R-96-01

MARICOPA GROUND WATER TREATMENT STUDY

Water Treatment Technology Program Report No. 15

February 1996

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Technical Service Center
Environmental Resources Team
Water Treatment Engineering and Research Group

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 070443188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
February 1996

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Maricopa Ground Water Treatment Study—
Water Treatment Technology Program Report No. 15

5. FUNDING NUMBERS
PR

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
Technical Service Center
Denver CO 802250007

6. PERFORMING ORGANIZATION REPORT NUMBER
R-96-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
Denver Federal Center
PO Box 25007
Denver CO 802250007

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DIBR

11. SUPPLEMENTARY NOTES
Hard copy available at the Technical Service Center, Denver, Colorado

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Available from the National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield, Virginia 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Bureau of Reclamation, in cooperation with the GRIC (Gila River Indian Community) and the cities of Avondale and Chandler, Arizona, performed this field study to determine the suitability of several water treatment processes on ground water that contains high levels of nitrate, chloride, and total dissolved solids. This report provides general discussion of three water treatment processes-ED (electrodialysis), RO (reverse osmosis), and NF (nanofiltration). Pilot scale testing of ED and RO reduced concentrations of nitrate, total dissolved solids, and chloride. This report recommends the use of NF or ED membranes for ground water typical of the study area. Cost projections presented in this report contain criteria to assist in the choice between ED NF water treatment.

14. SUBJECT TERMS- -water treatment/ desalting/ nanofiltration/ electrodialysis/ reverse osmosis/ ground water/ nitrate/ total dissolved solids/ Water Treatment Technology Program

15. NUMBER OF PAGES
117

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	16. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UL	UL	UL	UL

R-96-01

MARICOPA GROUND WATER TREATMENT STUDY

Chandler + Arizona
Where Values Make The Difference

Water Treatment Technology Program Report No. 15

by

Robert A. Jurenka
Michelle Chapman-Wilbert

Water Treatment Engineering and Research Group
Environmental Resources Team
Technical Service Center
Denver, Colorado

February 1996

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

ACKNOWLEDGMENTS

We would like to thank all of the people at the cities of Avondale and Chandler and the GRIC (Gila River Indian Community) who made this field study a success. Special thanks go to Steve Mitchell (Avondale) and Clifford Antone (GRIC) for their expert assistance in monitoring and keeping the equipment running properly. We also want to thank Jim Mitchell and Esmie Avilla of the City of Avondale for their support and the staff at Westech Laboratories, Inc., for their prompt attention.

U.S. Department of the Interior
Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

CONTENTS

CONTENTS — CONTINUED

TABLES

FIGURES

CONTENTS — CONTINUED

FIGURES — CONTINUED

APPENDIXES

ACRONYMS AND ABBREVIATIONS

ADEQ	Arizona Department of Environmental Quality
BPV	back pressure valve
cfu	colony forming units
ED	electrodialysis
EDR	electrodialysis reversal
ENR	*Engineering News Record*
EPA	Environmental Protection Agency
FCV	flow control valve
GRIC	Gila River Indian Community
HDPE	high density polyethylene
HPC	heterotrophic plate count
ICP	inductively-coupled plasma
LOTW	locally-owned treatment works
MCL	maximum contaminant level
Mgal	million gallons
NF	nanofiltration
NPF	normalized permeate flow
NDP	net driving pressure
ntu	nephelometric turbidity unit
O&M	operations and maintenance
PID	proportional integral derivative
PLC	programmable logic controller
RO	reverse osmosis
SDI	silt density index
SDWA	Safe Drinking Water Act
SEM	scanning electron microscopy
SR	salt rejection
TCF	temperature correction factor
TDS	total dissolved solids
TFC	thin-film composite
THM	trihalomethane
THMFP	trihalomethane formation potential
TOC	total organic carbon

CHEMICAL FORMULAS

Al^{+3}	aluminum ion
Ba^{+2}	barium ion
Ca^{+2}	calcium ion
$CaCO_3$	calcium carbonate
$Ca(OH)_2$	calcium hydroxide (hydrated lime)
Cl	chloride ion
Cl_2	chlorine
ClO_2	chlorine dioxide
Fe^{+2}	ferrous ion
Fe^{+3}	ferric ion
H	hydrogen ion
HCO,	bicarbonate ion
H_2O	water
H_2SO_4	sulfuric acid
Na^+	sodium ion

CHEMICAL FORMULAS — CONTINUED

Na_2CO_3	sodium carbonate (soda ash)
Ni^{+2}	nickel ion
NO,	nitrate ion
O_3	ozone
SiO_2	silica
SO_4^{-2}	sulfate ion

USEFUL TERMS

Blending - mixing of desalted water with un-desalted water to obtain the following advantages: the addition of hardness and alkalinity from undesalted water helps to reduce the corrosivity of the product water; the amount of post-treatment chemical and the water treatment plant size are reduced, thereby lowering capital and operating costs.

Concentrate (or brine) - the salt waste stream produced as a byproduct of RO or nanofiltration treatment of water containing salts.

Electrodialysis - a water treatment process that removes dissolved salts from water using a direct current electrical potential.

Electrodialysis reversal - an automatic operating feature of some ED units that reverses the electrical potential applied to the two electrodes about every 15 minutes to promote cleaning of the unit.

Locally-owned treatment works - the facility that accepts and treats the community's wastewater.

Membrane selectivity - the ability of a membrane to selectively remove certain ions over others by being composed of selectively charged ionic groups.

Nanofiltration - a selective form of reverse osmosis that has a lower rejection rate for monovalent ions than multivalent ions, and thus, can operate at significantly lower operating pressures than RO membranes.

Net driving pressure - pressure available to force water through the membrane, and is calculated as follows:

$$NDP = P_f - P_p - P_o$$

where:
P_f = average feed pressure (average of feed and reject pressures)
P_p = pressure in the permeate line (gauge pressure)
P_o = average osmotic back pressure of the feed water (estimated by averaging the TDS feed and reject concentrations, in mg/l, and dividing by 100)

Normalized permeate flow - the total permeate flow adjusted to standard temperature (25 °C) and to normalized *NDP* at startup, and is calculated as follows:

$$NPF = NDP_{startup}/NDP_{today} \times TCF \times F_p$$

where:
TCF = temperature correction factor
F_p = permeate flow

USEFUL TERMS — CONTINUED

Permeate - the product water from a desalting process.

Pre-treatment - treatment units located upstream from a desalting process necessary to remove compounds that are detrimental to the membranes and which would shorten the life of the desalter.

Recovery - the amount of product water attainable, expressed as a percent of the feed flow.

Rejection - the rate at which an ion is removed, expressed as a percent:

$$= (1 - C_P/C_F) \times 100$$

where: C_P = the product ion concentration
C_F = the feed ion concentration

Reverse osmosis - the process of applying to water in contact with a semi-permeable membrane, a pressure in excess of its osmotic pressure, so that clean water permeates through the membrane; ions in the water do not pass through the membrane, but are collected separately.

Silt density index - a measure of the fouling potential of the feed from colloidal-size materials.

Total dissolved solids - inorganic salts, organic matter, or dissolved gases that do not filter readily from water. Results of analyses are either reported directly from the laboratory or from the sum of ions reported from the laboratory.

SI METRIC CONVERSIONS

From	To	Multiply by
ft	m	3.048 000 E-01
in	m	2.540 000 E-02
ft^2	m^2	9.290 304 E-02
kgal	m^3	3.785 412
Mgal	m^3	3.785 412 E+3
acre-ft	m^3	1.233 489 E+3
lb/in^2	kPa	6.894 757
°F	°C	$t_C = (t_F - 32)/1.8$

1. EXECUTIVE SUMMARY

Reclamation (Bureau of Reclamation) and the study participants of the GRIC (Gila River Indian Community) and the cities of Avondale and Chandler, Arizona, pursued a pilot study to determine the suitability of several water treatment processes on ground water that contains high levels of nitrate, chloride, and TDS (total dissolved solids). This report summarizes the work performed during a 6-week pilot test at the city of Avondale's well s5, a well representative of water quality problems found at wells used by the three study participants. The report also provides general discussion of the three principal water treatment processes-ED (electrodialysis), RO (reverse osmosis), and NF (nanofiltration), as well as recommendations of which process to use at actual well sites. Planning level cost estimates are provided to compare the options available.

Pilot scale testing of both electrodialysis and reverse osmosis, with adequately pretreated ground water, reduced concentrations of nitrate, TDS, and chloride in Avondale's well s5 to the levels indicated below:

	Electrodialvsis			Reverse Osmosis		
	Raw Water	Finished Water	Pct Removed	Raw Water	Finished Water	Pct Removed
Nitrate, mg/L	9.7	3.7	62	9.0	0.8	91
TDS, mg/L	1700	970	43	1467	41.6	97
Chloride, mg/L	760	240	68	557	10.7	98

Subsequent to this study's pilot testing, certain manufacturers of nanofiltration membranes claimed significant improvements of nitrate removal with their newly developed, thin-film composite membranes. After comparing advantages and disadvantages of RO to NF, this report recommends the use of nanofiltration membranes or electrodialysis membranes for ground waters typical of the study area (i.e., when the ionic character of the ground water does not warrant the high salt removal rates from reverse osmosis).

Cost projections presented in this report favor the use of electrodialysis or nanofiltration water treatment as follows:

- When the TDS of a ground water is about 1100 mg/L or less, and the nitrate concentration is about 23 mg/L or less, electrodialvsis is recommended.

- When several contaminants of concern are present in the raw water and the TDS is greater than 1100 mg/L, then nanofiltration is the recommended process based on capital, operating, maintenance, and replacement costs.

Concentrate disposal is recommended to be accomplished at the LOTW (locally-owned treatment works). Costs for treatment will increase significantly if brine disposal is accomplished by either evaporation or spray irrigation systems. The concentrations of ions in the waste stream from an ED or NF water treatment plant are not hazardous, but may be toxic to microorganisms in a LOTW. However, the dilution effect from other wastewater flows is expected to eliminate this potentially adverse condition.

The total **present worth** of a 2-Mgal/d (million gallons per day) (product) electrodialysis plant, excluding brine disposal, is $6,729,900; for nanofiltration, also excluding brine disposal, total present worth is $6,780,600, based on the assumptions made in this report and the life cycle cost analysis for 20 years at an interest rate of 6.5 percent.

The total **annualized cost** of a 2-Mgal/d (product) electrodialysis plant, excluding brine disposal, is $610,900 ($0.84/1000 gal); for nanofiltration, also excluding brine disposal, total annualized cost is $615,500 ($0.84/1000 gal), based on the assumptions made in this report and the life cycle cost analysis for 20 years at an interest rate of 6.5 percent.

The total **present worth** of a 2-Mgal/d (product) electrodialysis plant, including brine disposal, is $10,929,000; for nanofiltration, also including brine disposal, total present worth is $10,077,200, based on the assumptions made in this report and the life cycle cost analysis for 20 years at an interest rate of 6.5 percent.

The total **annualized cost** of a 2-Mgal/d (product) electrodialysis plant, including brine disposal, is $992,100 ($1.36/1000 gal); for nanofiltration, also including brine disposal, total annualized cost is $914,700 ($1.25/1000 gal), based on the assumptions made in this report and the life cycle cost analysis for 20 years at an interest rate of 6.5 percent.

2. INTRODUCTION

2.1 Purpose and Scope

This ground water treatment study has been prepared for the cities of Avondale and Chandler and the GRIC (Gila River Indian Community), all in Arizona. These cooperating partners, together with the Bureau of Reclamation, have jointly funded this study to evaluate selected ground water treatment options. Each cooperating partner is faced with many challenges of growth in an arid climate where water is a precious and limited natural resource. One of these challenges is the need to provide a reasonable level of water treatment to ensure the delivery of safe and palatable drinking water to their residents.

The cooperating partners agreed to use Avondale's well s5 because it shares many of the characteristic "problem" contaminants found in their sources of water that exceed primary and secondary drinking water standards. These parameters are nitrates, chlorides, and TDS (total dissolved solids). A 6-week pilot test period targeting two water treatment processes ensued to confirm process performance and efficiency. Based on the results of this testing, process recommendations and cost estimates are provided, along with design considerations for scale-up. The cost estimates include both capital and O&M (operation and maintenance) costs for a full-scale treatment plant with a capacity of 2 Mgal/d.

The cost estimates contained in this report are to be used as planning estimates for decision making and not as final estimates of construction. The cost estimates were obtained from several sources, but predominantly from Reclamation's "Cost Estimation Program," a computer program that modifies and updates the EPA's (Environmental Protection Agency) construction cost curves found in Volume 2 of EPA-600/2-79-162b for water treatment processes. O&M cost estimates include current prices for electric power and, when available, chemicals and supplies. Materials, equipment, and labor are based on updated Bureau of Labor Statistics and *Engineering News Record* indices.

The final treatment process recommendations made in this report should be integrated with other design factors that address each community's comprehensive needs. In this way, each community can assess individual issues such as capacity, water sources, level of treatment, and location to determine appropriate treatment.

2.2 Background

The Bureau of Reclamation, long known for its expertise in dam building, has recently redirected its mission from water resource development to water resource management. Reclamation now emphasizes water management practices that promote efficient use of water, multiple uses of water, and water reuse. Understanding water treatment problems and implementing efficient water treatment systems is one example of how best to use the limited amount of water available. Reclamation has developed an expertise in water treatment and pre-treatment, especially in the area of desalting, and advocates processes that minimize water loss or promote reuse of generated wastewater.

To better understand how various water treatment processes work and to confirm that such processes will work successfully on certain contaminated water, Reclamation owns and operates a 6-gal/min mobile pilot water treatment plant. A programmable controller can select conventional treatment with up to seven different chemical feed systems; advanced treatment such as ion exchange or granular activated carbon; desalting using either nanofiltration, reverse osmosis or electrodialysis; or as many as four types of disinfection.

Information about the mobile pilot plant was obtained by the cooperating partners, who formulated an agreement with Reclamation to perform this work. Each cooperating partner completed a questionnaire prior to the piloting period. The questionnaire allowed Reclamation to obtain site specific information about each community. From this information, the following commonalities were noted:

- The aquifer being tapped is generally of good quality, but can contain localized high concentrations of nitrates, TDS, turbidity, chloride, fluoride, and sometimes iron and manganese.
- New wells are drilled to avoid poorer water quality areas
- Wellhead treatment is preferred over centralized, larger treatment plants
- The combined capacity of wells for treatment is 1000 to 2000 gal/min
- An overall decline of aquifer water levels and water production exists.

For these reasons, each community is interested in knowing what type of treatment will work best for them, taking into consideration reusing as much of the water as possible. The 6-week pilot test program was formulated, reviewed with each partner on February 9, 1995, and performed from March 7 to April 18, 1995. The site selected for this study is well s5 in the City of Avondale, a suburb about 40 miles west of Phoenix, Arizona. Figure 1 is a location map and site plan of well s5, which is located on the southeast corner of Main and 2nd streets in Avondale. This 500-foot-deep well has a 24-inch-diameter surface casing for 30 feet and a 16-inch-diameter well casing to full depth that is screened from 185 feet to 480 feet. The 125-horsepower pump is set 185 feet below grade and is equipped with a low water cut-off alarm. Piping at the wellhead is lo-inch diameter and includes a pump control valve and air release valve. Prior to and throughout the pilot test, the well was flushed to waste by city personnel. Water for the pilot test was diverted daily to an off-line 10,000-gallon horizontal tank using 4-inch-diameter pipe.

3. CONTAMINANTS OF CONCERN

Primary drinking water standards of the SDWA (Safe Drinking Water Act) are established to protect consumer health and welfare. Secondary SDWA standards, for secondary contaminants, provide guidelines regarding taste, odor, color and other aesthetic aspects of water. Water contaminants above the Primary SDWA levels common to all three communities and present at the City of Avondale's well s5 are nitrates and turbidity.

Nitrates may occur naturally or may be found in agricultural areas where fertilizer or secondary treated effluent has been applied. Pollution from leaking wastewater treatment units such as septic tanks may also produce nitrates. Concentrations of nitrates in drinking water above 10 mg/L as nitrogen have been found harmful to humans, especially infants.

Turbidity is a measure of the suspended material in water and is measured by the transmission of light passing through the water. Sources of the suspended material can be inorganic such as clay or silt, or organic such as plankton, bacteria, or algae.

Secondary contaminants common to all three communities and present at the City of Avondale's well s5 are chloride and TDS.

Sources of chloride include leaching of marine sediment or the residue left from evaporated sea water, brine, or a pollution source. All waters contain some chloride, and surface waters usually contain more chloride than ground water (Corbitt, 1990).

Total dissolved constituents in water consist mainly of inorganic salts, organic compounds, and dissolved gases. As water seeps downward over rocks and soils, it picks up and dissolves some of the minerals. These dissolved solids are not typically captured on a filter, and most of the inorganic dissolved solids are in the ionic form. Because these substances contribute to the capacity of a sample to pass an electric current, measuring this capacity through specific conductance is also a measure of dissolved solids.

Table 1 presents the historic record of measured water quality parameters for well s5 that existed prior to piloting. The primary or secondary MCL (maximum contaminant levels) for these measured parameters are also shown.

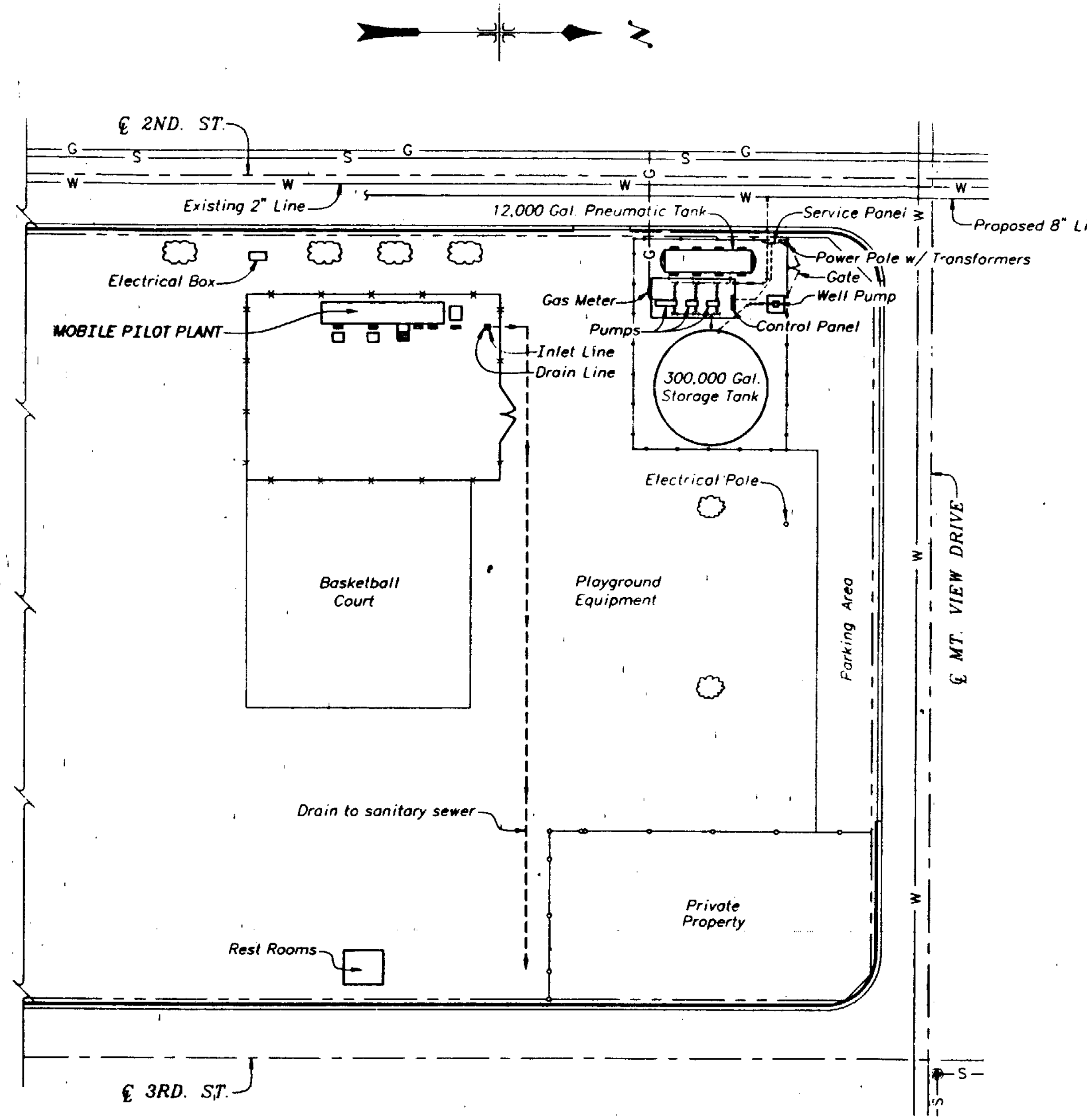
4. APPLICABLE WATER TREATMENT PROCESSES

4.1 General

Treatment processes producing an effluent which fully complies with both Primary and Secondary limits of the SDWA were considered for piloting.

For pretreatment, that is, treatment of raw water prior to desalting, a determination of the amount of dissolved versus undissolved iron and manganese was made to see if an oxidation step was necessary. Oxidation would be required if transition metals (i.e., iron and manganese) were dissolved or soluble. Because no appreciable amount of dissolved iron or manganese was found in the most current sample of well water, oxidation followed by settling would not be required. Based on size and characteristics of the suspended solids, direct filtration was piloted for turbidity removal. A coagulant aid, ferric sulfate, flocculation, and clarification would be available if turbidity levels after filtration exceeded acceptable limits.

LOCATION MAP



SITE PLAN

30 0 30 60 90
SCALE OF FEET
SITE PLAN

NOTES

Trailer specifications:
Utility type, aluminum, Serial No. 7U81076010
Length = 45-0, width = 8-0, height = 13-2
Landing gear located on ℄ at 9-0 from front
Rear axles located on ℄ at 5-10 and 10-0 from rear
Minimum turning radius required = 50-0

Electrical utility requirements:
Service should match rating of generator which is 35KW, 120/240V, 1 phase and connect to main service side of double throw switch in trailer through 2-inch conduit with weatherhead on outside of trailer.
Overhead service drop options:
1. Single phase pole transformer, standard sizes 37.5 or 50 KVA.
2. Revenue metering socket for utility's meter.
3. Cable between pole/meter socket to double throw switch on exterior of trailer.
If underground lateral service is provided requirements include: pad for transformer, 2- to 3-inch conduit between utility's hook-up point and trailer's double throw switch, and meter and socket.
If nearby building tap-off is provided, the same requirements of underground lateral are required, plus ensuring existing service can handle the additional load. Also provide tie point that will meet code/safety/fire requirements.

Mechanical requirements:
Trailer is equipped with 1-inch quick disconnects. (Insta-Lock 2 arm type, MIL-C-27487)

ALWAYS THINK SAFETY

UNITED STATES
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WATER TREATMENT TECHNOLOGY PROGRAM
MARICOPA GROUNDWATER TREATMENT STUDY - AVONDALE, AZ

AVONDALE WELL S5
LOCATION MAP AND SITE PLAN

Figure 1. - Avondale well s5 location map and site plan.

AutoCAD Release 12 c2 | MARICOPA LOCATION | DECEMBER 08, 1995
DENVER, COLORADO | DECEMBER 21, 1994

Table 1. • Available ground water analyses for well s5.

Parameter:	Date: Mar. 9, '76	Sep. 30, '76	Aug. 8, '79	Oct. 10, '79	Dec. 20, '94	Average Value	Primary or	Secondary MCL
Cations:								
Calcium	236.00	277.00		121.00	190.00	206.00		
Magnesium	79.00	99.00		162.00	72.00	103.00		
Sodium	123.00	125.00		143.00	140.00	132.75		
Iron	0.05	0.35		0.11	1.30	0.45	S	0.3
Barium				0.69	0.11	0.40	P	1.00
Manganese	0.05	0.05		0.05	0.08	0.06	S	0.05
Anions:								
Sulfate	180.00	160.00		203.00	250.00	198.25	S	250.00
Chloride	548.00	710.00		769.00	650.00	669.25	S	250.00
Nitrate (as Nitrogen)	26.00	29.00		1.70	13.00	17.43	P	10.00
Fluoride	0.19	0.15		0.25	0.31	0.23	P	4.00
Alkalinity, as CaC03	140.60	172.00		152.00	160.w	156.00		
Hardness,as CaC03	920.00	1080.00	998.00		770.w	942.w		
Copper	0.05	0.05		0.05	0.08	0.06	P	1.30'
Zinc	0.05	0.05		1.61	<0.05	0.44		5.00
Trace Metals Summary	< MCL	< MCL						
Physical:								
Turbidity	<5.00	<5.00			13.00	7.60	P	0.5
Total Susp'd Solids			3.20			3.20		
Solids Residue	1407.00	1761.00				1584.00		
Sp. Resistance	430.00	400.00				415.00		
Color	<5.00	<5.00			3.00	4.30	S	15.00*
Odor	<3.00	<3.00			2.00	2.70	S	3.00*
Total Dissolved Solids			2448.00		1800.00	2124.00	S	500.00
pH	7.40			7.70	7.39	7.50	S	6.5 to 8.5

Notes:
Boldface type indicates value exceeds the allowable limit as set by the Safe Drinking Water Act.
p=Primary Drinking Water Act limit, s= Secondary Drinking Water Act limit.
• Copper requires treatment when the concentration exceeds the action level of 1.3 mg/L.
• Color, 15 color units; Odor, 3 threshold odor number
Average value is computed using the detection limit when the lab reports less than the detection limit.
On 1/23/95, a dissolved iron concentration of <0.05 ppm was noted.

Common types of water treatment processes that remove nitrate and dissolved salt from water are membrane separation, distillation, and to a limited degree, ion exchange and lime softening. Because the level of sulfates and other ions in the raw water was appreciable and these ions would compete with nitrate in an anion exchange system (i.e., these competing ions would be removed preferentially before nitrate ion), an anion exchange system was eliminated from further consideration. Because lime softening achieves only partial compliance with SDWA limits and its chemistry is well known, piloting this process was considered but was determined to be of little benefit to the participating communities.

The use of membrane separation processes in the water treatment field has grown significantly in the recent past because of technological improvements and specialization of the membranes themselves. Membrane separation processes use either hydrostatic pressure or electric charge to separate ions from the water. In electrodialysis, a pair of electrodes work with cationic and anionic membranes to allow ions to pass through and be separated from the product water. In reverse osmosis, a hydrostatic pressure is applied to brackish or sea water, forcing clean product water through the membrane.

Typically, RO membranes remove 90 to 99 percent of most ions. The rejection of ED is about 55 to 60 percent per stage. Thus, ED systems are arranged by number of stages, depending on feed-water quality being treated, and the product water quality goal. For example, treating a water of 2,000 mg/L TDS will require two ED stages. RO systems are also staged but not for rejection purposes. They are staged for increased production (Morin, 1994).

4.2 ED (electrodialysis)

An ED unit, shown on figure 2, has anion and cation transfer membranes stacked between a positively charged anode, and a negatively charged cathode. As feed water (or diluting stream) containing dissolved salts passes between alternate membrane pairs, negatively charged ions are attracted toward the anode and are allowed to pass through the anion transfer membrane. The positively charged ions are drawn toward the cathode and are allowed to pass through the cation transfer membranes. A portion of the feed stream, termed the concentrating stream, is used to carry the dissolved salts out of the system.

Transfer of Ions In Electrodialysis

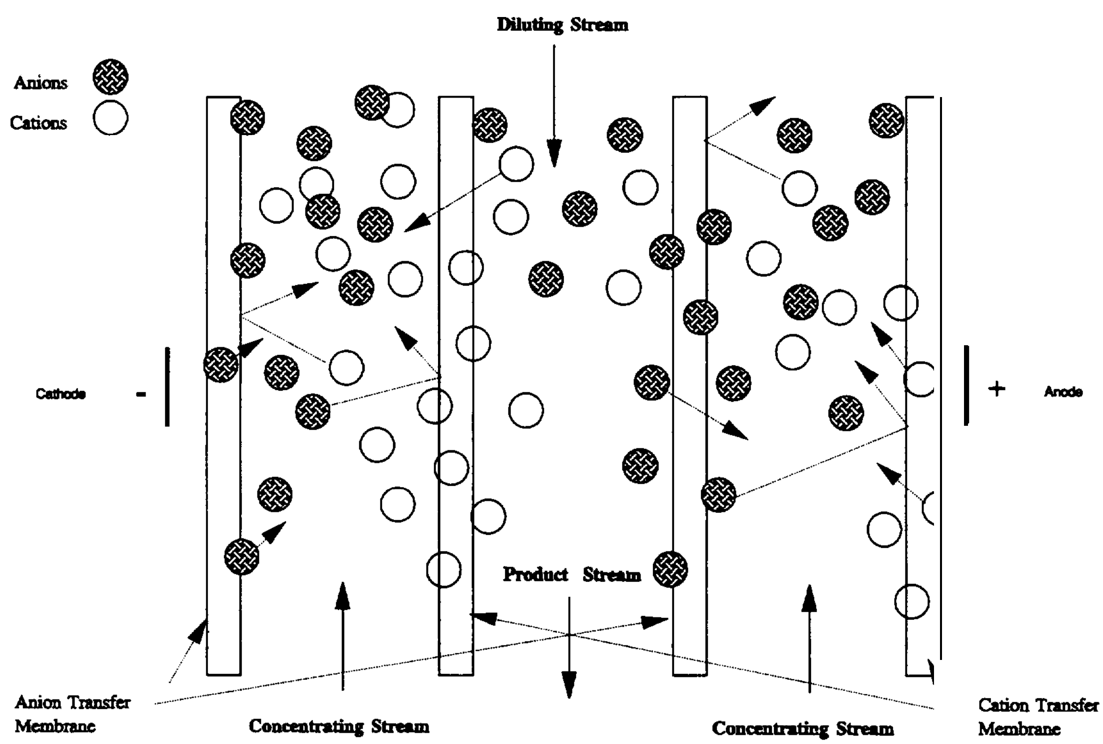


Figure 2. - Transfer of ions in an electrodialysis stack (Asahi Glass Co., Ltd.).

Figure 3 shows how the four separate streams flow through the stack. They are kept separate within framed nylon spacers that are set between each membrane pair. Because of the way they are cut, the spacers disperse water over the entire active area of the membrane and then collect it into the proper channel at the other end as shown on figure 4. When the stack of membrane and spacers is properly compressed with the peripheral bolts, water does not leak from the spacer channels. Although some water molecules are transferred with the ions, ED membranes are not permeable to unassociated whole water molecules, only to dissociated water, i.e., hydrogen and hydroxide ions. Some regrouping of H^+ and OH^- occurs on the other side of the membrane, but it is insignificant compared to the volume of water passing through the system.

ED membranes are formed from polymers with charged chemical groups or elements incorporated into the membrane matrix. For instance, cation transfer membranes have fixed negative ion groups, such as the sulfonate group, SO,, and positively charged, relatively freely moving counter ions, such as Na^+. Conversely, anion transfer membranes have positively charged fixed groups and negatively charged counter ions. The fixed ion groups repel like-charged ions in the feed solution while attracting oppositely charged ions, which are allowed to pass through.

ED membranes are much more durable than RO membranes and can tolerate pH from 1 to 10 for cleaning. They are not sensitive to chlorine and can tolerate a temperature as high as 46” C. They can be removed from the unit and scrubbed if necessary. If the concentrate stream becomes too saturated, salts may begin to adsorb onto the membrane surface, which increases electrical resistance within the unit. These solids can usually be washed off easily by turning off the power supply and letting water circulate through the stack. ED membranes have a life expectancy of at least 10 years. If operated correctly, they can last twice as long.

4.3 RO (Reverse Osmosis)

Reverse osmosis is a pressure-driven membrane process. The reverse osmosis process uses a semipermeable membrane to allow certain (water) molecules and ions to pass through while retaining others. A major portion of the water's impurity (dissolved salts) remains behind and is discharged as a waste stream, while relatively pure (product or permeate) water emerges at near atmospheric pressure. A typical operating pressure range for reverse osmosis is 200 to 400 lb/in^2 for brackish water and 800 to 1000 lb/in^2 for sea-water desalination. Ion rejections achieved with RO usually are in the 90 to 99 percent range. Factors that may influence overall operation and efficiency are temperature, feed-water composition, salinity, and recovery.

Reverse osmosis semipermeable membranes are either a hollow fine fiber material or a spirally wound or rolled sheet. Spiral wound membranes are most popular for brackish water treatment and will be the focus of this study. In spiral wound membranes, the semipermeable sheet is rolled up with a spacer material in the same pressure vessel. This arrangement allows separation of the treated water from the concentrated water and passage through the vessel to separate outlets on the vessel's end. Figure 5 shows two views of a spiral wound membrane.

