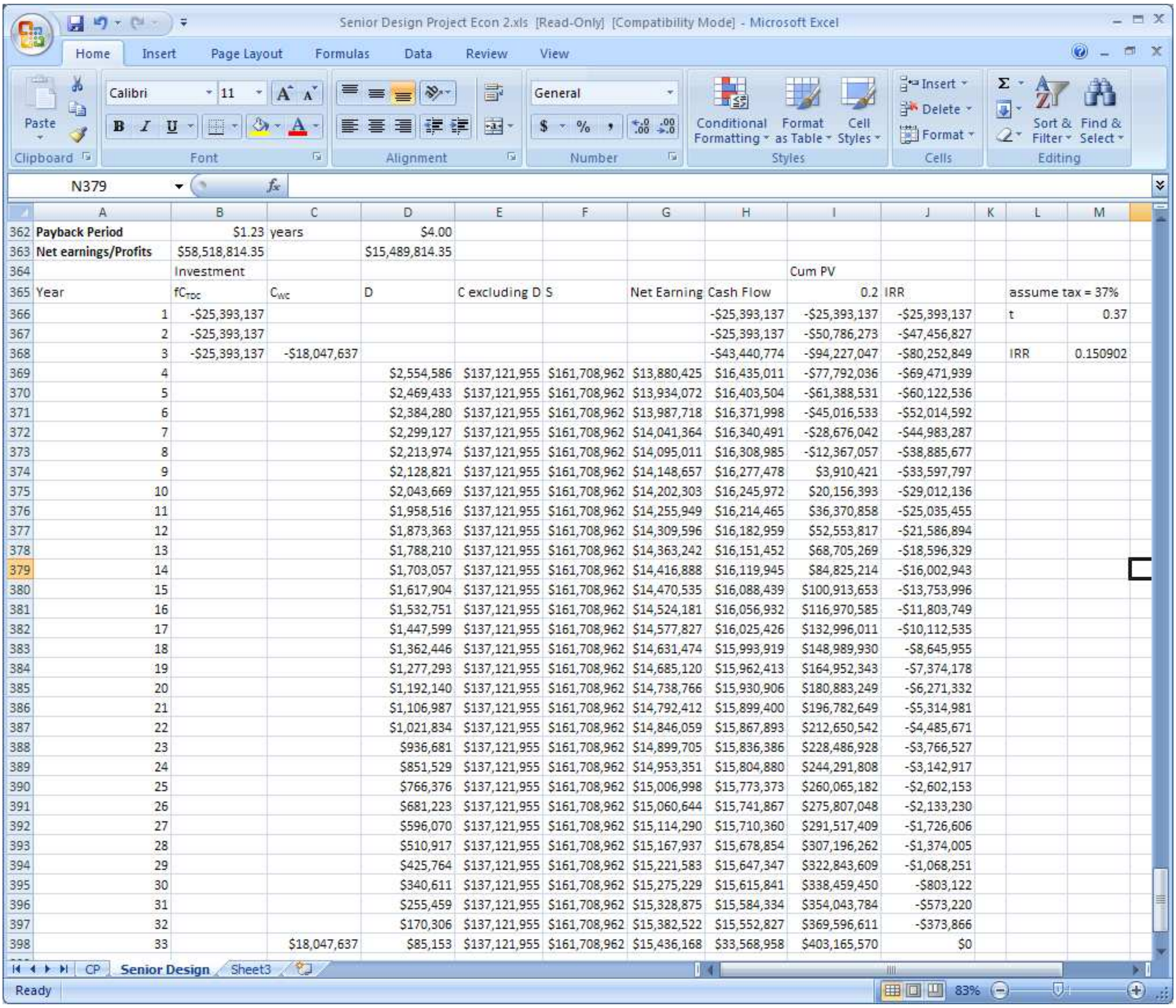
Spreadsheet for the calculation of Drying Time/Filling Time/Area Optimization:



