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LAKE HAVASU CITY WATER TREATMENT RESEARCH STUDY

Water Treatment Technology Program Report No. 8

September 1995

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

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The Bureau of Reclamation and Lake Havasu City conducted a jointly funded research study to evaluate selected ground-water treatment options to assist the city in planning for water treatment expansion. The study included pilot testing at well S6, one of 14 city-owned wells. The ground water from this well, and others in the vicinity, is in full compliance with all EPA (Environmental Protection Agency) primary drinking water standards. However, the concentrations of other constituents, such as hardness, sulfate, TDS (total dissolved solids), and manganese, are in excess of secondary MCLs (maximum contaminant levels). High manganese levels are of particular concern to the community because precipitates, formed in the water from chlorination, accumulate in the distribution system and cause discoloration of tap water.

Two processes were pilot tested: $KMnO_4$ (potassium permanganate) oxidation followed by greensand filtration to remove Mn^{+2} (manganese); and nanofiltration to reduce the concentrations of not only manganese, but also sulfate, hardness, and TDS as well. Process recommendations, cost estimates, and design considerations for scale-up are provided in the report based on the results of this testing.

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by

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Denver, Colorado

September 1995

UNITED STATES DEPARTMENT OF THE INTERIOR ★ **BUREAU OF RECLAMATION**

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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.

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ACRONYMS AND ABBREVIATIONS

ADEQ	Arizona Department of Environmental Quality
BPV	back pressure valve
cfu	colony forming units
ENR	*Engineering News Record*
EPA	Environmental Protection Agency
FCV	flow control valve
HDPE	high density polyethylene
HPC	heterotrophic plate count
ICP	inductively-coupled plasma
LHC	Lake Havasu City
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
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
UV	ultraviolet

CHEMICAL FORMULAS

Al^{+3}	aluminum ion
$Al_2(SO_4)_3 \cdot 14.3H_2O$	aluminum sulfate (alum)
Ba^{+2}	barium ion
Ca^{+2}	calcium ion
$CaCO_3$	calcium carbonate
$Ca(OH)_2$	calcium hydroxide (lime)
Cl^-	chloride ion
Cl_2	chlorine
ClO_2	chlorine dioxide
Cr	chromium
Fe^{+2}	ferrous iron
Fe^{+3}	ferric iron
H^+	hydrogen ion
HCO_3^-	bicarbonate ion
H_2O	water

CHEMICAL FORMULAS — CONTINUED

H_2SO_4	sulfuric acid
K^+	potassium ion
$KMnO_4$	potassium permanganate
Mg^{+2}	magnesium ion
Mn^{+2}	manganese ion
MnO	manganous oxide
MnO_2	manganic dioxide
MnO_4^-	permanganate ion
Na^+	sodium ion
Na_2CO_3	sodium carbonate (soda ash)
Ni	nickel
NO_3^-	nitrate ion
O_3	ozone
SiO_2	silica
SO_4^{-2}	sulfate ion

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

The Bureau of Reclamation (Reclamation) and LHC (Lake Havasu City) conducted a jointly-funded research study to evaluate selected ground-water treatment options to assist the city in planning for water treatment expansion. The study included pilot testing at well S6, one of 14 city-owned wells. In this report, Reclamation is providing process recommendations, cost estimates, and design considerations for scale-up based on the results of this testing.

Based on available data, the city water supply is in full compliance with primary drinking water standards. However, concentrations of other constituents such as hardness, sulfate, TDS (total dissolved solids) and manganese exceed secondary MCLs (maximum contaminant levels). High manganese levels in several wells are of concern to the community because precipitates formed in the water from chlorination accumulate in the distribution system. Poor quality ground water is commonly made acceptable by blending with better quality wells. However, with established wells declining in quality, this approach is becoming impractical or unavailable.

Two processes were selected for pilot testing: $KMnO_4$ (potassium permanganate) oxidation followed by greensand filtration to remove Mn^{+2} (manganese); and NF (nanofiltration) to reduce the concentrations of not only manganese, but sulfate, hardness, and TDS as well. Nanofiltration is capable of producing product water that meets *all* secondary MCLs.

$KMnO_4$ oxidation and greensand filtration were effective in reducing the concentration of Mn^{+2} in well S6 ground water to 0.05 mg/L, the secondary MCL. The optimum $KMnO_4$ dose was about 1.1 mg/L. Considering the average reduction of Mn^{+2} (0.62 mg/L [influent] - 0.05 mg/L [effluent]), this dose is equivalent to 1.93 mg/L $KMnO_4$ per mg/L Mn^{+2}, which is essentially the same as the stoichiometric requirement. The reaction is fast. About 90 percent of the Mn^{+2} is oxidized within the first 1-1/2 minutes. The initial reaction rate was determined to be second order dependent on both $[MnO_4^-]$ and $[Mn^{+2}]$ with a rate constant of -0.198/mol·sec.

Greensand effluent turbidity measurements were at or below 0.09 ntu (nephelometric turbidity units), indicating efficient filtration. The greensand filter media was also effective in controlling the over- and under-dosing of $KMnO_4$. Interestingly, water samples collected just prior to filtration contained less Mn^{+2} (0.02-0.03 mg/L) than the filter effluent when operating near the optimum $KMnO_4$ dose of 1.1 mg/L (this observation is based on Hach analyses in the field). This result suggests that $KMnO_4$ could be removed more efficiently with conventional dual- or multi-media filtration, assuming an effective control could be employed for chemical dosing.

Jar test results showed that alum concentrations of 20 to 40 mg/L could be used to coagulate and settle MnO_2 (manganic dioxide [oxidized Mn^{+2} particles]); however, the required settling time of 90 minutes was excessive and the floc produced was very fragile. Thus, this report concludes that alum is not effective for this application, and apparently is not necessary to produce acceptable filter effluent turbidities as described above.

The nanofiltration test system employed 18 FilmTec NF90-2540 elements in a 12:6 (2-stage) array. The feed flow rate and product recovery were maintained at 18.2 L/min (4.8 gal/min) and 80 percent, respectively. The initial feed pressure was 570 kPa (83 lb/in^2). Hypersperse AF 200^{TM} and sulfuric acid were added for scale control. The system was operated for about 1000 hours to allow time for any potential membrane degradation from fouling or scaling to develop. UV (ultraviolet) disinfection was used for the control of microbial contamination.

Nanofiltration effectively reduced the concentrations of all contaminants of concern to below MCLs. The average TDS rejection for the 984-hour test was 90.9 percent. The percent rejection for specific ions of interest was: Ca^{+2} (calcium) - 98.1; Mg^{+2} (magnesium) - 98.5; SO_4^{-2} (sulfate) - 97.4; and Mn^{+2} - $\geq$90.3. The average TDS for the feed and permeate (product) was 826 and 75 mg/L, respectively. This low permeate concentration allows blending to obtain higher overall net product recoveries.

The test data show that biofouling probably occurred during the 6 weeks of operation. NPF (normalized permeate flow) dropped about 16 percent during this period, and feed pressure increased from 75 to 89 lb/in^2. A membrane autopsy was performed to determine the cause of the performance degradation. SEM (scanning electron microscopy) imaging was also used in an attempt to visually identify fouling or scaling components. The results of these procedures, along with high heterotrophic plate counts measured throughout the test system, all pointed to biofouling as the most likely cause. Because of high microbial populations present in the feed water (7900 cfu/mL measured at the wellhead sample tap), a more aggressive disinfection will be needed, e.g., the use of chloramines or chlorination followed by dechlorination. However, any Mn^{+2} oxidized by these chemicals would have to be removed by media filtration prior to membrane desalting.

Lake Havasu City may choose a treatment plant for manganese removal alone, such as a potassium permanganate oxidation plant, or may elect treatment that would reduce the concentrations of all EPA-regulated primary and secondary drinking water parameters to below MCLs. This report concludes that several options are available to the city to provide the latter defined, full compliance, water quality. These options include nanofiltration alone or nanofiltration blended with water from either Lake Havasu or treated ground water. Lime-softened ground water can also be blended with treated water from either Lake Havasu or ground water that has received nanofiltration treatment.

If Lake Havasu City selects a nanofiltration treatment plant, the reject brine produced will have to be disposed of in a manner that is consistent with Arizona Department of Environmental Quality rules. Methods available to the city for reject brine disposal include evaporation ponds, reuse using irrigation of brine-tolerant plants or landscaped areas when the salt concentrations are appropriately adjusted (diluted), and creation of a wetlands environment.

2. INTRODUCTION

2.1 Purpose and Scope

In light of a rapid population increase over the last 15 years, Lake Havasu City is facing several challenges concerning their water supply and distribution system. 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 the residents of the city. To address this need, and to assist the city in planning for water treatment expansion, Reclamation and Lake Havasu City conducted a jointly-funded research study to evaluate selected ground-water treatment options.

The study included the pilot testing of selected water treatment processes to confirm their 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 12 Mgal/day. Capital cost estimates are based on a combination of direct quotes from manufacturers, plus allowances for installation, and cost curves prepared by the EPA (Environmental Protection Agency) using current indices of the ENR (*Engineering News Record*). O&M cost estimates include current prices for electricity, chemicals, and supplies, when available. Most estimates for materials, equipment, and labor are based on updated ENR values. Consequently, the estimates found herein are valuable for a comparison of the alternatives presented, and are not final construction estimates.

The final treatment process recommendations made in this report should be integrated with other design factors that address the city's comprehensive needs. It is recommended that consideration be given to such issues as capacity, water sources, desired level of treatment, and location, in an engineering analysis to arrive at a final determination of an appropriate treatment scheme.

2.2 Background

Lake Havasu City receives all of its potable water supply from fourteen city-owned and operated wells located along the shoreline of Lake Havasu (fig. 1). The wells are grouped into three separate well fields: north, central and south. The total combined pumping capacity of the wells is about 24 Mgal/day (HDR Engineering, 1992).

Poor quality ground water in the study area is commonly made acceptable by blending with better quality wells. In the past, the city drilled wells to avoid poorer water quality areas. However, with established wells declining in quality, new wells must be located where only poor quality ground water is available and where blending is impractical or unavailable.