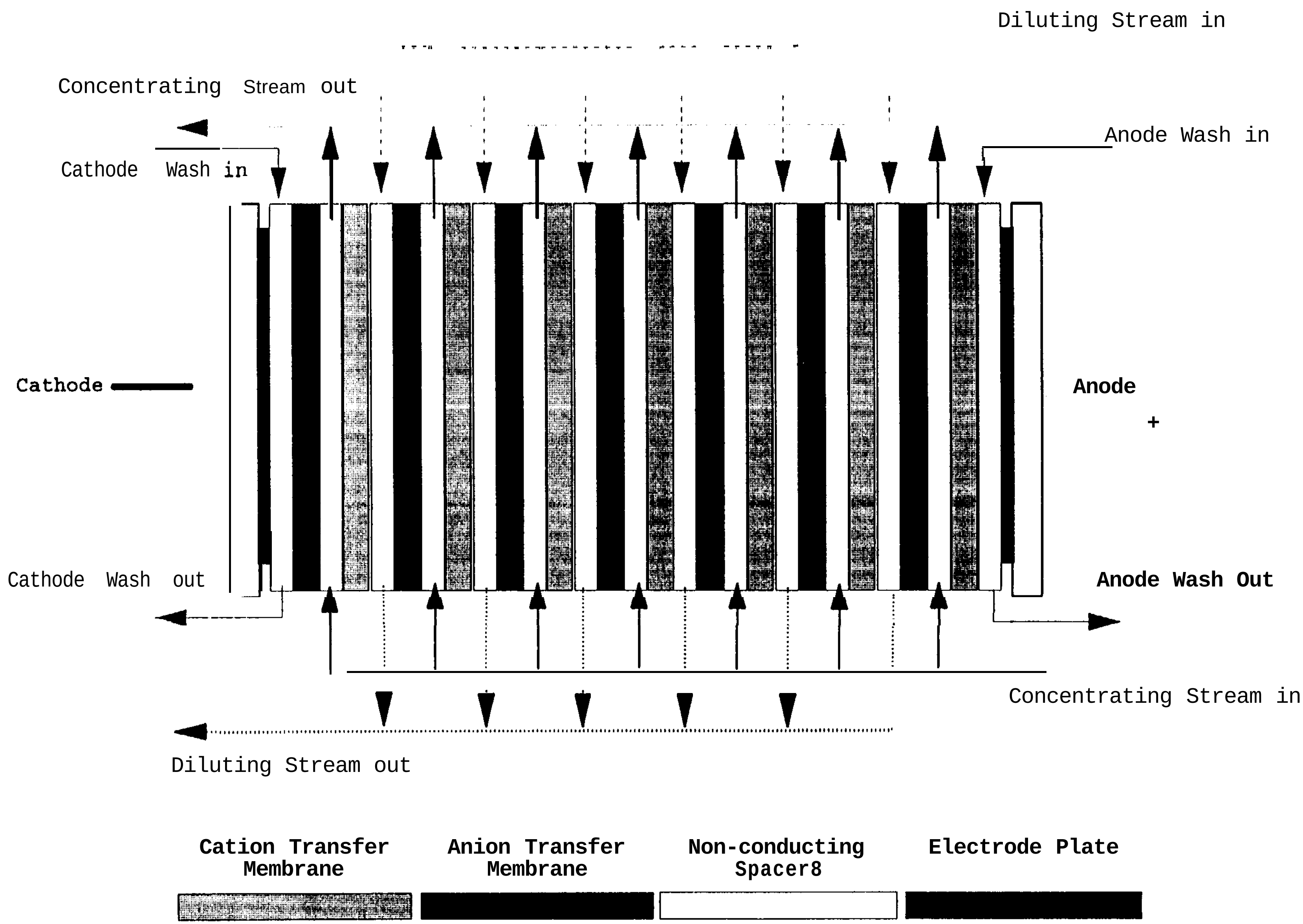
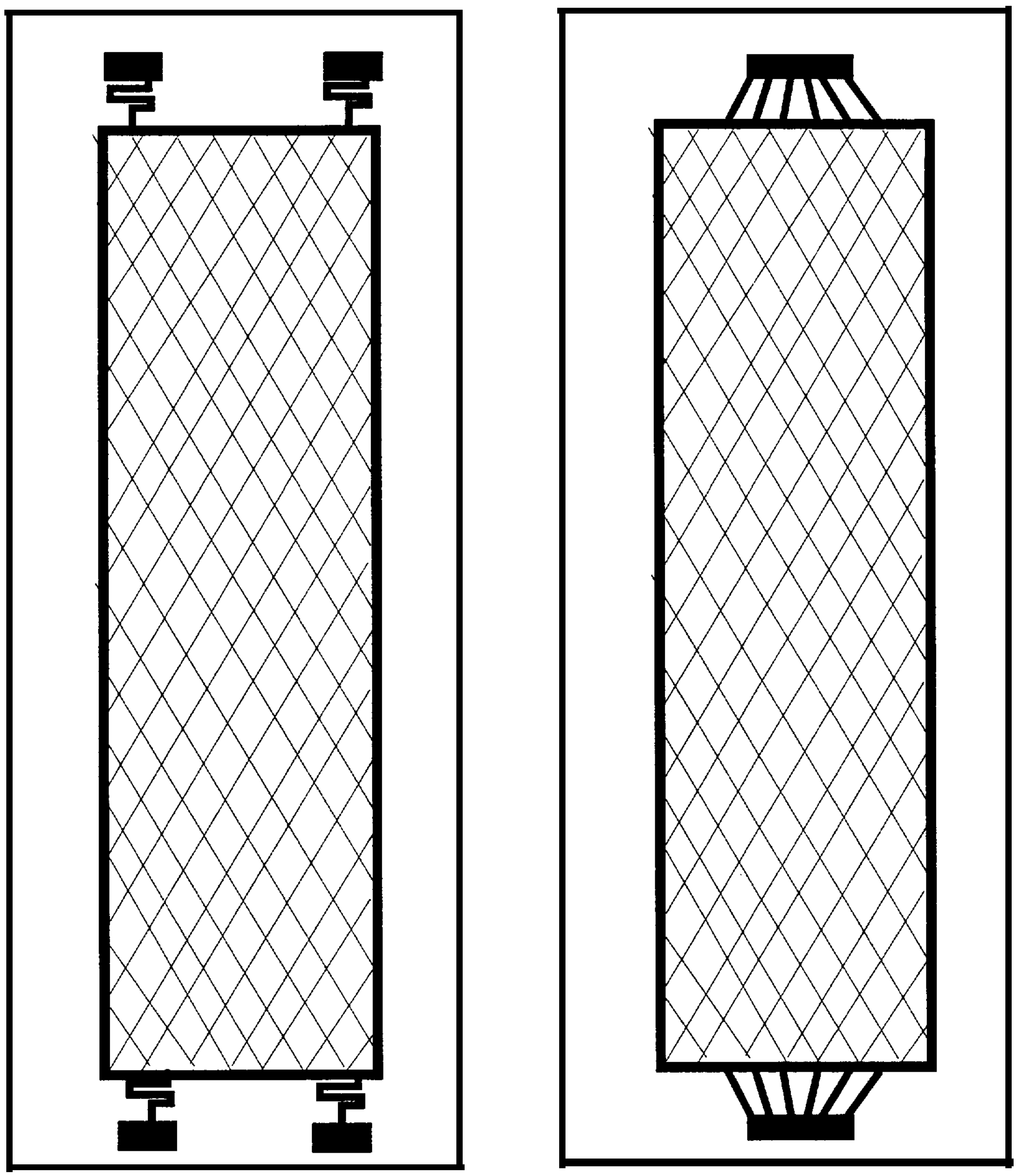


Figure 3. - Flow within an electrodialysis stack.

The anode and cathode washes flow through spacers next to either electrode. Electrode washes carry the byproducts of electrode reactions out of the system. The byproducts are hydrogen formed in the cathode spacer and oxygen and chlorine gas formed in the anode spacer. If the chloride is not removed, chlorine gas may form. Acid is added to the cathode wash to neutralize the sodium hydroxide which forms in the cathode compartment.



Concentrate **Spacer** **Diluate Spacer**

Figure 4. - Electrodialysis flow spacers (Asahi Glass Co., Ltd.).

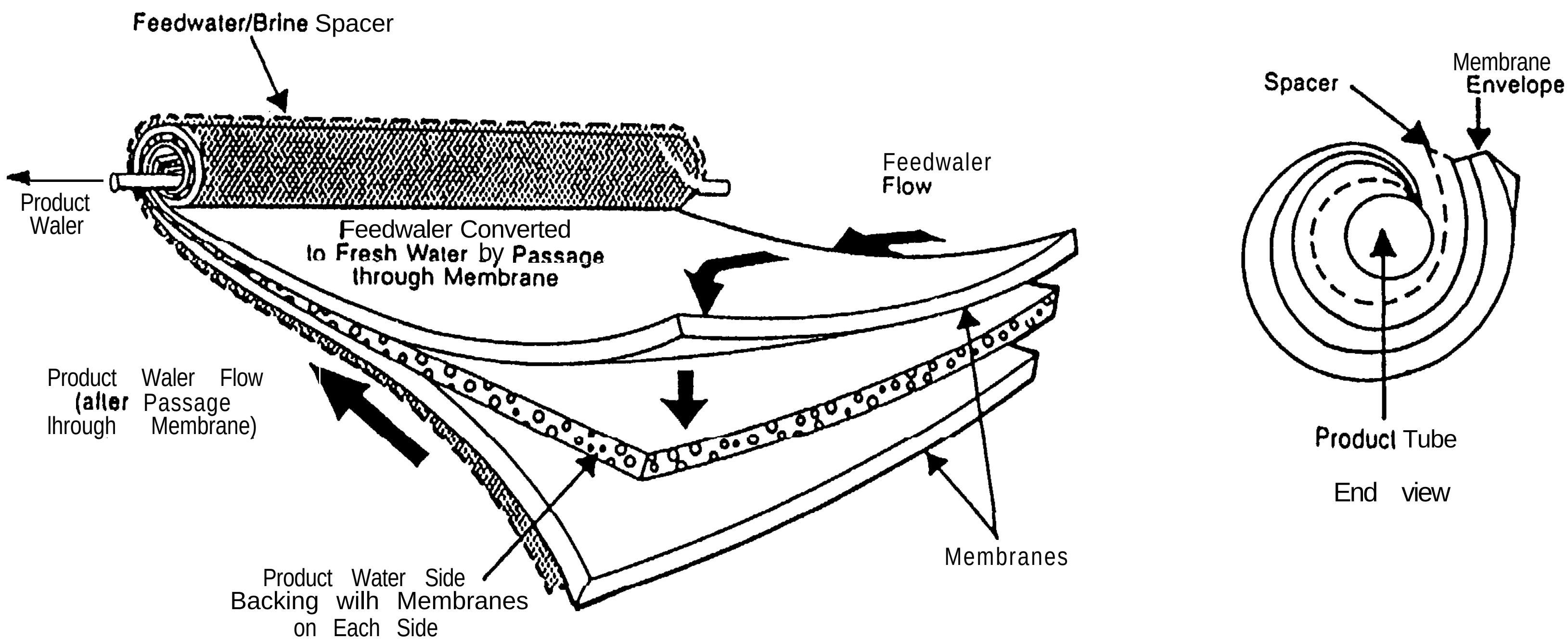


Figure 5. • Cut-away diagram of a spiral-wound RO element (Conlon, 1991).

Reverse osmosis can be used to reduce the concentration of both nitrates and dissolved solids to drinking water standards as specified by EPA. Rejection of divalent ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}), monovalent ions (Na^+, Cl^-, HCO_3^-, NO;), and organics are typically around 97 percent. Other applications for reverse osmosis membranes include the removal of color, THM (trihalomethane) precursors, TOC (total organic carbon), and radium.

Reverse osmosis requires extensive pretreatment to prevent the membranes from fouling, biofouling, or scaling. Fouling is the clogging of a membrane from suspended solids like colloids, silt, and clays, or from upstream equipment such as particles from pump packings, pipe fibers, and filter media. As previously discussed, the means to remove fouling agents is pretreatment filtration. Cartridge filters are typically used upstream from the RO unit to remove these contaminants. Fouling on the membrane surface caused by the accumulation of live or dead suspended biomass is referred to as biofouling. Some bacteria can grow with no light or oxygen and can destroy metals and membranes. They also can reproduce at alarmingly fast rates. Algae, a one-celled plant that usually requires light for cell metabolism, and other microorganisms, such as fungi, can also biofoul membranes. For these reasons, when reverse osmosis is used, it is important to disinfect and filter the feed water to remove all biological agents.

Scaling is the formation of a crust layer attributable to a precipitation or crystallization of a salt compound or solid. When feed water is concentrated, the amount or concentration of those ions that were rejected (unable to pass through the semi-permeable membrane with the water) increases to a point where insufficient water is available to keep the ion soluble and precipitation or scaling occurs. Because the concentration of both monovalent and divalent ions increases in RO as the water passes through each element, the likelihood of scaling is high. Antiscalants are commonly used in RO pretreatment to prevent scaling of the membranes. An antiscalant raises the solubility limit and thus inhibits chemical precipitation.

Reverse osmosis, like ED, will have waste stream disposal requirements that need to be considered for full scale operation. These requirements include the concentrate stream from the RO reject and the backwash wastewater from the filters used in pretreatment.

5. PILOT TEST DESCRIPTION

5.1 Site Preparation and Pilot Plant Equipment

Prior to starting the 6-week pilot test, the City of Avondale, with help from the City of Chandler and the Gila River Indian community, provided the following at Avondale's well s5:

- ZOO-ampere, single-phase power
- 15,000 gal/d of raw well water
- Drain line for 6 gal/min to the sanitary sewer system
- Deionized water
- Forklift and operators for equipment offloading
- Level concrete pad, 8 feet by 40 feet by 8 inches
- Secured area with vehicular access
- Sanitation facilities
- Professional analytical services for control testing

This work enabled the pilot plant to run on an acceptable and reliable power supply, receive adequate flow, dispose of finished water, and operate in a safe and efficient manner for the duration of the test.

Reclamation's Mobile Water Treatment Pilot Plant was used at Avondale for the field testing described herein. This pilot plant incorporates skid-mounted equipment to test numerous unit treatment processes, including: chemical precipitation, oxidation (ozone and permanganate), ion exchange, activated carbon, and membrane separation. Most of the process equipment is controlled by a PLC (programmable logic controller). Automatic data acquisition and a 35-kilowatt generator is available but was not required at this location.

Figures 6 and 7 diagram the treatment processes that were pilot tested at Avondale. Water from well s5 was pumped into an existing lO,OOO-gallon tank which provided about 1.5 days of storage for testing. The individual skid-mounted equipment shown on figures 6 and 7 were then used to measure flows, check turbidity and pH levels, add coagulants as necessary, remove the turbidity, disinfect, and add antiscalant prior to the ED or RO skids, respectively. Upon completion of treatment, both the product water and the concentrated waste stream were recombined prior to disposal to the city's sanitary sewer.

5.2 Process Selection

The following two treatment processes were selected to solve the problems of high turbidity, nitrates, chlorides, and TDS:

- Pressure clarifier, multi-media filtration, and ED with selective anion and non-selective cation membranes manufactured by Asahi Glass Co., Ltd.

- Pressure clarifier, multi-media filtration, and RO with polymer addition and pH adjustment. Membranes elements were manufactured by the Dow Filmtec Co.

5.2.1 Electrodialysis - An Asahi DB-0-1136 system was used for pilot studies in Avondale. The system contains regular CMT (cation transfer membrane); but the anion transfer membrane is selective AST (against sulfate ion). This selectivity means that other anions, like chloride and nitrate, are transferred in preference to sulfate. Some sulfate is transferred, but slowly. Using this membrane provides two benefits: (1) nitrate transfer is higher than with regular anion transfer membrane and (2) because sulfate is left in the product stream, less scaling occurs in the concentrate stream and higher recoveries are possible. The CMT/AST combination was chosen for the Avondale site because anticipated levels of nitrate in the water analysis were considered too high to remove using non-selective membranes.

The following are advantages of using ED over RO:

- Lower operating pressure
- Low energy requirement
- More tolerant of turbidity excursions
- Can produce a less concentrated waste stream
- Does not require antiscalant
- Quieter to operate
- Smaller footprint
- Membrane durability

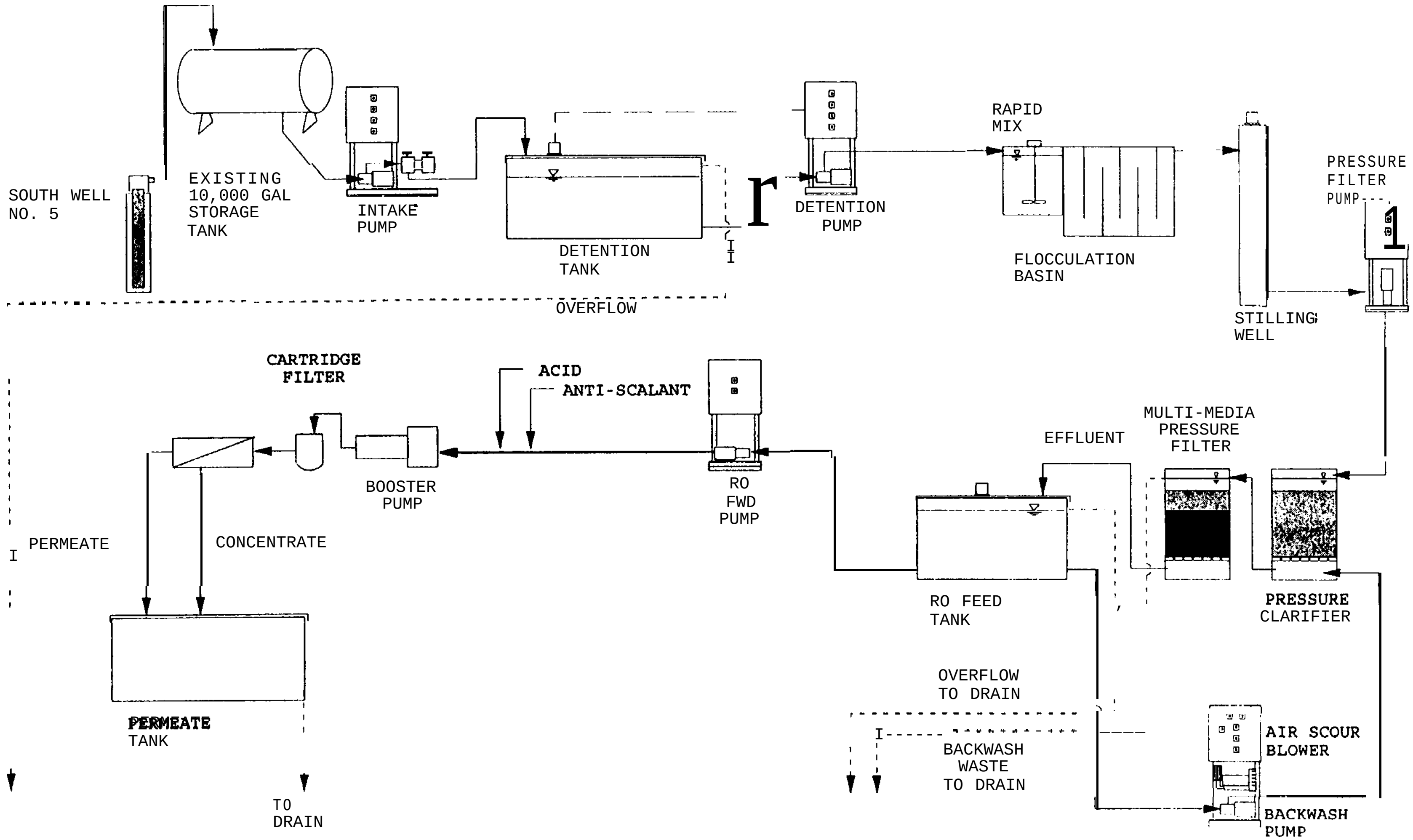


Figure 6. - Reverse osmosis pilot plant equipment.

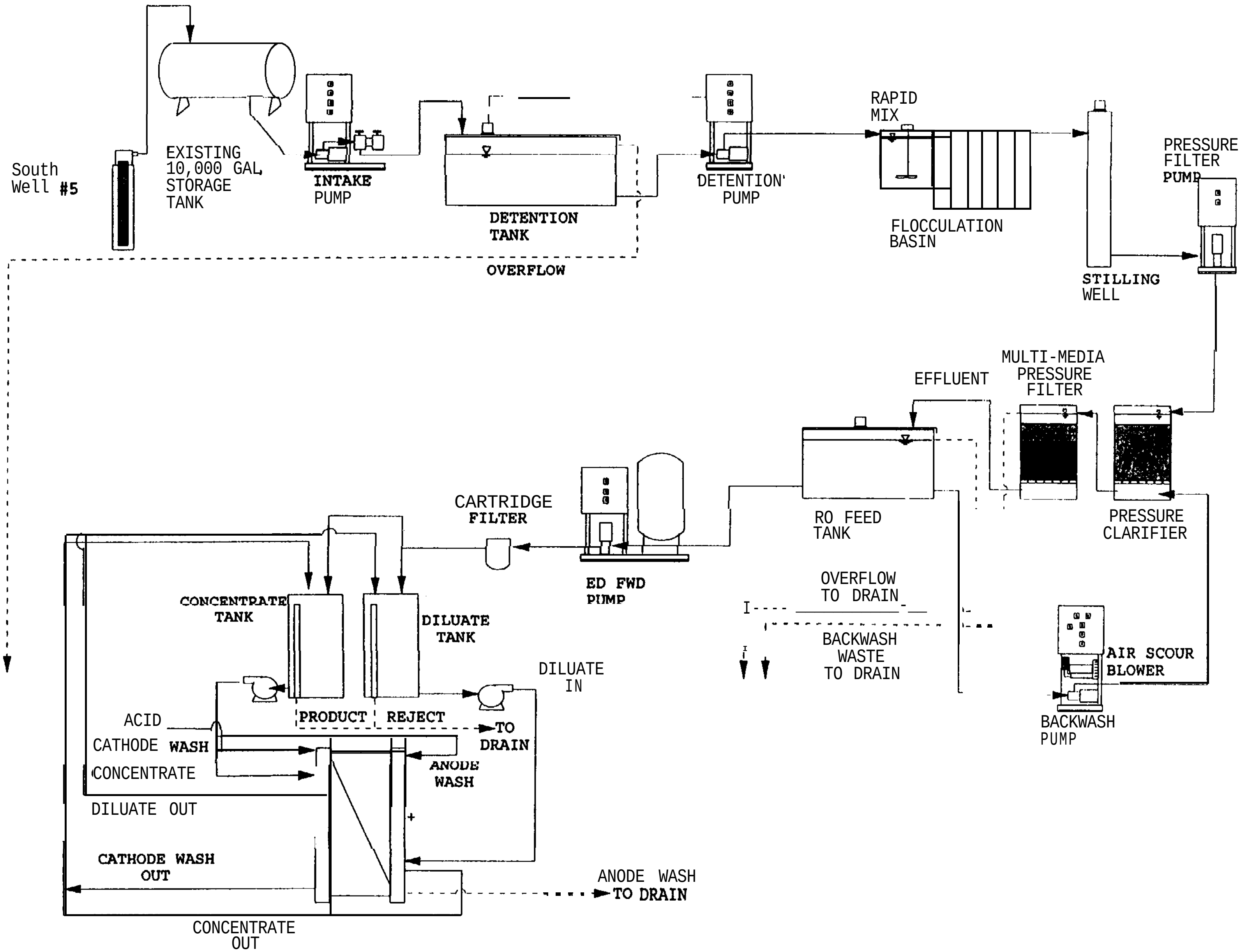


Figure 7. • Eiectrodialysis pilot plant equipment.

The proportion of salts removed with one pass through the membrane depends on resistance within the ED stack, flow rate of the demineralized stream, desired reduction in TDS, and the voltage applied. The feed and bleed systems were used to attain the minimum TDS level possible. Feed water was mixed with the demineralized stream and recycled to the ED stack at a ratio of 1:10. Raw water was blended with the concentrating stream at a ratio of 1:10. The overall design recovery was 90 percent.

Use of antiscalants was not necessary during the ED pilot operation because sulfate and carbonate ions were not concentrated in the reject waste stream. This is because of the selectivity of the membranes and the addition of acid to the concentrate stream caused the bicarbonate to convert to carbon dioxide.

5.2.2 **Reverse Osmosis -** Reverse osmosis was selected for field testing because of its ability to produce water which completely meets or exceeds drinking water standards at high overall net recoveries. Reverse osmosis allows high quality RO product water to be blended with other water so that the total amount produced per day costs less and the amount of the byproduct waste stream is also less.

Reducing the turbidity is a necessary requirement for pretreating the water prior to RO. This improvement can be achieved by the addition of a polymer to enhance the settling of suspended solids (i.e., iron, manganese) and the use of a clarifier and a dual media gravity filter. The other concern is biological fouling of the membrane. Laboratory results imply that a biological concern will not exist, but if biological fouling is noticed, the use of chloramine disinfection will be implemented.

5.3 Pilot Test Objectives

5.3.1 Electrodialysis - The principal objectives of the electrodialysis testing were to:

- Determine adequate pre-treatment requirements.
- Determine conditions under which a unit using anion selective membranes removes enough nitrate to meet drinking water standards.
- Determine conditions under which the CMT/AST membrane configuration produce water with a TDS concentration of 500 mg/L or less.
- Determine the volume and water quality characteristics of the waste stream produced.

5.3.2 Reverse Osmosis

The principal objectives of the reverse osmosis testing were to:

- Determine adequate pretreatment requirements.
- Evaluate the overall performance of the FilmTec BW30-2540 membrane for reducing nitrate and TDS in the well s5 water.
- Assess blending opportunities (RO permeate with pretreated well water) to maximize net recoveries.

- Determine potential long-term adverse effects on the membranes from colloidal fouling, biofouling, or scaling.

- Determine the volume and water quality characteristics of the waste stream produced.

5.4 Test Procedures

5.4.1 Pretreatment System - Turbidity, conductivity, pH, and temperature of water from the well, detention tank, pressure clarifier, and media filter were monitored at least twice per day. These tests determined the raw water quality and the effect of these tanks, plus contact with air, on temperature and suspended solids removal. The media filters were backwashed when rises in turbidity or pressures in the pretreatment system were observed.

For both the pretreatment and the two desalting processes of electrodialysis and reverse osmosis, the water quality parameters listed in table 2 were submitted to Westech Analytical Services, Inc., in Phoenix, for process performance evaluation.

5.4.2 Electrodialysis - Electrodialysis tests were designed to identify maximum performance parameters of the Asahi CMT/AST membrane configuration by varying detention time and voltage. Table 3 presents the recommended and experimental ranges of the operating test parameters used at the site. Detention time can be varied by adjusting feed water flow into the diluate and concentrate tanks. When the feed flow to the diluate tank equals the product outlet flow, the detention time can be determined from the diluate tank volume (110 liters):

$$\textit{Detention} = \frac{V_d}{F_{fd}}$$

where V_d is the diluate tank volume and F_{fd} is the equilibrium flow rate to the diluate tank.

Increasing the detention time simulates increased membrane area. The diluting stream flows through the stack at 92 L/min, so the contents of the diluting tank will pass through the stack once in about 1.2 minutes. With a 5-minute detention time, the contents of the diluting tank will pass through the stack about 4.2 times. This time is comparable to increasing the membrane area 4.2 times.

$$\textit{No. Passes} = \frac{F_{rd} * Det}{V_d}$$

where F_{rd} is the diluate flow rate to the stack (92 L/min), V_d is the diluate tank volume (110 liters), and Det is the detention time (5 minutes).

At the start of the test, both diluate and concentrate were filled with well water. The power supply was set at the test voltage and/or current, and the system was operated for the calculated detention time. Samples were taken from the feed stream, diluate and concentrate tanks, and diluate and concentrate return flow from the stack. Resistance within the stack was monitored by recording power supply current and measuring voltage across the stack. Conductivity, temperature, pH, and nitrate concentration were measured for each sample.

5.4.3 **Reverse Osmosis -** The reverse osmosis system design parameters that were followed for this test are summarized in table 4.

Table 2. - Analytical requirements for RO and ED piloting.

Parameter	Units	Number of Samples/Readings (RO)	(ED)	Responsibility for Testing/Recording	Preservation	Container Type	Minimum Volume (ml)	Maximum Holding Time
Flow	L/min	Many	Many	Operator				
Temperature	deg C	Many	Many	Operator				
pH		Many	Many	Operator				
Turbidity	NTU	Many	Many	Operator		-	-	
Conductivity	uS/cm	Many	Many	Operator				
Silt Density Index (SDI)		Many	Many	Operator, SDI Test kit		-		
Calcium, Ca	mg/L	3	3		Store at 4 deg C	Plastic	200	28 days
Magnesium, Mg	mg/L	3	3	Professional Lab	Store at 4 deg C	Plastic	200	28 days
Sodium, Na	mg/L	3	3	Professional Lab	Store at 4 deg C	Plastic	200	28 days
Potassium, K	mg/L	3	3	Professional Lab	Store at 4 deg C	Plastic	200	28 days
Aluminum, Al (total) . '	mg/L	3	3	Professional Lab	Nitric, < pH 2	Plastic	250	8 months
Iron, Fe (total)	mg/L	3	3	Operator, Hach	Nitric, < pH 2	Plastic	256	6 months
Manganese, Mn (total)	mg/L	3	3	Operator, Hach	Nitric, < pH 2	Plastic	250	6 months
Bicarbonate, HCO3	mg/L	3	3	Professional Lab	Store at 4 deg C	Plastic. glass	100	14 days
Chloride, Cl	mg/L	3	3	Professional Lab	Store at 4 deg C	Plastic, glass	50	28 days
Sulfate, SO4	mg/L	3	3	Professional Lab	Store at 4 deg C	Plastic, glass	50	28 days
Nitrate, NO3	mg/L	3	3	Professional Lab	Store at 4 deg C	Amber plastic, glass	100	48 hours
Hardness (as CaC03)	mg/L	3	3	Professional Lab	Nitric, < pH 2	Plastic, glass	100	6 months
Alkalinity (as CaC03)	mg/L	3	3	Professional Lab	Store at 4 deg C	Plastic, glass	100	14 days
Silica, SiO2	mg/L	3	3	Professional Lab	Store at 4 deg C	Plastic	-	28 days
Total Organic Carbon (TOC)	mg/L	3	4	Professional Lab	4 deg C; HCl, < pH 2 & 4 drops 10% ST.	Amber glass: TFE cap	100	7 days
Standard Plate Count (SPC)	CFUs/mL	3	4	Professional Lab	Store at 4 deg C	Sterilized glass, plastic	100	8 hours
Headloss	psig	Many		Operator				
Backwash (B/W) Frequency	hours	Many		Operator				

NOTES:
RO = Reverse Osmosis
ED = Electrodialysis

Table 3. - Electrodialysis operating parameters (Asahi Glass Co., Ltd.).

Parameter	Recommended Value	Experimental Range
Number of membrane pairs	100	92
Membrane area/pair	414 cm^2	N/A
Spacer thickness	0.15 cm	N/A
Diluate flow to stack	92 L/min	84 - 87 (max obtainable)
Concentrate flow to stack	12.3 L/min	11 - 13
Cathode wash flow	3 L/min	3
Anode wash flow	1.5 L/min	1.5 - 3
Feed flow to diluate tank	10 L/min	6.5 - 13.5
Feed flow to concentrate tank	1.6 L/min	1 - 3
Recovery	86 pct	up to 93 pct
Current	4.2 Amps	2.75 (max is 3.0)
Voltage	79 Volts	50 - 110
Cathode wash pH	2	-2
Concentrate pH	5	2 - 7.8

Table 4. - Reverse osmosis operating parameters.

Parameter	Recommended Value
Configuration	12:6, 2 stage (refer to appendix C or E)
Element	FilmTec BW30-2540
Recovery	80 pct
Initial feed pressure	225 lb/in^2 @ 25 °C
Feed flow	18.2 L/min (4.8 gal/min)
Projected permeate TDS	50 mg/L

The following chemicals were added to the flow stream during the RO pilot test:

- Antiscalant - Hypersperse AF 200™ @ 3.0 p/m
- Sulfuric acid for pH adjustment to 7.0
- Ferric sulfate, if needed for turbidity control

The RO system was operated for nearly 700 hours to observe any potential membrane degradation from colloidal fouling, biofouling, or scaling. System startup was at operating pressures required to achieve 80-percent recovery. Process instrument data were manually recorded four times per day. Just prior to data collection, the operator adjusted the system pressure to 210 lb/in^2 (gage) by adjusting the BPV (back pressure valve) on the high pressure pump recycle line and the FCV (flow control valve) on the concentrate line.

An SDI (silt density index) measurement of the cartridge filter effluent stream was made once a day. SDI is a measure of fouling potential of the feed from colloidal-size materials.

Samples of the feed, interstage, permeate, and concentrate (reject) streams were collected after 4, 364, and 720 hours of operation. These samples were sent to a contract laboratory for the analyses listed in table 2. The 5-µm cartridge filter elements on the RO skid were changed about every 3 to 4 days. A PID (proportional integral derivative) controlled chemical feed pump was used to regulate the addition of sulfuric acid for feed pH adjustment. A 5-percent solution of the antiscalant was prepared about every 4 days and added with a manually-controlled chemical feed pump.

6. PILOT TEST RESULTS AND CONCLUSIONS

6.1 Results

6.1.1 Pretreatment System - The effectiveness of the pressure clarifier and pressure multi-media filter in removing turbidity is shown on figure 8. The pressure clarifier alone was able to produce water below 1 ntu (nephelometric turbidity unit) for 5 days. On the fifth day, the turbidity coming out of the pressure clarifier was higher than that of the well water. This parameter was used as an indication of when to backwash the media filters.

The pressure clarifier reduced the load on the multi-media filters, but after pumping the well for 2 weeks, the turbidity dropped from 15 to 8 ntu. The pressure clarifier was removing most of the turbidity without chemical additives and one backwash cycle per week. Recorded historic nitrate levels had been as high as 29 mg/L as nitrogen; however, during the test period, the nitrate concentration was much lower and ranged from 5.7 to 7.4 mg/L as nitrogen.

6.1.2 Electrodialysis System - The first task in interpreting the ED results was to determine the relationship between conductivity and concentration for the well water, ED product, and concentrate streams. Water analyses were performed on the three waters twice during ED testing. A supplemental analysis was performed on the product water at the end of testing. This final sample had the lowest conductivity. Figure 9 shows conductivity data correlated with reported TDS.

6.1.2.1 Nitrate reduction - The ED system brought nitrate levels down to 3 mg/L or less at all operation settings as shown on figure 10. Nitrate levels in the well water fell from 9.7 mg/L at the start of testing to a stable concentration of about 5.5 mg/L by the end of the first week. This level is substantially less than historical levels of 29 mg/L. One possible explanation for the reduction in nitrate levels is that nitrate had been accumulating in the well and/or in the aquifer near the column pipe and was flushed out after 1 week of operation. It is recommended that nitrate be monitored on this well for a year before committing to a treatment technology geared toward nitrate removal.

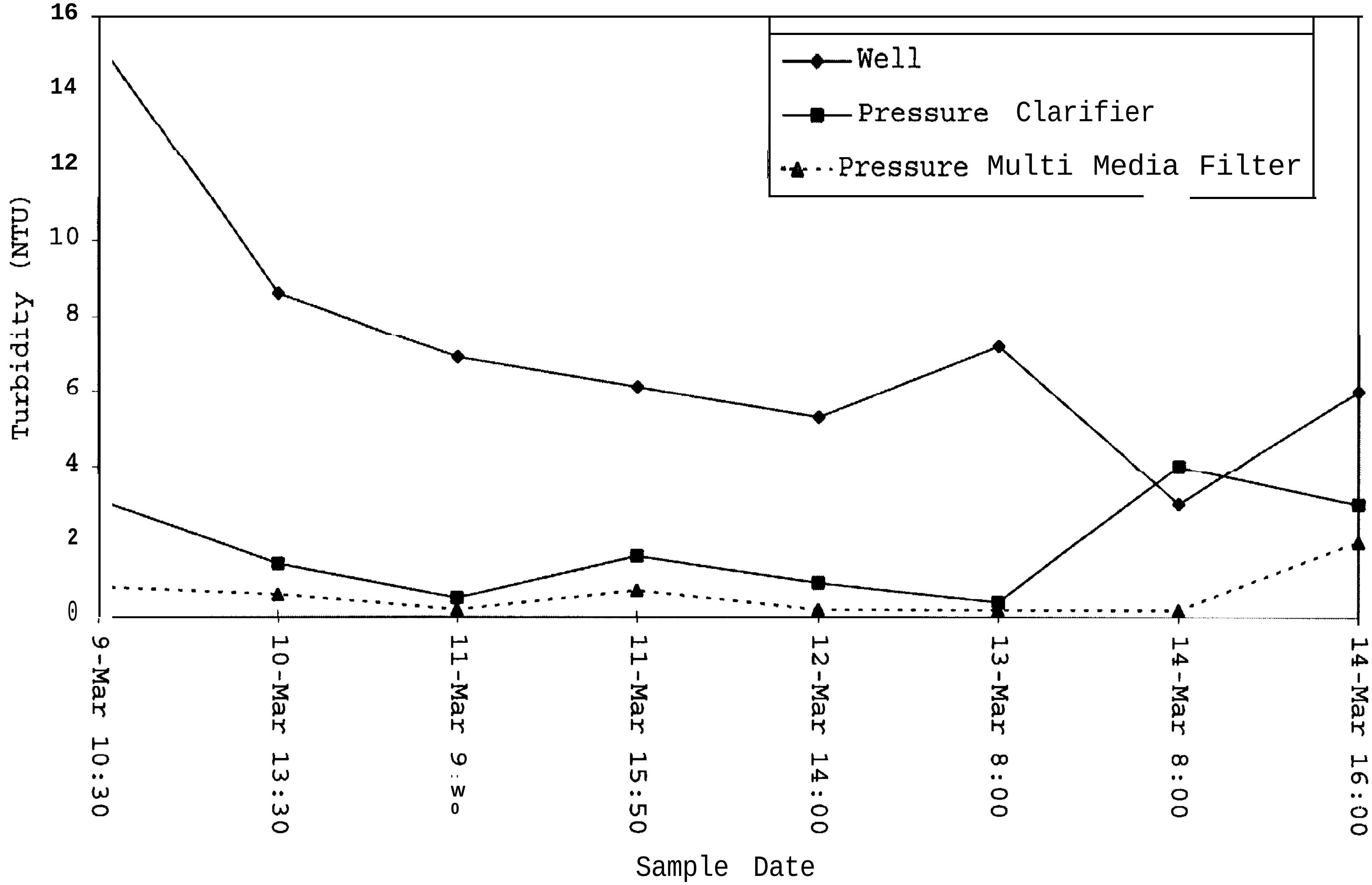


Figure 8. • Effectiveness of the pretreatment system in controlling turbidity.