	A	B	C	D	E
82					
83		**Drying Time**			
84	Time to reach saturation		eqn: dV/dt = -EA + RA		
85	a	868683.2068			
86	b	-22.83640109			
87	Start volume	1932114.807			
88	End volume	492987.7865		at Vsat	-1069524.296
89	time	1493382.711	min	at Vo	-2562907.007
90	time	1037.071327	days		
91					
92	Time after pond reaches saturation				
93	volume (implic	381802.3593	(try to set to zero)		
94	t2 (at sat)	5275.871956	min		
95	t2 (at sat)	3.66379997	day		
96	End volume	123671.6021	density = 2.68 g/cm3 (anhyc		[18,873 mol/m3]
97	time (explicit)	17524.46295	min		
98	time (explicit)	12.16976594	days		
99					
100	Time to reach saturation (using avg. concentration)				
101	volume	-1004834.579	(try to set to volume at saturation)		
102	t1	112466.5689	min		
103	t1	78.10178397	day		
104					
105	**total time**	1049.241093	total time		
106					
107	Saturation data for Na2SO4				
108	15.93	g/100mL	(at 20 C)	source: Solubility and density isotherms by Okorafor	
109	28.89	g/100mL	(at 30 C)		
110	22.41	g/100mL	(at 25 C)		
111	224.1	g/L			
112	1578.169014	mol/m3			
113	0.2551545	(new volume fraction at new concentration/saturation)			
114	492987.7865	(volume at saturation)			
115	average conce	990.4229695	(between Co and Ce)		
116					
117					
118					
119					

	I	J	K	L	M	N	O	P
83	Finding alpha for Na2SO4				kp (in/month*mmHg)			
84	Na2SO4 temperature effects				0.7735			
85	Vapor Pressure of Na2SO4 solution							
86				Concentration [mol/m^3]				
87	T [°C]	0	500	1000	2000	3000		
88	10	9.2000	9.0475	8.8974	N/A	N/A		
89	20	17.5000	17.2099	16.9243	16.3740	15.7914		
90	30	31.8000	31.2728	30.7539	29.7539	28.6953		
91	40	55.3000	54.3832	53.4809	51.7419	49.9010		
92	50	92.5000	90.9664	89.4572	86.5484	83.4691		
93	60	149.5000	147.0214	144.5822	139.8809	134.9041		
94	70	239.8000	235.8244	231.9118	224.3708	216.3879		
95	80	355.5000	349.6062	343.8059	332.6264	320.7920		
96	90	526.0000	517.2795	508.6974	492.1561	474.6458		
97	100	760.0000	747.4000	735.0000	711.1000	685.8000		
98	Ratio	N/A	0.0166	0.0329	0.0643	0.0976		
99								
100	Concentrati	delta p	evap rate (ir	evap rate (m/m	Psalt/Pwater			
101	0	17.4	13.4589	7.80493E-06	1		solving for alpha:	
102	500	16.99132895	13.142793	7.62162E-06	0.976513158		slope	3.58173E-10
103	1000	16.58914474	12.831703	7.44122E-06	0.953399123		alpha	4.58906E-05
104	2000	15.81396711	12.232104	7.0935E-06	0.908848684			
105	3000	14.99338158	11.597381	6.72542E-06	0.861688596			