3. CONTAMINANTS OF CONCERN

Based on available data, the city's water supply is in full compliance with all primary drinking water standards. However, the concentrations of other constituents such as hardness, sulfate, TDS (total dissolved solids), and manganese are in excess of secondary MCLs (maximum contaminant levels). High manganese (Mn^{+2}) levels are of particular concern to the community because precipitates, formed in the water from chlorination, accumulate in the distribution system and cause discoloration of tap water. Elevated manganese concentrations are generally confined to the central and south well fields (wells C2, C9, S4 and S6).

4. PILOT TEST OBJECTIVES

4.1 $KMnO_4$ (Potassium Permanganate) Oxidation

The principal objectives of the $KMnO_4$ (potassium permanganate) oxidation testing were to:

- Determine the concentration of $KMnO_4$ needed to reduce the Mn^{+2} (manganese) level in well S6 ground water to below 0.05 mg/L (EPA secondary drinking water standard).
- Determine the required reaction time and attempt to develop an initial rate constant.
- Assess the ability of manganese-greensand filtration to compensate for over- and under-dosing of $KMnO_4$.

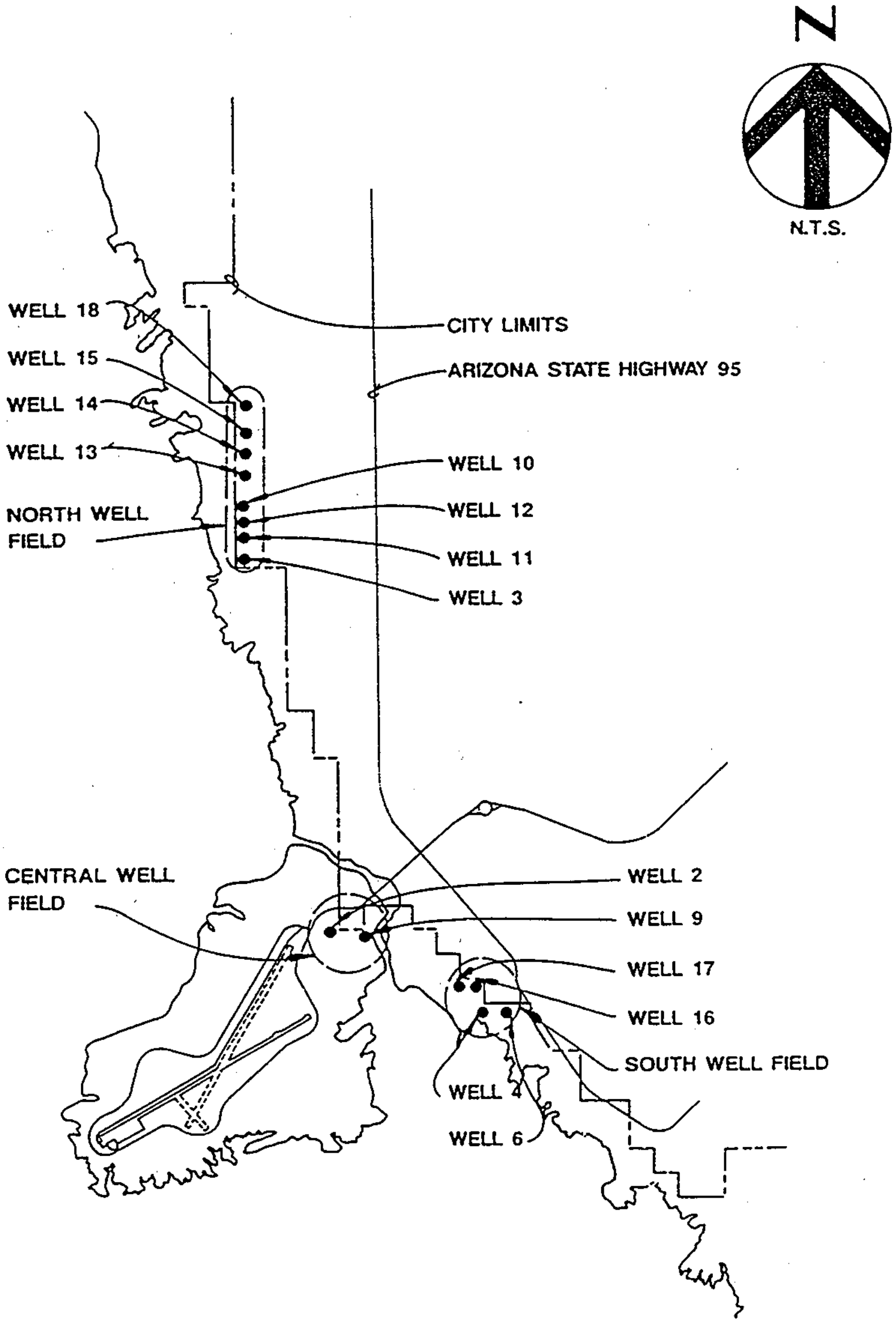


Figure 1. - Lake Havasu City well fields (HDR Engineering, 1992).

- Evaluate the efficiency of the greensand filter in removing MnO_2 (manganic dioxide [oxidized manganese particles]).

- Evaluate the effectiveness of alum (aluminum sulfate) for coagulating and settling MnO_2 precipitates.

4.2 Nanofiltration

The principal objectives of the nanofiltration testing were to:

- Evaluate the performance of FilmTec NF-90 nanofiltration membrane elements for reducing TDS, hardness, sulfate, and manganese levels in the well S6 water.

- Assess blending opportunities (NF permeate with filtered well water) to achieve high overall net recoveries.

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

5. PILOT TEST DESCRIPTION

5.1 Site Selection

Site selection for ground-water testing focused on the city-owned wells that contained manganese in 1993: C2, C9, S4, and S6 (fig. 1). Of these four wells, the 1992-93 average concentration for manganese and TDS indicated C2 and S6 as the leading candidates. The 2-year data base showed well C2 had an average of 0.28 mg/L manganese and 1227 mg/L TDS, and well S6 had an average of 0.50 mg/L manganese and 764 mg/L TDS. Because manganese is the primary contaminant of concern for Lake Havasu City, it was decided that testing at well S6 would yield the most useful data.

Table 1 shows the most recent chemical analysis (existing prior to this test program) for well S6. Corresponding primary and secondary federal drinking water standards are also included in the table for comparison. The constituents that exceed secondary MCLs are highlighted with an asterisk. Well S6, with a drilled depth of 160 feet, is rated at 900 gal/min and has a usable capacity of 550 gal/min.

5.2 Process Selection

Two approaches to treatment were considered for evaluation in the field: the first, an oxidation and filtration process for the removal of manganese; and the second, a softening process (lime or membrane) to reduce the concentrations of not only manganese, but also sulfate, hardness, and TDS.

5.2.1 $KMnO_4$ oxidation. - The most effective oxidants available for the treatment of Mn^{+2} (manganese) are O_3 (ozone), ClO_2 (chlorine dioxide) and $KMnO_4$. Of the three, $KMnO_4$ is the more commonly used in the United States, and is generally favored for waters with high manganese content (Glase, 1990). Both O_3 and ClO_2 require on-site generation, which involves a greater equipment and capital investment. Cl_2 (chlorine) will also oxidize manganese, but care must be exercised when the THMFP (trihalomethane formation potential) of the water is high.

Table 1. - Available ground-water analysis for well S6.

				Federal MCL	
Cations			Concentration	(Primary)	(Secondary)
Calcium	Ca	mg/L	100		
Magnesium	Mg	mg/L	35		
Sodium	Na	mg/L	110		
Potassium	K	mg/L	1.8		
Strontium	Sr	mg/L	1.3		
Barium	Ba	mg/L	0.05	1	
Iron	Fe	mg/L	0.05		0.3
Manganese*	Mn	mg/L	0.55		0.05
Anions					
Bicarbonate	HCO_3	mg/L	232		
Carbonate	CO_3	mg/L	0		
Sulfate*	SO_4	mg/L	300		250
Chloride	Cl	mg/L	95		250
Nitrate	NO_3 (as N)	mg/L	1	10	
Fluoride	F	mg/L	0.64	4.0	
Ammonia (N)	NH_3 (N)	mg/L	0.2		
Silica (soluble)	SiO_2	mg/L	15		
Silica (total)	SiO_2	mg/L	17		
Alkalinity	as $CaCO_3$	mg/L	190		
Hardness	as $CaCO_3$	mg/L	390		
TDS (reported)*		mg/L	790		500
TDS (summation)*		mg/L	880		500
pH			7.62		6.5-8.5

A combination of $KMnO_4$ oxidation and manganese-greensand filtration was selected for testing. Manganese-greensand provides effective filtration and also controls under- and over-dosing of $KMnO_4$ (prevents the development of pink water breakthrough). Manganese (II) removal depends on the precipitation of $MnO_2(s)$ (manganese [IV] [manganic dioxide]), as follows:

$$3Mn^{+2} + 2KMnO_4 + 2H_2O = 5MnO_2(s) + 2K^+ + 4H^+$$

Manganic dioxide is essentially insoluble over the entire pH range of interest in drinking water treatment. Also, the oxidation of both Mn^{+2} and Fe^{+2} (ferrous iron) using $KMnO_4$ is reported to be quite rapid at pH 7 and higher (Glase, 1990).

The stoichiometry for manganese and iron oxidized with permanganate is:

1.92 mg/L $KMnO_4$ per mg/L of Mn^{+2} removed
0.94 mg/L $KMnO_4$ per mg/L of Fe^{+2} removed

5.2.2 Nanofiltration. - Lime softening and membrane softening (nanofiltration) can be used to reduce hardness and TDS. Lime softening can remove carbonate hardness (calcium and magnesium bicarbonates) to the level of $CaCO_3$ (calcium carbonate) solubility by stoichiometric additions of $Ca(OH)_2$ (lime). Further reduction of noncarbonate hardness (calcium and magnesium sulfates or chlorides) requires addition of Na_2CO_3 (soda ash). Lime softening also causes effective chemical precipitation of manganese as MnO (manganous oxide) when the pH of the water is in the range of 9.5 to 10.0. No reduction in sulfate is achieved with this process.

RO (reverse osmosis) and NF are processes used for desalting water by the application of hydrostatic pressure to drive feed water through a semi-permeable membrane. Most of the water's impurity (dissolved salts) remain behind and is discharged as waste brine; relatively pure product water (permeate) emerges at near atmospheric pressure. A typical operating pressure range for RO is 200 to 400 lb/in^2 for brackish water and 800 to 1000 lb/in^2 for seawater desalination. Ion rejections achieved with RO usually are in the mid-to-high 90-percent range.