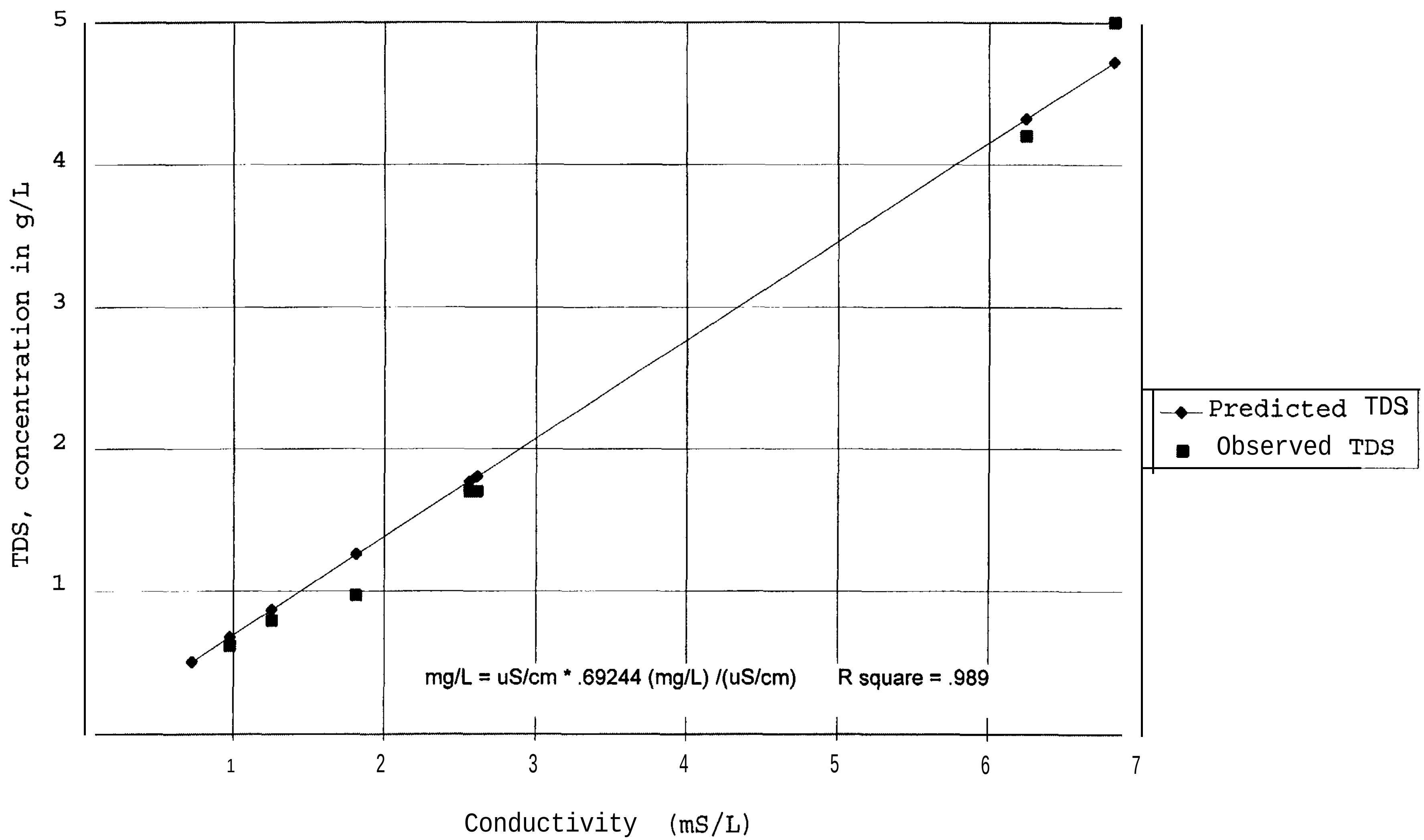


Figure 9. - Relation between conductivity of ED streams and TDS concentration.

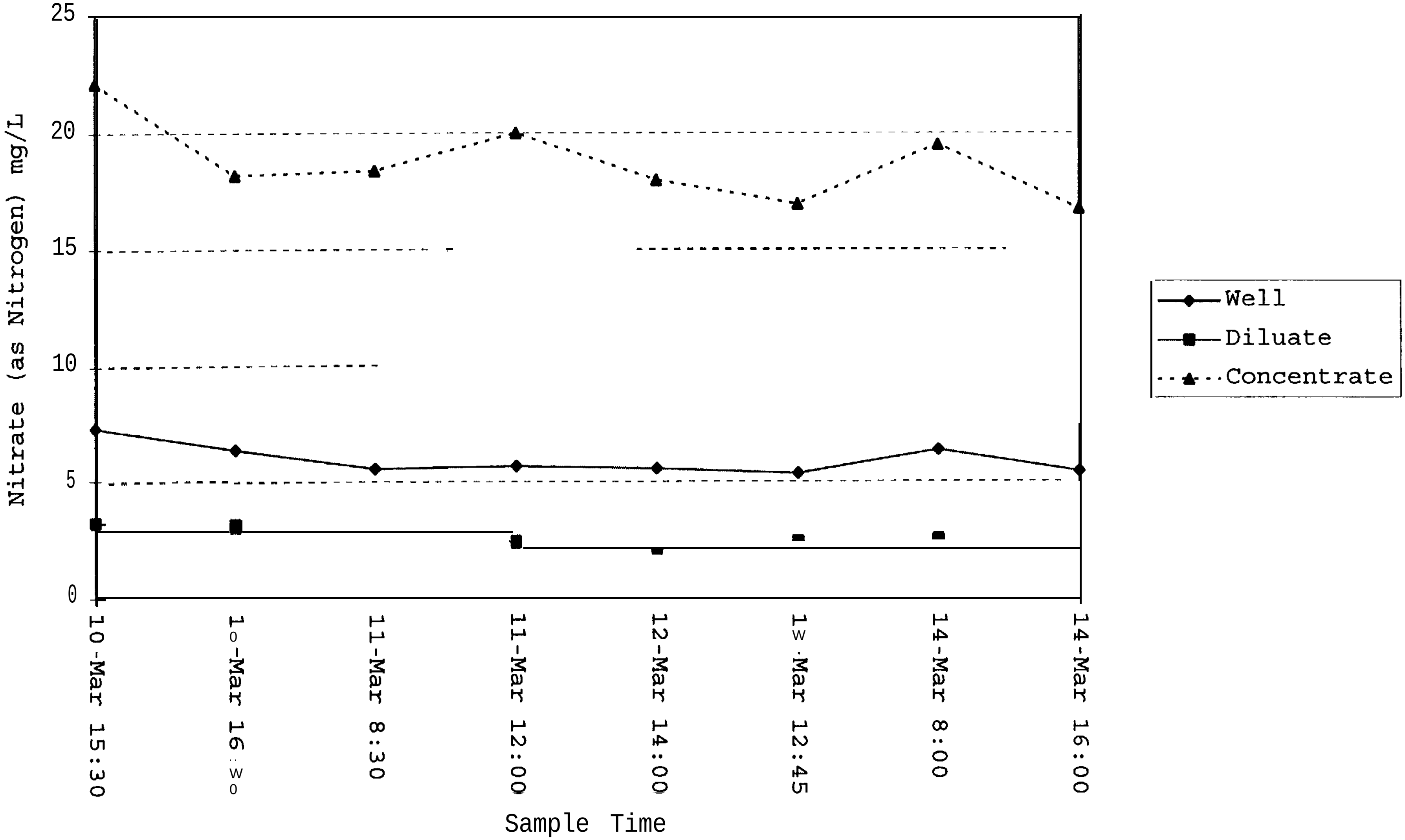


Figure 10. - Nitrate removal with selective electrodialysis.

6.1.2.2 Total Dissolved Solids Reduction - Reducing TDS to drinking water levels with this system would be more difficult than it would have been if standard CMT/AMT ED membranes had been used. The lowest product salinity attained was 613 mg/L TDS while operating at 100 volts, 1.71 amperes, 83-percent recovery, and with an H-minute detention time. At these operating conditions, chlorine gas production in a full scale plant would warrant controlling the fumes. This off-gas could be used to disinfect product water before distribution, thereby saving on the cost of chlorine.

A summary of the electrodialysis water quality data for the feed, product, and reject flow streams is found in table 5. Results of variation in detention time and voltage studies are presented on figures 11 and 12. In general, the effect of increasing voltage was greater than increasing detention time. The maximum voltage recommended for this ED stack, however, is 100 volts. If the experimental system was to produce water with a TDS of 500 mg/L, the detention time would have to be about 27 minutes, or 32 times the membrane area contained in the pilot study, assuming that the performance would continue as it had at shorter detention times. Figure 11 seems to indicate that the detention time would not be much different for lower voltages.

Table 5. - Electrodialysis water quality data.

Ion	Feed	Product	Reiect	Percent Reduction
Aluminum	0.69	0.39	1.70	43.48
Calcium	210.00	92.00	590.00	56.19
Magnesium	84.00	50.00	290.00	40.48
Manganese	0.11	0.06	0.30	45.45
Potassium	4.00	2.60	9.30	35.00
Sodium	140.00	120.00	220.00	14.29
Bicarbonate	170.00	130.00	2.00	23.53
Chloride	760.00	240.00	2000.00	68.42
Nitrate	9.70	3.70	42.00	61.86
Sulfate	260.00	230.00	1300.00	11.54
Total (Sum)	1200.00	604.00	3344.00	49.67
TDS (Reported)	1700.00	970.00	4200.00	42.94

Power requirement for the various operating modes is depicted on figure 13. All of the modes fall close to a line that would indicate a power requirement of about 0.6 kWh/m^3 to produce water with 500 mg/L TDS from the water tested.

The complete operational data for the ED system are found in appendix A.

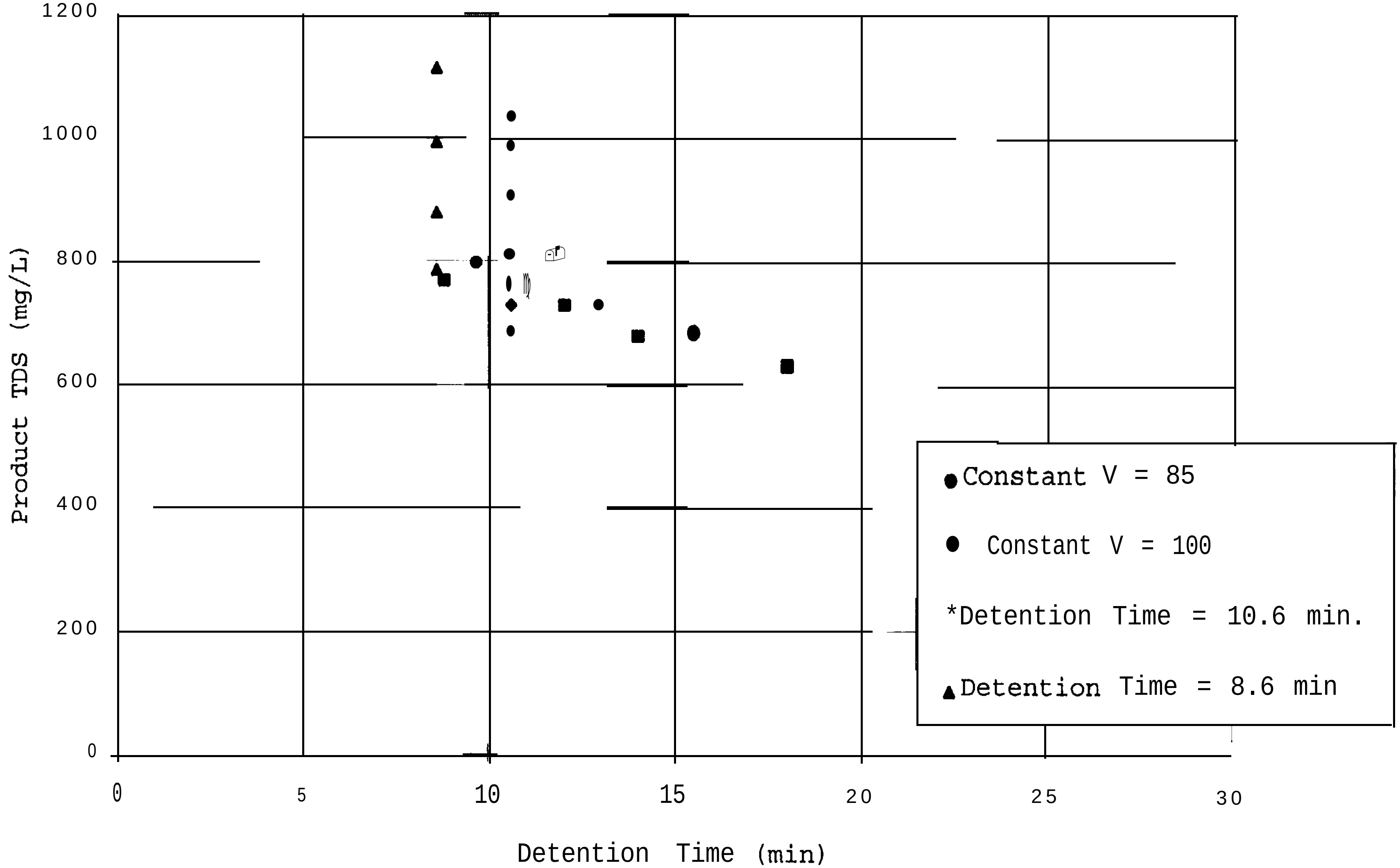


Figure 11. - Effect of detention time on product quality.

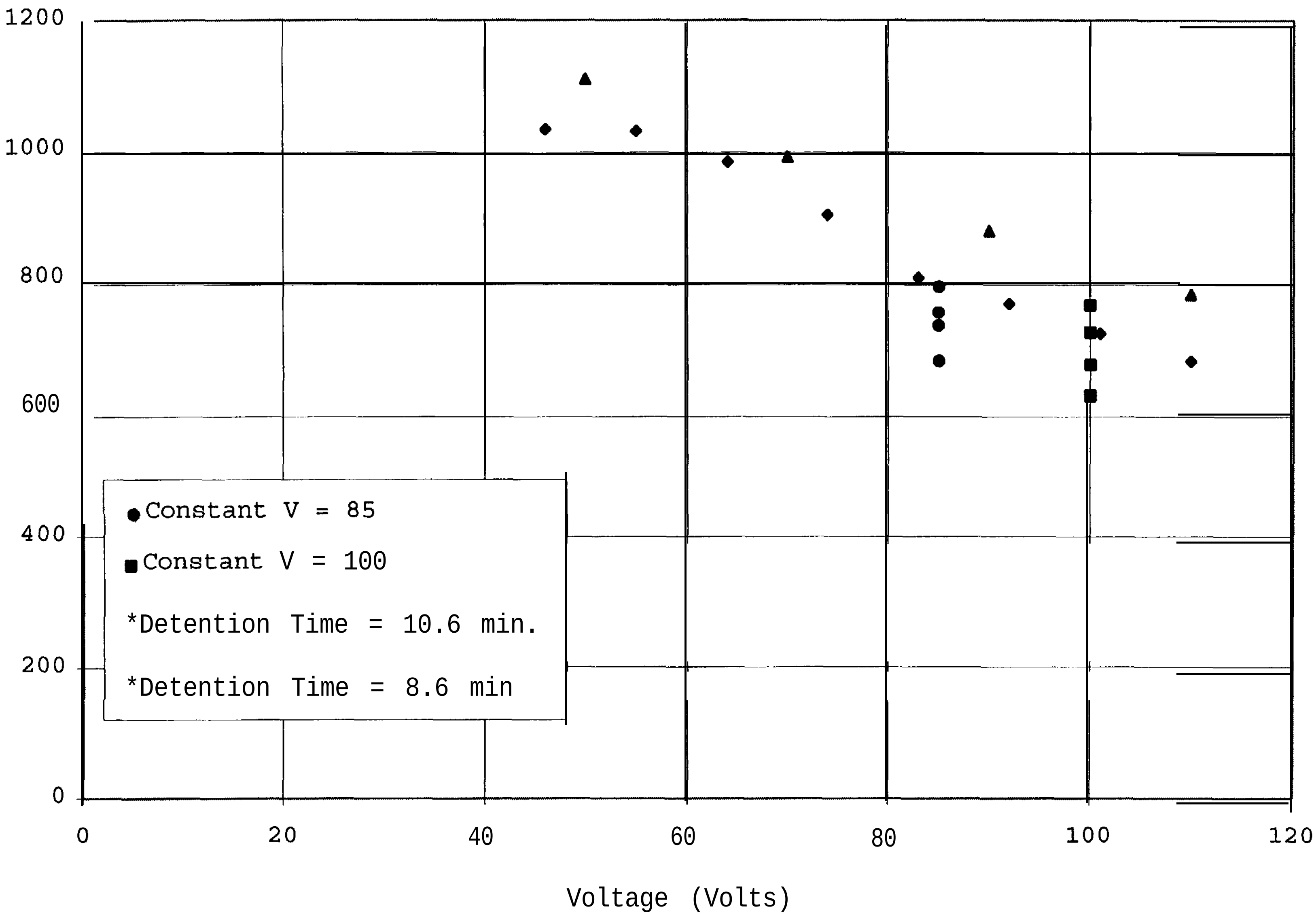


Figure 12. - Effect of voltage on ED salt removal.

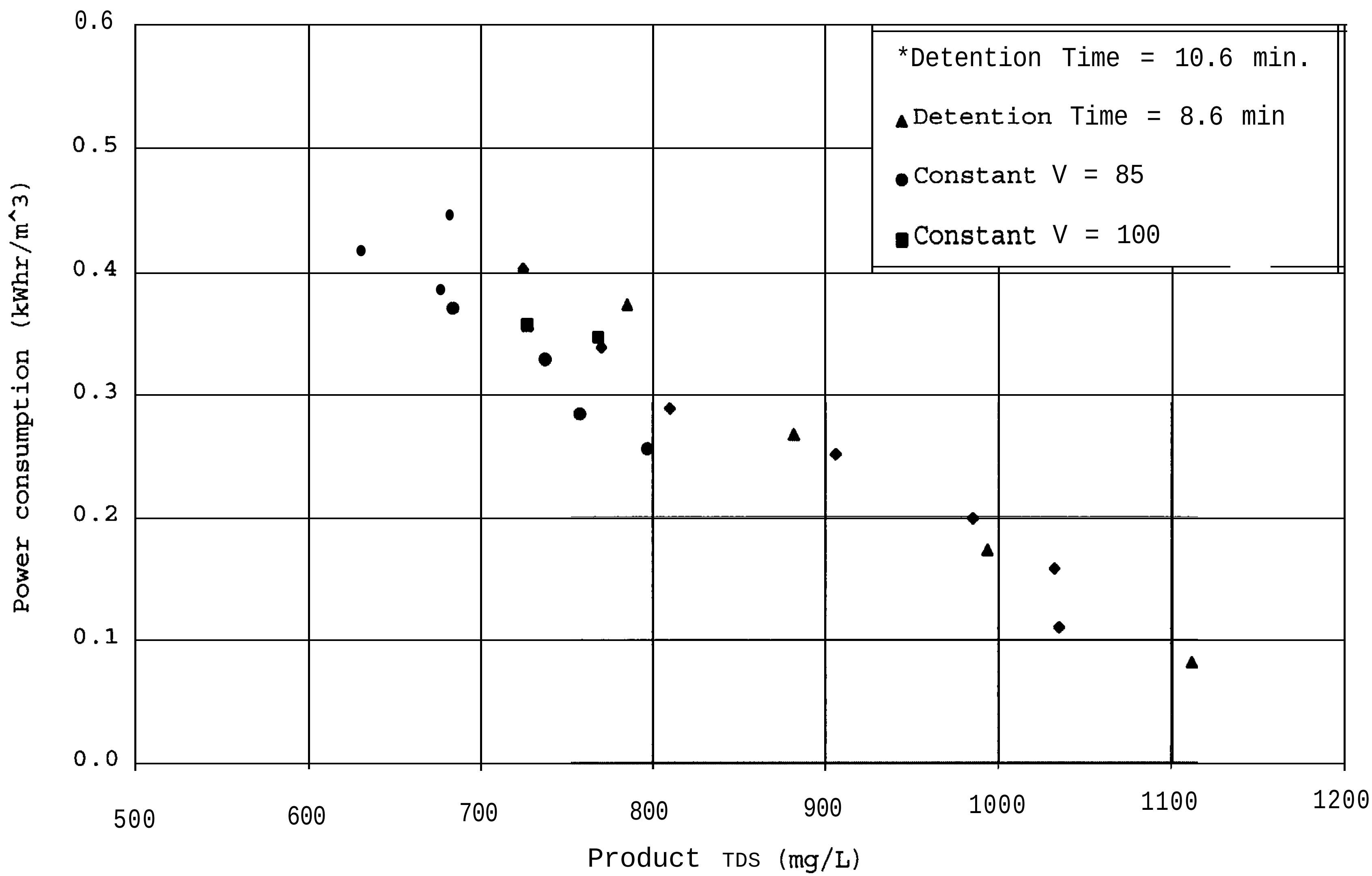


Figure 13. • Relation between power consumption and ED product water quality.

6.1.3 **Reverse Osmosis** - The testing described below was designed to determine the following:

1. The overall performance of the FilmTec BW30-2540 reverse osmosis membrane element in reducing TDS and nitrate levels in well s5 ground water.

2. The potential long-term adverse effects on the membranes from fouling and/or scaling.

3. The blending ratio (RO permeate with filtered well water) to achieve high overall net recoveries.

6.1.3.1 Operational data.- A total of 720 hours of operation accrued on the RO elements during this test phase. The raw data collected by the plant operators and other calculated values are tabulated in appendix B. Flow, temperature, conductivity, and pressure data are also graphically depicted on figures 14 through 20.

Figure 14 shows the system flow rates of feed, reject, stage 1 (vessels 1 and 2) product flows, and stage 2 product flows. These flows were allowed to fluctuate while the feed pressure was held constant at 210 lb/in^2. An 80-percent recovery of desalted water (permeate) was achieved during this test. The total amount of permeate recovered is the summation of the following three flows:

- Stage 1, vessel 1 permeate (orange symbols)
- Stage 1, vessel 2 permeate (yellow symbols)
- Stage 2 permeate (blue symbols)

Figure 15 shows both the diurnal and long-term variation in feed temperature. This measurement was taken at the feed end of the first stage. Temperature has a significant effect on membrane performance and is used in later calculations of net permeate flow, which is normalized to 25 “C.

Figure 16 displays system conductivities as µS/cm (microsiemens per centimeter). For better resolution, figure 17 shows an expanded view of the permeate conductivities. Note that the permeate conductivities gradually decrease throughout the test period, but so does the feed conductivity.

Figure 18 plots the RO system's operating pressures in pounds per square inch (lb/in^2), for the entire 720-hour test period, for the feed, interstage, and reject stages. It is interesting to note that although the feed pressure was manually maintained at 210 lb/in^2, the interstage and reject pressures show marked decreases at 320 and 470 hours of operation. These pressure drops are attributable to scaling and/or fouling of the membranes as later discussed in section 6.1.3.2. Figure 19 shows the pressure drops across the first and second stages. The pressure drops across the first stage at about hours 320 and 470 indicate that it was this stage that was affected. Appendix C contains a diagram that shows the location of the RO data obtained during the pilot test.

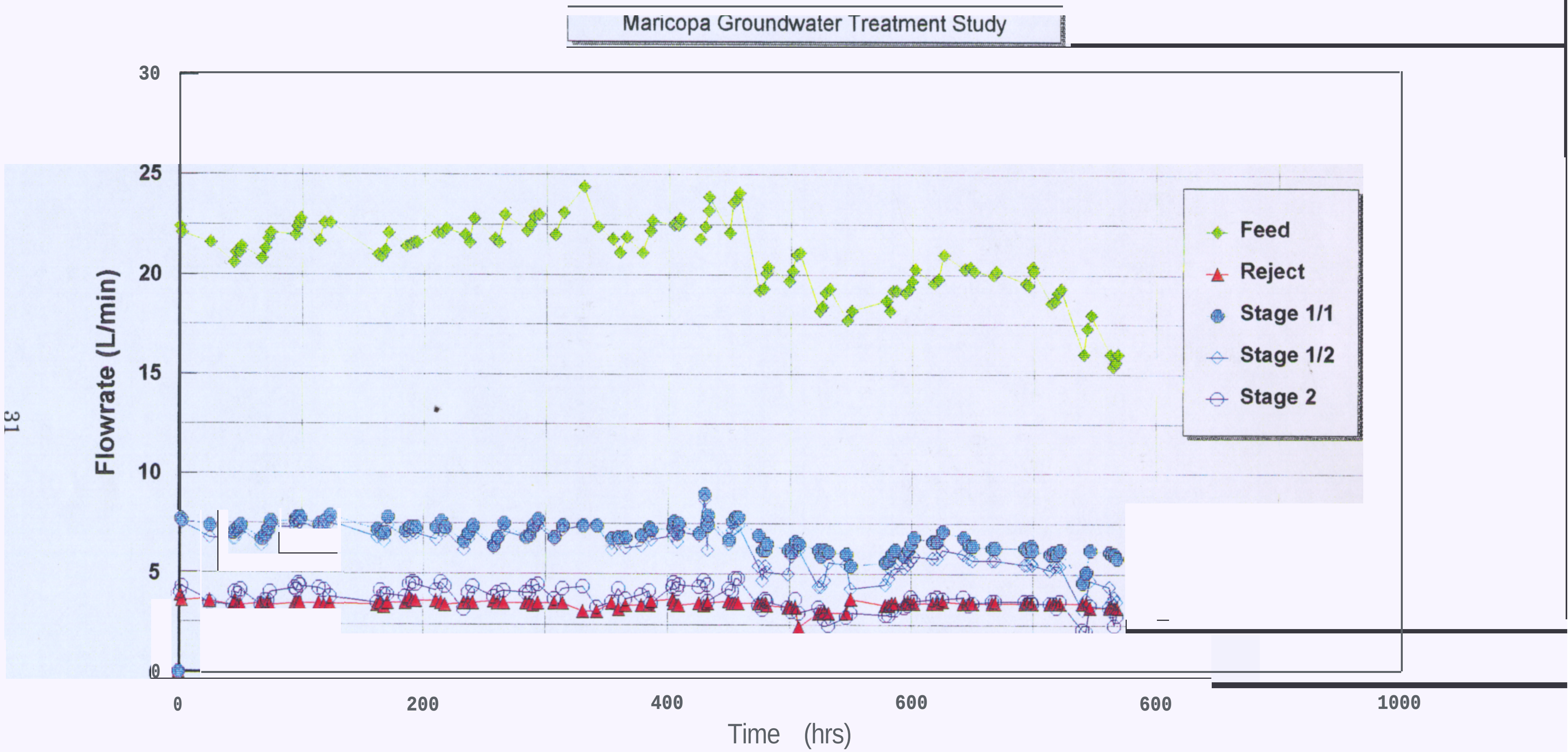


Figure 14. ▪ RO system flow rates

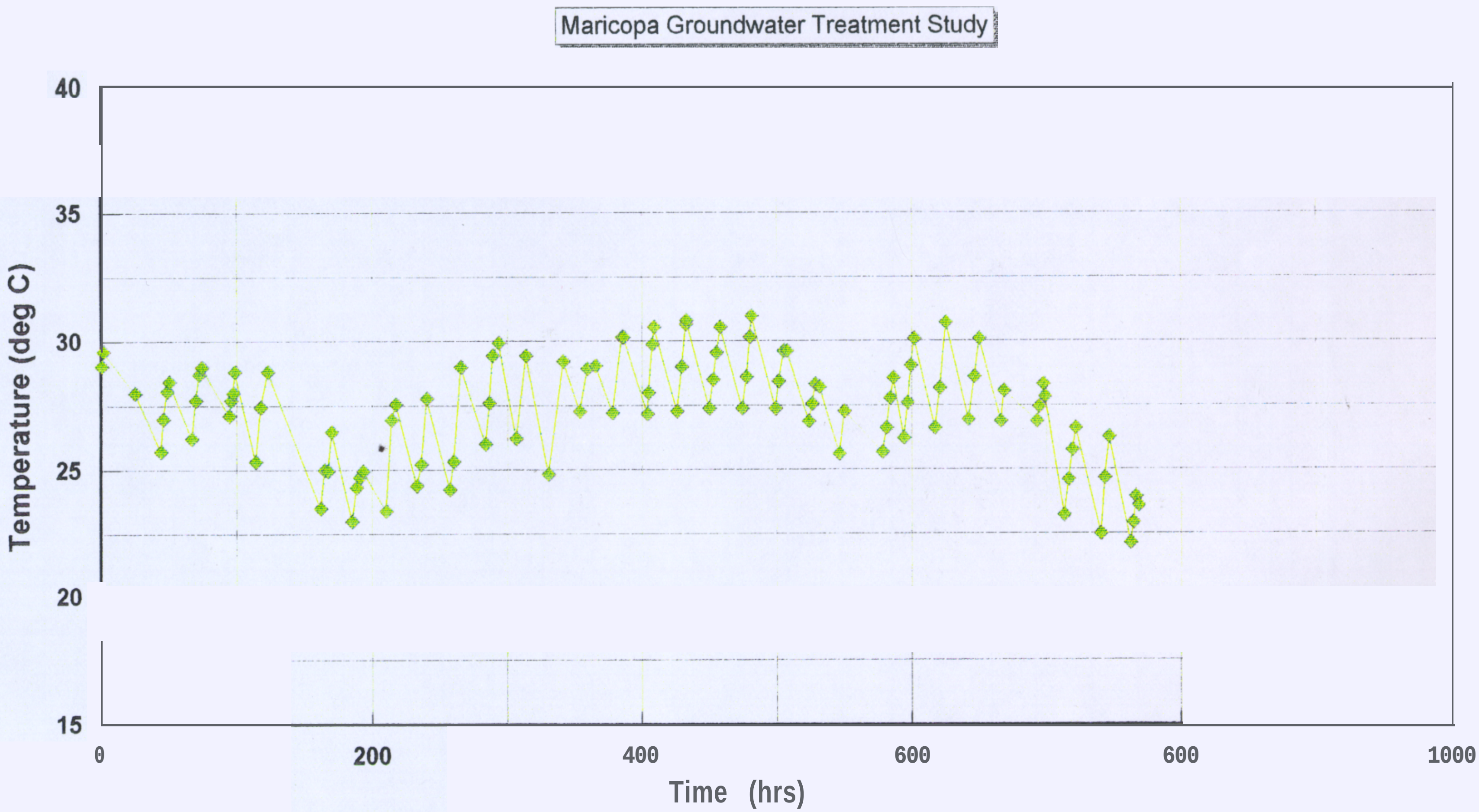


Figure 15. - RO feed temperature.

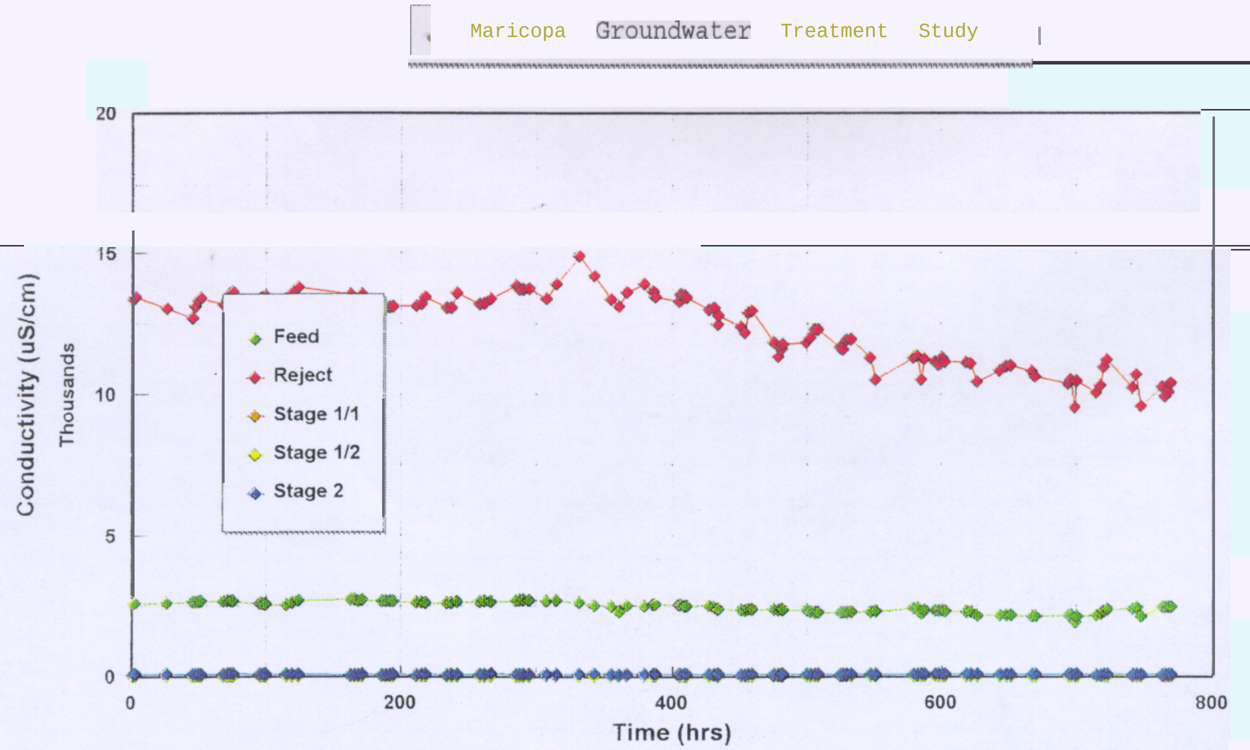


Figure 16. - RO system conductivities.