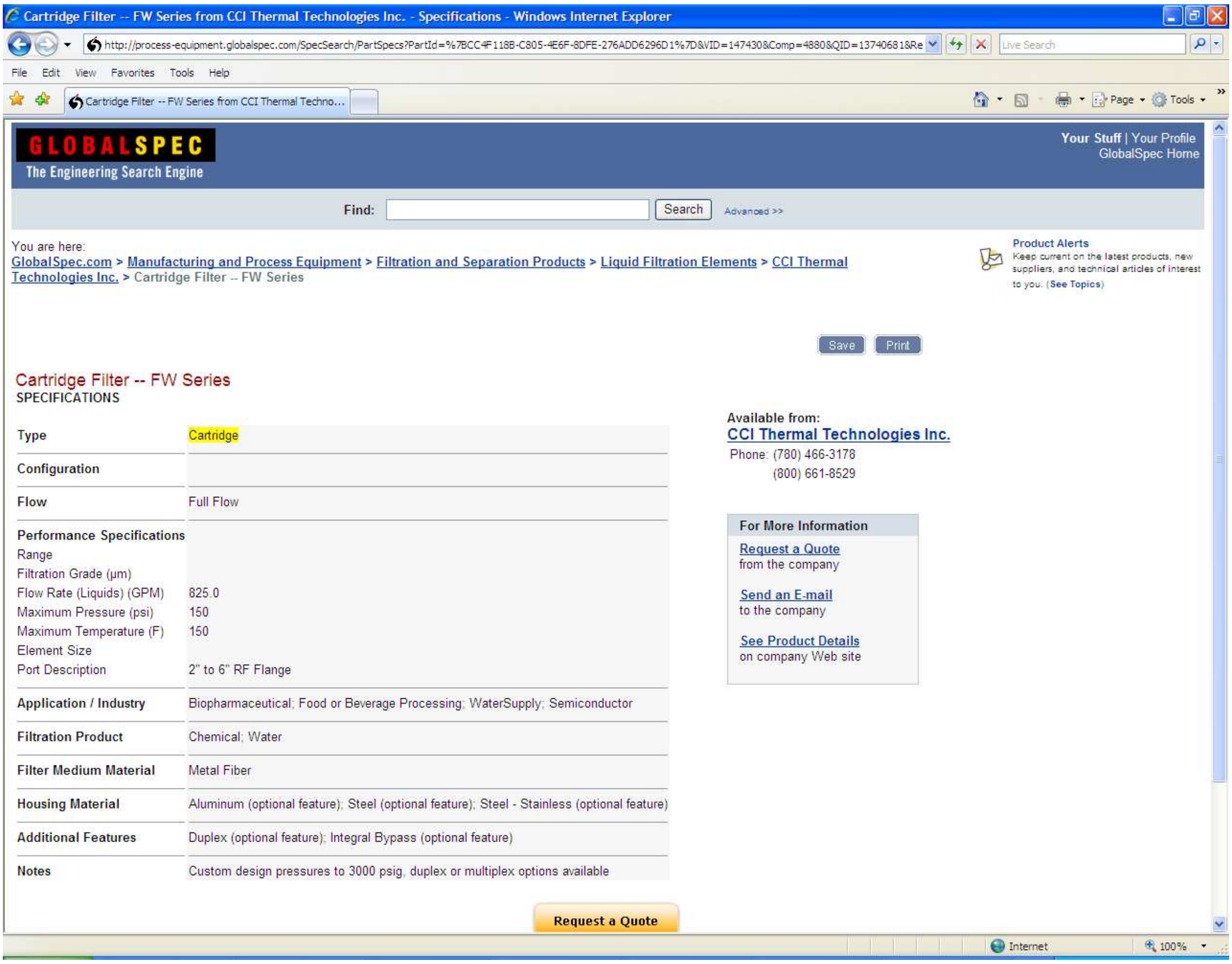
Spreadsheet for Payback period, Net earnings, and IRR:



	A	B	C	D	E	F	G	H	I	J	K	L	M
362	**Payback Period**	$1.23	years	$4.00									
363	**Net earnings/Profits**	$58,518,814.35		$15,489,814.35									
364		Investment							Cum PV				
365	Year	fC_{TDC}	C_{WC}	D	C excluding D	S	Net Earning	Cash Flow	0.2	IRR		assume tax = 37%	
366	1	-$25,393,137						-$25,393,137	-$25,393,137	-$25,393,137		t	0.37
367	2	-$25,393,137						-$25,393,137	-$50,786,273	-$47,456,827			
368	3	-$25,393,137	-$18,047,637					-$43,440,774	-$94,227,047	-$80,252,849		IRR	0.150902
369	4			$2,554,586	$137,121,955	$161,708,962	$13,880,425	$16,435,011	-$77,792,036	-$69,471,939			
370	5			$2,469,433	$137,121,955	$161,708,962	$13,934,072	$16,403,504	-$61,388,531	-$60,122,536			
371	6			$2,384,280	$137,121,955	$161,708,962	$13,987,718	$16,371,998	-$45,016,533	-$52,014,592			
372	7			$2,299,127	$137,121,955	$161,708,962	$14,041,364	$16,340,491	-$28,676,042	-$44,983,287			
373	8			$2,213,974	$137,121,955	$161,708,962	$14,095,011	$16,308,985	-$12,367,057	-$38,885,677			
374	9			$2,128,821	$137,121,955	$161,708,962	$14,148,657	$16,277,478	$3,910,421	-$33,597,797			
375	10			$2,043,669	$137,121,955	$161,708,962	$14,202,303	$16,245,972	$20,156,393	-$29,012,136			
376	11			$1,958,516	$137,121,955	$161,708,962	$14,255,949	$16,214,465	$36,370,858	-$25,035,455			
377	12			$1,873,363	$137,121,955	$161,708,962	$14,309,596	$16,182,959	$52,553,817	-$21,586,894			
378	13			$1,788,210	$137,121,955	$161,708,962	$14,363,242	$16,151,452	$68,705,269	-$18,596,329			
379	14			$1,703,057	$137,121,955	$161,708,962	$14,416,888	$16,119,945	$84,825,214	-$16,002,943			
380	15			$1,617,904	$137,121,955	$161,708,962	$14,470,535	$16,088,439	$100,913,653	-$13,753,996			
381	16			$1,532,751	$137,121,955	$161,708,962	$14,524,181	$16,056,932	$116,970,585	-$11,803,749			
382	17			$1,447,599	$137,121,955	$161,708,962	$14,577,827	$16,025,426	$132,996,011	-$10,112,535			
383	18			$1,362,446	$137,121,955	$161,708,962	$14,631,474	$15,993,919	$148,989,930	-$8,645,955			
384	19			$1,277,293	$137,121,955	$161,708,962	$14,685,120	$15,962,413	$164,952,343	-$7,374,178			
385	20			$1,192,140	$137,121,955	$161,708,962	$14,738,766	$15,930,906	$180,883,249	-$6,271,332			
386	21			$1,106,987	$137,121,955	$161,708,962	$14,792,412	$15,899,400	$196,782,649	-$5,314,981			
387	22			$1,021,834	$137,121,955	$161,708,962	$14,846,059	$15,867,893	$212,650,542	-$4,485,671			
388	23			$936,681	$137,121,955	$161,708,962	$14,899,705	$15,836,386	$228,486,928	-$3,766,527			
389	24			$851,529	$137,121,955	$161,708,962	$14,953,351	$15,804,880	$244,291,808	-$3,142,917			
390	25			$766,376	$137,121,955	$161,708,962	$15,006,998	$15,773,373	$260,065,182	-$2,602,153			
391	26			$681,223	$137,121,955	$161,708,962	$15,060,644	$15,741,867	$275,807,048	-$2,133,230			
392	27			$596,070	$137,121,955	$161,708,962	$15,114,290	$15,710,360	$291,517,409	-$1,726,606			
393	28			$510,917	$137,121,955	$161,708,962	$15,167,937	$15,678,854	$307,196,262	-$1,374,005			
394	29			$425,764	$137,121,955	$161,708,962	$15,221,583	$15,647,347	$322,843,609	-$1,068,251			
395	30			$340,611	$137,121,955	$161,708,962	$15,275,229	$15,615,841	$338,459,450	-$803,122			
396	31			$255,459	$137,121,955	$161,708,962	$15,328,875	$15,584,334	$354,043,784	-$573,220			
397	32			$170,306	$137,121,955	$161,708,962	$15,382,522	$15,552,827	$369,596,611	-$373,866			
398	33		$18,047,637	$85,153	$137,121,955	$161,708,962	$15,436,168	$33,568,958	$403,165,570	$0			

Appendix F – WEB Printouts

Cartridge Filter specifications:



You are here:
GlobalSpec.com > Manufacturing and Process Equipment > Filtration and Separation Products > Liquid Filtration Elements > CCI Thermal Technologies Inc. > Cartridge Filter -- FW Series

Product Alerts
Keep current on the latest products, new suppliers, and technical articles of interest to you. (See Topics)