NF membranes are generally used to treat low TDS waters where the reduction of hardness ions is desirable. 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; thus the name "softening membranes." Monovalent ions (Na^+, Cl^-, HCO_3^-) are rejected at around 60 to 70 percent. Typical applications for NF include the removal of TDS, hardness, color, THM (trihalomethane) precursors, TOC (total organic carbon), and radium. Operating pressures are in the range of 75 to 150 lb/in^2, depending on temperature, feed-water constituents, salinity, and recovery (FilmTec Corporation, undated).

Both softening processes have disposal requirements: $CaCO_3$ sludge with lime precipitation; and reject brine with NF.

NF was selected for field testing because of its ability to meet *all* secondary MCLs, and because of blending opportunities to achieve high overall net recoveries (reducing brine disposal requirements).

5.3 Pilot Plant Equipment and Site Layout

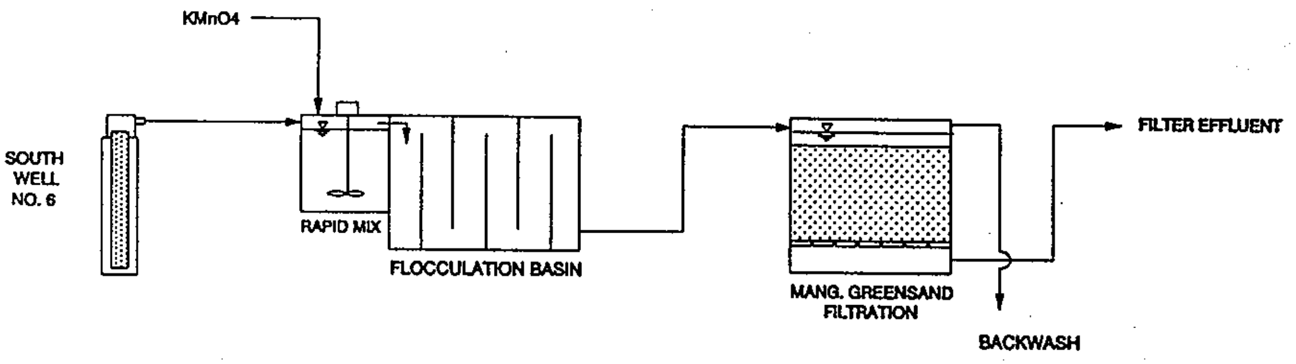
Reclamation's Mobile Water Treatment Pilot Plant was used at Lake Havasu City for the field testing described herein. This pilot plant incorporates skid-mounted equipment to test many unit treatment processes, including chemical precipitation, oxidation (ozone, permanganate), ion exchange, activated carbon, and membrane separation. Most of the process equipment is controlled using an Allen-Bradley SLC 500 programmable controller, and provisions are included for automatic data acquisition; however, data acquisition for this test program was performed manually. A 35-kW generator is available for remote-site operations where commercial power is not available.

Figure 2 presents schematic diagrams of the treatment processes that were pilot tested at Lake Havasu City:

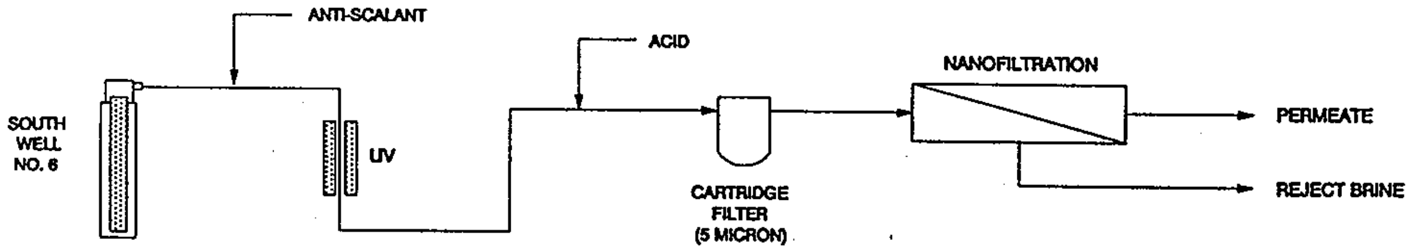
- $KMnO_4$ (potassium permanganate) oxidation followed by manganese-greensand filtration
- Nanofiltration preceded by anti-scalant addition and UV (ultraviolet) disinfection

Post-chlorination was not included in the testing, but would be incorporated as part of the prototype treatment plant(s).

Figures 3 and 4 show the equipment setups and interconnections (plumbing and level sensor) for the two processes.



Potassium permanganant (KMnO4) oxidation; greensand filtration



Anti-scalant addition; UV disinfection; nanofiltration

Figure 2. - Ground-water treatment processes selected for pilot testing.

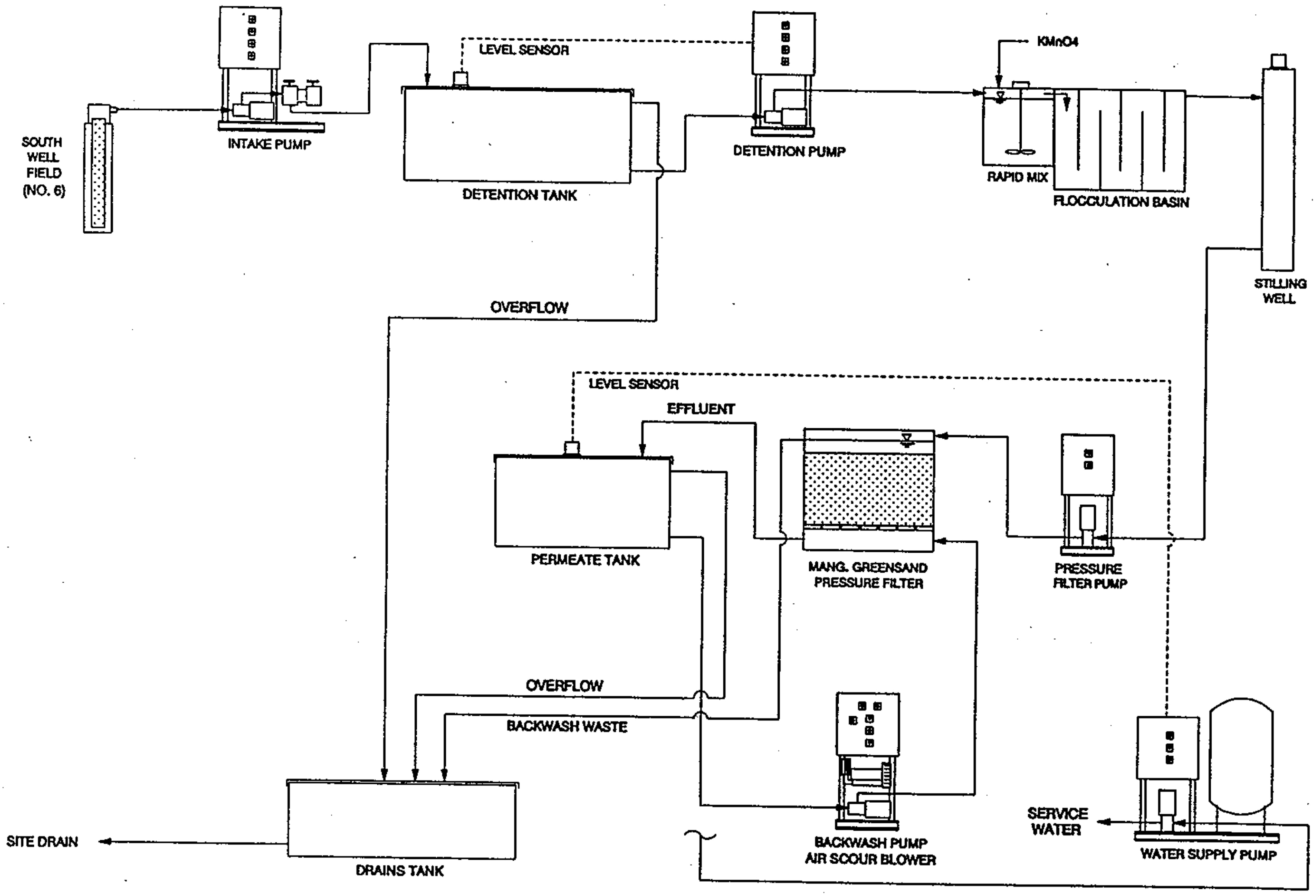


Figure 3. - Equipment setup for ground-water treatment process No. 1 ($KMnO_4$ oxidation and manganese-greensand filtration).