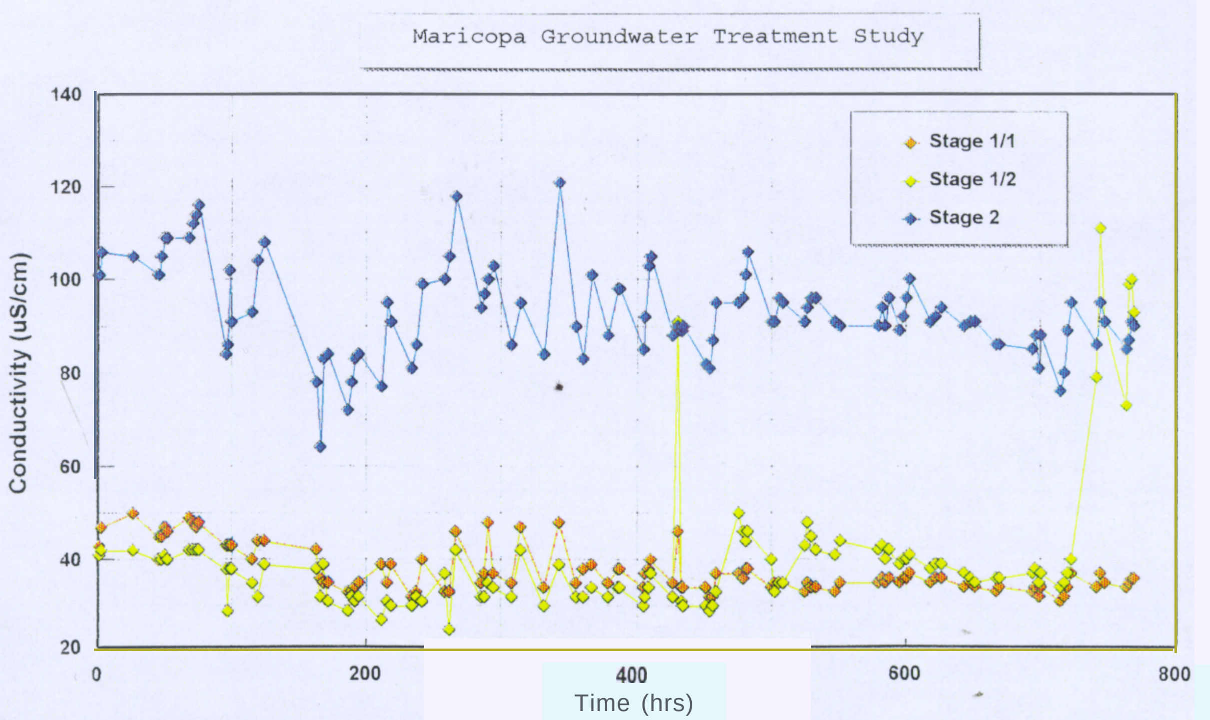


Figure 17. RO permeate conductivities.

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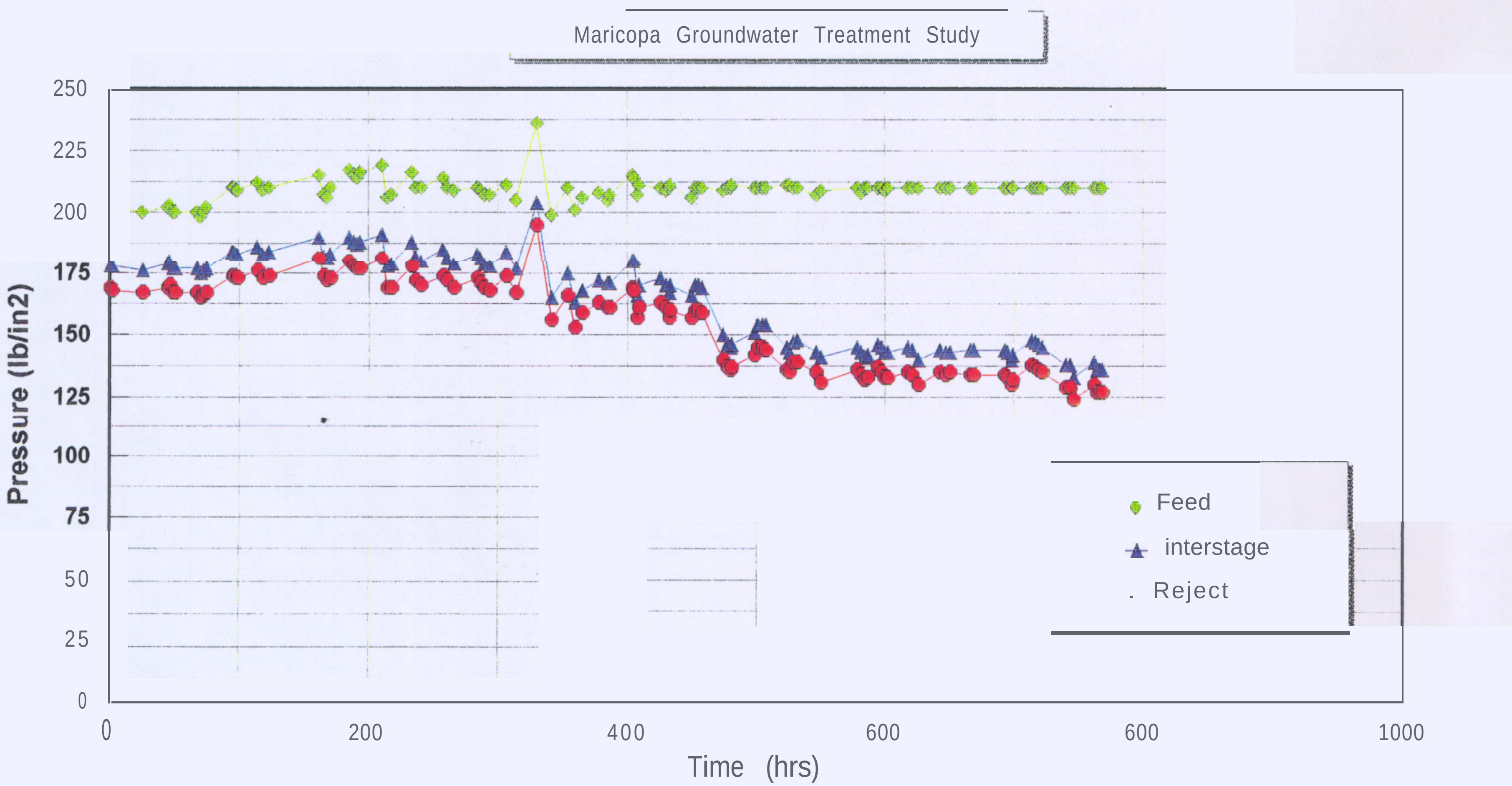

Figure 18. RO system pressures

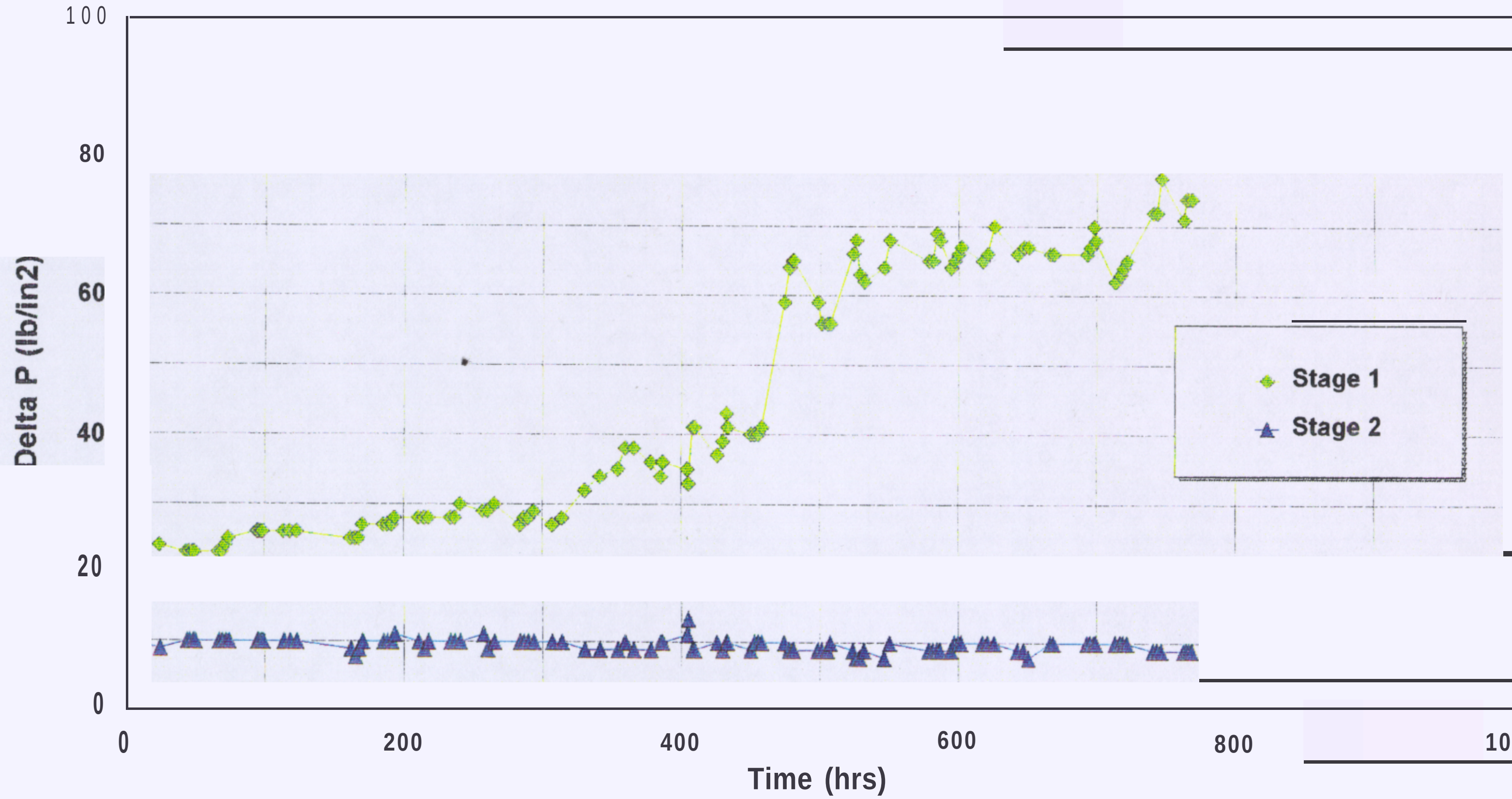

Figure 19. RO pressure drops by stage

Chemical analyses were performed at 4,364, and 720 hours into the test program on the four separate RO process streams of feed, interstage, permeate (combined), and reject, for the following constituents:

- Cations (Ca, Mg, Na, K)
- Anions (HCO,, Cl, SO,, NO,, F)
- Metals (Al, Ba, Sr, Fe, Mn, P)
- Silica

Results of these analyses are shown in appendix D.

Table 6 summarizes the amount of salt rejected, in percent removed, for each of the 3 analytical rounds for the RO pilot system. The values shown as ">" result from the permeate concentration falling below the detection limit. As shown, the average reduction in all ions including TDS, nitrates, and chlorides exceeds 90 percent.

Table 6. - RO salt rejections.

Ion	3.5hour	364-hour	720-hour	Average
Calcium	99.71	99.75	99.37	99.61
Magnesium	99.70	99.64	99.30	99.55
Sodium	96.07	93.33	91.88	93.76
Bicarbonate	92.50	90.63	96.76	93.29
Chloride	99.02	97.92	97.17	98.04
SO_4	>98.2	>97.8	>97.9	98.00
Nitrate as N	>94.1	91.67	88.76	91.50
TDS (Sum)	96.87	97.07	97.53	97.16
Average				96.36

In addition to the analyses indicated above, bacteriological tests of standard (heterotrophic) plate counts were run on well water and RO product and concentrate flows. Plate counts taken on well water at 364- and 720-hour sampling times were high at 6400 and 3600 cfu/mL (colony forming units per milliliter), respectively. These data are summarized in table 7.

Table 7. Bacterial counts during RO testing (cfu/mL).

Source	3.5-hour	364-hour	720-hour
Feed	380	6,400	3,600
Combined Product	110	21	320
Concentrate	320	No Data	19,000

At least one SDI measurement was performed on the RO feed water, downstream of the 5µ cartridge filter, each day of testing. SDI is a measure of fouling potential of the feed from colloidal-size materials. The maximum SDI specified by the manufacturer for the BW-30 reverse osmosis membrane is 5.0. Forty SDI tests were performed during the 6-week test period, with values ranging from 0.07 to 6.17. The average SDI was 2.02 with a standard deviation of 1.45.

6.1.3.2 Performance degradation. - Figures 20 and 21 present the average *NDP* (net driving pressure) and *NPF* (normalized permeate flow) for this test.

The *NPF* can be used to monitor the degree to which membranes are being fouled or if damage is occurring. It is commonly used to determine the time at which membranes should be chemically cleaned. A decrease in *NPF* with time is expected, and for the thin-film composite membranes used in this study, a 15- to 20-percent decline over a 3- to 5-year period might be anticipated. The roughly 11-percent drop in *NPF* experienced in this test program over a 720-hour test period is excessive by comparison.

Two possible causes were considered for this decline in system performance: (1) the deposition of silt and colloidal particles or metal precipitates such as iron oxide on the membrane surface and (2) biofouling. During the 6-week pilot test, the well water received the following pretreatment: stored in a 10,000 gallon storage tank; screened with a 40-µm (opening) basket strainer; additional settling; media clarification and filtration; and 0.1-µm cartridge filtration.

At times, the water from the 10,000-gallon storage tank was noticeably red, the same color of sediment found inside the 10,000-gallon storage tank. Throughout the pilot test, the intake skid's duplex basket strainer collected fine material that coated the strainer, and a marked decrease in flow was noted. It became evident that the material was smaller than 40 pm when tanks downstream from the strainer also were coated with the reddish material.

In addition, these process tanks, which were just upstream from the desalting equipment, collected an algal bloom. This algae was removed from the tanks, piping, and upstream treatment units at the midpoint of the pilot test period by shock chlorination, after which the tanks were covered with a solid plastic tarp. Evidence of algae passing onto the RO cartridge filter was found when this filter was changed daily and, on occasion, was found to be green in color.

6.1.3.3 Membrane autopsy and SEM (Scanning Electron Microscopy) analysis - Autopsies were performed on May 2, 1995, on 2 of the 18 RO elements, one of the lead elements in stage 1 (serial No. A2495040, refer to appendix E) and the mid-element in stage 2 (serial No. A2495047). Initial observations of the lead element membrane surface revealed substantial amounts of a brown-gray, fibrous solid material plastered against the inlet end. Second, the vexar (plastic feed-water/brine spacer located between membrane envelopes) showed signs of being pushed into the element between the layers of membrane leaf. Similar material was found in the middle element of the second stage, but to a lesser degree.

Two l-inch-square membrane samples were cut from the second leaf of each element for SEM (scanning electron microscopy) imaging to determine if a particular contaminant or biological cell structure could be identified to cause membrane plugging. Some of the samples were gold-coated to enhance the imaging resolution and detail. On both lead and second stage elements, cylindrical shaped silicon fragments and carbon-rich, irregularly shaped particles were found along with minor amounts of biological material. On the lead element, few to several irregularly shaped iron- and chromium-rich particles were found. No attempt was made to classify specific bacterial types/strains because, based on the quantities found, these strains were believed to play a minor role in the decreased performance of the membranes. Figure 22 shows two of the photographs that were found on these membranes. The complete memorandum of results of the SEM analysis is included in appendix F.

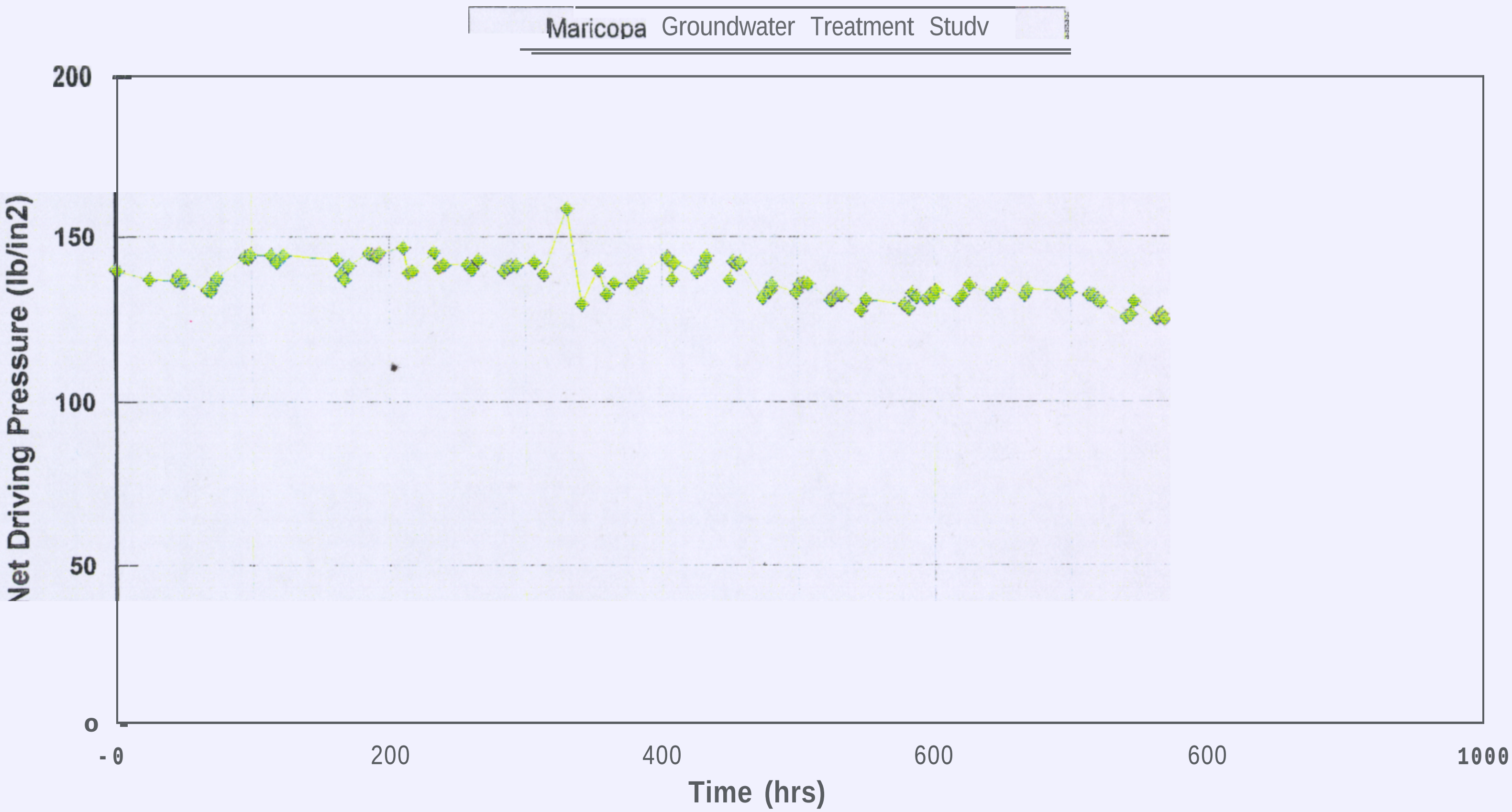

Figure 20. RO average net driving pressure.

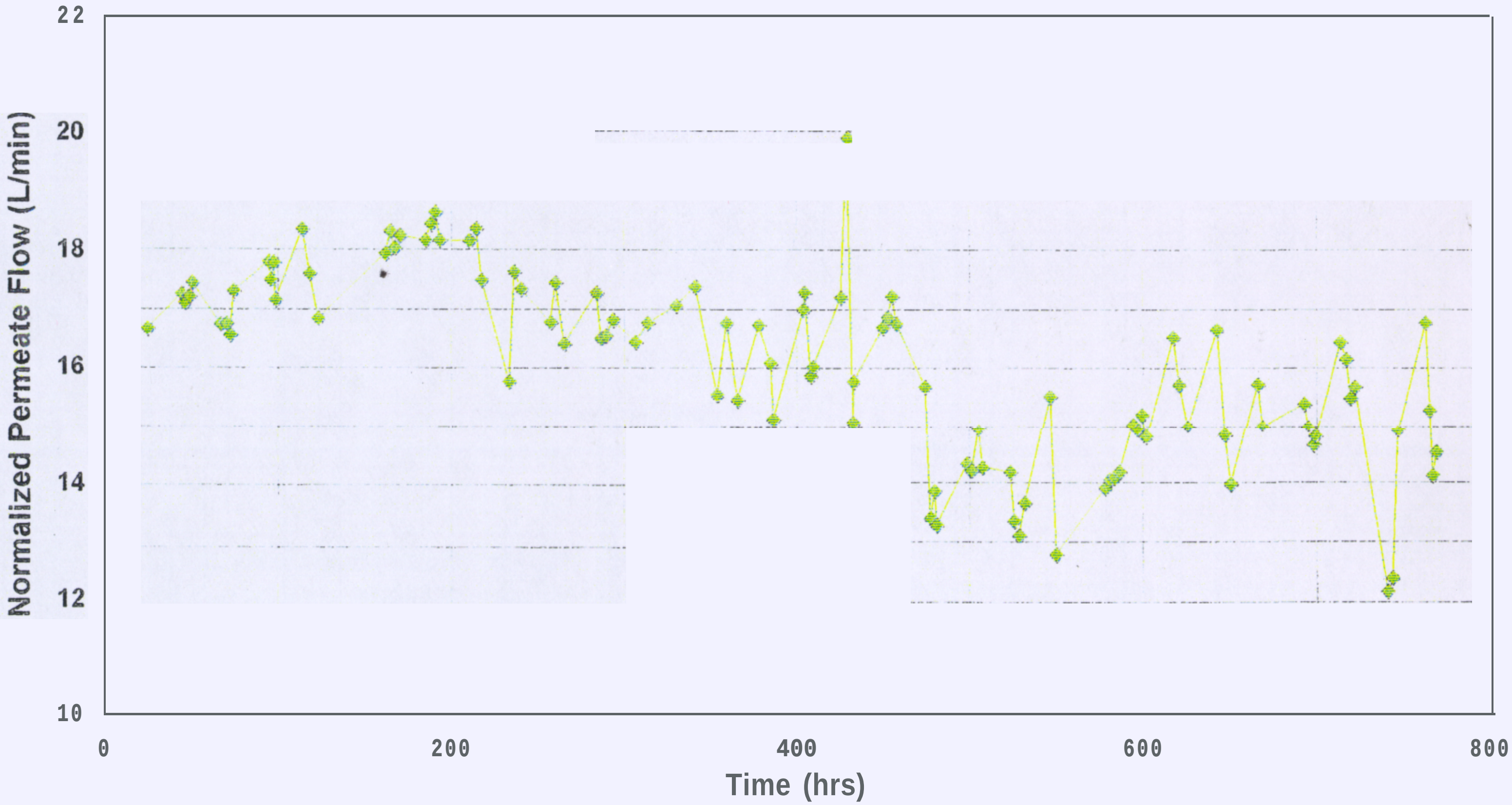

Figure 21. RO normalized permeate flow.

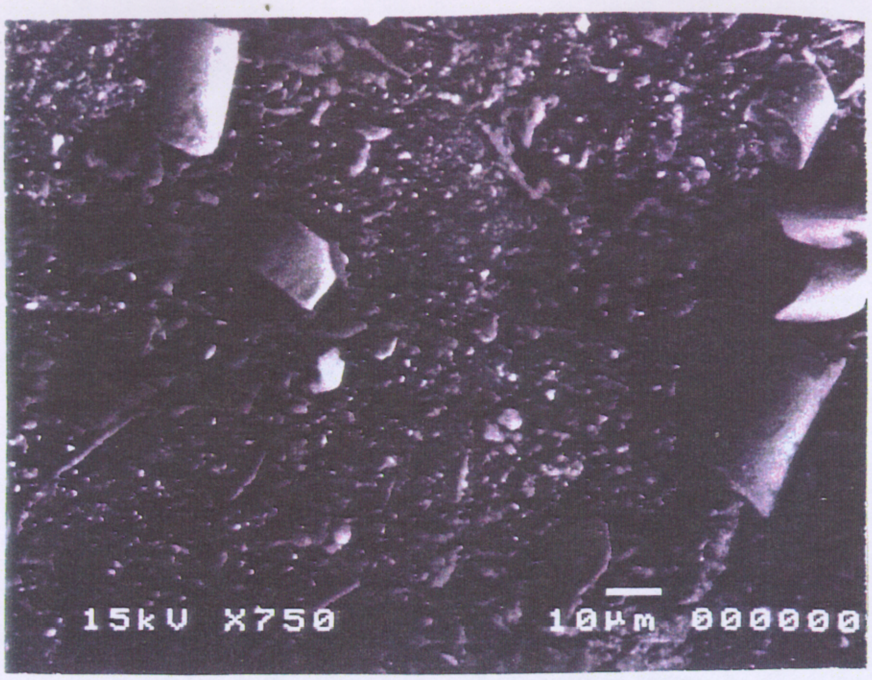

Figure 22a. - SEM photograph of numerous fragments of silicon-rich cylindrical particles found in both the first and second stage RO elements.

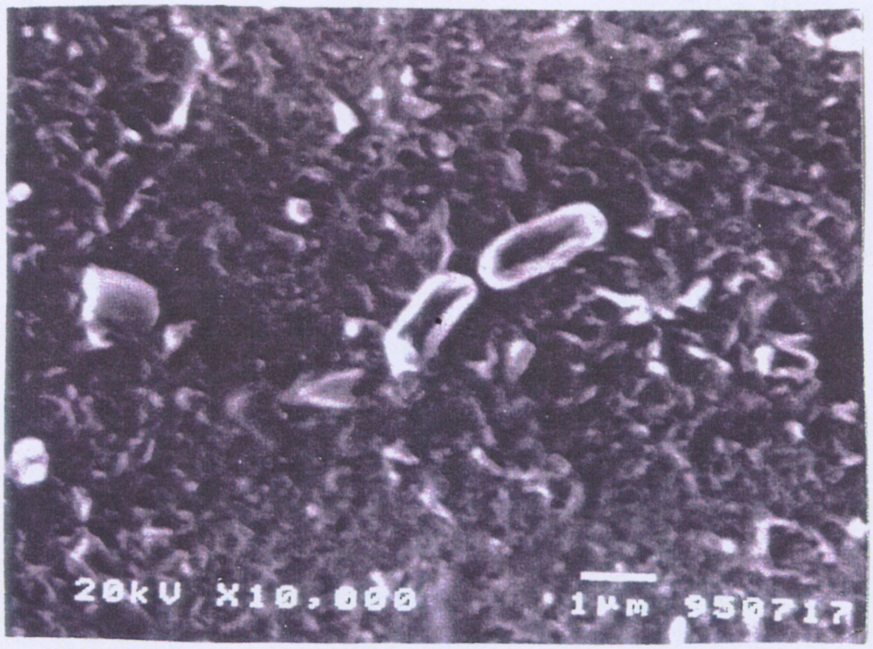

Figure 22b. - SEM photograph of bacteria present in the second stage element.

6.2 Conclusions

6.2.1 Electrodialysis - The following conclusions were reached as a result, of this test phase:

- Adequate pretreatment to remove turbidity and biological organisms from attacking the ED membranes is required for successful long-term ED performance. No such problems were encountered during this pilot test.

- The electrodialysis process, using Asahi nitrate (anion) specific membranes, achieved a 6%percent reduction in nitrates, a 68-percent reduction in chloride, and a 43-percent reduction in TDS. The nitrate specific membranes produced an effluent that met the nitrate MCL, but that level was still over the 500 mg/L secondary MCL for TDS.

- For every 100 gallons of well water treated, the ED process piloted was able to produce 80 gallons of water (80-percent recovery) of the quality shown in table 5.

6.2.2 **Reverse Osmosis -** The following conclusions were reached as a result of this test phase:

- RO effectively reduced the concentrations of all contaminants of concern to below MCLs. The average TDS rejection for the 720-hour test was 97.2 percent. Specific ions of interest were removed as follows.

Table 8. - RO piloting results on contaminants of concern.

Constituent	Percent Rejection	Permeate Average Concentration (mg/L)
Nitrates	91.5	0.8
Chloride	98.0	11.1
TDS	97.2	41.7

- Average TDS (summation of ions [appendix D]) for feed and permeate were 1467 and 42 mg/L, respectively. By blending NF permeate and filtered well water at a ratio of about 1:0.47, a net overall recovery of 87 percent at 500 mg/L TDS could be achieved.

- *NPF* (normalized permeate flow) dropped by about 11 percent during the 6 weeks of testing as shown on figure 21. During this same period, while the feed pressure was held constant at 210 lb/in^2, the pressure of the interstage decreased from about 181 to 144 lb/in^2 (fig. 18) with similar drop in reject pressure noted. The membrane autopsy, SEM analysis, and high heterotrophic plate counts indicate scaling and biofouling occurred.

- Although historic bacteria counts were low in the well water, the decision not to disinfect prior to the RO unit resulted in the deposition of biological matter onto the cartridge filter. Biofouling may have contributed to decreased membrane performance. Chloramine, or chlorination with dechlorination, would provide more effective control; however, feed water with high microbial populations and subsequent residual cell components of microorganisms killed during disinfection would have to be removed.

- Colloids from either well water or the lO,OOO-gallon tank bottom may have contributed to the decline of membrane performance through membrane fouling. A pretreatment system, such as a series of bag or cartridge filters, can be used to eliminate this water quality condition.

7. FULL SCALE TREATMENT

7.1 General

The cities of Avondale and Chandler and the Gila River Indian community have many choices and decisions to make regarding the construction of full scale water treatment plants. Among these choices are plant location and size, level of treatment, and the method of disposing of any residuals generated in the treatment process.

Each of the cooperating partners has indicated a need to provide wellhead treatment at wells that produce a volume of between 1 to 2 Mgal/d. This report presents treatment plant options at 2-Mgal/d capacity and, in section 8, presents planning level construction cost estimates for consideration in final design.

As previously discussed, well s5 historically contained nitrate and turbidity which exceeded Primary SDWA limits, and chloride and TDS which exceeded Secondary SDWA limits. Based on this information, Reclamation was asked to perform pilot testing at well s5 using processes that would remove or reduce these contaminants to acceptable levels. The full scale treatment alternatives presented in this report were planned to cover electrodialysis and reverse osmosis, the two processes piloted. However, since the start of this study, developments in thin film composite membranes have occurred so that now nanofiltration membranes are available which are selective to remove multivalent ions and also achieve high removals of nitrate. A brief review of the differences between RO and NF follows.

7.2 Comparison Between Reverse Osmosis and Nanofiltration

A review of operating, maintenance, and capital costs between RO membranes and the new thin film composite nanofiltration membranes was performed and is presented on figure 23. As shown, nanofiltration and electrodialysis are cheaper to operate than RO and are preferred when contaminant concentration levels do not warrant the high removals of RO.

Reverse osmosis and nanofiltration are membrane separation processes which use high pressure to separate the solids or ions in the water. The major difference between nanofiltration and reverse osmosis is the size of the openings in the membranes and the ability of each to selectively reject various dissolved solids. Membrane openings in reverse osmosis range between 1 and 15 angstroms, whereas in nanofiltration they range between 8 and 80 angstroms. Some dissolved ions may pass through membranes but the net ionic charge on both sides of the membrane must balance. An equivalent charge of anions and cations must pass at the same time. This process is more likely to occur with nanofiltration membranes because of the larger pores than RO membranes. Divalent cations such as calcium, sodium, magnesium, and manganese must bring two monovalent anions with them to pass through a nanofiltration membrane and therefore are less likely to pass through.

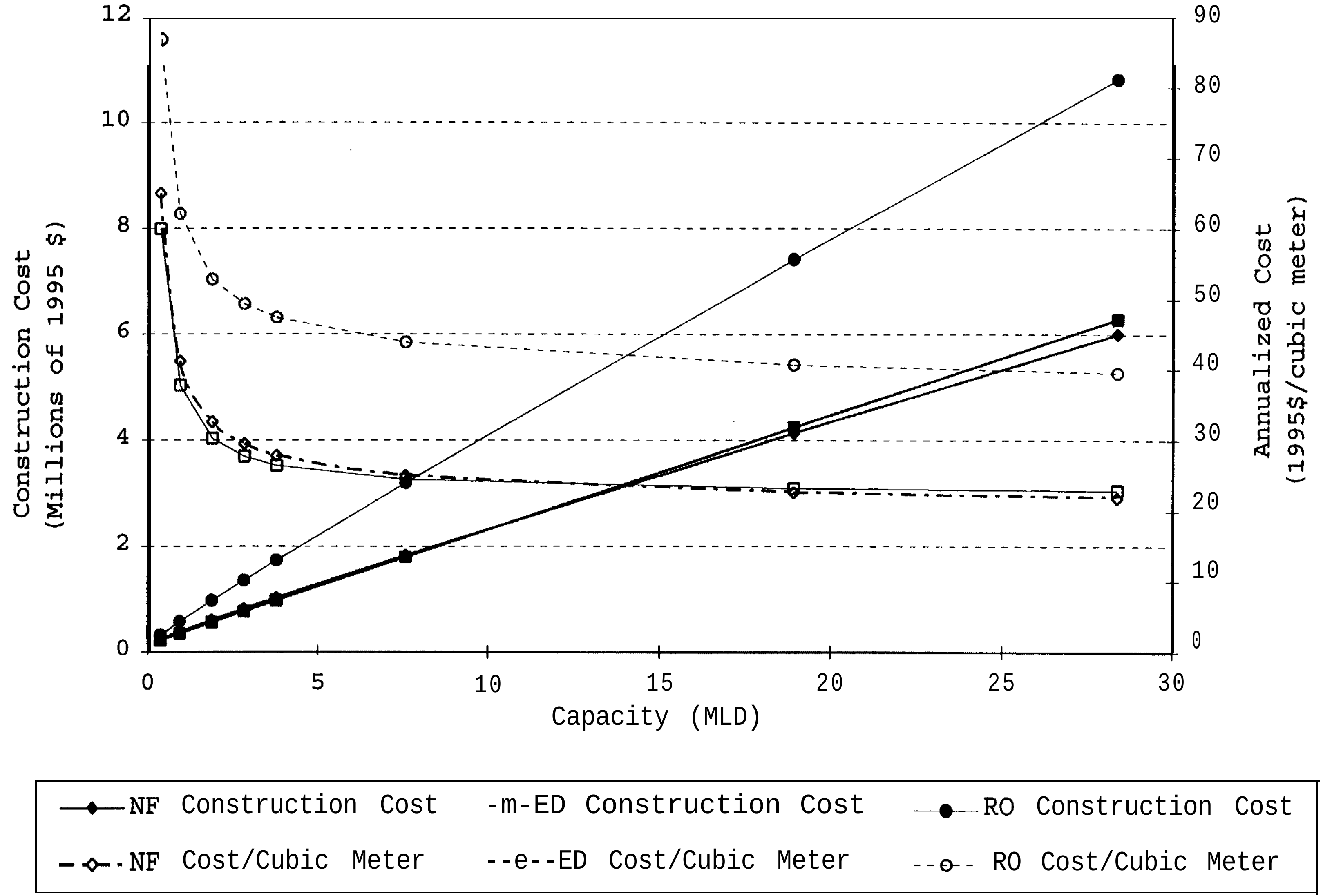

Figure 23. • Cost comparison: NF, RO, and ED.

A significant operational difference between these two processes is that RO operates at 200 to 400 lb/in^2 for brackish water desalination, whereas nanofiltration runs at pressures usually below 100 lb/in^2. Actual operating pressures are proportional to the amount of dissolved solids or salts in the flow stream.

Nanofiltration membranes offer the following advantages over reverse osmosis membranes:

- Reduced operating pressures, which subsequently reduce operating costs
- Higher recovered product water

Nanofiltration membranes are generally used to treat low TDS waters where the reduction of hardness ions is desirable; hence, they are often referred to as softening membranes. The rejection of divalent ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}) and organics having a molecular weight above 200 is very high, typically above 95 percent. Monovalent ions (Na^+, Cl^-, HCO_3^-) are rejected at typically 60 to 70 percent. Typical applications for nanofiltration include the removal of TDS, hardness, color, THM precursors, TOC, and radium.

Based on the above considerations, the full-scale treatment plant descriptions and costs are for electrodialysis and nanofiltration. Each of these membrane treatment processes requires adequate pretreatment to protect the membranes from scaling and biofouling. These pretreatment steps, for both options, include predisinfection for bacterial control and filtration for suspended solids reductions. Included in the estimate for each desalting option is the addition of an antiscalant and acid to adjust the chemical make-up of the feed to be compatible with the membranes and a cartridge filter which removes any suspended material greater than 0.5μm, that may have passed through the dual media filter.