Cartridge Filter -- FW Series
SPECIFICATIONS

Type	Cartridge
Configuration	
Flow	Full Flow
Performance Specifications	
Range	
Filtration Grade (µm)	
Flow Rate (Liquids) (GPM)	825.0
Maximum Pressure (psi)	150
Maximum Temperature (F)	150
Element Size	
Port Description	2" to 6" RF Flange
Application / Industry	Biopharmaceutical; Food or Beverage Processing; WaterSupply; Semiconductor
Filtration Product	Chemical; Water
Filter Medium Material	Metal Fiber
Housing Material	Aluminum (optional feature); Steel (optional feature); Steel - Stainless (optional feature)
Additional Features	Duplex (optional feature); Integral Bypass (optional feature)
Notes	Custom design pressures to 3000 psig, duplex or multiplex options available

Available from:
CCI Thermal Technologies Inc.
Phone: (780) 466-3178
(800) 661-8529

For More Information
Request a Quote
from the company

Send an E-mail
to the company

See Product Details
on company Web site

Sand Filter specifications:

Horizontal Commercial Sand Filters

- ★ *100% Corrosion Resistant*
- ★ *210 - 1,500 GPM Flow Rates*
- ★ *21 - 75 Sq.Ft. of Filtration Area*
- ★ *NSF Listed*
- ★ *Automatic air release*
- ★ *4" Media Drain*
- ★ *16" Manhole*
- ★ *Improved 1.5" Lateral Design*
- ★ *Dual Pressure Gauge Panel*

ASTRALPOOL has now expanded its line of horizontal commercial filtration systems with the addition of 48", 63" and 79" diameter vessels. These increases in diameter are capable of providing filtration areas of up to 75 sq.ft. in a single vessel. In addition to the increase in their diameter, lengths of 75", 91", 106", 118" and some models of 138" are now available. The horizontal commercial sand filters mirror the construction of our already proven vertical filters. The horizontal filters are constructed of polyester resins and fiberglass which will provide for many years of corrosion free operation. All internals and connections are assembled with SCH 80 PVC. We've incorporated our improved 1.5" 360° lateral design and added a 16" manhole for easier media installation. Horizontal filters are a great option in tight spaces or equipment rooms with a small footprint. These filters can be stacked to maximize floor space without compromising filtration area. Our new expanded line of horizontal filters carry a 15-year limited warranty including 3-years on PVC internals and a lifetime warranty on laterals. Our horizontal filters feature a 50 psi working pressure and a 75 psi test pressure. ASTRALPOOL horizontal commercial sand filters are NSF listed up to 20 gpm/ft² for the entire range of vessels up to 20 gpm/sq.ft. Written specifications and other information for project specification are available upon request. We are pleased to assist you with any in-house engineering and sizing assistance required.

APPENDIX G – PERSONAL COMMUNICATION LOGS

Phone Logs

Phone Log 1: Date: April 14, 2009

Members Present (name of senior design group members plus name and title of person providing information)

- Mia McCorkel
- Michael Winterbourne, North American Sales for SOLMAX International

Summary of Information, that pertains to the report (costs, flow rates, sizes, assumptions).

- PVC price estimate for a 30 ml grade of PVC lining:
  $0.29 per square foot
  $0.05-0.06 per square foot for installation

Phone Log 2: Date: 4/14/2009

Members Present (name of senior design group members plus name and title of person providing information)

- Ritika Mohan and Mike (Technician, Alar Engineering)

Summary of Information, which pertains to the report (costs, flow rates, sizes, assumptions).

- Price for a carbon filter - **$20,000 per filter**. This cost is for a typical feed water flow rate of 151 L/s with TDS 750 mg/L.
- 14 such filters are decided to use for a flow rate of about 1969 L/s

Phone Log 3: Date: 4/15/2009

Members Present (name of senior design group members plus name and title of person providing information)

- Ritika Mohan and Jason Marie (Engineer, CCI Thermal Technologies Inc.)

Summary of Information, which pertains to the report (costs, flow rates, sizes, assumptions).