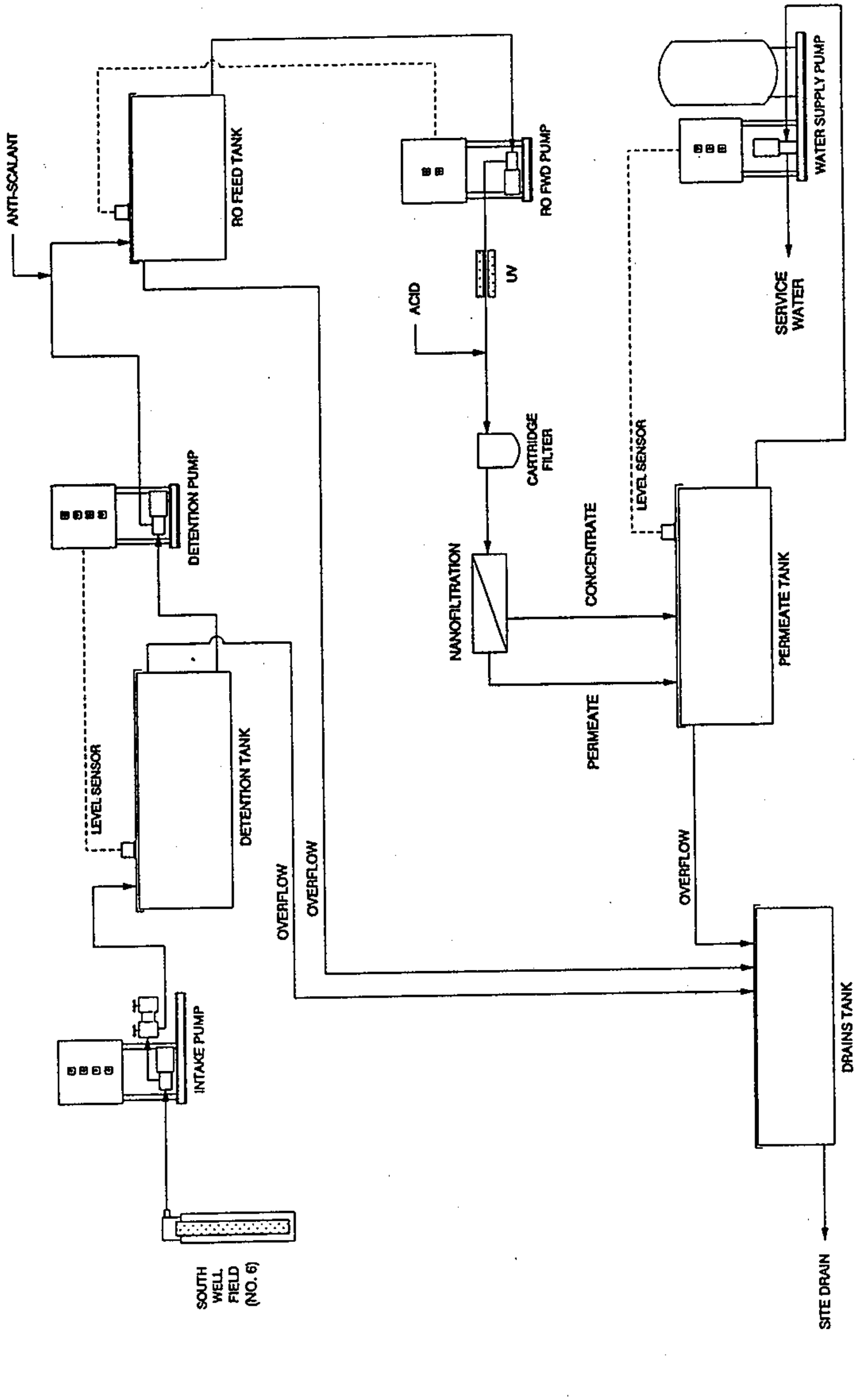


Figure 4. - Equipment setup for ground-water treatment process No. 2 (anti-scalant, UV disinfection, and nanofiltration).

Figure 5 shows the actual layout of the trailer, tanks, and exterior skids at well S6. The intake pump skid (not shown) was used to transfer feed water from the well to the intake pump connection on the trailer located just behind the stairway. All process effluent and drain flows were directed to the gravel drain shown next to the fence line behind the trailer.

5.4 Test Procedures

5.4.1 $KMnO_4$ oxidation. - From the stoichiometry described earlier, the concentration of $KMnO_4$ required to completely oxidize 0.55 mg/L Mn^{+2} and 0.05 mg/L Fe^{+2} would be 1.10 mg/L. Based on this requirement, the range of $KMnO_4$ concentrations selected for evaluation in this test phase was 0.60 to 1.80 mg/L (this range represents 55 to 165 percent of the stoichiometric value).

Initially, each test was run at 22.7 L/min (6 gal/min), which provided about 55 minutes of reaction time before greensand filtration. Later, four additional tests were run at a reduced reaction time of 12 minutes. For each test, the $KMnO_4$ feed concentration was set in the morning and allowed to stabilize for about 10 hours. During this time, physical parameters (flow, pH, turbidity, and filter ΔP) were monitored and manually recorded on the operator's data sheet. Four recordings were made each day. At the end of each day's testing, two separate samples were collected of the raw feed and the greensand filter influent and effluent. One set was sent to a contract lab for manganese and iron analyses (refer to table 2), and a second set was analyzed in the field using Hach reagents. The two sets of data were later compared as a quality-control measure. Immediately after collection, the greensand filter *influent* samples were vacuum-filtered into a flask containing sodium bisulfite (1.5 times stoichiometric). This procedure was done to remove accumulated oxidation particles and to stop the reaction by neutralizing any residual $KMnO_4$.

An LMI (Liquid Metronics, Inc.) pump was used to feed a 0.5-percent $KMnO_4$ solution directly to the rapid mix tank. The chemical feed rates for a process flow of 22.7 L/min were as follows:

$KMnO_4$ dosage (mg/L)	mL/min of 0.5% $KMnO_4$
0.6	2.72
0.8	3.63
1.0	4.54
1.2	5.45
1.4	6.36
1.6	7.26
1.8	8.17

Permanganate dosages were checked daily by observing and recording the level change in the chemical feed tank. Also, periodic spot checks of the feed rate were made using a 10-mL graduated cylinder and stopwatch.

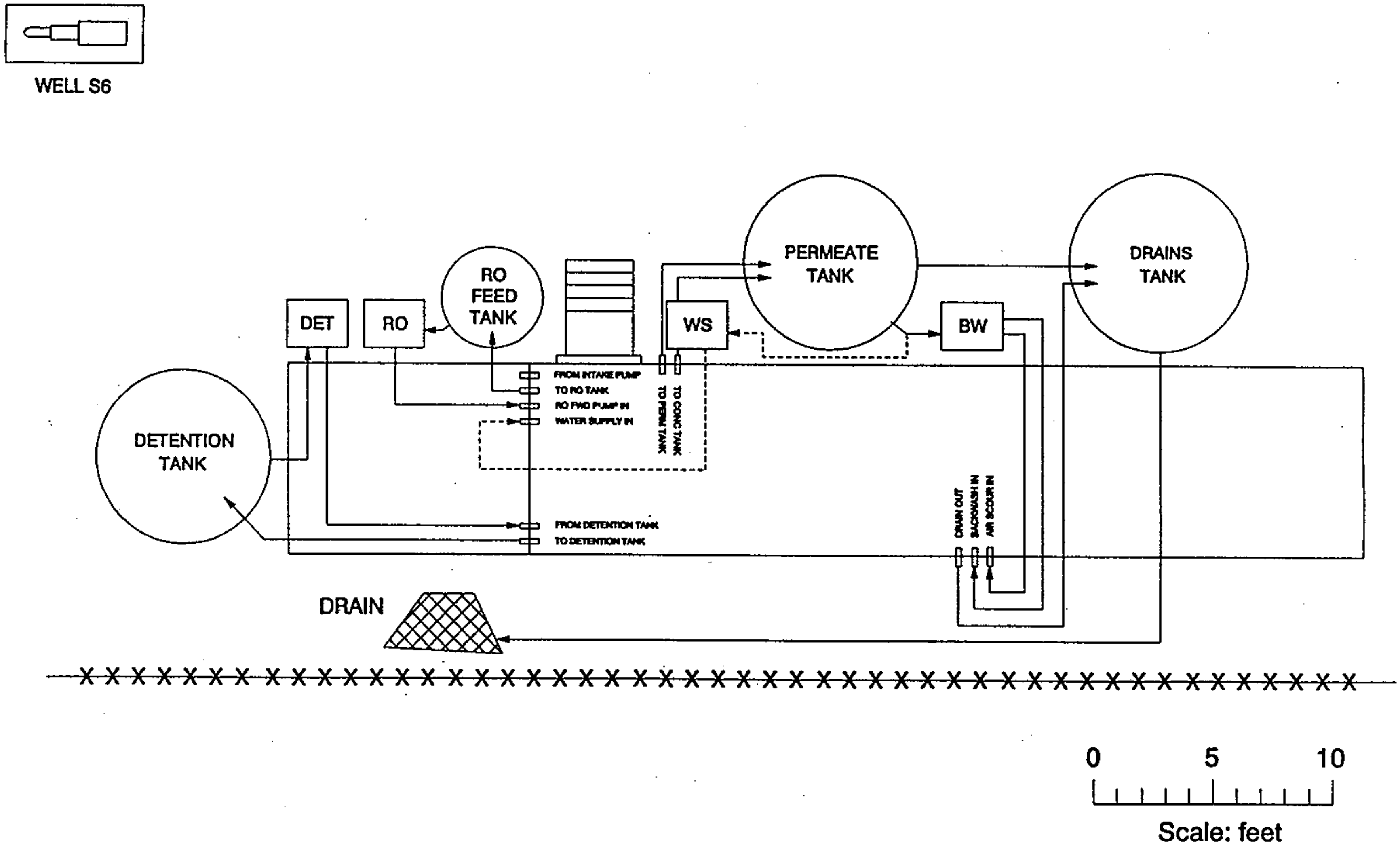


Figure 5. - Pilot plant equipment layout at the well S6 site.

Table 2. - Lake Havasu City water treatment study analytical requirements.

Parameter	Units	Number of Samples/Readings GW#1	GW#2	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	Operator	-	-	-	-
Silt Density Index (SDI)	-		40	Operator, SDI Test kit	-	-	-	-
Calcium, Ca	mg/L	2	16	LHC	Store at 4 deg C	Plastic	200	28 days
Magnesium, Mg	mg/L	2	16	LHC	Store at 4 deg C	Plastic	200	28 days
Sodium, Na	mg/L	2	16	LHC	Store at 4 deg C	Plastic	200	28 days
Potassium, K	mg/L	2	16	LHC	Store at 4 deg C	Plastic	200	28 days
Strontium, Sr (total)	mg/L		16	LHC				
Barium, Ba (total)	mg/L		16	LHC	Nitric, < pH 2	Plastic	250	6 months
Aluminum, Al (total) **	mg/L	2	16	LHC	Nitric, < pH 2	Plastic	250	6 months
Iron, Fe (total)	mg/L	42	16	LHC/Operator, Hach	Nitric, < pH 2	Plastic	250	6 months
Manganese, Mn (total)	mg/L	42	16	LHC/Operator, Hach	Nitric, < pH 2	Plastic	250	6 months
Bicarbonate, HCO3	mg/L	2	16	LHC				
Chloride, Cl	mg/L	2	16	LHC	Store at 4 deg C	Plastic, glass	50	28 days
Flouride, F	mg/L		16	LHC	None required	Plastic	300	28 days
Sulfate, SO4	mg/L	2	16	LHC	Store at 4 deg C	Plastic, glass	50	28 days
Nitrate, NO3	mg/L	2	16	LHC	Store at 4 deg C	Amber plastic, glass	100	48 hours
Phosphate, PO4	mg/L	2	16	LHC	Store at 4 deg C	Amber plastic, glass	100	48 hours
Hardness (as CaCO3)	mg/L	2	16	LHC	Nitric, < pH 2	Plastic, glass	100	6 months
Alkalinity (as CaCO3)	mg/L	2	16	LHC	Store at 4 deg C	Plastic, glass	100	14 days
Silica, SiO2	mg/L		16	LHC	Store at 4 deg C	Plastic	-	28 days
Total Organic Carbon (TOC)	mg/L		4	LHC	4 deg C; HCl, < pH 2 & 4 drops 10% S.T.	Amber glass; TFE cap	100	7 days
Standard Plate Count (SPC)	CFUs/mL		4	LHC	Store at 4 deg C	Sterilized glass, plastic	100	8 hours
Headloss	psig	Many		Operator	-	-	-	-
Backwash (B/W) Frequency	hours	Many		Operator	-	-	-	-

GW#1 - Groundwater treatment process no. 1 (KMnO4 oxidation; filtration)
GW#2 - Groundwater treatment process no. 2 (Nanofiltration)

** Only if alum is being used in the process

The manganese-greensand filter was charged initially using a 3-percent $KMnO_4$ solution injected at a rate of 0.2 to 0.3 gal/min, until a total of 8 gallons had been pumped through the media (manufacturer's recommendation). During operation, the filter was backwashed when the ΔP had increased by about 10 lb/in^2 over its original startup value.