7.3 Electrodialysis

A result of electrodialysis pilot testing is that it successfully removes nitrate, but only partially removes the TDS. This treatment process may not always produce water which meets all MCLs. Additionally, ED produces more waste flow than nanofiltration, though the waste stream from electrodialysis contains ions that are less concentrated than the waste stream from nanofiltration. Therefore, the ED waste stream can be easier to dispose of from a regulatory standpoint. Electrodialysis is recommended in those instances where nitrates are a problem and the TDS is below 1100 mg/L.

Advantages of an electrodialysis system are:

- ED does not require pressurization. Distribution line pumps can be used to pump water through the system. This capability also means that ED can be a much quieter process than NF and will be more acceptable in a residential area.

- Selective ED does not concentrate sulfate in the waste stream, so adding antiscalants is unnecessary, and scaling of the membranes and waste disposal system will decrease.

- ED systems have a longer life expectancy than NF systems because the spiral wound configuration of NF is difficult to clean and the fouling layers are formed under pressure and are difficult to dislodge. ED systems are not pressurized and the fouling layers are adsorbed to the membrane through the influence of the electrical potential.

When the electrical current is turned off, foulants can be cleaned off quite easily with a low pH rinse. The units can even be taken apart and scrubbed if necessary.

Disadvantages of an electrodialysis system are:

- They produce more of a waste stream than NF.

- Systems like the one used in the pilot study are produced in Japan. Acquisition of equipment, parts, or supplies for these systems will take longer than locally available supplies. ED is manufactured in Canada and Ionics is a company in the United States that produces EDR systems.

- A single stage ED system can only remove 50 percent of the dissolved solids. If a source water has more than 1000 mg/L TDS, ED product would need to be blended with higher quality water from a different source or run through a second stage to meet drinking water standards.

A full-scale electrodialysis ground water treatment plant, sized to produce 2.0 Mgal/d of product water, would require a raw water influent flow rate of 2.5 MgaL/d and would produce a brine flow of 0.5 Mgal/d. The entire treatment process is likely to consist of the following unit processes as shown on figure 24: raw water pumping, predisinfection using either chloramine or chlorination and dechlorination, filtration, electrodialysis, post-chlorination with adequate detention time, and finished water pumping. The brine produced from this process would contain the ions as shown in table 5. Brine production and disposal is further discussed in section 7.5.

The following are the primary ED design factors which must be considered for a full-scale operation (Mason and Kirkham, 1959):

- Composition of the feed water-Only ionized substances can be separated with ED. Uncharged solutes are generally unaffected by the electrical current. The feed water must conduct the current through the stack. If the concentration of ions is very low, as with RO permeate, the process will require much more power to remove more ions than if the conductivity is higher. Current is given by Ohm's Law:

  $$I = E/R$$

  where I = current, E = voltage, and R = resistance

  If the resistance of the feed water doubles (conductivity is cut in half), the voltage will have to be doubled to maintain the same current.

- Membrane selectivity-The selectivity of the membrane, or how exclusively it transfers ions of one charge, depends on the concentration of ions embedded in its framework and the thickness of the membrane. Other factors that affect selectivity are related to the concentration and type of salts in the diluting and concentrating streams. High salt concentration and low temperatures decrease membrane selectivity because of the higher osmotic pressure gradient with high concentration and the lower ionic mobilities at low temperatures.

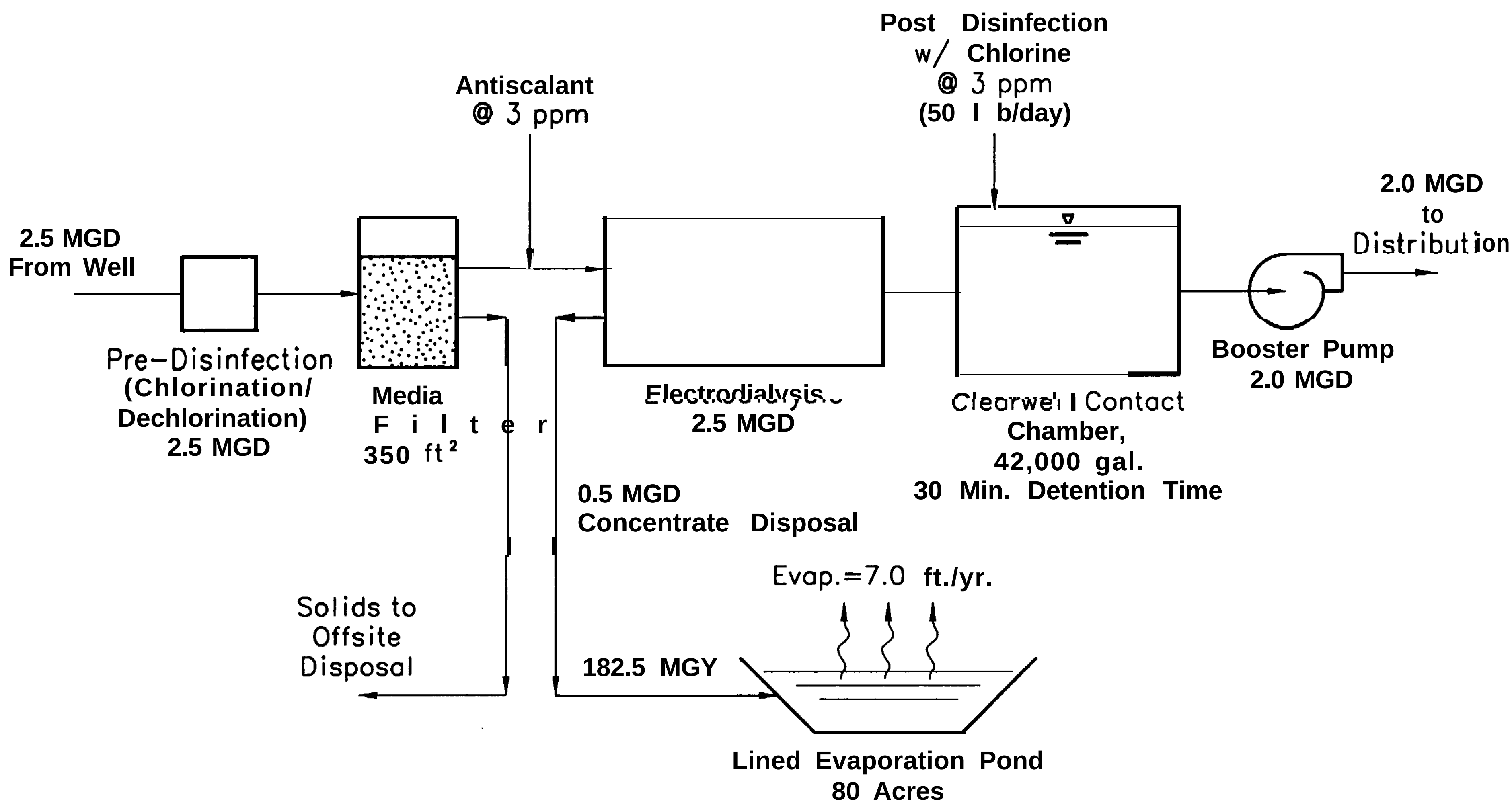

Figure 24. • Electrodialysis water treatment system-Maricopa Ground Water Treatment Study-2.0 Mgal/d.

- Faraday's Law - Faraday's Law suggests that the passage of 96,500 amperes of electric current for 1 second will transfer one gram equivalent of salt. This quantity, 96,500 ampere-seconds, is known as a Faraday. The gram equivalent of an ion is its MW (molecular weight) in grams, divided by its charge, and is expressed as N (normality), or gram equivalents per liter. A gram equivalent of sodium is 23 grams (MW 23/1 charge), and a gram equivalent of calcium is 20 grams (MW 40/2 charge). If the composition of the water is not known, the gram equivalence can be estimated assuming the dissolved solids are entirely sodium chloride. For instance, if the TDS is 5000 mg/L, then the normality of the solution is 0.086 N (5000 mg/L ÷ 58,400 mg per equivalent). The current required to remove a given number of gram equivalents is calculated with Faraday's Law as follows:

$$I = \frac{F * F_d * \Delta N}{e * N}$$

where:

I	=	direct electric current in amperes
F	=	Faraday's constant = 96,500 ampere seconds/ equivalent
ΔN	=	change in normality of demineralized stream between the inlet and outlet of the membrane stack
F_d	=	flow rate of the demineralized stream through the stack (L/s)
e	=	current efficiency
N	=	number of cell pairs
v	=	current efficiency
N	=	number of cell pairs

The voltage requirement is calculated from Ohm's Law, which states that "the potential (E) of an electrical system is equal to the product of current (I) and the system resistance (R)." E is expressed in volts, I in amperes, and R in ohms. The resistance of the membrane is made up of four components: the resistance of the cation membrane, the resistance of the anion membrane, the resistance of the concentrate stream, and the resistance of the demineralized stream. Overall resistance decreases with higher temperature and solution concentration and with increasing percentages of sodium or chloride ions in the solution.

7.3.1 EDR (Electrodialysis Reversal) - Because many recently built plants are using electrodialysis reversal and this report recommends ED in certain applications, EDR should also be considered because it improves the longevity of ED membranes. In 1975, the ED process was advanced by the development of the reversal feature. EDR is an automatic operating feature that regularly reverses the electrical potential. This feature assists in washing out scale that may have adhered to the membranes during operation, thereby keeping them cleaner for longer periods (Morin, 1994). The concentrate stream is then converted to the feed stream, and the feed stream becomes the concentrate stream. This process requires more plumbing and electrical systems than ED. Also, a period of off-specification water production at each flow reversal occurs that must be directed to waste. Reversing the flow increases the life of the electrodes and helps clean the membranes. When the membranes are operated in the same direction all the time, precipitants (scale and foulants) can build up on the concentrate side walls.

7.4 Nanofiltration

A proposed flow scheme for nanofiltration is shown on figure 25. This scheme is based on an overall rejection of salts of 88.6 percent, a value that was derived from a previous pilot study using nanofiltration membranes and applying the rejection rates of salts found to those salts that are present at well s5. The nanofiltration option includes blending with partially treated ground water so that the volume of water treated by nanofiltration is reduced.

In nanofiltration, like RO, pretreatment is critical to protect the membranes from either plugging from scale deposits and/or turbidity, or fouling from microbiological attack. For the ground water found in well s5, pretreatment for nanofiltration is recommended to consist of disinfection to destroy bacteria, filtration to remove the dead microbiological wastes, antiscalant, post-chlorination with adequate detention time, and finished water pumping.

Using the feed-water concentrations of parameters measured during the 6-week RO pilot test, the likely ion concentrations of a nanofiltration product and reject water are shown in table 9 along with expected rejection rates. Blending product water with water that is available either from other wells or already in the distribution system will provide water that is both safe and palatable. The concentrate from the nanofiltration process can also be mixed with locally available water to lower the ion concentrations, thereby lending itself to the disposal options described in the following section.

Table 9. - Typical NF salt rejections and expected water quality.

Ion	Feed	Product	Reject	Percent Reduction
Calcium	186.67	3.73	918.40	98.40
Magnesium	79.00	1.58	388.68	98.50
Sodium	153.33	3.07	754.40	83.00
Bicarbonate	160.00	3.20	787.20	89.00
Chloride	556.67	11.13	2738.80	78.30
Nitrate as N	9.01	0.18	44.31	78.00
Sulfate	250.00	5.00	1230.00	97.40
TDS (Sum)	1800.00	36.00	8856.00	88.60

Notes:
1. Feed concentration is the average concentration found. during RO testing.
2. Product and reject concentrations are based on an 80-percent product water recovery, no blending.
3. Product concentrations will be higher with blending.
4. Reject concentrations will be lower with blending.
5. Percent rejections are based on test results from Filmtec NF-90-2540 membranes.

Advantages of a nanofiltration system are:

- NF systems are produced by several companies in the United States, so parts, consulting assistance, and training for the operators would be readily available.

- NF membranes, such as Filmtec NF-90 series membranes, can remove 90 percent of TDS, so it should be adequate for sites with up to 5000 mg/L TDS (Filmtec).

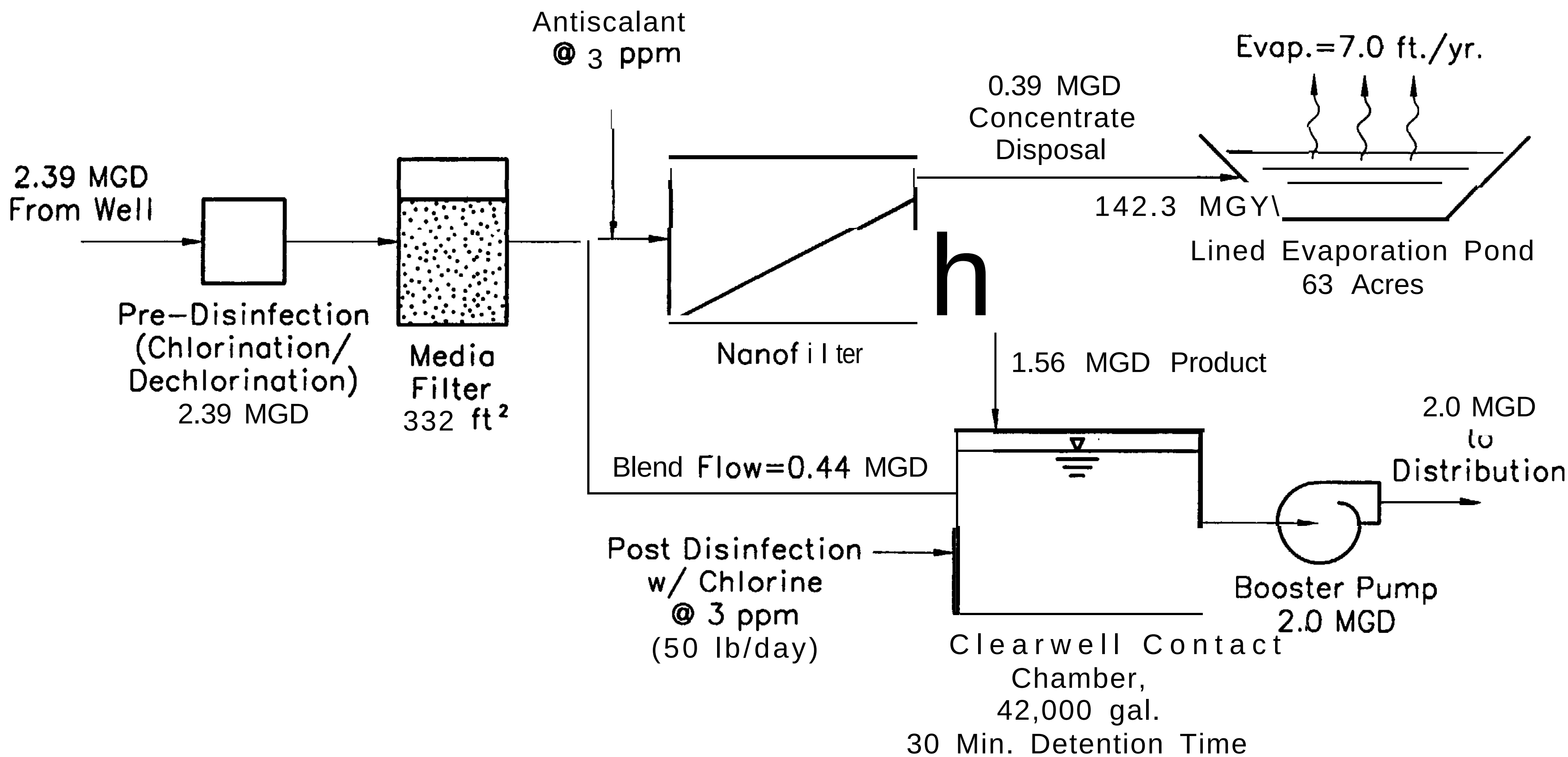

Figure 25. • Nanofiltration water treatment system-Maricopa Ground Water Treatment Study-2.0 Mgal/d.

Disadvantages of a nanofiltration system are:

- NF systems need trained operators. Changes in the feed-water characteristics can have adverse affects on the system. Cartridge filters must be replaced promptly when needed. The membranes must be cleaned when performance begins to decline. If maintenance is put off, or the system is not monitored closely, the membranes can be irreversibly damaged within a very short time.

7.5 Brine Production and Disposal Options

7.5.1 Brine production - Brine, or concentrate, is the waste stream resulting from either ED or the NF process. This waste stream contains the concentrated impurities (dissolved salts) which, for well s5, are estimated in table 5 for ED and in table 9 for the NF process. At these concentrations, the waste is characterized as having a high salt content. Although not hazardous, this high salt content may be toxic to certain microbiological organisms in a wastewater treatment system.

At a rate of 2.0 Mgal/d, about 0.5 Mgal/d of brine will be produced from the electrodialysis process, and about 0.39 Mgal/d can be expected from the nanofiltration process.

7.5.2 Brine disposal - The most common means of concentrate disposal include

- Surface water discharge
- Discharge to sewers
- Land application (i.e., spray irrigation)
- Injection wells
- Evaporation ponds (Mickley et al., 1993)

In addition, much work has been done lately regarding the use of wetlands as a treatment technique prior to final disposal. These choices are all restricted from a regulatory standpoint. Several brine concentrators are available which can reduce the volume of the waste stream further. These concentrators, because of their high cost, are recommended for use in areas where no other option for brine disposal exists.

Discharge to a nearby surface water, if allowed with minimal treatment, would be the least costly brine disposal option. Surface water discharges are regulated by the Clean Water Act and, as such, would require permit restrictions. It is highly unlikely that the ADEQ (Arizona Department of Environmental Quality), under the National Pollutant Discharge Elimination System program, would allow a high saline discharge to any of the surface waters that run toward the already salt-rich Colorado River. Cost-prohibitive treatment requirements or blending with sufficient volumes of another water source to reduce the concentrations to acceptable levels is worth considering, but will likely make this option infeasible.

Discharging concentrate to a local wastewater treatment plant is the easiest means of disposal. If this option exists for the study participants at little or no cost, it is highly recommended, based on economics and impacts to lands when other options are considered.

Ground water injection is possible; however, an aquifer protection permit is required. This option is also likely to be cost prohibitive because of extremely low discharge limits. In addition, one must prove that injection of the brine is not adversely impacting sub-surface aquifers. This proof can be obtained with geohydraulic modeling of the aquifer when the aquifer characteristics are known and understood.

The three remaining options for brine disposal are evaporation, spray irrigation, and the creation of wetlands. The ADEQ must approve such a plan through their regulatory submittal process. In some cases, the permittee must show that local ground water will not be impacted by water that may percolate through the soil.

The final selection of the type of disposal depends on many factors. Combinations of these options are also possible and may satisfy several goals of the Gila River Indian Community, or the cities of Avondale or Chandler. The actual alignment and elevations between the sewer or disposal site and the full scale water treatment plant will determine whether a gravity pipeline or pumps with a force main are needed.

'7.5.2.1 Evaporation - Evaporation ponds, like wetlands, can create a natural environment which can attract waterfowl and brine tolerant plants. Although not as attractive as a wetland area, a series of evaporation ponds in a desert environment could be a welcome sight to the public if properly planned. For electrodialysis, an evaporative drying pond of about 80 surface acres would evaporate the 0.5 Mgal/d of brine generated, based on an evaporation rate of 7 feet per year. For nanofiltration, an evaporative drying pond of about 63 surface acres would evaporate the 0.39 Mgal/d of brine, based on the same evaporation rate. The evaporation rate, 7.0 feet per year, was derived after reviewing 56 years of historical precipitation rates for the Phoenix area (7.66 in/yr) and 21 years of historical evaporation data from Arizona University's experiment station in Mesa (92.71 in/yr).

The pond area can be separated into several ponds to suit the desired goals and objectives of this disposal option. The liner for the ponds is likely to be PVC (polyvinylchloride) or HDPE (high-density polyethylene). A force main system from the plant to the pond, a storage tank at the plant sized for 5 days production, and a pump station operating at 5 times the daily reject flow rate are essential components of this system.

7.5.2.2 Spray Irrigation - In the arid southwest, it is critically important to place a high priority on both water conservation and reuse of wastewater to lower water consumption. For this reason, the use of brine from either the electrodialysis or nanofiltration process, to irrigate salt-tolerant plants, is an important consideration for brine disposal. This option affords the benefits of a reduction in water demands and the creation of green, landscaped areas around selected land uses.

Landscaped areas such as open space, greenbelts, golf courses, highway medians, and resort complexes that use appropriate salt-tolerant grasses and foliage can be irrigated at an application rate of about 0.3 inches per day. At this rate, the acreage required to dispose of the brine from the electrodialysis and nanofiltration processes is 62 and 50 acres, respectively. Irrigation systems typically require storage in the form of a tank or lined holding pond, a pump station sized for twice the average daily flow, (for a 12-hour per day operation), and a distribution network of pressure piping to the irrigation sites.

7.5.2.3 Wetlands - A wetlands in a desert environment is aesthetically pleasing. A wetlands environment supports several salt-tolerant plants and will attract various species of waterfowl and animals. In Hemet, California, alkali bulrush and spikerush plants have survived and flourished in brine from an RO demonstration plant.

More than 800 acres of palustrine wetlands are mapped along the Gila River channel, within the GRIC, south from the confluence with the Salt River. These scrub/shrub wetlands were described by Rae as overgrown with pure stands of exotic winter-deciduous salt-cedars (*Tamarix ramoissima*) (Mock and Walker, 1993).

A 2-Mgal/d product water treatment facility requires a wetland area of 3.1 acres to dispose of the 0.5 Mgal/d of brine produced from electrodialysis, and a 2.4-acre wetland is required to dispose of the 0.39 Mgal/d of brine produced from the nanofiltration. This area is based on an application rate of 6 in/d, which is the application rate in use at Hemet California, a site similar in climate to the Phoenix area. Other main features of a wetland brine disposal system would be a storage tank or lined holding pond, a pump station to transfer the brine from the plant to the wetland, and a force main to convey the brine from the treatment plant to the wetland.

8. TREATMENT COSTS

8.1 General

Cost estimates for constructing a 2-Mgal/d water treatment plant and corresponding yearly operations and maintenance costs are presented for the electrodialysis and nanofiltration processes. The choice of which process to use and whether or not full compliance is achieved with both Primary and Secondary SDWA standards depends on specific well-water quality.

Capital cost estimates are based on a combination of direct quotes from manufacturers plus allowances for installation or Reclamation's cost estimation program which uses cost curves prepared by the EPA. This program uses the raw water quality from the site and current indices from both the Bureau of Labor Statistics and the ***Engineering News Record,*** to calculate both construction and O&M cost estimates.

Capital costs are for individual treatment units, including all equipment, but do not include costs for land ownership, rights of way, special sitework, easements, or yard and offsite piping. Also not included are costs for an intake structure, grit removal equipment, or buildings for chemical feed and storage, administration, or a laboratory. Legal administrative and engineering costs for permitting, water quality monitoring, testing, and modeling are not included, nor are general contractor overhead and profit, fees for engineering, legal, and fiscal services, and interest during construction. For these reasons, the cost estimates found herein are valuable for a comparison of the alternatives presented and are not final construction estimates.

The basis for Reclamation's cost estimation program is the Environmental Protection Agency's Research and Development manual numbered EPA-600/2-79-162a and titled, "Estimating Water Treatment Costs" (Gumerman et al., 1979). Each unit process is defined in terms of the following eight subcategories: excavation and sitework, manufactured equipment, concrete, steel, labor, pipe and valves, electrical equipment and instrumentation, and housing. These subcategories are linked to various cost indices and, for this report, have been updated to November 1995. Each unit's estimate includes a standby or spare unit plus a 15-percent allowance for miscellaneous and contingency items.

Operations and maintenance costs are updated for electrical energy costs, maintenance materials, chemicals, and labor. Chemical costs are estimated from recent contacts with chemical supply companies or from a chemical periodical. Labor has been estimated at $25.00 per hour and the cost of electricity is $0.07/kWh.

This report recommends that consideration be given to centralized treatment to reduce the number of treatment plants and associated costs. If this approach is followed, a new water treatment plant may be larger in size than the 2-Mgal/d plant size estimated and the cost per daily gallon of product water will be lower than that presented because of economies of scale.

Costs for the water treatment plant, without brine disposal, are identified separately because of the higher level of uncertainty associated with brine disposal options. Water treatment plant costs common to both ED and NF are listed below. Sections 8.3 and 8.4 list plant components unique to ED and NF, respectively.

Raw water pumping is included because the pressure at the well may be insufficient to pump the water to a centralized plant. Prechlorination, using chlorine gas fed at 3 mg/L, is added to destroy microorganisms found in the raw water. Post-chlorination, also fed at 3 mg/L, is added to provide final disinfection and to meet regulatory requirements of a chlorine residual in the distribution system. A concrete clearwell, sized at 42,000 gallons, provides 30 minutes detention for post-chlorination and also is a wetwell for finished water pumping. This pumping is sized at 2 Mgal/d, and, like the raw water pumping, includes some valving, instrumentation, piping, and electrical work.

8.2 Brine Disposal

The range of costs associated with the disposal of brine from either the ED or the NF water treatment process is significant. If, as this report recommends, each cooperating partner can enter into an agreement with a locally owned treatment works for wastewater to accept the waste stream at a minimal charge, then the costs for water treatment and brine disposal are attractive. If such an agreement can not be reached, then the costs for disposing of the waste stream may approximate those identified in table 10 for an evaporation pond system or a spray irrigation system.

Evaporation will encompass 90 and 70 acres of total land area for the ED and NF water treatment processes, respectively, based on an evaporation rate of 7 feet per year. Spray irrigation encompass 335 and 308 acres of total land area for the ED and NF water treatment processes, respectively, based on applying irrigation water at 0.3 in/d (9 ft/yr).

An evaporation pond system, and to a greater degree, a spray irrigation system, are land intensive and compound the uncertainty of non-sewer disposal options because of the cost of land. Table 10 presents, for both ED and NF concentrate waste streams, (0.5 Mgal/d and 0.39 Mgal/d, respectively) brine disposal costs for these options, with and without land costs. Figure 26 illustrates these options in bar chart form. Also shown on figure 26 is a scenario which is based on a 50-percent split between evaporation and spray irrigation. Costs are presented in tables 11 and 12 for ED and NF, with and without brine disposal. This brine disposal cost is based on the 50-percent combination option, an option which may be more appropriate than complete evaporation or spray irrigation as a non-sewer disposal option.

Table 10. - Comparison of brine disposal costs considering land value.

Item	Construction Costs without I and cost	
	Electrodialysis	Nanofiltration
Evaporation Pond		
Pond System. Complete	$4,320,000	$3,360,000
Total	$4,320,000	$3,360,000
Spray Irrigation		
Header	$71.800	$53.000
Submain	$110,400	$71.800
Laterals	$331,200	8303.600
Sprinklers	$64.100	$58.800
Pumping	$16,600	$13,200
Storage	$500.000	$390,000
Total	$1,094,100	$890,400

Item	Construction Costs with Land costs	
	Electrodialysis	Nanoliltration
Evaporation Pond		
Pond System, Complete	$4,320,000	$3,360,000
Land cost @ $5,000/ac.	$450.000	$350,000
Total	$4,770,000	$3,710,000
Spray Irrigation		
Header	$71,800	$53.000
Submain	$110,400	$71,800
Laterals	$331.200	$303.600
Sprinklers	$64,100	$58.800
Pumping	$16.600	$13,200
Storage	$500.000	$390.000
Land cost @ $3,000/ac.	$1,008,000	$924.000
Total	$2,102,100	$1,814,400

Notes:

Costs are in Nov. 1995 dollars.

Costs for evaporation system are from USBOR estimates. Costs for spray Irrigation are from AWWA's Membrane Concentrate Disposal " reference

Storage costs are for 1 day volume at $1.00 per gal. Spray irrigation systems is not underdrained.

Land area for evaporation is 90 and 70 acres for ED & NF, respectively.

Land area for spray irrigation is 335 and 308 acres for ED & NF, respectively.

Cost per acre for spray irrigation is less than for evaporation due to economy of scale.

Assuming 50% evaporation and 50% spray irrigation:

Item	Construction Costs without I and cost	
	Electrodialysis	Nanofiltration
Evaporation Pond	$2,160,000	$1,680,000
Spray Irrigation	$547,050	$445,200
Total w/o Land Costs	$2,707,050	$2.125.200
O&M @ 5% of Construction	$135,353	$106,260

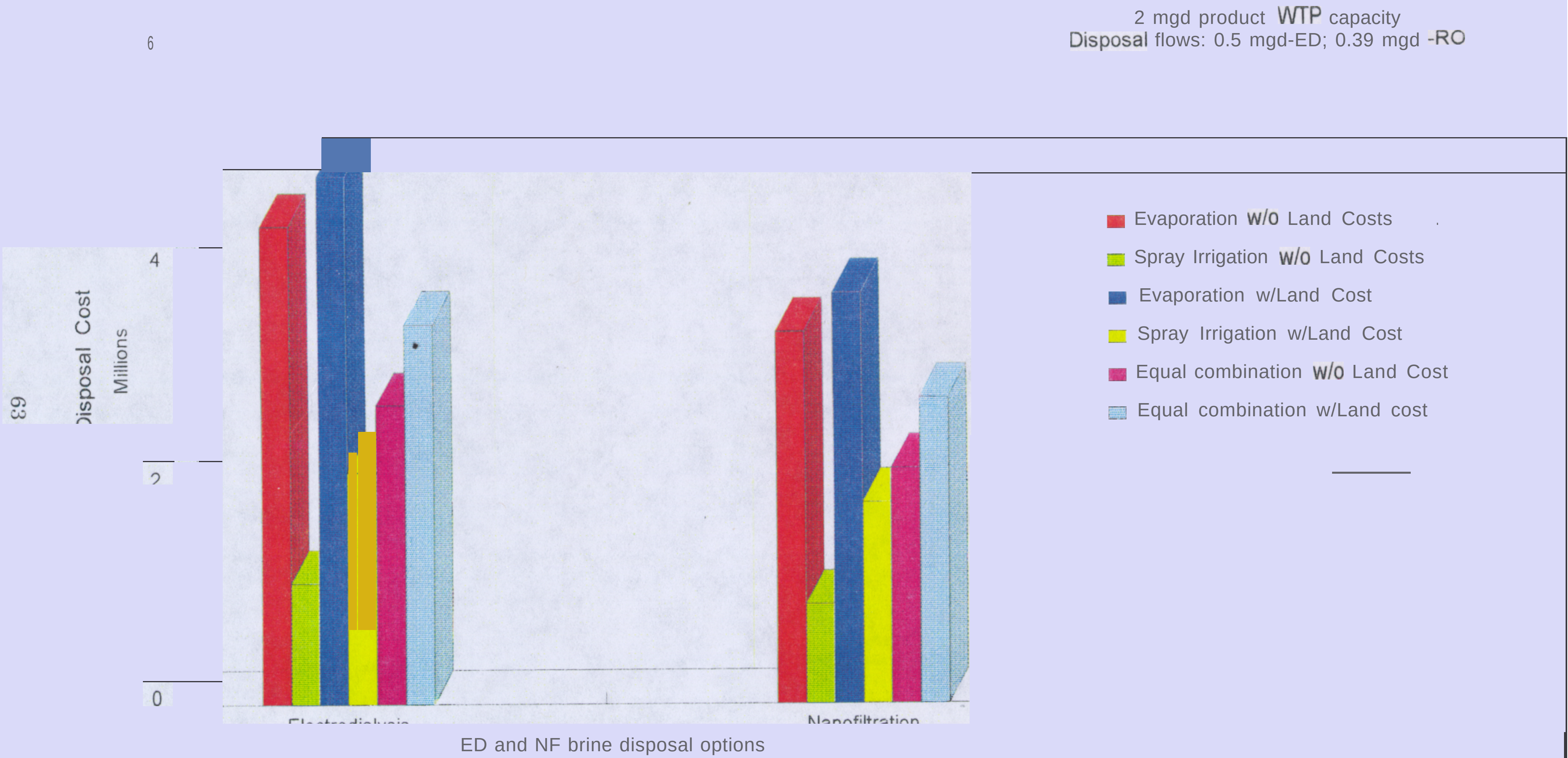

Figure 26 Comparison of evaporation and spray irrigation costs with and without land value

8.3 Electrodialysis

ED is likely to provide water that meets the SDWA limits when the well water is less than 1100 mg/L TDS and 23 mg/L nitrate. This process operates at 80-percent recovery.

8.3.1 Construction Cost - The total estimated construction cost for an electrodialysis plant producing 2.0 Mgal/d of potable water is $2,141,600, as shown in table 11. The cost estimates for electrodialysis include the following assumptions:

- Raw feed flow for pretreatment and pumping is 2.5 Mgal/d
- Product flow is 2.0 Mgal/d
- Concentrate flow is 0.5 Mgal/d
- A rapid-rate, gravity filter using sand and anthracite and sized at 5 gal/min/ft^2, or about 350 square feet with centrifugal backwash pump
- A polymer feed system to feed sodium bisulfite, a dechlorination agent, at a feed rate of 2 mg/L
- Electrodialysis system with acid and antiscalant, cartridge filtration, and chemicals for cleaning and membrane replacement costs every 15 years

Table 11. - Construction and operations and maintenance costs, 2-Mgal/d electrodialysis plant.

Item	Construction Cost	Ooerations and Maintenance Cost
Raw Water Pumping	$37,300	$13,000
Chlorine Disinfection	37,400	17,100
Gravity Filtration	179,500	42,600
Filter Backwash Pump	148,200	7,100
Polymer Addition	40,900	11,100
Electrodialysis	1,462,200	290,900
Post Chlorination	37,400	17,100
Clearwell	84,000	4,200
Finished Water Pumping:	34,700	5,300
Building, 2000 sf @ $40.00/sf	80,000	8,000
Subtotal	$2,141,600	$416,400
Combined brine disposal system	2,707,100	135,400
TOTAL COST	$4,848,700	$551,800

Note: Brine disposal is accomplished by 50 pct to an evaporation pond and 50 pct through spray irrigation. Land costs are not included.

If disposal of the brine is not to a LOTW, but to a combined evaporation/spray irrigation system, the construction cost estimate is $4,848,700 and disposal facilities would include about 40 acres of evaporation pond and about 160 acres of irrigable land area.

8.3.2 Operations and Maintenance Cost - The total estimated annual operations and maintenance cost for a 2.0-Mgal/d (product) electrodialysis water treatment plant is $416,400, without brine disposal and $551,800 with brine disposal, as shown in table 11.

8.4 Nanofiltration

A water treatment plant which employs the nanofiltration process will remove all Primary and Secondary drinking water contaminants to levels below their maximum contaminant level. In fact, the nanofiltration process works so well that blending with water of lower water quality will still produce a product with the desired levels. The conclusions from the piloting performed in this study and the salt rejections observed at a nanofiltration pilot operation in Lake Havasu City, Arizona, indicate that a full scale water treatment plant that produces 2.0 Mgal/d of water can operate at a net recovery of about 84 percent, as illustrated on figure 25.

8.4.1 Construction Cost - The above described nanofiltration water treatment plant, shown schematically on figure 25, excluding brine disposal, is estimated to cost $2,295,900, as shown in table 12. The cost estimates for nanofiltration include the following assumptions:

- Raw feed flow for pretreatment and pumping is 2.39 Mgal/d
- Product flow is 2.0 Mgal/d
- Concentrate flow is 0.39 Mgal/d
- A rapid-rate, gravity filter using sand and anthracite and sized at 5 gal/min/ft^2, or about 332 square feet with centrifugal backwash pump
- A polymer feed system to feed sodium bisulfite, a dechlorination agent, at a feed rate of 2 mg/L
- A nanofiltration system with acid and antiscalant, cartridge filtration, chemicals for cleaning and membrane replacement costs every 3 years

Table 12. - Construction and operations and maintenance costs, 2-Mgal/d nanofiltration plant.