- Price for a carbon filter - **$27,000 per filter**. This cost is for a typical feed water flow rate of 52 L/s with TDS > 700 mg/L. The housing material for this type of filter is stainless steel.
- 39 such filters are decided to use for a flow rate of about 1969 L/s

Phone Log 4: Date: 4/13/09

Members Present (name of senior design group members plus name and title of person providing information)

- Elizabeth Pedersen and Steve Wolfson

Summary of Information, that pertains to the report (costs, flow rates, sizes, assumptions).

- Cost of each sand filter, handling 1,500 gpm, is $22,000
- Sand filters must be replaced every 5 years

Phone Log 5: Date: 4/16/09

Members Present (name of senior design group members plus name and title of person providing information)

- Elizabeth Pedersen, Kent Robertson (Catclaw Contractors)

Summary of Information, that pertains to the report (costs, flow rates, sizes, assumptions).

- Cost of excavation is $2.23/m^3

Phone Log 6: Date: 04/14/2009

Members Present (name of senior design group members plus name and title of person providing information)

- Ritika Mohan and Charlie (Senior Engineer, Carollo)

Summary of Information, that pertains to the report (costs, flow rates, sizes, assumptions).

- Due to large flow rates involved (1969 L/s), it was advised by Charlie from Carollo to design the pretreatment using conventional media filtration instead of new technologies such as ultrafiltration. He suggested that it might be economically more feasible to use conventional pretreatment design, and make the venture profitable.

Email Communications

Between Ritika Mohan and Rob Goodlett:

On Tue, Apr 14, 2009 at 11:23 AM, Rob Goodlett <rgoodlett@avistatech.com> wrote:
Coagulants in the form of metal salts are approximately $0.50 per pound and polymers are around $1.50/pound.

From: ritika mohan [mailto:ritikamohan@gmail.com]
Sent: Tuesday, April 14, 2009 11:05 AM
To: Rob Goodlett
Subject: Re: mineral analysis-read this one please.

Hi Rob,
Thanks for the information. That does help a lot.
Do you by any chance also know how much do coagulants usually cost?
thanks
ritika
On Tue, Apr 14, 2009 at 8:26 AM, Rob Goodlett <rgoodlett@avistatech.com> wrote:
Dear Ritika,
Based on the analysis provided please accept the following.

1. Barium was reduced to 0.2 due to BaSO4 saturation.
2. Hydrochloric acid was required due to the SO4 concerns.

3. RO recovery was limited to 66%
4. pH was reduced from 8.0 to 8.5, 3.1 PPM of acid was required.
5. 7.5 PPM of Vitec 3000 antiscalant was required in the feed.
6. **Antiscalant cost for budgetary reasons, $1.75/pound, 10-pounds per gallon.**

I hope this information helps your efforts.
Rob Goodlett

From: ritika mohan [mailto:ritikamohan@gmail.com]
Sent: Monday, April 13, 2009 2:19 PM
To: Rob Goodlett
Subject: mineral analysis-read this one please.

Hi Rob,
Here is the mineral analysis. I just need a very rough estimate of amounts of chemicals and their costs. Thanks again.
Since the file you sent me was a pdf, I was not able to write in it. I am typing the minerals etc below:

sodium	439.02
calcium	360.19
magnesium	148.21
potassium	23
strontium	5.75
barium	0.52
manganese	0
aluminum	0
chloride	402
sulfate	1600
phosphate	<0.2
iron	0
F	0.9
nitrate	<0.1
silica	<30
alkalinity(carbonate)	0

pH average is 7.5 with maximum pH being 8.5
thanks
ritika mohan

Between Ritika Mohan and Debbie Geffert, Weatherford A&M Composites Customer Service:

Ritika, here is your price for the following:

Qty	PN	Description	Price Each
1	RO80160	8” RO pressure vessel, 1000psi, end port, for 6 40” elements	**$2,237.00**

I hope this provides the info that you require for your project. Let me know if you need anything else. As I stated earlier, we no longer make this product and I am providing for purposes of your class project only.

Thanks,
Debbie Geffert
Customer Service
WEATHERFORD A&M COMPOSITES
Big Spring, TX
Tel: 432-267-6525
Fax: 432-267-6599