Finally, a series of jar tests were performed to evaluate alum $[Al_2(SO_4)_3 \cdot 14.3H_2O]$ as a coagulant for the removal of suspended particles (oxidized Mn^{+2}). Required settling time, supernatant turbidity and floc stability were used as the determining factors for judging the effectiveness of the coagulant.

5.4.2 Nanofiltration. - The NF test system design parameters were as follows:

• Array	12:6 (2-stage) (refer to appendix C for diagram)
• Element	FilmTec NF90-2540
• Recovery	80 percent
• Initial feed pressure	570 kPa (83 lb/in^2) @ 25 °C
• Feed flow	18.2 L/min (4.8 gal/min)
• Projected permeate TDS	271 mg/L

The following chemical additions were added for scale control:

- Hypersperse AF 200^{TM} @ 3.0 p/m
- Sulfuric acid to pH 7.00

The NF system was operated for nearly 1000 hours to allow time for any potential membrane degradation from fouling or scaling to develop. System startup was at operating pressures required to achieve 80-percent recovery at a feed flow of 18.2 L/min (4.8 gal/min). Thereafter, these same flows were maintained and system pressures were allowed to vary.

Process instrument data were manually recorded four times per day, with about 4 hours between observations. Just before data collection, the operator adjusted the system flows to the following:

• Feed	18.2 L/min (4.80 gal/min)
• Concentrate	3.6 L/min (0.96 gal/min)

These flows were achieved 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 5, 362, 693 and 984 hours of operation. These samples were sent to a contract laboratory for the following analyses: major anions and cations, selected metals, hardness, alkalinity, and SiO_2 (silica). In addition, feed samples were analyzed for TOC and standard (heterotrophic) plate count (refer to table 2 for the specific constituents).

The 5u cartridge filter elements on the NF skid were changed about every 3 to 4 days.

A PID-controlled LMI chemical feed pump was used to regulate the addition of a 10-percent H_2SO_4 (sulfuric acid) solution for pH adjustment (fig. 4). Hypersperse AF 200 (anti-scalant) was added using a manually-controlled LMI pump. A fresh 5-percent solution was prepared about every 4 days.

6. PILOT TEST RESULTS AND CONCLUSIONS

6.1 Results

This section presents the test results for both the potassium permanganate oxidation and nanofiltration processes. Tabulations of the raw data and calculated parameters are presented in appendices A and B, respectively.

6.1.1 $KMnO_4$ oxidation. - The testing described below was designed to determine the following:

(1) The concentration of $KMnO_4$ needed to reduce the Mn^{+2} level in well S6 ground water to below 0.05 mg/L (EPA secondary drinking water standard)
(2) The required reaction time and an initial rate constant
(3) The ability of manganese-greensand filtration to compensate for over- and under-dosing of $KMnO_4$
(4) The efficiency of the greensand filter in removing oxidized manganese particles (MnO_2)
(5) The effectiveness of alum for coagulating and settling MnO_2 precipitates

6.1.1.1 *Optimization of $KMnO_4$ dosage.* - Figure 6 shows the variation in manganese ion concentration in the raw feed water, and in the greensand influent and effluent, with increasing $KMnO_4$ dosage. The greensand influent curve appears to verify the optimum dose of 1.10 mg/L $KMnO_4$ (based on stoichiometry). Permanganate additions above and below this level result in significantly higher residual Mn^{+2} levels. Also, the greensand filter media seems to be effective in controlling the over- and under-dosing of $KMnO_4$. It is interesting to note, however, that the water apparently picked up Mn^{+2} from the greensand in the region of optimum $KMnO_4$ dosage. From figure 6, the overall process appears to have an effectiveness limitation of about 0.05 mg/L.

6.1.1.2 *Permanganate reaction kinetics.* - Reaction kinetic experiments were conducted to optimize detention time prior to greensand filtration. Because of the pilot plant configuration, detention time was fixed (for a given process flow rate) by the combined capacities of the rapid mix tank, flocculation basin, and clearwell. At a process flow rate of 22.7 L/min (6 gal/min), this detention time was 55 minutes. The tests described below were designed to find out if a shorter detention time could be used.

Test water was taken from the detention tank. The optimum $KMnO_4$ dose of 1.1 mg/L was added to water in a jar test apparatus. After a brief rapid mixing period, stirring was slowed to mimic the stirring in the flocculation basin. At a predetermined reaction time the contents of the jar were vacuum filtered, through a Whatman #40 filter paper, into a flask containing $NaHSO_3$ to stop the oxidation. The Mn^{+2} concentration was then measured using the Hach DR/2000. This procedure was repeated for the following reaction times: 1, 1.25, 2, 5, 11, 21, 31, 41, 51, and 60 minutes. Results of this testing are shown on figure 7.

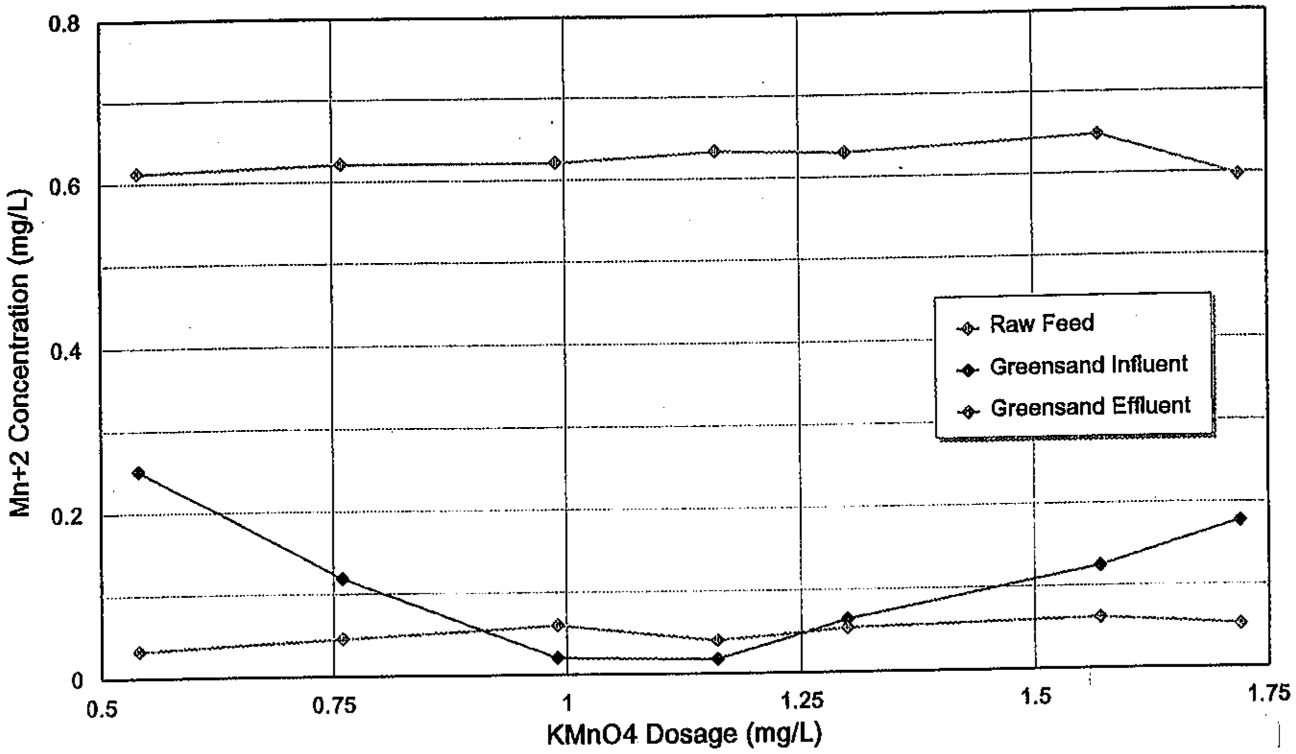


Figure 6. - Optimization of $KMnO_4$ dosage.