Item	Construction Cost	Operations and Maintenance Cost
Raw Water Pumping	$37,300	$13,000
Chlorine Disinfection	36,400	16,800
Gravity Filtration	175,900	42,000
Filter Backwash Pump	148,200	7,100
Polymer Addition	40,700	10,800
Nanofiltration	1,478,300	268,600
Post Chlorination	36,400	16,800
Clearwell	84,000	4,200
Finished Water Pumping:	34,700	5,300
Building, 5600 sf @ $40.00/sf	224,000	22.400
Subtotal	$2,295,900	$407,000
Combined brine disposal system	2,125,200	106,300
TOTAL COST	$4,421,100	$513,300

Note: Brine disposal is accomplished by 50 pct to an evaporation pond and 50 pct through spray irrigation. Land costs are not included.

If disposal of the brine is not to a LOTW, but to a combined evaporation/spray irrigation system, the construction cost estimate is $4,421,100 and disposal facilities would include about 32 acres of evaporation pond and about 140 acres of irrigable land area.

8.4.2 Operations and Maintenance Costs - The total estimated annual operations and maintenance cost for a 2.0-Mgal/d, ground water treatment plant using nanofiltration is $407,000 without brine disposal and $513,300 with brine disposal, as shown in table 12.

8.5 Cost Analysis

A life cycle cost analysis, using the construction and O&M cost estimates found in tables 11 and 12, is presented in tables 13 and 14. The analysis is presented both in terms of total present worth and total annual cost. A final cost per 1000 gallons of treated water is also shown. This analysis assumes a 20-year life, no salvage value, and interest at 6.5 percent. Table 13 reflects the water treatment costs without brine disposal, and table 14 includes the 50-percent combined evaporation/spray irrigation system described in section 8.2, without land costs.

Table 13. - Life cycle costs for ground water treatment options without brine disposal.

Basic Assumptions		
Study Period	20 years	
Annual Interest Rate	6.5 pct	
Capital Recovery Factor	0.0908	
Present Worth Factor	11.019	
	Ekctrodialysis	Nanofiltration
Capital Cost	$ 2,141,600	$ 2,295,900
[1]Present Worth of Annual Operating Cost	$ 4,588,300	$ 4,484,700
Total Present Worth	$ 6,729,900	$ 6,780,600
[2]Annualized Capital Cost	$ 194,500	$ 208,500
Annual Operating Cost	$ 416,400	$ 407,000
Total Annualized Cost	$ 610,900	$ 615,500
[3]Annualized cost/1000 Gal of Product	$ 0.84	$ 0.84

[1] Present worth of Annual Operating Cost is Annual O&M cost times the Present Worth Factor
[2] Annualized Capital Cost is Capital cost times Capital Recovery Factor
[3] Total annualized cost/(365x2,000)

Table 14. - Life cycle costs for ground water treatment options with brine disposal.

Basic Assumptions		
Study Period	20 years	
Annual Interest Rate	6.5 pct	
Capital Recovery Factor	0.0908	
Present Worth Factor	11.019	
	Electrodialysis	Nanofiltration
Capital Cost	$ 4,848,700	$ 4,421,100
[1]Present Worth of Annual Operating Cost	$ 6,080,300	$ 5,656,100
Total Present Worth	$10,929,000	$10,077,200
[2]Annualized Capital Cost	$ 440,300	$ 401,400
Annual Operating Cost	$ 551,800	$ 513,300
Total Annualized Cost	$ 992,100	$ 914,700
[3]Annualized cost/1000 Gal of Product	$ 1.36	$ 1.25

[1] Present worth of Annual Operating Cost is Annual O&M cost times the Present Worth Factor
[2] Annualized Capital Cost is Capital cost times Capital Recovery Factor
[3] Total annualized cost/(365x2,000)

9. CONCLUSIONS

This report concludes the following:

1. When nitrate or TDS are excessive in ground water, electrodialysis, reverse osmosis, and nanofiltration can be used to successfully reduce these contaminants to safe levels.

2. Nanofiltration and electrodialysis have nearly equal costs and both are considerably cheaper to install and operate than a reverse osmosis system.

3. Electrodialysis or nanofiltration should be considered for water treatment of ground water in the study area when nitrates and TDS are present. Combining flows from several wells for treatment in a centralized water treatment plant is generally cheaper than individual wellhead treatment. If ground water contains TDS in excess of 1100 mg/L, then nanofiltration is preferred because it removes more of these contaminants than electrodialysis. If the ground water has TDS of 1100 mg/L or less and nitrate of 23 mg/L or less, then electrodialysis is preferred because of lower pretreatment and operational requirements.

4. Contaminants of concern which exceeded SDWA limits prior to piloting were nitrate, chloride, turbidity, and TDS. For most of the 6-week piloting period, the levels of nitrates averaged less than half of what had historically been found and were just below the MCL. Fortunately, the nitrate levels were substantial enough to evaluate the performance of the electrodialysis membranes. Chlorides and TDS, found in the raw well water during piloting, were above SDWA limits. The sulfate concentration increased from an average of 181 mg/L prior to testing to 240 mg/L during the 6-week pilot test period.

5. Pilot scale testing of both electrodialysis and reverse osmosis, with adequately pretreated ground water, reduced the concentrations of nitrate, TDS, and chloride in Avondale's well s5 to the levels indicated below:

	Electrodialvsis			Reverse Osmosis		
	Raw Water	Finished Water	Pct Removed	Raw Water	Finished Water	Pct Removed
Nitrate, mg/L	9.7	3.7	62	9.0	0.8	91
TDS, mg/L	1700	970	43	1467	41.6	97
Chloride, mg/L	760	240	68	557	10.7	98

- Reverse osmosis achieved such a high reduction in ions that its product water fully complies with Primary and Secondary SDWA parameters, even with blending. The blending ratio, computed after reviewing the pilot test results, is 82-percent reverse osmosis product water to H-percent filtered water. The overall average rejection rate for drinking water contaminants was 96.4 percent.

- The electrodialysis process, using Asahi nitrate specific membranes, achieved a 62-percent reduction in nitrates and a 43-percent reduction in TDS. The nitrate specific membranes produced an effluent that met the nitrate MCL, but that was still over the MCL for TDS. As the piloting period progressed, the average nitrate concentration decreased to 8.8 mg/L.

6. Planning level construction cost estimates for a 2-Mgal/d (product) treatment plant using ED and the unit operations in table 11 range from $2,141,600 ($1.08/Mgal/d) without brine disposal to $4,848,700 ($2.42/Mgal/d) with brine disposal using an equal combination of evaporation and spray irrigation and excluding land costs. Yearly O&M cost estimates range from $416,400 without brine disposal to $551,800 with brine disposal.

7. Planning level construction cost estimates for a 2-Mgal/d product treatment plant using NF and the unit operations listed in table 12 range from $2,295,900 ($1.15/Mgal/d) without brine disposal to $4,421,400 ($2.21/Mgal/d) with brine disposal using an equal combination of evaporation and spray irrigation and excluding land costs. Yearly O&M cost estimate ranges from $407,000 without brine disposal to $513,300 with brine disposal.

8. A 2-Mgal/d water treatment plant that uses electrodialysis or nanofiltration and the unit operations displayed on figures 24 or 25 will generate about 500,000 and 390,000 gal/d, respectively, of concentrate. This wastewater can be disposed of to a locally owned wastewater treatment works, to an evaporation pond, or in a reclaimed water capacity such as a spray irrigation system that could lower irrigation water demands. The creation of a wetland is another possible brine disposal option.

9. The total **present** worth of a 2-Mgal/d (product) electrodialysis plant, excluding brine disposal, is $6,729,900; for nanofiltration, also excluding brine disposal, total present worth is $6,780,600 based on the assumptions made in this report and the life cycle cost analysis for 20 years at an interest rate of 6.5 percent.

10. The total **annualized cost** of a 2-Mgal/d (product) electrodialysis plant, excluding brine disposal, is $610,900 ($0.84/1000 gal); for nanofiltration, also excluding brine disposal, total annualized cost is $615,500 ($0.84/1000 gal) based on the assumptions made in this report and the life cycle cost analysis for 20 years at an interest rate of 6.5 percent.

11. The total **present worth** of a 2-Mgal/d (product) electrodialysis plant, including brine disposal, is $10,929,000; for nanofiltration, also including brine disposal, total present worth is $10,077,200 based on the assumptions made in this report and the life cycle cost analysis for 20 years at an interest rate of 6.5 percent.

12. The total **annualized cost** of a 2-Mgal/d (product) electrodialysis plant, including brine disposal, is $992,100 ($1.36/1000 gal.); for nanofiltration, also including brine disposal, total annualized cost is $914,700 ($1.25/1000 gal), based on the assumptions made in this report and the life cycle cost analysis for 20 years at an interest rate of 6.5 percent.

10. RECOMMENDATIONS

Based on the conclusions noted above, the following recommendations are made:

1. As witnessed during this study's 6-week pilot test, water quality in well s5 fluctuated from historic nitrate levels that averaged 19 mg/L to an average for this pilot test of 8.8 mg/L. Prior to deciding on a specific ground water treatment scheme for any well, recent water quality data on the well for a period of at least 1 year should be obtained and reviewed.

2. Based on the pilot test results for electrodialysis and reverse osmosis, wells with TDS and nitrates substantially above the MCLs of 500 mg/L and 10 mg/L, respectively, are recommended to be treated with nanofiltration membranes. The electrodialysis process was successful in nitrate removal; however, the pressure membrane process was superior in reducing salts or dissolved solids to safe levels.

3. Electrodialysis is recommended for wells where the nitrates are about 23 mg/L or less and the TDS are about 1100 mg/L or less.

4. If either of the cities of Avondale or Chandler, or the Gila River Indian Community, pursue treating ground water with nanofiltration or electrodialysis, the process concentrate is recommended to he disposed of to the locally-owned treatment works. If this option is infeasible, then brine disposal to either evaporation ponds, a spray irrigation system, or to a wetland system that uses plants having a tolerance for salt water is recommended. The latter two alternatives offer the benefits of water reuse and may lower total water demands for the owner.

11. REFERENCES

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APPENDIX A

Electrodialysis Test Data

Maricopa Groundwater Treatment Study

ED Data:								
	pril 4, 1994, Avondale. AZ ariation in Voltage							
Cell Pair5 = 92								
Recovery:	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
Fd	10	10	10	10	10	10	10	10
F c	2	2	2	2	2	2	2	2
Total stack Flow L/min	95	95	95	95	95	95	95	95
Diluate Recycle L/min	a3	a3	a3	a3	a3	a3	a3	a3
volts	46	55	64	74	a3	92	101	110
Current	1.43	1.72	1.86	2.03	2.08	2.2	2.39	2.43
# of Passes	a.3	a.3	a.3	a.3	a.3	a.3	a.3	a.3
Cond Feed	2.56	2.53	2.52	2.51	2.49	2.49	2.49	2.49
pH Feed	7.43	7.46	7.44	7.48	7.45	7.49	7.47	7.47
Eq/L Fd	0.029	170.028	0.028	170.028	0.023	0.028	0.028	0.028
Fd mg/L	1772.65		1744.95		1724.18	1724.18	1724.18	1724.18
Cond Di	1.622	1.61	1.552	1.442	1.33	1.268	1.271	1.2
pH Di	7.29	7.39	7.41	7.38	7.31	7.33	7.27	7.21
Eq/L Di	0.011	0.011	0.011	0.010	0.009	0.009	0.009	0.008
Di mg/L	1123.14	11 14.83	1074.67:.	998.50	920.95	878.01	880.09	830.93
Cond Do	1.495	1.491	1.423	1.308	1.17	1.113	1.048	0.987
pH Do	7.34	7.38	7.37	7.39	7.25	7.32	7.22	7.17
Eq/L Do	0.011.	0.011	0.010	0.009	0.008	0.008	0.007	0.007
Do mg/L	1035.20	1032.43	985.34	905.71	810.15	ml.69	725.88	688.44
Cond Ci	5.92	6.61	6.81	7.02	7.39	7.74	a.05	a.29
pH Ci	2.84	2.83	6.96	6.38	6.06	5.99	7.89	6.41
Eq/L Ci	0.075	0.084.	0.988	0.089	0.093	0.098	0.102	0.105
Ci mg/L	4099	4577	4716	4861	6117	5359	5574	5740
Cond Co	6.31	7.16	7.57	7.82	8.17	a.54	a.94	9.16
pH co	3.08	2.98	6.98	6.48	6.33	6.26	7.85	6.49
Eq/L Co	0.080	0.091"	0.096	0.099	0.103	0.108	0.113	-0.116
Co mg/L	4369	4958	5242	5415	5657	5913	6190	6343
VI	46.6	55.4	64.1	74.3	83.2	91.7	100.8	110.3
V2	1.23	1.45	1.945	1.8	1.18	1.76	2.02	1.81
V3	3.7	4.03	4.38	4.6	4.75	4.94	5.16	5.36
V4	41.3	49.7	57.5	67	76.6	84.6	92.4	102.4
Difference	0.37	0.22	0.275	0.9	0.67	0.4	1.22	0.73
V/cell	0.500	0.598	0.696	0.804	0.902	1.000	1.098	1.196
V4/cell	0.449	0.540	0.625	0.728	0.833	0.920	1.004	1.113
Delta N: F-Do	0.018	0.018	0.018	0.019	0.020	0.020	0.021	0.021
Delta N: Di-Do	0.001	0.001	0.001	0.001	0.001	0.001	0.0016	0.002
Delta N: Co-F	0.051	0.062	0.067	0.071	0.075	0.0ao	0.085	0.088
Delta N: Co-Ci	0.005	0.007	0.010	0.010	0.010	0.010	0.011	0.011
Ave Delta N:	0.067	6.077	0.095	0.100	0.106	0.106	0.133	0.128
Delta TDS F-Do	737	719	760	832	914	953	998	lo41
pH: F-Do	0.140	0.070	0.030	0.100	0.140	0.160	0.200	0.260
pH: Do-Di	0.050	-0.010	-0.040	0.010	-0.060	-0.010	-0.050	-0.040
pH: Co-Ci	0.240	0.150	0.020	0.100	0.270	0.270	-0.040	0.080
Rstack Ohms	32.168	31.977	34.409	36.453	39.904	41.818	42.259	45.267
in	0.699	0.581	0.538	0.493	0.481	0.455	0.418	0.412
Efficiency per cell	0.82	0.78	0.90	0.86	0.89	0.84	0.97	0.92
Delta Nt/(min*Volt)	4.78E-05	3.93E-05	3.45E-05	3.10E-05	2.87E-05	2.64E-05	2.46E-05	2.31E-05
m=Fr/Fp	7.917	7.917	7.917	7.917	7.917	7.917	7.917	7.917
Dil Balance	0.409	0.389	0.414	0.414	0.480	0.454	0.654	0.609
Conc Balance	1.011	1.000	0.977	0.976	0.985	0.988	0.983	0.989
Average Concentration	0.020	0.022	0.022	0.021	0.021	0.021	0.022	0.022
Demin fraction 1pass	0.078	0.074	0.083	0.093	0.120	0.122	0.175	0.178
Demin fraction tot	0.634	0.630	0.646	0.673	0.705	0.720	0.736	0.7511

ED Data:	\pril 5, 1994, Avondale, AZ								
	/ariation in Detention Time					Variation in Voltage			
Cell Pairs = 92									
Recovery:	0.83	0.83	0.83	0.84	0.83	0.93	0.93	0.93	0.93
Fd	12	10.6	8.8	7.6	5.9	13.5	13.5	13.5	13.5
Fc	2.45	2.2	1.8	1.5	1.2	1	1	1	1
Total stack Flow L/min	95	95	95	95	95	92	92	92	92
Diluate Recycle L/min	83	83	83	83	83	80	80	80	80
volts	100	100	100	100	100	50	70	90	110
Current	2.49	2.27	2.03	1.9	1.71	1.32	2	2.4	2.75
# of Passes	6.9	7.8	9.4	10.9	14.1	5.9	5.9	5.9	5.9
Cond Feed	2.35	2.31	2.32	2.31	2.31	2.31	2.32	2.32	2.32
pH Feed	7.47	7.42	7.51	7.51	7.47	7.52	7.52	7.52	7.52
Eq/L Fd	0.026	0.026	0.026	0.026	0.026	0.626	0.026	0.026	0.026
Fd mg/L	1627.23	1599.54	1666.46	1599.54	1599.54	1599.54	1606.46	1606.46	1666.46
Cond Di	1.297	1.309	1.105	1.035	0.957	1.735	1.583	1.509	1.383
pH Di	7.15	8.81	7.18	7.2	7.07	7.48	7.43	7.39	7.39
Eq/L Di	0.009	0.009	0.008	0.067	0.007	0.012	0.011	0.011	-0.010
Di mg/L	898.09	906.40	765.15	716.68	662.67	1201.38	1096.13	1644.89	957.64
Cond Do	1.11	1.05	0.979	0.912	0.83	1.606	1.435	1.273	1.135
pH Do	7.1	6.72	7.13	7.14	7.01	7.51	7.41	7.33	7.27
Eq/L Do	0.008	0.007	0.007	0.006	0.006	0.011	0.010	0.009	0.008
Do mg/L	768.61	727.06	677.90	631.51	574.73	1112.06	993.65	881.48	785.92
Cond Ci	8.49	5.09	7.05	7.69	8.57	7.84	9.79	11.79	13.21
pH Ci	2.37	3.65	7.76	7.87	5.69	7.39	3.21	3.02	5.72
Eq/L Ci	0.107	0.064	0.089	0.097	0.108	: 0.099	0.124	0.149	-0.167
Ci mg/L	5879	3525	4882	5325	5934	5429	6779	8164	9147
Cond Co	9.21	6.02	7.83	8.42	9.19	8.41	10.67	12.35	14.09
pH Co	2.49	4.33	7.7	7.83	6.02	7.37	6.01	3.8	6.66
Eq/L Co	0.117	0.076	0.099	0.107	0.116	0.106	It.135	0.156	0.178
Co mg/L	6377	4168	5422	5830	6364	5823	7388	8552	9756
V1	100.2	99.9	100	100	99.9	50.3	70.5	89.9	110.1
V2	1.33	1.97	1.86	1.88	1.05	1.77	1.2	1.2	1.33
v3	5.11	5.35	5.34	5.3	5.25	44.6	64.8	83.2	102.8
v4	92.7	91.8	91.3	91.6	92.6	3.64	4.3	4.86	5.65
Difference	1.06	0.78	1.5	1.22	1	0.29	0.2	0.64	0.32
V/cell	1.087	1.087	1.087	1.067	1.087	0.543	0.761	0.978	1.196
V4/cell	1.008	0.998	0.992	0.996	1.007	0.040	0.047	0.053	0.061
Delta N:F-Do	0.019	0.019	0.019	0.020	0.020	0.015	0.016	0.017	0.018
Delta N: Di-Do	0.00132	0.0018	0.0009	0.0009	0.0009	0.001	0.001	0.002	0.002
Delta N: Co-F	0.090	0.050	0.073	0.081	0.090	0.080	0.109	0.130	0.152
Delta N: Co-Ci	0.009	0.012	0.010	0.009	0.008	0.007	0.011	0.007	0.011
Ave Delta N:	0.109	0.146	0.096	0.091	0.084	0.080	0.109	0.109	0.137
Delta TDS F-Do	859	872	929	968	1025	487	613	725	821
pH: F-Do	0.320	-1.390	0.330	0.310	0.400	0.040	0.090	0.130	0.130
pH: Do-Di	-0.050	-2.090	-0.050	-0.080	4.060	0.030	-0.020	-0.060	-0.120
pH: Co-Ci	0.120	0.680	-0.060	-0.040	0.330	-0.020	2.800	0.780	0.340
Rstack Ohms	40.161	44.053	49.261	52.632	58.480	37.879	35.000	37.500	40.000
in	0.402	0.441	0.493	0.526	0.585	0.758	0.500	0.417	0.364
Efficiency per cell	0.77	1.13	0.83	0.84	0.86	1.06	0.95	0.79	0.87
Delta Nt/(min*Volt)	2.69E-05	2.37E-05	2.04E-05	1.79E-05	1.43E-05	4.95E-05	3.85E-05	3.21E-05	2.78E-05
m=Fr/Fp	6.574	7.422	8.962	10.440	13.380	6.345	6.345	6.345	6.345
Dil Balance	0.502	0.810	0.435	0.485	0.623	0.420	0.444	0.684	0.679
Conc Balance	1.027	0.917	0.972	0.978	0.986	1.039	1.031	1.077	1.061
Average Concentration	0.022	0.017	0.019	0.020	0.020	0.024	0.026	0.026	0.030
Demin fraction 1pass	0.144	0.198	0.114	0.119	0.133	0.074	0.093	0.156	0.179
Demin fractiontot	0.704	0.715	0.735	0.752	0.7751	0.564	0.612	0.656	0.6931

ED Data:									
	/ariation in Dt, V=85				March 10. 1994. Avondale. AZ Variation in Voltage				
Cell Pairs = 92									
Recovery:	0.93	0.93	0.93	0.93	0.87	0.87	0.87	0.87	0.87
Fd	12	10.5	9	7.5	87	87	87	87	87
Fc	0.846	0.769	0.648	0.57	13	13	13	13	13
Total stack Flow L/min	92	92	92	92	100	100	900	100	100
Diluate Recycle L/min	80	80	80	80	87	87	8 7	87	87
					No Recycle				
Volts	85	85	85	85	61	70	85	90	98
Current	2.16	2.1	2.09	1.98	1.27	1.44	1.74	1.85	2.06
# of Passes	6.7	7.6	8.9	10.7	1.0	1.0	1.0	1.0	1.0
Cond Feed	2.32	2.32	2.32	2.31	2.58	2.48	2.37	2.5	2.57
pH Feed	7.55	7.52	7.52	7.56	6.63	7.02	2.36	7.41	7.37
Eq/L Fd	0.026	0.026	0.026	0.026	0.029	0.028	0.027	0.028	0.029
Fd mg/L	1606.46	1606.46	1806.46	1599.54	1786.50	'1717.25	1641.08	1731.10	1779.57
Cond Di	1.295	1.278	1.209	1.108					
pH Di	7.35	7.26	7.17	7.03					
Eq/L Di	0.009	0.009	0.009	0.008					
Di mg/L	896.71	884.94	837.16	767.22					
Cond Do	1.151	1.094	1.065	0.988	2.44	2.41	2.36	2.36	2.39
pH Do	0.008	7.23	7.14	7	7.07	7.11	7.31	7.46	7.43
Eq/L Do	797.00	0.008	. . 737.45 '0.008	0.007	160.017	1668.78	1634.16 0.017	1634.16 0.017	0.017
Do mg/L		757.53		684.13					1654.93
Cond Ci	13.84	14.56	16.4	18.12					
pH Ci	2.79	2.42	2.19	1.96					
Eq/L Ci									
Ci mg/L	9583	10082	11356	12547					
Cond co	04175	04104	0207	08298	3.62	3.85	3.98	4.38	4.49
pH Co	3.1	2.53	2.25	1.99	6.79	7.03	7.2	7.31	7.34
Eq/L Co	0.180	0.189	0.212	-0233	0.046	0.049	0.050	0.055	0.057
Co mg/L	9874	10345	11612	12727	2507	2666	2756	3033	3109
V1	85	85.1	85.2	85.1	46.6				
V2	1.15	1.12	1	1.1	1.23				
v3	79	79.1	79.1	78.3	3.7				
V4	4.74	4.68	4.68	4.71	41.3				
Diirence	0.11	0.2	0.42	0.99	0.37	0	0	0	0
V/cell	0.924	0.924	0.924	0.924	0.663	0.761	0.924	0.978	1.065
V4/cell	0.052	0.051	0.051	0.051	0.449	o.ooo	0.000	0.000	0.000
Delta N:F-Do	0.018	0.018	0.019	0.019	0.012	0.011	0.010	0.011	0.012
Delta N: Di-Do	0.061	0.001	0.001	0.001	-0.017	-0.017	-0.017	-0.017	-0.017
Delta N: Co-F	0.154	0.163	0.186	0.207	0.017	0.021	0.024	0.027	0.028
Delta N: Co-Ci	0.005	0.005	0.005	0.003	0.046	0.049	0.050	0.055	0.057
Ave Delta N:	0.073	0.081	0.069	0.054	-0.451	-0.423	-0.397	-0.364	-0.365
Delta TDS F-Do	809	849	869	915	97	48	7	97	125
pH: F-Do	0.200	0.260	0.350	0.530	6.630	7.020	2.360	7.410	7.370
pH: Do-Di	-0.020	-0.030	-0.030	-0.030	7.070	7.110	7.310	7.460	7.430
pH: Co-Ci	0.310	0.110	0.060	0.030	6.796	7.030	7.200	7.310	7.340
Rstack ohms	39.352	40.476	40.670	43.367	48.031	48.811	48.851	48.649	47.573
in	0.463	0.476	0.478	0.510	0.787	0.694	0.575	0.541	0.485
Efficiencypercell	0.59	0.67	0.57	0.48	8.21	-5.14	-3.99	-3.44	-3.09
Delta Nt/(min*Volt)	3.17E-05	2.84E-05	2.46E-05	2.10E-05	1.94E-04	1.56E-04	1.18E-04	1.28E-04	1.23E-04
m=Fr/Fp	7.162	8.164	9.536	11.400	1.000	1.000	1.006	1.000	1.600
Dil Balance	0.429	0.620	0.551	0.531	-0.593	-0.609	-0.625	-0.592	-0.583
Conc Balance	1.084	1.076	1.067	1.062	0.000	0.000	0.000	0.000	0.000
Average Concentration	0.030	0.031	0.033	0.036	0.025	0.025	0.024	0.025	0.025
Deminfractionlpass	0.111	0.144	0.119	0.108					
Demin fraction tot	0.689	0.704	0.712	0.7321	0.407	0.391	0.375	0.408	0.417

ED Data:									
Cell Pairs = 92									
Recovery:	0.55	0.55	0.55	0.55	0.78	0.78	0.78	0.78	0.78
Fd	16	16	16	16	10.6	10.6	10.6	10.6	10.6
F c	13	13	13	13	3	3	3	3	3
Total stack Flow L/min	100	100	100	100	100	100	100	100	100
Diluate Recycle L/min	87	87	87	87	87	87	87	87	87
	)iluate Recycle				Dt=10, vary v				
volts	60	70	80	90	60	70	81	90	95
current	1.32	1.54	1.76	1.98	1.74	2.05	2.34	2.58	2.69
# of Passes	5.4	5.4	5.4	5.4	8.2	8.2	8.2	8.2	8.2
Cond Feed	2.32	2.29	2.13	1.88	2.64	2.75	2.63	2.56	2.32
pH Feed	6.66	7.03	7.26	7.54	7.55	7.54	7.61	7.55	7.79
Eq/L Fd	0.026	0.026	0.024	0.021	0.033	0.031	0.030	0.029	0.026
Fd mg/L	1606.46	1685.69	1474.90	1301.79	2035.77	1904.21	1821.12	1772.65	1606.46
Cond Di									
pH Di									
Eq/L Di									
Di mg/L									
Cond Do	2.24	2.22	2	1.8	2.23	1.98	2.33	1.813	1.9
pH Do	6.4	7.09	7.3	7.49	7.68	7.65	7.84	7.73	7.83
Eq/L Do	0.016	0.016	0.014	0.013	0.016	0.0140	0.016	0.013	0.013
Do mg/L	156f .07	1537.22	1384.88	1246.39	1544.14	1371.03	1613.39	1255.39	1315.64
Cond Ci									
pH Ci									
Eq/L Ci									
Ci mg/L									
Cond Co	3.29	3.35	3.46	3.481	4.8	5.25	6.06	6.24	6.78
pH Co	6.79	7.04	7.19	7.32	7.37	7.36	7.53	7.39	7.45
Eq/L Co	0.042	0.042	0.044	0.044	0.061	0.066	0.077	0.079	0.086
co mg/L	2278	2320	2398	2410	3324	3635	4196	4321	4695
V1									
V2									
V3									
v 4									
Difference	0	0	0	0	0	0	0	0	0
V/cell	0.652	0.761	0.870	0.978	0.652	0.761	0.880	0.978	1.033
V4/cell	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Delta N: F-Do	0.010	0.010	0.010	0.008	0.017	0.017	0.013	0.016	0.013
Delta N: Di-Do	-0.016	-0.016	-0.014	-0.013	-0.016	-0.014	-0.016	-0.013	-0.013
Delta N: Co-F	0.016	0.017	0.020	0.023	0.028	0.035	0.047	0.050	0.060
Delta N: Co-Ci	0.042	0.042	0.044	0.044	0.081	0.066	0.077	0.079	0.086
Ave Delta N:	-0.417	-0.406	-0.329	-0.266	-0.290	-0.176	-0.217	-0.043	-0.026
Delta TDS F-Do	55	48	90	55	492	533	208	517	291
pH: F-Do	6.660	7.030	7.260	7.548	7.556	7.540	7.610	7.550	7.796
pH: Do-Di	6.400	7.090	7.300	7.496	7.680	7.650	7.840	7.730	7.830
pH: Co-Ci	6.790	7.040	7.190	7.320	7.370	7.360	7.530	7.390	7.456
Rstack Ohms	45.455	45.455	45.455	45.455	34.483	34.146	34.615	34.884	35.316
1/I	0.758	0.649	0.568	0.505	0.575	0.488	0.427	0.388	0.372
Efficiency par cell	-5.52	4.61	-3.27	-2.35	-2.91	-1.56	-1.62	-0.29	-0.17
Delta Nt/(min*Volt)	3.16E-05	2.65E-05	2.27E-05	1.73E-05	3.52E-05	2.95E-05	1.98E-05	2.17E-05	1.63E-05
m=Fr/Fp	3.448	3.448	3.448	3.448	7.353	7.353	7.353	7.353	7.353
Dil Balance	-2.088	-2.097	-2.031	-2.071	-3.498	-3.320	4.085	-3.266	-3.777
Conc Balance	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Average Concentration	0.021	0.021	0.019	0.018	0.023	0.022	0.025	0.022	0.023
Demin fraction 1 pass									
Demin fraction tot	0.394	0.392	0.411	0.400	0.524	0.548	0.444	0.556	0.486

ED Data:									
		11-Mar Data							
Cell Pairs = 92									
Recovery:	0.78	0.78	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Fd	10.6	10.6	12	12	12	12	12	12	12
Fc	3	3	3	3	3	3	3	3	3
Total stack Flow L/min	100	100	100	100	100	100	100	100	100
Diluate Recycle Umin	87	87	67	87	87	87	87	99	99
		Dt=8.8, vary V						Dt =10.6, vary V	
Volts	72	72	72	a2	84	89	95	85	90
Current	2.4	2.4	2.4	2.5	2.6	2.7	2.8	2.45	2.55
# of Passes	8.2	8.2	7.3	7.3	7.3	7.3	7.3	8.3	8.3
Cond Feed	2.73	2.76	2.7	2.7	2.74	2.73	2.74	2.73	2.72
pH Feed	7.41	7.41						7.34	7.34
Eq/L Fd	0.631	0.031	0.030	0.030	0.031	0.031	0.031	0.031	0.031
Fd mg/L	1890.36	1911.13	1669.59	1869.59	1897.29	1890.36	1897.29	1690.36	1883.44
Cond Di		1.738	1.7	1.654	1.601	1.58	1.57	1.469	1.455
pH Di		7.35						7.24	7.15
Eq/L Di		0.012	0.012	0.012	0.011	0.011	0.011	O.MO	0.010
Di mg/L		1203.46	1177.15	1145.30	1108.66	1094.06	1667.13	1017.19	1007.50
Cond Do	1.71	1.581	1.58	1.5	1.48	1.42	1.396	1.324	1.314
pH Do	7.33	7.24						7.24	7.07
Eq/L Do	0.012	0.011	0.011	0.011	0.010	0.010	0.01 0	0.009	0.009
Do mg/L	1184.07	1094.75	1094.06	1038.66	1024.81	98326	96665	916.79	909.87
Cond Ci		6.75						8.70	8.65
pH Ci		3.08						2.91	3.31
Eq/L Ci		0.085						0.111	"Ct.169
Ci mg/L		4674						6080	5990
Cond Co	7.23	7.56						9.43	9.29
pH Co	2.94	3.38						3.21	4.87
Eq/L Co	6.091	0.096						0.119	0.118
Co mg/L	5006	5235						6530	6433
V1	72.4								
v2	1.68								
v3	4.68								
V4	65.7								
Difference	0.34	0	0	0	0	0	0	0	0
V/cell	0.783	0.783	0.783	0.891	0.913	0.967	1.033	0.924	0.978
V4/cell	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Delta N: F-Do	0.019	0.020	0.019	0.020	0.020	0.021	0.021	0.021	0.021
Delta N: Di-Do	-0.012	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Della N: Co-F	0.061	0.065	-0.030	-0.030	-0.031	-0.031	-0.031	0.089	0.087
Delta N: Co-Ci	0.091	0.010	0.000	0.000	0.000	0.000	0.000	0.008	0.008
Ave Delta N:	0.070	0.115	0.037	0.047	0.037	0.049	0.053	0.055	0.053
Delta TDS F-Do	706	816	776	831	872	907	931	974	974
pH: F-Do	7.410	0.060	0.000	0.000	0.000	0.000	0.000	0.100	0.190
pH: Do-Di	7.330	-0.110	0.000	0.000	0.000	0.000	0.000	0.000	-0.080
pH: Co-Ci	2.940	0.300	0.000	0.000	0.000	0.000	0.000	0.300	1.560
Rstack Ohms	30.000	30.000	30.000	32.800	32.308	32.963	33.929	34.694	35.294
in	0.417	0.417	0.417	0.400	0.365	0.370	0.357	0.408	0.392
Efficiency per cell	0.51	0.84	0.27	0.33	0.25	0.32	0.33	0.39	0.37
Delta Nt/(min*Volt)	3.16E-65	3.37E-05	3.68E-05	3.33E-05	3.35E-05	3.21E-05	3.05E-05	3.05E-05	2.87E-05
m=Fr/Fp	7.353	7.353	6.667	6.667	6.667	6.667	6.667	6.667	6.667
Dil Balance	-2.889	0.434	0.307	0.387	0.291	0.365	0.414	0.335	0.326
Conc Balance	0.000	0.971	0.000	0.000	0.000	0.000	0.000	1.031	1.031
Average Concentration	0.023	0.023	0.012	0.012	0.012	0.012	0.011	0.013	0.013
Demin fraction 1 pass		0.090	0.071	0.093	0.076	0.101	0.111	0.099	0.097
Demin fraction tot	0.607	0.641	0.633	0.652	0.661	0.674	0.680	Q.696	0.697

ED Data:									
			12-Mar V=98, vary Dt		13-Mar			14-Mar	
Cell Pairs = 92									
Recovery:	0.80	0.80	0.79	0.76	0.84	0.78	0.78	0.75	0.75
Fd	12	12	7.5	6.5	10.5	7	7	6	6
Fc	3	3	2	2	2	2	2	2	2
Total stack Flow L/min	100	100	97	96.5	96	96.5	96.5	94.9	94.9
Diluate Recycle L/min	99	99	85	85	84	84.5	84.5	83	83
volts	98	107	98	98	100	100	100	104	104
Current	2.65	2.75	2.11	2.01	2.16	2.04	2	1.66	1.71
# of Passes	8.3	8.3	11.3	13.1	8.0	12.1	12.1	13.8	13.8
Cond Feed	2.73	2.73	2.36	2.13	2.35	2.4	2.49	2.5	2.61
pH Feed	7.33	7.34	7.51	7.47	7.42	7.41	7.39	7.37	7.43
Eq/L Fd	0.031	0.031	0.027	0.024	0.026	0.027	0.028	0.028	0.029
Fd mg/L	1890.36	1890.38	W4.16	1474.90	1627.23	1661.66	1724.18	1731.10	1807.27
Cond Di	1.415	1.394	1.176	1.057	1.49	1.317	1.408	1.362	1.58
pH Di	7.21	7.19	7.34	7.25	7.29	7.2	7.25	7.39	7.36
Eq/L Di	0.010	0.010	0.008	0.007	6.011	0.009	0.010	0.010	0.011
Di mg/L	979.80	965.28	814.31	731.91	1031.74	911.94	974.96	943.10	1094.06
Cond Do	1.263	1.219	1.042	1.051	1.308	1.169	1.278	1.251	1.258
pH Do	7.21	7.17	7.32	7.28	7.29	7.14	7.14	7.38	7.4
Eq/L Do	0.009	0.009	0.007	0.007	0.009	0.008	0.009	0.009	0.009
Do mg/L	874.55	844.08	721.52	727.75	905.71	809.46	884.94	866.24	871.09
Cond Ci	8.61	8.78	6.02	5.8	6.86	8.05	6.69	5.94	5.96
pH Ci	5.57	6.19	7.27	6.95	7.14	2.38	6	5.67	6.59
Eq/L Ci	0.109	0.111 I	0.078	0.073	0.087	0.102	0.085	0.675	0.075
Ci mg/L	5962	6080	4168	4016	4750	5574	4632	4113	4127
cond co	9.52	9.66	6.89	6.37	7.62	8.51	7.44	6.82	9.88
pH Co	6.07	6.35	7.31	6.95	7.18	2.42	6.13	5.98	6.65
Eq/L Co	0.120	0.122	0.987	0.081	0.096	0.168	0.094	0.086	0.125
Co mg/L	6592	6689	4771	4411	5276	5893	5152	4722	6841
V1			98.5		100.1	100.1	100	103.8	103.8
v2			2.95		3.072	2.1	2.2	3.33	2.01
v3			5		4.75	4.47	4.5	4.38	4.38
v4			90.3		92	93.4	93	95.7	97.3
Difference	0	0	0.25		0.278	0.13	0.3	0.39	0.11
V/cell	1.065	1.163	1.065	1 065	1.087	1.087	1.087	1.130	1.130
V4/cell	0.000	0.000	0.982	0 000	1.000	1.015	1.011	1.040	1.058
Delta N:F-Do	0.022	0.022	0.019	0.017	0.017	0.019	0.019	0.019	0.020
Delta N: Di-Do	0.001	0.901	0.001	o.ooc	0.001	0.001	0.001	0.001	0.002
Delta N: Co-F	0.090	0.091	0.061	0.057	0.070	0.081	0.066	0.058	0.098
Delta N: Co-Q	0.012	0.011	0.011	0.007	0.010	0.066	0.009	0.011	0.050
Ave Delta N:	0.059	0.067	0.106	0.043	0.112	0.079	0.096	0.099	0.389
Delta TDS F-Do	1016	1046	913	747	722	852	839	865	936
pH: F-Do	0.120	0.150	0.170	0.180	0.130	0.210	0.140	-0.020	0.070
pH: Do-Di	0.000	-0.020	-0.020	-0.010	0.000	-0.060	-0.110	-0.010	0.040
pH: Co-Ci	0.500	0.160	0.040	0.040	0.040	0.040	0.130	0.310	0.060
Rstack Ohms	36.981	38.905	46.445	48.756	46.296	49.020	50.900	62.651	60.819
in	0.377	0.364	0.474	0.498	0.463	0.490	0.500	0.602	0.585
Efficiency per cell	0.39	0.42	0.88	0.38	0.90	0.68	0.84	1.04	3.98
Delta Nt/(min*Volt)	2.70E-05	2.51E-05	1.73E-05	1.29E-05	2.15E-05	1.55E-05	1.57E-05	1.34E-05	1.42E-05
m=Fr/Fp	6.667	6.667	10.211	11.353		10.722	10.722	11.663	11.863
Dil Balance	0.345	0.394	0.529	0.029	0.000	0.632	0.544	0.602	1.486
Conc Balance	1.002	1.007	0.932	0.965	3.282	1.011	0.956	0.919	0.641
Average Concentration	0.013	0.012	0.018	0.017	0.021	0.021	0.020	0.019	0.024
Demin fraction 1pass	0.107	0.126	0.114	0.008	0.122	0.112	0.092	0.081	0.294
Demin fraction tot	0.710	0.720	0.723	0.691	0.651	0.695	0.678	0.686	0.698

ED Demonstration Water Analyses

	Original Feed	Feed 1	Diluate 1	Concentrate 1	Feed 2	Diluate 2	Concentrate 2	Diluate 3
	1 O-Mar-95					14-Mar-95		1-Jul-95
Cations								
Aluminum	3.9E-1	6.9E-1	3.9E-1	1.7E+0	7.3E-1	3.0E-1	1.8E+0	
Ammonium				-		-		
Calcium	1.8E+2	2.1E+2	9.2E+1	5.9E+2	2.0E+2	6.0E+1	6.0E+2	4.8E+1
Copper			.					
Hydrogen	2.4E-8	2.4E-8	1.7E-7	1.2E-6	2.4E-8	4.2E-8	1 .OE-6	5.8E-7
Ferrous	1.9E-2		.	9.1E-1				.
Ferric								.
Magnesium	8.5E+1	8.4E+1	5.0E+1	2.9E+2	8.2E+1	3.6E+1	2.9E+2	2.6E+1
Manganese	8.1 E-2	I.IE-1	6.0E-2	3.0E-1	7.0E-2		2.0E-1	
Potassium	4.8E+0	4.0E+0	2.6E+0	9.3E+0	3.7E+0	2.1E+0	8.9E+0	2.6E+0
Sodium		1.4E+2	1.2E+2	2.2E+2	1.6E+2	1.2E+2	2.8E+2	1.1E+2
Anions								
Bicarbonate	1.9E+2	1.7E+2	1.3E+2	2.0E+0	1.6E+2	1.1E+2	1.2E+2	8.1 E+0
Carbonate	-	-	-			-	-	-
Chloride	5.6E+2	7.6E+2	2.4E+2	2.0E+3	6.8E+2	1.7E+2	2.2E+3	1.1E+2
Fluoride	-	-	-	-		.	-	-
Iodide		-	-	.				-
Hydroxide	4.2E-7	1 .OE-14	6.0E-8	8.3E-9	4.2E-7	2.4E-7	9.5E-9	1.7E-8
Nitrate	1.1E+1	9.7E+0	3.7E+0	4.2E+1	9.1 E+0	2.5E+0	5.2E+1	.
Phosphate (3)	-	-	-		-	-	-	-
Phosphate (2)		-	-		-			
Phosphate (1)		-	-			-		-
Sulfate	2.3E+2	2.6E+2	2.3E+2	1.3E+3	2.6E+2	6.6E+0	5.0E+2	2.2E+2
Bisulfate		-	-		.	.		.
Sulfite		-	-	-	-			
Bisulfite			-	-	-	.		-
Sulfide								.
Totals mg/L	991	1200	604	3344	1109	289	2872	336
TDS reported mg/L:	1420	1700	970	4200	1700	790	5000	613
Conductivity		2.560	1.813	6.240	2.610	1.256	6.88	0.974
Eq/mS/cm		1.2E-2	7.7E-3	1.4E-2	1.1E-2	5.5E-3	1.1E-2	8.0E-3

Appendix A: ED Data

Nitrate Removal Data

Date	10-Mar 15:30	10-Mar 16:30	11-Mar 8:30	11-Mar 12:00	12-Mar 14:00	13-Mar 12:45	14-Mar 6:00	14-Mar 16:00
Well	7.3	6.4	5.6	5.7	5.6	5.4	6.4	5.5
Diluate	3.2	3.1	2.9	2.4	2.1	2.4	2.5	1.6
Concentrate	22.1	16.2	10.4	20	18	17	19.5	16.8

Turbidity Data

	10-Mar 10:30	10-Mar 13:30	11-Mar 9:30	11-Mar 15:50	12-Mar 14:00	13-Mar 8:00	14-Mar 8:00	14-Mar 16:00
Well	15.3	6.6	6.9	6.1	5.3	7.2	3	6
Pressure Clarifier	3.1	1.4	0.5	1.6	0.9	0.4	4	3
Pressure Multi Media Filter	0.8	0.6	0.2	0.7	0.2	0.2	0.2	2

APPENDIX B

Reverse Osmosis Test Data

Maricopa Groundwater Treatment Study

Maricopa Groundwater Treatment Study Reverse Osmosis Test Data

Appendix B

Elapsed Time (hours)	Flowrates Feed (L/min)	Reject (L/min)	Permeate Stage 1/1 (L/min)	Permeate Stage 1/2 (L/min)	Permeate Stage 2 (L/min)	Conductivity Feed (uS/cm)	Reject (uS/cm)	Permeate Stage 1/1 (uS/cm)	Permeate Stage 1/2 (uS/cm)	Permeate Stage 2 (uS/cm)	Pressure Feed (lb/in2)	Interstage (lb/in2)	Reject (lb/in2)	Temperature Feed (deg F)	Feed (deg C)	Turbidity Feed - after cart. filter (ntu)
1.0	22.4	3.9	7.7	7.6	4.0	2600	13360	43	41	101	203	176	169	84.3	29.1	0.184
2.3	22.1	3.6	7.6	7.5	4.3	2610	13440	47	42	106	202	178	168	85.3	29.6	0.110
25.8	21.6	3.7	7.4	6.8	3.6	2620	13040	50	42	105	200	176	167	82.4	28.0	0.071
45.2	20.6	3.5	7:0	6.7	3.5	2680	12700	45	40	101	202	179	169	78.3	25.7	0.088
46.8	21.1	3.7	7.1	6.7	4.1	2660	13110	45	40	105	203	180	170	80.6	27.0	0.084
40.4	21.1	3.5	7.3	7.0	4.0	2660	13300	47	41	109	200	177	167	82.5	28.1	0.080
51.1	21.4	3.5	7.4	7.2	4.2	2670	13400	46	40	109	200	177	167	83.2	28.4	0.074
67.8	20.8	3.6	a.7	6.4	3.5	2670	13170	49	42	108	200	177	167	79.2	26.2	0.125
70.8	21.3	3.5	6.9	6.7	3.7	2690	13330	48	42	112	198	175	165	81.9	27.7	0.078
72.9	21.8	3.4	7.2	7.0	3.7	2690	13560	47	42	114	200	176	166	S3.7	28.7	0.068
74.8	22.1	3.5	7.6	7.4	4.1	2690	13620	48	42	116	202	177	167	64.2	29.0	0.082
95.3	22.0	3.6	7.7	7.4	4.3	2600	13300	43	38	a4	210	184	174	80.8	27.1	0.088
96.3	22.4	3.6	7.8	7.5	4.2	2580	13400	43	29	86	210	184	174	61.8	27.7	0.084
98.1	22.6	3.6	7.8	7.6	4.5	2570	13420	43	38	102	209	183	173	62.4	28.0	0.061
99.3	22.8	3.6	7.6	7.6	4.4	2570	13470	43	38	91	209	183	173	83.9	28.8	0.054
114.6	21.7	3.6	7.5	7.3	4.3	2550	12890	40	35	93	212	186	176	77.6	25.3	0.054
118.8	22.6	3.5	7.6	7.4	4.2	2610	13560	44	32	104	209	183	173	61.4	27.4	0.052
123.0	22.6	3.6	7.9	7.6	3.9	2700	13780	44	39	106	210	164	174	83.9	28.8	0.048
162.6	21.0	3.6	7.2	6.8	3:s	2750	13530	42	38	78	216	190	181	74.3	23.5	0.045
165.6	20.9	is	7.0	6.9	4.2	2750	13290	36	32	64	207	182	174	77.0	25.0	0.045
168.1	21.2	3.4	7:0	6.6	4.0	2670	13360	35	39	83	206	181	172	76.9	24.9	0.042
171.1	22.1	3.6	7.6	7.4	4.0	2720	13530	35	31	84	210	183	173	79.7	28.5	0.048
185.9	21.4	3.6	7.1	6.8	3.9	2680	13000	33	29	72	217	190	180	73.4	23.0	0.043
lw.e	21.5	3.8	7.3	6.9	4.6	2680	13050	33	32	78	216	188	178	75.8	24.3	0.043
191.6	21.6	3.7	7.3	7.1	4.6	2690	13090	34	31	83	214	187	177	76.5	24.7	0.041
194.1	21.6	3.7	7.3	7.0	4.5	2690	13110	35	32	a4	216	188	177	76.9	24.8	0.042
211.1	22.1	3.7	7.3	6.7	4.2	2630	13130	39	27	77	219	191	181	74.1	23.4	0.055
215.1	22.1	3.6	7.6	7.1	4.6	2630	13190	35	31	95	206	in	169	S0:5	26.9	0.053
218.1	22.3	3.6	7.3	7.1	4.4	2620	13450	39	30	91	207	179	169	81.6	27.6	0.042
233.8	22.0	3.0	6.6	6.2	3.3	2610	13070	32	30	81	216	186	178	76.8	24.4	0.046
237.1	21.6	3.6	7.0	6.7	4.1	2610	13050	33	32	86	210	IS2	172	77.4	25.2	0.045
241.1	22.8	3.6	7.4	7.2	4.4	2680	13590	40	31	99	210	180	170	82.0	27.8	0.048
258.1	21.8	3.7	6.4	6.3	3:s	2660	13190	33	37	100	214	185	174	75.6	24.2	0.040
261.1	21.6	3.6	6.8	6.7	4.1	2670	13230	33	25	105	210	181	172	77.6	25.3	0.046
288.1	23.0	3.6	7.5	7.1	4.2	2650	13380	46	42	118	209	179	169	84.2	29.0	0.068
284.6	22.2	3.6	6.6	6.8	4.1	2710	13850	35	32	94	210	183	173	78.8	26.0	0.045
267.1	22.5	3.6	6.9	6.9		2720	13710	37	32	97	209	181	171	81.7	27.6	0.041
290.1	22.9	3.5	7.4	7.2	1::	2720	13710	48	36	100	207	179	169	85.0	29.4	0.036
294.1	23.0	3.6	7.7	7.4	4.5	2710	13740	37	34	103	207	178	168	85.9	29.9	0.039
307.3	22.0	3.6	6.6	6.7	3.8	2690	13390	35	32	86	211	164	174	79.2	26.2	0.036
314.3	23.1	3.6	7.4	7.2	4.3	2710	13900	47	42	95	205	177	167	85.0	29.4	0.050
331.1	24.4	3.2	7.4	7.4	4.4	2640	14890	34	30	a4	236	204	195	76.7	24.0	0.041
3421	22.4	3.2	7.4	7.4	3.4	2530	14190	48	39	121	199	165	156	84.6	29.2	0.392
354.6	21.8	3.6	6.6	6.2	3.7	2510	13350	35	32	80	210	175	166	81.1	27.3	0.125
360.1	21.1	3.3	6.6	6.7	4.3	2290	13110	38	32	83	201	163	153	84.1	28.9	0.300
366.1	21.9	3.5	6.8	a.3	3.8	2520	13610	39	34	101	206	168	159	84.3	29.1	0.057
378.6	21.1	3.6	6.9	a.4	4:0	2500	13900	35	32	88	208	172	163	61.0	27.2	0.041
385.5	22.2	3.5	7.3	6.9	4.2	2550	13640	38	34	98	205	171	161	86.3	30.2	0.042
587.0	22.7	3.7	7.2	6.7	3.6	2560	13450	38	34	98	207	171	161	86.3	30.2	0.036
404.6	22.5	3.8	7.3	6.9	4.4	2550	13280	34	30	85	215	180	169	80.9	27.2	0.035
405.6	22.6	3.6	7.6	7.1	4.6	2540	13550	37	32	92	214	181	168	82.4	26:0	0.041
408.4	226	3.5	7:0	6.6	4.3	2500	13490	38	34	103	207	166	157	65.6	26.6	0.042

Appendix B Maricopa Groundwater Treatment Study Reverse Osmosis Test Data

Page 2

Elapsed Time (hours)	Flowrates: Feed (L/min)	Flowrates: Reject (L/min)	Flowrates: Permeate Stage 1/1 (L/min)	Flowrates: Permeate Stage 1/2 (L/min)	Flowrates: Permeate Stage 2 (L/min)	Conductivity: Feed (uS/cm)	Conductivity: Reject (uS/cm)	Conductivity: Permeate Stage 1/1 (uS/cm)	Conductivity: Permeate Stage 1/2 (uS/cm)	Conductivity: Permeate Stage 2 (uS/cm)	Pressure: Feed (lb/in2)	Pressure: Interstage (lb/in2)	Pressure: Reject (lb/in2)	Temperature: Feed (deg F)	Temperature: Feed (deg C)	Turbidity: Feed - after cart. filter (ntu)
409.8	22.8	3.5	7.5	7.1	4.5	2500	13420	40	37	105	211	170	161	87.0	30.6	0.036
426.4	21.8	3.6	7.0	6.9	4.4	2520	13000	35	32	88	210	173	163	81.1	27.3	0.051
430.2	22.4	3.5	9.0	8.7	4.7	2450	13050	46	91	90	209	170	161	84.2	29.0	0.036
433.1	23.2	3.6	7.4	6.2	4.5	2390	12480	34	31	89	210	167	157	87.2	30.7	0.114
433.6	23.9	3.6	7.9	7.6	3.7	2380	12790	34	30	90	211	170	160	87.5	30.8	0.092
450.6	22.1	3.7	6.7	6.5	4.3	2360	12380	34	30	82	208	166	157	81.3	27.4	0.044
453.5	23.6	3.6	7.6	7.2	4.2	2340	12180	32	29	81	210	170	160	83.3	28.5	0.133
455.8	23.8	3.6	7.8	7.3	4.6	2380	12870	32	30	87	210	170	160	85.2	29.6	0.067
456.5	24.1	3.6	7.8	7.4	4.8	2360	12940	37	33	95	210	169	159	87.0	30.6	0.057
475.0	18.2	3.6	6.9	5.4	3.5	2360	11830	37	50	95	209	150	140	81.3	27.4	0.125
478.2	19.3	3.6	6.2	4.7	3.3	2370	11330	36	46	96	210	146	137	83.5	28.6	0.098
480.6	20.1	3.6	6.2	5.4	3.8	2380	11020	38	44	101	210	145	136	86.3	30.2	0.066
481.7	20.4	3.5	6.5	5.1	3.7	2370	11770	38	46	106	211	146	137	87.8	31.0	0.066
499.3	19.7	3.4	6.2	5.0	3.4	2370	11830	34	40	91	210	151	142	81.3	27.4	0.294
501.8	20.2	3.4	6.1	5.9	3.2	2300	12000	35	33	91	210	154	145	83.2	28.4	0.124
505.6	21.0	3.4	6.6	6.2	3.8	2280	12280	35	35	96	210	154	145	85.3	29.6	0.121
506.1	21.1	2.4	6.5	6.2	3.1	2280	12290	35	36	95	210	154	144	85.3	29.6	0.126
524.4	16.2	3.1	6.2	4.4	3.4	2270	11660	33	43	91	211	145	136	80.4	26.9	0.154
526.6	16.4	3.1	5.9	4.4	3.2	2270	llwo	35	48	94	211	143	135	81.6	27.6	0.127
529.4	18.1	3.2	6.2	4.7	2.8	2280	11920	34	45	96	210	147	139	83.0	28.3	0.095
532.4	10.3	3.1	6.1	5.6	2.5	2300	11950	34	42	96	210	148	139	82.8	28.2	0.092
547.0	17.7	3.1	6.0	5.5	2.9	2290	11290	33	41	91	207	143	135	78.1	25.6	0.057
550.8	18.2	3.8	5.4	4.3	3.1	2320	10520	35	44	90	209	141	131	81.1	27.3	0.079
579.1	16.7	3.5	5.6	4.5	3.0	2420	11290	35	42	90	210	145	136	78.2	25.7	0.056
582.1	18.2	3.5	5.7	4.8	3.0	2430	11380	36	43	94	208	143	134	79.9	26.6	0.060
584.6	19.2	3.6	6.0	5.2	3.3	2220	10520	35	40	90	210	141	132	82.0	27.8	0.177
587.3	19.2	3.6	6.2	5.3	3.3	2370	11250	36	42	96	210	142	133	83.4	28.6	0.069
595.1	10.1	3.6	5.9	5.3	3.4	2340	11160	35	39	89	210	146	137	79.2	26.2	0.053
597.8	10.3	3.7	6.2	5.5	3.5	2340	11050	36	40	92	210	145	135	81.7	27.6	0.048
600.3	le.7	3.6	6.5	5.7	3.9	2330	11300	36	40	96	209	143	133	84.3	29.1	0.050
602.6	20.3	3.6	6.8	5.9	3.7	2310	11150	37	41	100	210	143	133	86.2	30.1	0.052
618.1	19.6	3.6	6.6	5.8	3.8	2290	11140	35	38	91	210	145	135	79.9	26.6	0.061
621.6	19.8	3.6	6.6	5.6	3.9	2290	11090	36	39	92	210	144	134	82.7	28.2	0.047
626.4	21.0	3.7	7.1	6.2	3.8	2150	10460	36	39	94	210	140	130	87.3	30.7	0.081
643.1	20.3	3.6	6.8	6.0	3.9	2170	10650	34	37	90	210	144	135	80.5	26.9	0.053
647.6	20.4	3.6	6.4	5.8	3.5	2170	llooo	35	36	91	210	143	134	83.5	28.6	0.039
651.1	20.2	3.6	6.4	5.7	3.6	2170	11020	34	35	91	210	143	135	86.2	30.1	0.051
666.8	20.0	3.6	6.3	5.7	3.7	2130	10810	33	36	86	210	144	134	80.4	26.9	0.062
669.3	20.2	3.6	6.3	5.7	3.7	2130	10640	34	36	86	210	144	134	82.5	26.1	0.055
693.6	19.6	3.6	6.3	5.5	3.7	2170	10390	33	37	85	210	144	134	80.4	26.9	0.061
695.6	10.5	3.6	6.2	5.5	3.6	2180	10530	34	38	88	210	143	133	81.4	27.4	0.047
696.6	20.4	3.6	6.4	5.6	3.7	1930	9550	32	35	81	210	140	130	83.0	28.3	0.156
699.8	20.2	3.6	6.2	5.5	3.6	2140	10480	34	37	88	210	142	132	82.1	27.8	0.062
714.1	18.6	3.6	6.0	5.2	3.6	2190	10070	31	34	76	210	148	138	73.8	23.2	0.058
717.3	18.7	3.6	6.1	5.4	3.6	2220	10330	32	35	80	210	147	137	76.3	24.6	0.053
719.8	10.1	3.6	6.0	5.4	3.4	2320	10970	34	37	89	210	146	136	78.4	25.8	0.046
722.3	19.3	3.6	6.2	5.4	3.7	2390	11220	37	40	95	210	145	135	79.9	26.6	0.050
741.1	16.0	3.6	4.6	3.3	2.3	2400	10280	34	79	86	210	138	129	72.5	22.5	0.099
744.1	17.3	3.6	5.1	3.6	2.2	2460	10700	37	111	95	210	138	129	76.4	24.7	0.061
747.1	18.0	3.4	6.2	4.7	3.5	2130	9580	35	91	91	210	133	124	79.3	26.3	0.066
763.1	16.0	3.4	6.1	4.4	3.4	2460	10270	34	73	85	210	139	130	71.9	22.2	0.064
765.1	15.4	3.4	6.0	3.7	3.3	2460	9930	35	99	87	210	136	127	73.3	22.9	0.045
767.1	15.6	3.4	6.0	3.9	2.5	2460	10090	36	100	91	210	136	127	75.1	23.9	0.059
769.1	16.0	3.4	5.8	3.7	3.0	2480	10410	36	93	90	210	136	127	74.5	23.6	0.054

Maricopa Groundwater Treatment Study
Reverse Osmosis Test Data

Page 3

Elapsed Time (hours)	--- Delta P ------ Stage 1 (lb/in2)	Stage 2 (lb/in2)	Temperature Correction Factor (TCF)	Inverse Temp. Correction Factor (1/TCF)	Average Feed Pressure (lb/in2)	------- Concentration Feed Cf (mg/L)	Reject Cr (mg/L)	-------- Average (Cf+Cr)/2 (mg/L)	Average Osmosis Pressure (lb/in2)	Average Net Driving Pressure (lb/in2)	Normalized Permeate Flow (L/min)
1.0	25	9	1.126	0.888	186.0	1492	7664	4578	45.8	146.2	11.1
2.3	24	10	1.145	0.874	185.0	1473	7587	4530	45.3	139.7	17.0
25.8	24		1.092	0.915	183.6	1550	7714	4632	46.3	137.2	16.7
45.2	23	1x	1.022	0.078	185.5	1682	8032	4857	48.6	136.9	17.2
46.8	23	10	1.061	0.943	186.5	1620	7985	4803	48.0	138.5	17.1
49.4	23	10	1.094	0.914	163.5	1571	7855	4713	47.1	136.4	17.2
51.1	23	10	1.107	0.904	103.5	1559	7825	4692	46.0	136.6	17.4
67.8	23	10	1.037	0.964	183.5	1664	8207	4936	49.4	134.1	16.7
70.6	23	10	1.083	0.923	161.5	1604	7949	4777	47.5	133.7	16.7
72.9	24	10	1.115	0.896	183.0	1558	7854	4706	47.1	135.9	16.6
74.9	25	10	1.125	0.889	184.5	1546	7826	4686	46.9	18.6	11.3
95.3	26	10	1.064	0.940	182.0	1578	8074	4826	46.3	143.7	17.0
96.3	26	10	1.083	0.923	192.0	1539	7991	4765	47.6	144.4	17.5
98.1	26	10	1.092	0.915	181.0	1520	7938	4729	47.3	143.7	17.8
99.3	26	10	1.119	0.894	191.0	1484	7777	4631	46.3	144.7	11.1
114.6	26	10	1.010	0.990	194.0	1631	8247	4939	40.4	144.8	18.3
118.6	26	10	1.075	0.930	191.0	1569	8152	4861	48.6	142.4	17.6
123.8	26	10	1.110	0 . 0	192.0	1559	7956	4758	47.6	144.4	16.8
162.6	25	9	0.951	1.041	198.0	1849	9097	5473	54.7	143.3	17.9
165.6	25	8	1.000	1.000	180.6	1777	8567	5162	51.1)	135.7	16.3
168.1	25	9	0.999	I.061	169.0	1728	8645	5186	51.8	137.1	16.0
171.1	27	10	1.045	0.957	181.5	1681	8363	5022	50.2	141.3	16.2
165.0	27	10	0.948	1.055	198.5	1827	8860	5344	53.4	145.1	16.1
186.9	27	10	0.983	1.018	106.5	1762	8581	6171	51.7	144.6	18.4
181.6	27	10	0.993	1.007	195.5	1751	8519	5135	51.4	144.1	18.6
194.1	28	11	0.999	I.001	196.5	1741	8483	6112	61.1	le.4	18.2
211.1	28	10	0.958	1.044	200.0	1774	8855	5314	53.1	146.9	16.1
215.1	28	9	1.059	0.944	187.5	1604	8047	4826	48.3	139.2	15.4
218.1	28	10	1.078	0.927	188.0	1570	8060	4815	48.1	139.9	17.5
233.8	28	10	0.984	1.016	107.0	1714	8581	5147	51.5	145.6	15.8
237.1	28	10	1.007	0.993	191.0	1675	8377	5026	50.3	140.7	17.6
241:1	30	10	1.085	0.021	190.0	1584	8091	4837	48.4	141.6	17.3
258.1	29	11	0.980	1.021	101.0	1754	8698	5226	52.3	141.7	16.6
261.1	29	9	1.010	0.990	101.0	1708	8464	5086	50.9	140.1	17.4
266.1	30	10	1.125	0.889	189.0	1523	7688	4605	46.1	1429	16.4
284.6	27	10	1.030	0.971	191.5	1700	8688	5194	51.9	139.6	17.3
287.1	28	10	1.080	0.926	190.0	1627	8202	4915	49.1	140.8	16.5
286.1	28	10	1.139	0.878	188.0	1543	7777	4660	46.6	141.4	16.6
294.1	29	10	1.156	0.05	187.5	1515	7683	4599	46.0	141.5	16.8
307.3	27	10	1.037	0.964	192.5	1676	8344	5010	50.1	142.4	16.4
314.3	28	10	1.139	0.878	186.0	1537	7885	4711	47.1	138.9	16.8
331.1	32	9	0.996	1.004	215.5	1713	9663	5688	56.9	158.6	17.0
3421	34	0	1.132	0.884	177.5	1444	8101	4773	47.7	129.8	17.4
354.6	35		1.070	0.935	188.0	1516	8065	4791	47.9	140.1	15.5
360.1	38	1x	1.122	0.891	177.0	1318	7545	4432	44.3	1327	16.6
365.1	38	9	1.126	0.888	1526	1446	7808	4627	46.3	136.2	15.4
378.6	36	9	1.068	0.837	165.5	1513	8411	4962	i s	135.9	16.7
385.5	34	10	1.163	0.860	183.0	1417	7578	4497	45.0	138.0	16.1
367.0	36	10	1.163	0.860	184.0	1422	7473	4447	44.5	139.5	15.1
404.6	35	11	1.066	0.938	162.0	1546	8049	4797	48.0	144.0	17.0
405.6	33	13	1.092	0.915	191.0	1502	8015	4758	47.6	143.4	17.3
408.4	41	9	1.154	0.867	1520	1400	7555	4470	44.8	137.2	15.9

Appendix B Maricopa Groundwater Treatment Study

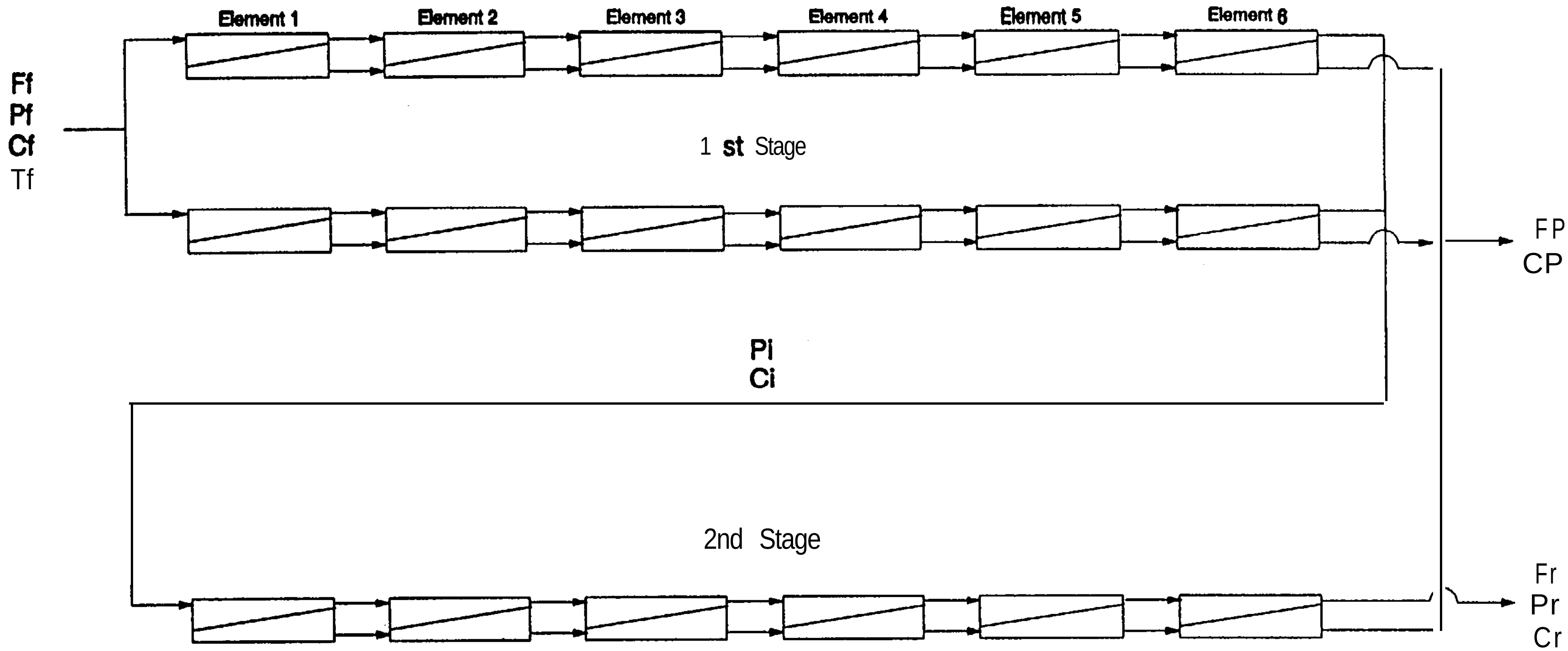
Elapsed Time (hours)	--- Delta P ------ Stage 1 (lb/in2)	Stage 2 (lb/in2)	Temperature Correction Factor (TCF)	Inverse Temp. Correction Factor (1/TCF)	Average Feed Pressure (lb/in2)	------- Concentration Feed Cf (mg/L)	Reject Cr (mg/L)	-------- Average (Cf+Cr)/2 (mg/L)	Average Osmosis Pressure (lb/in2)	Average Net Driving Pressure (lb/in2)	Normalized Permeate Flow (L/min)
409.8	41	9	1.176	0.850	186.0	1374	7373	4373	43.7	1423	16.0
426.4	37	10	1.070	0.935	186.5	1522	7854	4688	46.9	139.6	17.2
430.2	39	9	1.125	0.889	185.0	1408	7498	4453	44.5	140.5	19.9
433.1	43	10	1.180	0.848	183.5	1309	6835	4072	40.7	1428	15.1
433.6	41	10	1.186	0.844	185.5	1297	6971	4134	41.3	144.2	15.8
450.6	40	9	1.073	0.932	181.5	1421	7455	4438	44.4	137.1	16.7
453.5	40	10	1.108	0.902	105.0	1364	7101	4232	42.3	142.7	16.8
455.8	40	10	1.143	0.875	155.0	1346	7277	4312	U.l	141.8	17.2
458.5	41	10	1.176	0.850	184.5	1308	7110	4209	42.1	1424	16.7
475.0	59	10	1.073	0.932	174.6	1433	7124	4278	42.6	131.7	16.7
478.2	64	9	1.112	0.899	173.5	1377	6584	3981	39.8	133.7	13.4
480.6	65	9	1.163	0.860	173.0	1322	6456	3889	38.9	134.1	13.8
481.7	65	9	1.191	0.840	174.0	1286	6385	3835	38.4	135.6	13.3
499.3	59	9	1.073	0.932	178.0	1427	7124	4275	42.8	133.2	14.3
501.8	56	9	1.107	0.904	177.5	1343	7007	4175	41.8	135.7	14.2
505.6	56	9	1.145	0.874	177.5	1287	6933	4110	41.1	136.4	14.9
508.1	56	10	1.145	0.874	177.0	1287	6938	4113	41.1	135.9	14.2
524.4	66	9	1.057	0.946	173.6	1387	7125	4256	42.6	130.9	14.2
526.6	68	8	1.078	0.027	173.0	1360	6939	4150	41.5	131.5	13.4
529.4	63	8	1.103	0.907	174.5	1336	6983	4159	41.6	132.9	13.1
532.4	62	9	1.099	0.910	174.5	1352	7023	4187	41.9	132.6	13.7
547.0	64	8	1.018	0.982	171.0	1453	7164	4308	43.1	127.9	15.5
550.8	68	10	1.070	0.935	170.0	1402	6356	3879	38.8	131.2	128
579.1	65	9	1.020	0.980	173.0	1533	7152	4343	43.4	129.6	13.9
582.1	65	9	1.049	0.953	171.0	1497	6992	4245	42.4	128.6	14.0
584.6	69	9	1.085	0.921	171.0	1322	6263	3793	37.0	133.1	14.1
587.3	68	9	1.110	0.901	171.5	1370	6548	3964	39.6	131.9	14.2
595.1	64	9	1.037	0.964	173.5	1456	6955	4206	42.1	131.4	15.0
597.8	65	10	1.080	0.926	172.5	1400	6611	4005	40.1	132.4	14.8
600.3	66	10	1.126	0.888	171.0	1337	6483	3010	39.1	131.8	15.2
602.6	67	10	1.161	0.861	171.5	1285	6205	374s	37.5	134.0	14.0
618.1	65	10	1.049	0.953	172.5	1411	6863	4137	41.4	131.1	16.5
621.6	66	10	1.098	0.811	172.0	1340	6526	3938	30.4	132.6	15.7
626.4	70	10	1.182	0.846	170.0	1176	5720	3448	34.5	135.5	15.0
643.1	66	9	1.059	0.944	172.5	1324	6619	3972	39.7	132.8	16.7
647.6	67	9	1.112	0.899	1720	1261	6392	3027	38.3	133.7	14.8
651.1	67	8	1.161	0.861	172.6	1208	6132	3670	36.7	135.8	14.0
666.8	66	10	1.057	0.946	172.0	1302	6606	3954	39.5	132.5	15.7
669.3	66	10	1.094	0.914	172.0	1258	6284	3771	37.7	134.3	15.0
693.6	66	10	1.057	0.946	1720	1328	6349	3838	38.4	133.0	IS.4
695.6	67	10	1.075	0.930	171.6	1311	6331	3821	50.2	133.3	15.0
698.6	70	10	1.103	0.907	170.0	1131	5595	3363	33.6	138.4	14.1
699.8	68	10	1.087	0.920	171.0	1272	6229	3751	37.5	133.5	14.8
714.1	62	10	0.954	1.043	174.0	1484	6822	4153	41.5	132.5	16.4
717.3	63	10	0.990	1.010	173.5	1449	6743	4096	41.0	132.5	16.1
710.8	64	10	1.023	0.977	173.0	1465	6926	4196	42.0	131.0	15.5
722.3	65	10	1.049	0.953	172.1	1472	6912	4192	41.0	130.6	15.7
741.1	72	9	0.935	1.070	169.5	1659	7090	4374	43.7	125.8	122
744.1	72	9	0.991	1.009	169.5	1603	6974	4289	42.9	126.6	124
747.1	77	9	1.039	0.963	107.0	1325	5960	3643	36.4	130.6	14.0
763.1	71	9	0.926	1.080	170.0	1730	7164	4447	44.5	125.5	16.8
765.1	74	9	0.947	1.056	168.5	1693	6778	4236	42.4	126.1	15.3
707.1	74	9	0.973	1.028	168.5	1648	6703	4176	41.8	126.7	14.1
769.1	74	9	0.964	1.037	186.5	1662	6978	4320	43.2	125.3	14.5