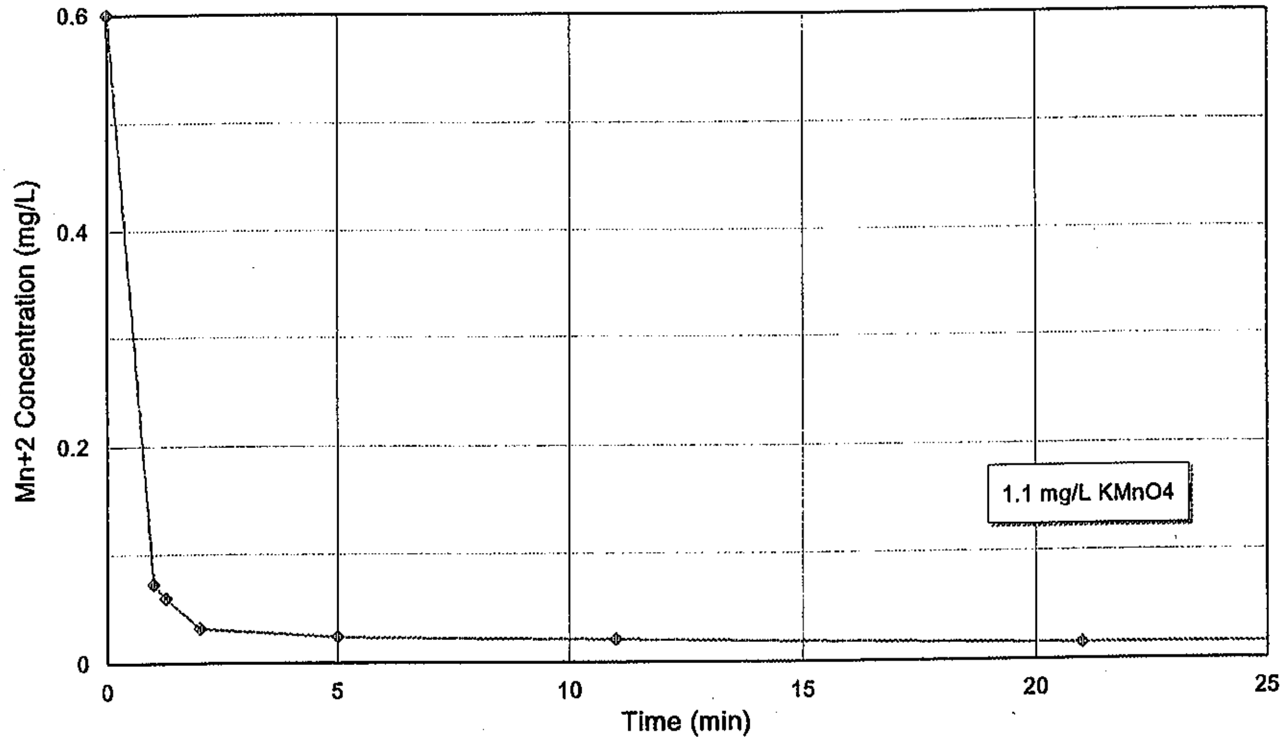


Figure 7. - Timed reaction test.

About 90 percent of the Mn^{+2} had been oxidized by the end of the first 1-1/2 minutes, and the reaction was complete within 20 minutes. By 40 minutes, distinct particles were forming. Shorter reaction times were attempted, but because the filtering process required about 2 minutes, obtaining a precise reaction stop time was difficult. Obviously, the permanganate reaction is not going to require significant detention time. The initial reaction rate was found to be second order dependent on both $[MnO_4^-]$ and $[Mn^{+2}]$ with a rate constant of -0.198/mol·sec.

6.1.1.3 *Filtration efficiency.* - Figure 8 shows turbidity data for the 22.7 L/min (55-minute detention) tests. The greensand *effluent* turbidities were all at or below 0.06 ntu, indicating very efficient filtration. The greensand *influent* turbidities ranged from 5 to nearly 20 ntu, generally increasing with $KMnO_4$, suggesting a greater number of suspended MnO_2 particles.

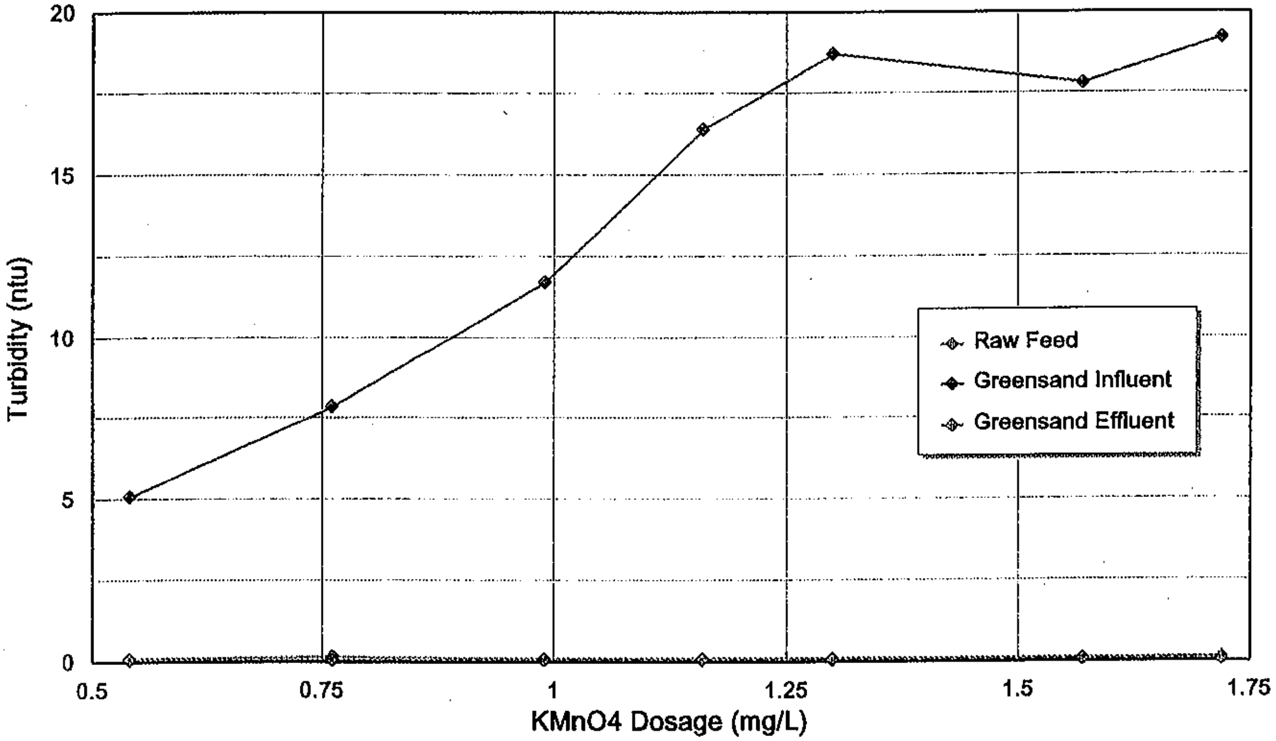


Figure 8. - Turbidity data.

Although Mn^{+2} is oxidized rapidly, it may still require time to form filterable particles. To check this possibility, additional pilot tests were run with a 12-minute detention time and the same optimum $KMnO_4$ dosage of 1.1 mg/L. This procedure was accomplished by bypassing the flocculation basin, i.e., flowing directly from the rapid mix tank to the clearwell. As expected, greensand filter effluent Mn^{+2} concentrations were not significantly different from the earlier 55-minute detention tests (refer to data in appendix A). Interestingly, the filter effluent turbidities were also not that much different than before, ranging from 0.06 to 0.09 ntu.

6.1.1.4 *Alum clarification.* - Filter alum was evaluated for coagulating and settling MnO_2 precipitates. Jar tests were performed to determine optimum dosage, settling time, and supernatant clarity (in terms of turbidity). The best floc formation was achieved within the range of 20 and 40 mg alum/L. However, the required settling time of 90 minutes was excessive and the floc produced was very fragile. Slight agitation of the samples would tend to break up floc particles.

6.1.2 Nanofiltration. - The testing described below was designed to determine the following:

(1) The performance of the FilmTec NF-90 membrane element in reducing TDS, hardness, sulfate, and manganese levels in well S6 ground water
(2) The potential long-term adverse effects on the membranes from fouling or scaling
(3) The blending ratio (NF permeate with filtered well water) to achieve high overall net recoveries

6.1.2.1 *Operational data.* - A total of 984 hours of operation accrued on the NF 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 9 through 14.

Referring to figure 9, feed and reject flows were held constant at 18.2 L/min (4.8 gal/min) and 3.6 L/min (0.95 gal/min), respectively, yielding an 80-percent recovery of desalted water (permeate). 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 10 shows 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 calculations of net permeate flow, which is normalized to 25 °C.

Figure 11 displays system conductivities as µS/cm (microSiemens per centimeter). Also, for better resolution, figure 12 shows an expanded view of the permeate conductivities. Note that the permeate conductivities show a gradual decrease throughout the test period, particularly in the second stage. This decrease may be the result of a "dynamic layer" developing on the membrane surface, either from biofouling or the deposition of colloidal-size particles (clays, silts). The greater effect in the second stage could be caused by the lower average brine velocity (about 16 percent less than the first stage). With reduced scouring action, microorganisms and colloidal particles settle out and attach to the membrane surface with greater ease. These contaminants are also present in greater numbers in the second stage.

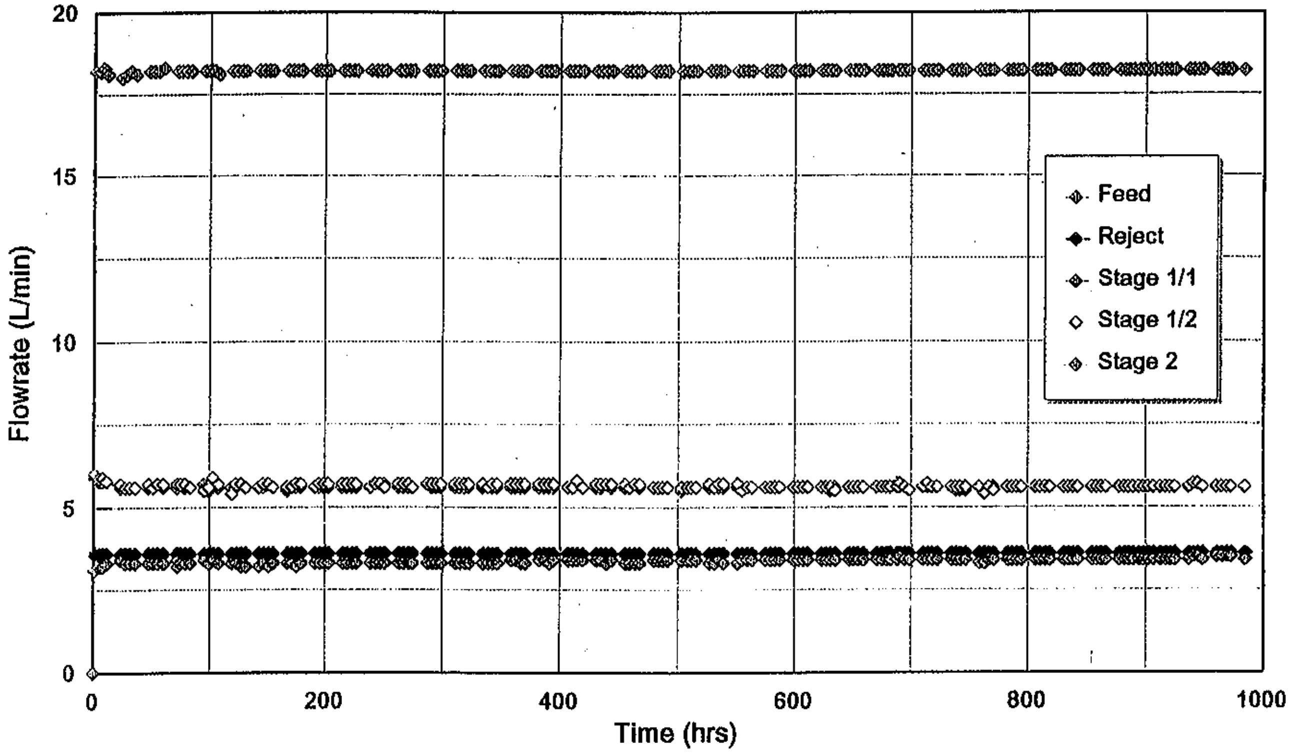


Figure 9. - System flow rates (nanofiltration).

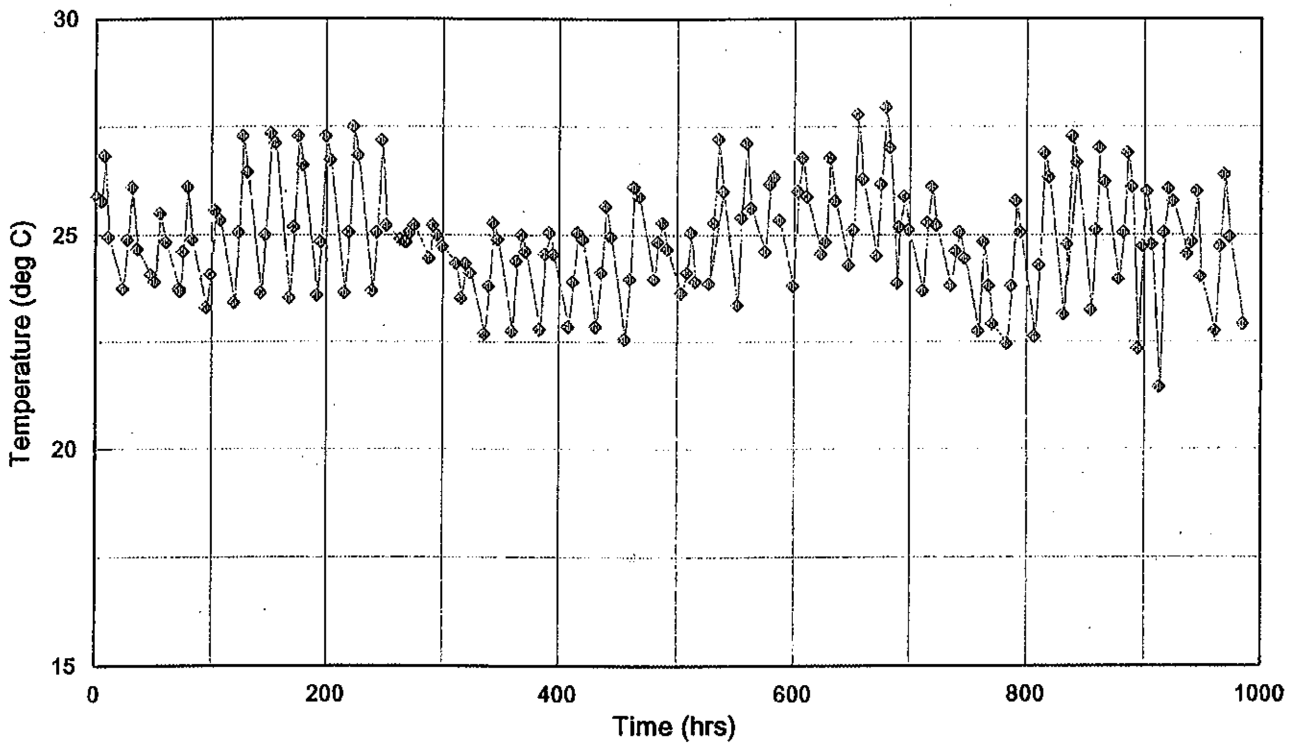


Figure 10. - Feed temperature.

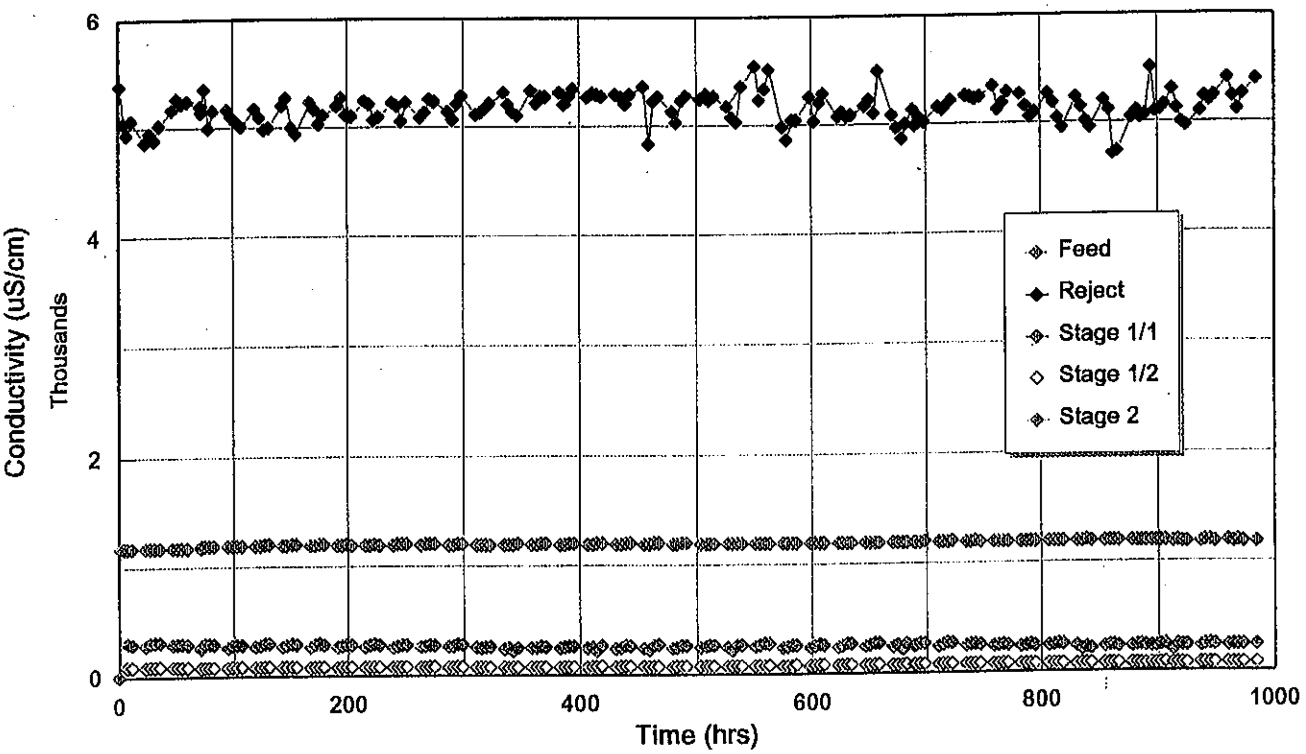


Figure 11. - System conductivities.

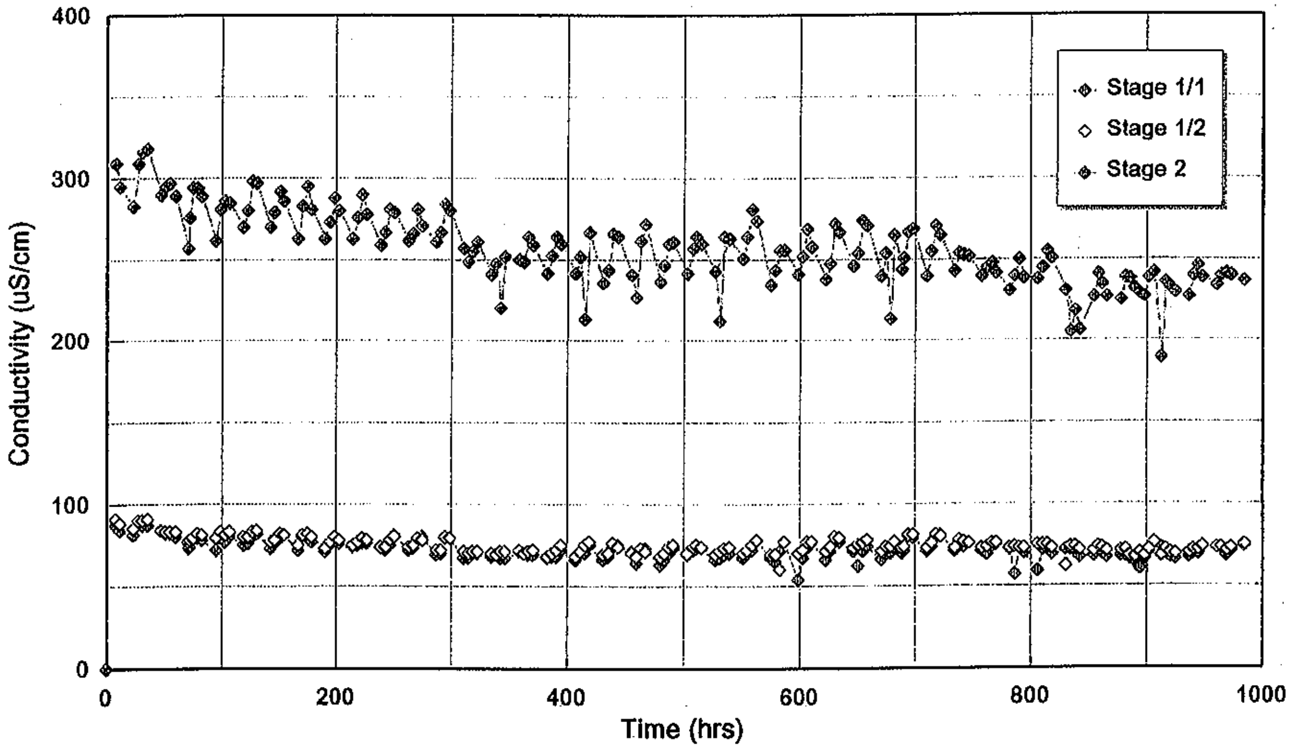


Figure 12. - Permeate conductivities.