APPENDIX C

Generalized RO Process Diagram For Checking Data Reduction

Maricopa Groundwater Treatment Study

Generalized RO Process Diagram for Checking Data Reduction



Ff - Flow, feed
Fr - flow, reject
Fp - flow, permeate

Cf - Conductivity, feed
Ci - Conductivity, interstage
Cr - Conductivity, reject
Cp - Conductivity, permeate

Pf - Pressure, feed
Pi - Pressure, interstage
Pr - Pressure, reject

Tf - Temperature, feed

APPENDIX D

Analytical Data For Reverse Osmosis Testing

Maricopa Groundwater Treatment Study

Appendix D

Analytical Data *for* Reverse Osmosis Testing

Maricopa Groundwater Treatment Study

			3.5-Hour Data				364-Hour Data				720-Hour Data			
			Well	Feed	Permeate	Reject	Well	Feed	Permeate	Reject (calc'd)	Well	Feed	Permeate	Reject
CATIONS														
Calcium	Ca	mg/L	190	180	0.53	900	190	190	0.47	1186.39	180	190	1.2	760
Magnesium	Mg	mg/L	81	81	0.24	290	78	77	0.28	480.33	78	79	0.55	380
Sodium	Na	mg/L	150	150	5.0	810	160	150	10	886.00	180	160	13	850
Potassium	K	mg/L	3.0	3.9	<1	21	3.9	4.7	<1	29.41	4.4	4.3	a.0	18
Aluminum	Al	mg/L	0.78	0.75	<0.20	3.3	0.65	0.61	<0.20	3.82	0.68	0.83	<0.20	2.4
Beryllium	Be	mg/L						<0.0005	<0.0005	0.00	<0.0005	<0.0005	<0.0005	<0.0005
Chromium	Cr	mg/L						0.004	<.004	0.00	0.035	0.005	<0.004	0.017
Iron	Fe	mg/L	0.34	<0.05	0.13	0.18	0.37	<0.05	<0.05	0.00	0.66	<0.05	<0.05	0.07
Manganese	Mn	mg/L	C0.05	<0.05	<0.05	0.22	<0.05	<0.05	<0.05	0.00	<0.05	<0.05	<0.05	0.08
Copper	Cu	mg/L						0.005	~0.005	0.03	0.007	9.005	<0.005	0.011
Cadmium	Cd	mg/L						<0.0005	0.0017	0.00	<0.0005	<0.0005	<0.0005	<0.0005
Mercury	Hg	mg/L					<0.001	<0.001	<0.001	0.00	<0.001	<0.001	<0.001	<0.001
Lead	Pb	mg/L						<0.005	~0.005	0.00	<0.005	<0.005	<0.005	<0.005
Antimony	Sb	mg/L						C0.004	<0.004	0.00	<0.004	<0.004	<0.004	<0.004
ANIONS														
Bicarbonate	HCO3	mg/L	160	180	12	810	160	160	15	022.29	160	160	520	360
Chloride	Cl	mg/L	820	810	8	3500	510	530	11	3258.48	520	530	15	2500
Sulfate	SO4	mg/L	250	280	<5	1700	230	230	<5	1439.14	240	240	<5	1400
Nitrate (N)	NO3 (N)	mg/L	12	8.5	<0.50	89	8.8	9	0.75	52.37	5.68	9.52	1.07	38.0
Arsenic	As	mg/L						<0.004	4.004	0.00	0.006	<0.004	<0.004	<0.004
										0.00				
Silica(total)	SiO2	mg/L					11	10	<0.21	82.57	27	25	0.35	110
Total Organic Carbon	TOC	mg/L	<0.5	1.7	1.1	5.7	a.5	<0.5	<0.5	0.00	0.8	0.7	s0.5	1.2
Standard Plate count	SPC	cfu	380	380	110	320	8400	8400	21	39935.31	1700	3600	320	19000
Alkalinity		mg/L	180	180	12	810	160	180	15	922.29	180	180	520	380
Conductivity (ops)		uS/cm		2.88		13.11		2.5		15.84		2.46		10.41
Total Dissolved Solids	TDS (sum)	mg/L	1600	1500	47	8600	1400	1400	41	8544.48	1500	1500	37	8800
Cations(Ca,Mg,Na,K)		meq/L	22.77	22.27	0.30	104.55	22.80	22.48	0.48	138.02	22.31	23.05	0.87	97.93
Anions(HCO3,Cl,SO4)		meq/L	25.32	25.88	0.37	144.12	21.80	22.36	0.58	136.99	22.29	22.57	8.94	105.57
Ratio Anions:Cations		-	1.11	1.15	1.21	1.38	0.96	1.00	1.18	0.99	1.00	0.98	13.34	1.06

RODATA.WK4

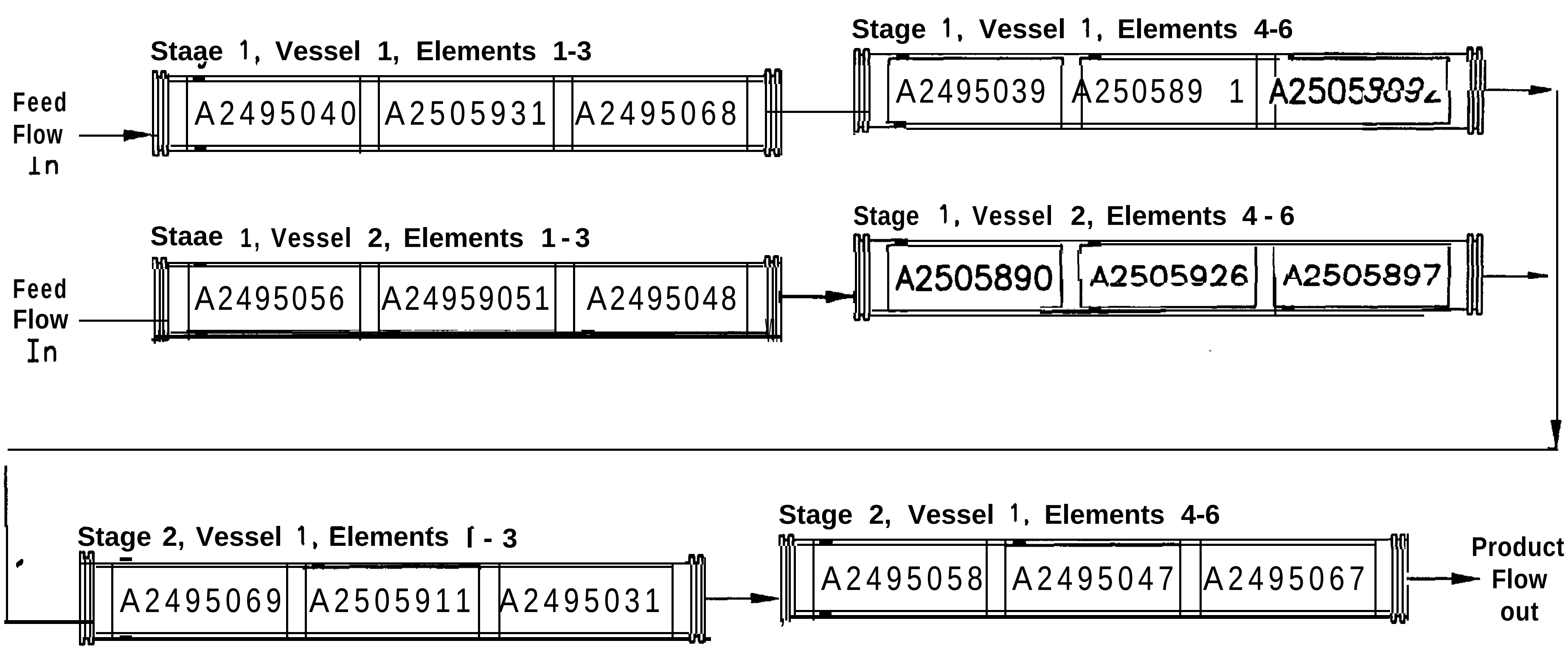
APPENDIX E

Reverse Osmosis Element Serial Numbers As Loaded
in Pressure Vessels

Maricopa Groundwater Treatment Study

Appendix E. – RO Element serial numbers as loaded in pressure vessels.

Manufacturer Fi Imtec ; Model BW30-2540 ; Date 3/14/95



APPENDIX F

Memorandum of Petrographic Examination of Used Membranes

Maricopa Groundwater Treatment Study

United States Department of the Interior

BUREAU OF RECLAMATION
Reclamation Service Center
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IN REPLY REFER TO:

D-8340
RES-3.40

NOV 7 1995

MEMORANDUM

To: Group Manager, Water Treatment Engineering and Research
Attention: R. Jurenka, D-8230

From: K. E. Krill
Geologist, Earth Sciences and Research Laboratory

Subject: Petrographic Examination of Contaminants from Used Water Treatment Membranes - Maricopa Groundwater Pilot Project - City of Avondale, Arizona

Earth Sciences and Research Laboratory Referral No. **8340-95-32**

Petrographic referral code: **95-10**

INTRODUCTION

Four samples were submitted to the Petrographic Laboratory by R. Jurenka, Water Treatment Engineering and Research Group, for examination. The samples were collected from Well No. 5 in March and April, 1995, and were labeled and identified as follows:

membrane No. 2495040, first stage element;
well-water sediment (submitted on filter paper);
scrapings from back of membrane No. 2495047; and
membrane No. 2495047, second stage element.

The purpose of the examination was to identify and/or characterize any materials which may plug the active surface of the membranes, with emphasis on any biological materials.

PETROGRAPHIC EXAMINATION AND RESULTS

Petrographic examination consisted of scanning electron microscope (SEM) and energy dispersive spectroscope (EDS) analysis of representative portions of the submitted samples. SEM photomicrographs and EDS results, consisting of qualitative elemental compositions, are included in the attached appendix 1.

Numerous types of materials to which membrane plugging may be attributable were present on the submitted samples. Two types of biological materials, diatom fragments and bacteria, were present in small amounts in the samples from the first and second stage elements, respectively. Diatom fragments are portions of silica walls secreted by these single-celled plants. Other types of particles, present in greater numbers, included:

- numerous broken fragments of cylindrically shaped, silicon-rich particles in the first stage element and in scrapings from the back of the second stage element;

- few to several irregularly shaped, iron- and chromium-rich particles in the first stage element;

- some carbon-rich filaments or strands in the first stage element; and

- numerous irregularly shaped, carbon-rich particles and particle masses in all four submitted samples which also exhibited notable silicon, sulfur, and aluminum.

Biological materials, diatom fragments and bacteria, were present in only trace to minor amounts in the first and second stage elements, and likely play only a minor role in membrane surface plugging.

K. E. Krill

Attachment

cc: D-8230 (Jurenka), D-8340 (3)

Appendix 1:

Scanning Electron Photomicrographs and

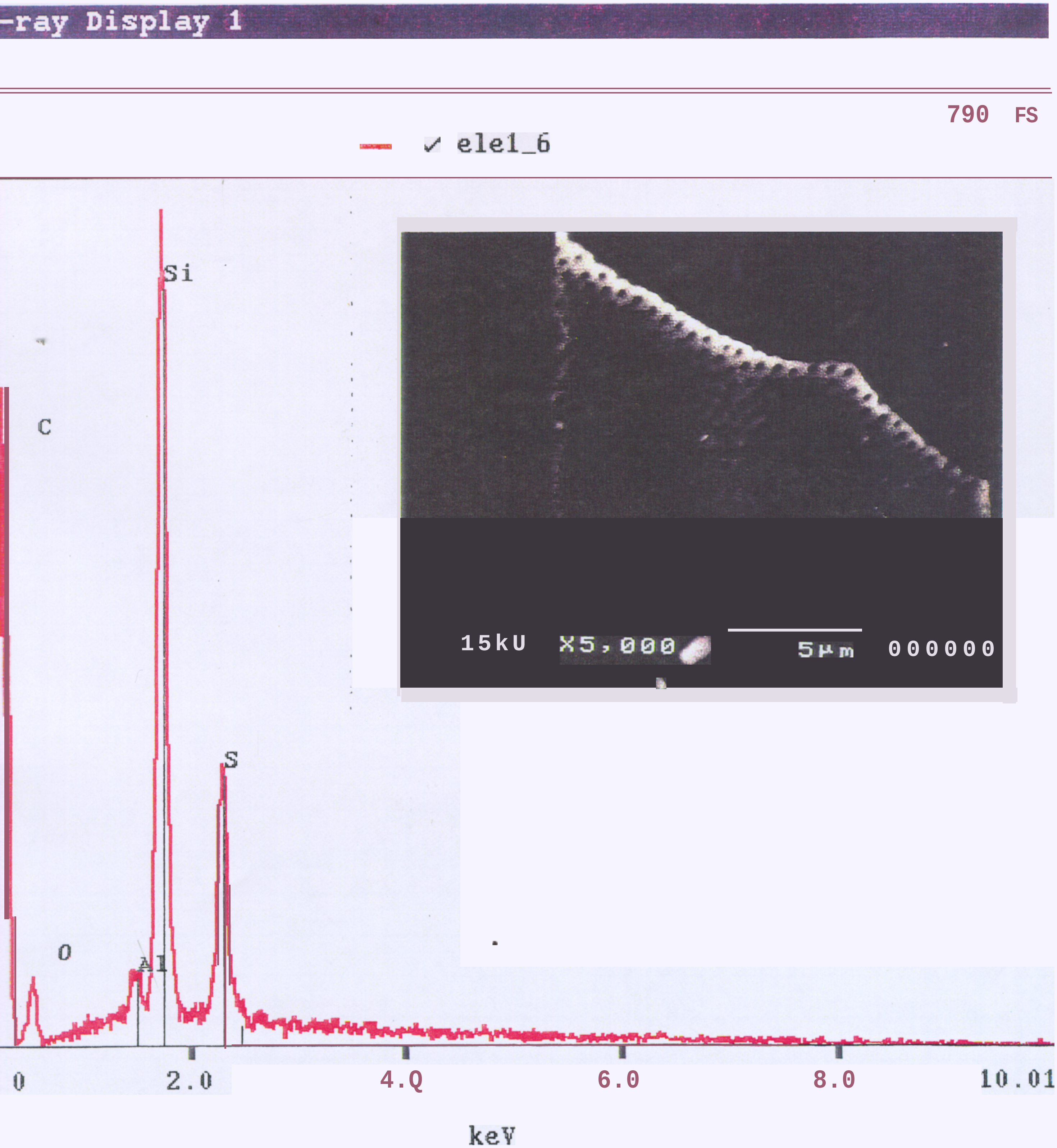
Energy Dispersive Spectra of Particles

Present in Examined Membrane Elements -

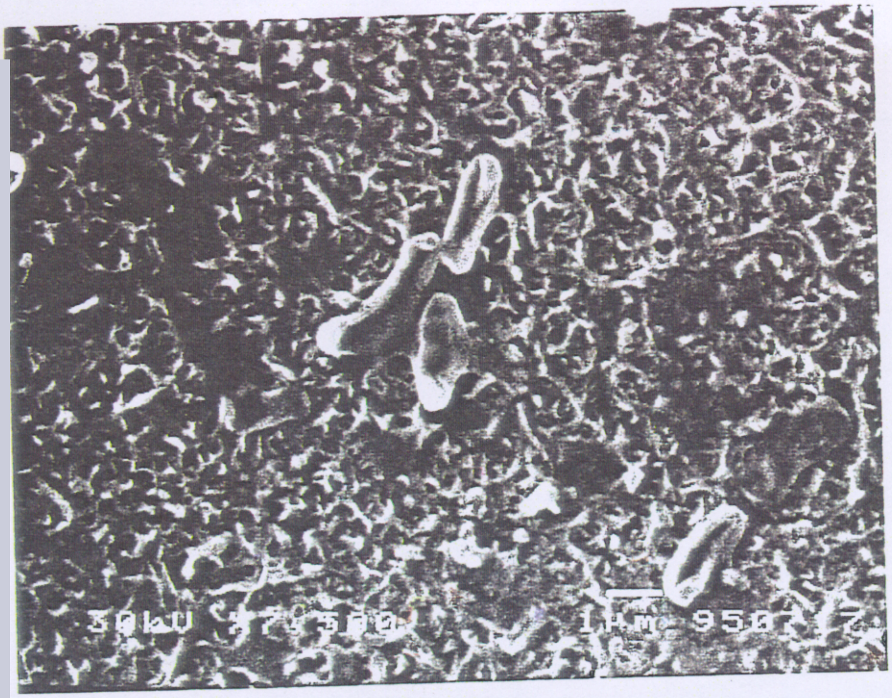
Maricopa Groundwater Pilot Project,

Well No. 5 -

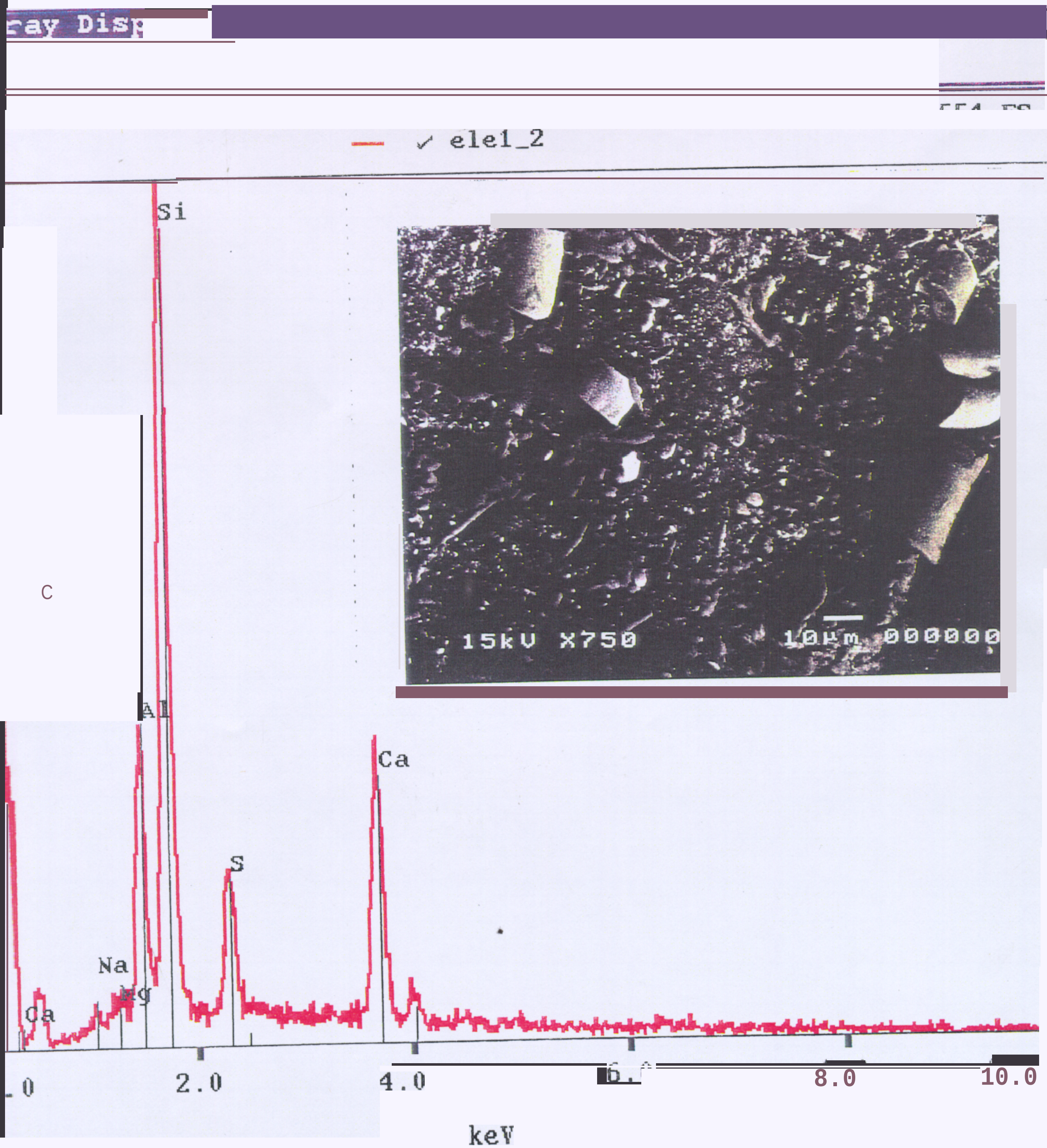
City of Avondale, Arizona



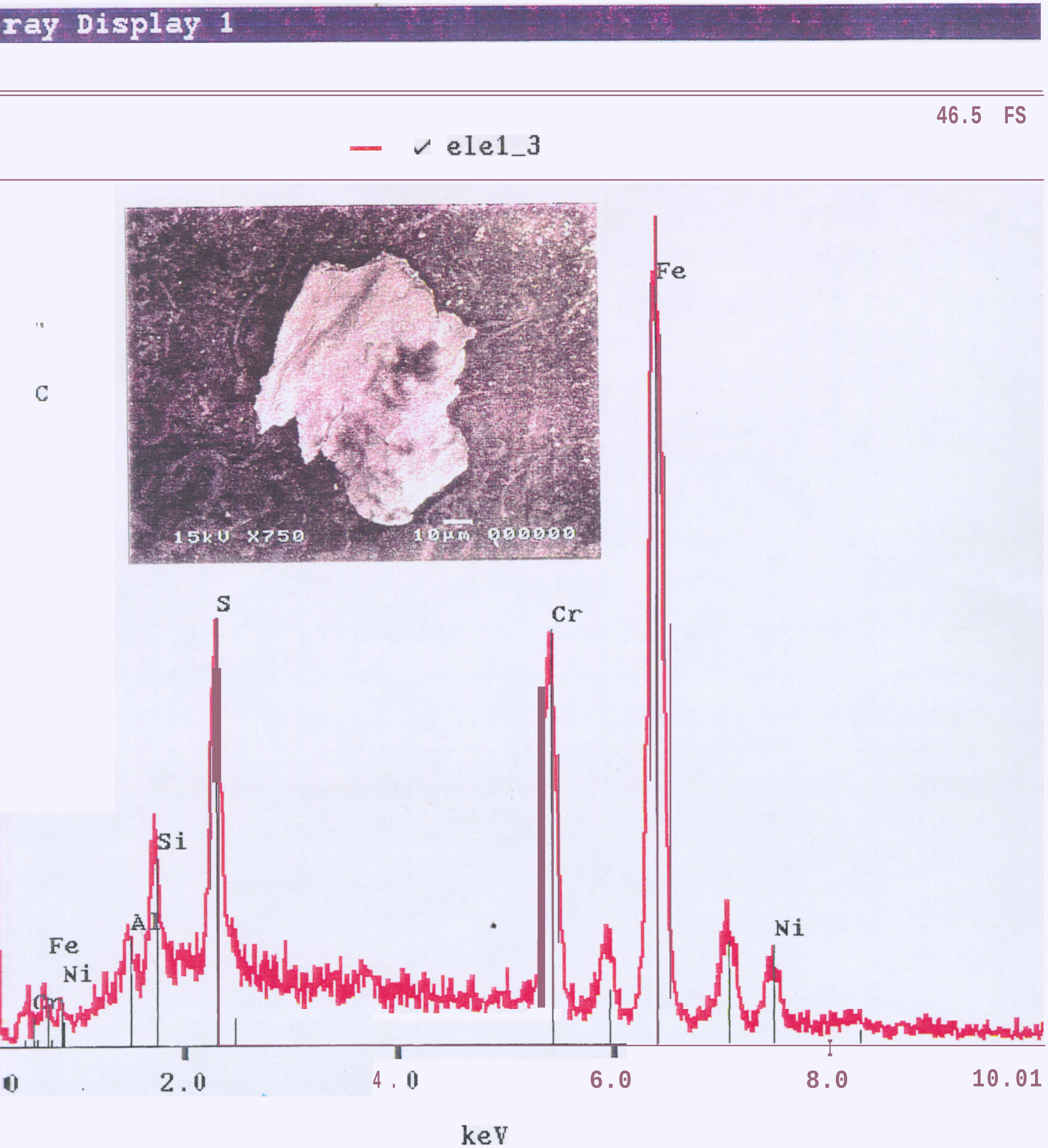
Diatom fragments were present in the examined first stage element sample.



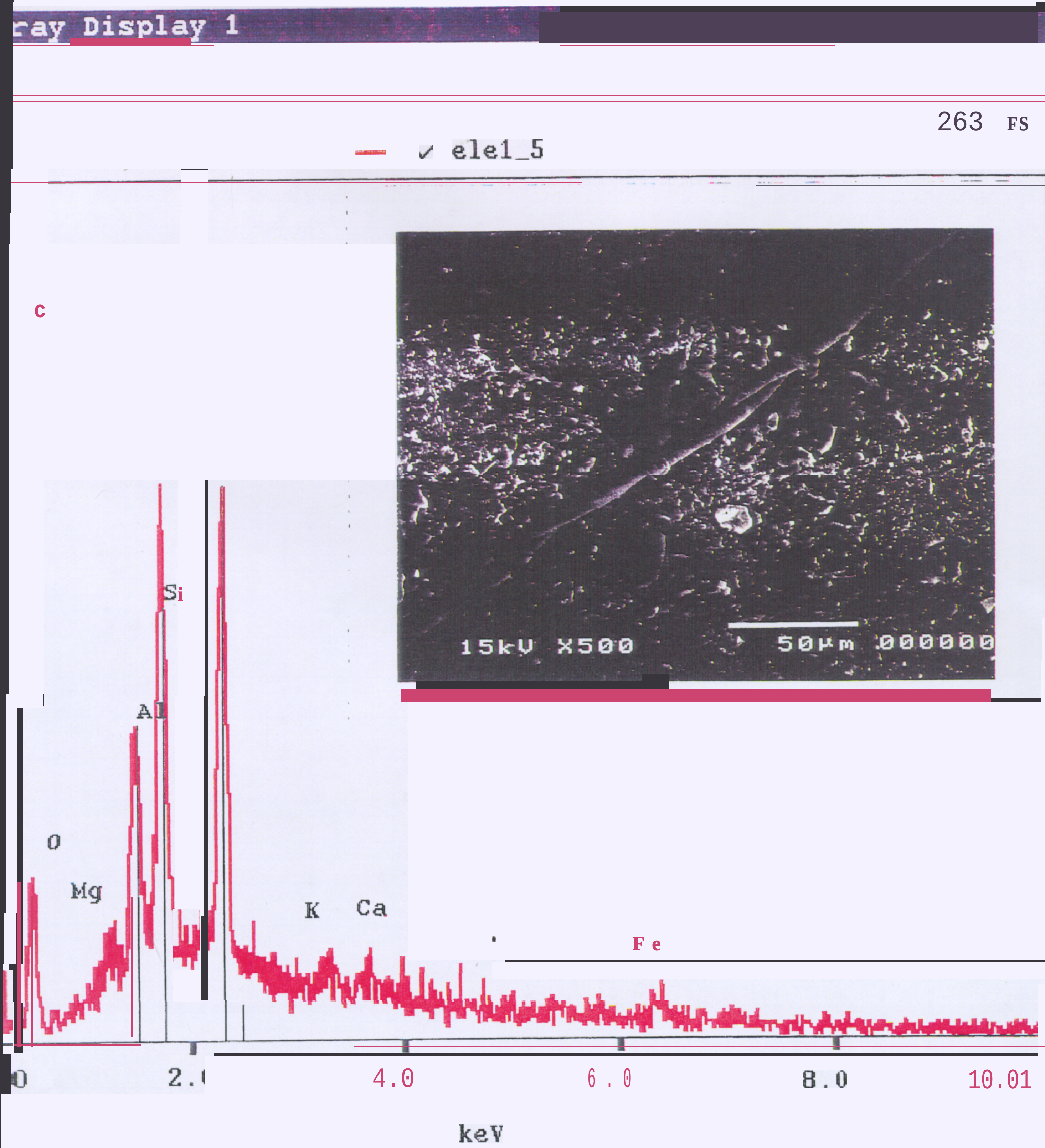
Scanning electron photomicrographs of bacteria present in second stage membrane element from Maricopa Well No. 5.



Numerous broken fragments of silicon-rich, cylindrically shaped particles are present in the first stage element and in scrapings from the back of the second stage element.



Few to several iron- and chromium-rich, irregularly shaped particles are present in the first stage element.



Some carbon-rich filaments or strands are present in the first stage element.

ray Display 1

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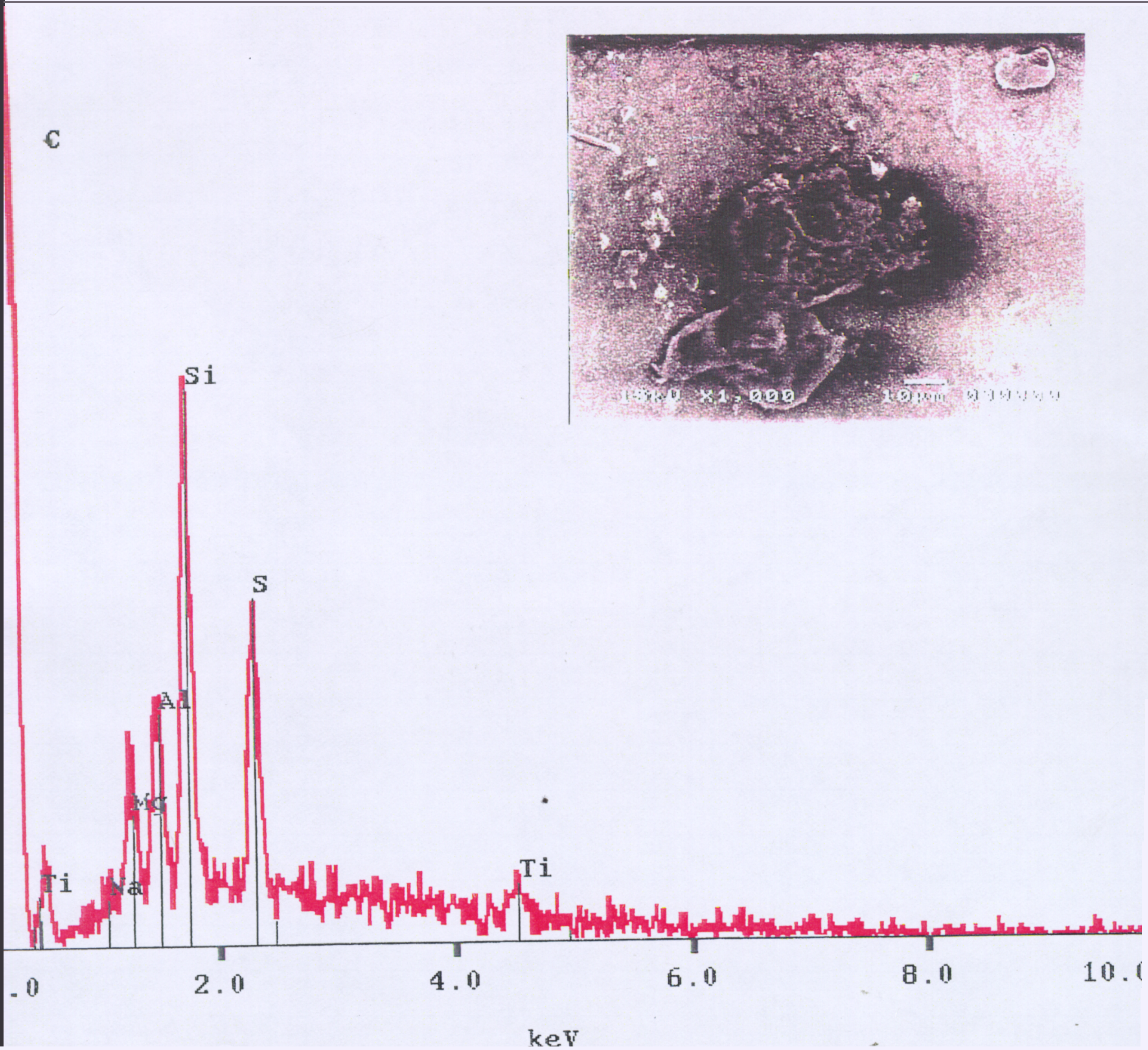

Numerous carbon-rich, irregularly shaped particles and particle masses occur in all four submitted samples. Analyses also indicated notable silicon, sulfur, and aluminum in these samples.