Figure 13 shows the feed, interstage, and reject operating pressures in lb/in^2. All three pressures are increasing with time, indicating again the possibility of membrane fouling or scaling (less likely). Also, referring to figure 14, the pressure drop across the first stage appears to increase at a slightly faster rate than across the second stage. The downward blip in the three data plots at about 30 hours elapsed time may have resulted from an initial instrument calibration problem (pressure or flow sensors). No other explanation is apparent from a review of the operator data sheets.

Chemical analyses were performed at 5, 362, 693, and 984 hours into the test program on four separate process streams (NF feed, interstage, permeate [combined], and reject), for the following constituents:

- Cations (Ca, Mg, Na, K)
- Anions (HCO_3, Cl, SO_4, NO_3, F)
- Metals (Al, Ba, Sr, Fe, Mn, P)
- Silica

Results of these analyses are shown in appendix D.

Table 3 summarizes %SR (percent salt rejections) for selected ions and for TDS that were calculated from the concentration data in appendix D. The values shown as "≥" result from the permeate concentration falling below the detection limit. The %SR for other constituents (Al, Ba, Fe and NO_3), where both the feed and permeate concentrations were below the detection limit, could not be calculated. As shown, the average reduction in TDS, sulfate, and manganese all exceeded 90 percent. Also, based on the Ca^{+2} and Mg^{+2} data in table 3, the average reduction in hardness exceeded 98 percent.

In addition to the analyses indicated above, TOC and standard (heterotrophic) plate counts were run on detention tank effluent. The plate counts taken at the 5- and 362-hour sampling times were high—5700 and 4000 cfu/mL (colony forming units per milliliter), respectively. Based on these values, it was decided that plate counts should be run at several locations within the process to better define what might be a potential problem. Samples collected on November 1, 1994, resulted in the following data:

• Wellhead (sample tap)	7900 cfu/mL
• Detention tank effluent	7200 cfu/mL
• NF feed water (after cartridge filter)	1100 cfu/mL
• Interstage	1200 cfu/mL
• Permeate (second stage)	790 cfu/mL
• Reject	1900 cfu/mL

Because well S6 is fairly shallow (160 feet) and close to Lake Havasu (within a few hundred meters), the high bacterial populations could result from lake recharge. Deep inland wells generally have much lower plate counts. The city's practice of continually adding food-grade oil (Unocal White Oil) to the well as a lubricant may also be exacerbating the problem. This oil is *biodegradable* and was found at the surface and along the walls of the detention tank.

At least one SDI measurement was performed on the NF feed water (downstream from the 5µ cartridge filter) each day of testing. SDI measures fouling potential of the feed from colloidal-size materials. The recommended maximum SDI specified by the manufacturer for the NF-90

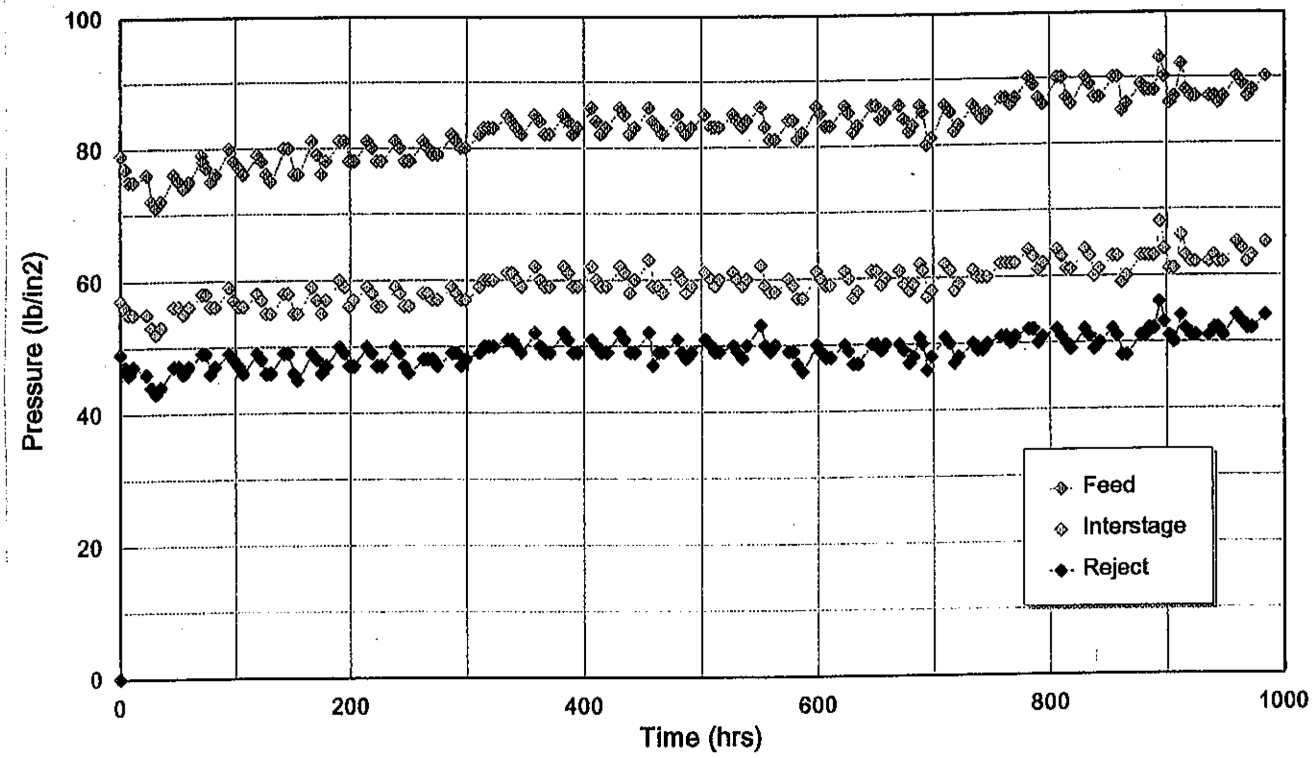


Figure 13. - System pressures.

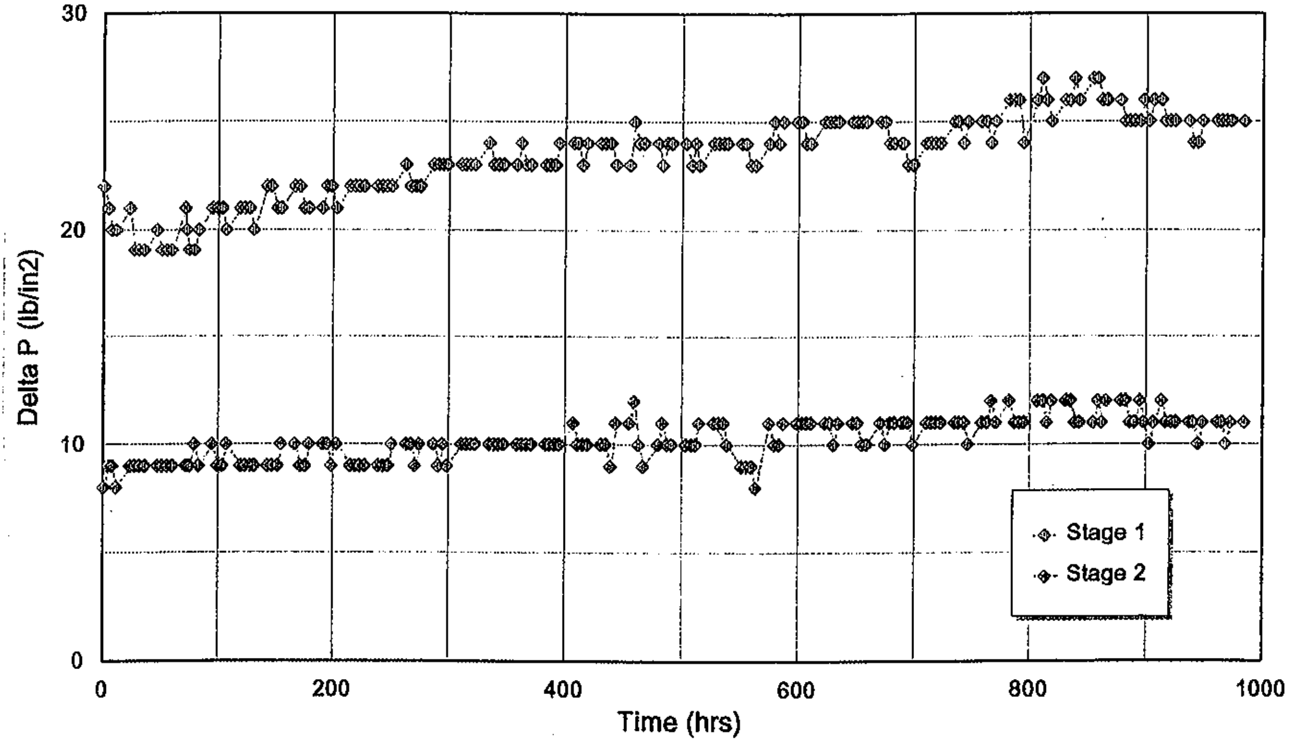


Figure 14. - Stage pressure drops.

Table 3. - Percent salt rejection data.

Constituent	5-Hour	362-Hour	693-Hour	984-Hour	Average
Calcium	97.8	98.2	98.4	99.0	98.4
Magnesium	97.7	98.8	98.5	98.9	98.5
Sodium	80.0	84.5	81.8	85.8	83.0
Potassium	74.4	68.6	≥68.6	≥63.0	-
Manganese	≥90.0	≥90.0	≥90.7	≥90.6	≥90.3
Bicarbonate	83.5	91.8	89.4	91.2	89.0
Chloride	70.2	83.1	80.8	78.9	78.3
Sulfate	96.6	97.5	97.6	97.9	97.4
Fluoride	87.5	84.8	84.9	83.1	85.1
Silica	70.0	82.2	80.2	82.6	78.8
TDS	88.0	92.1	91.1	92.5	90.9

membrane is 5.0. During the 6-week test period, a total of 64 SDIs were performed with values ranging from 1.68 to 4.28. The average SDI was 2.98 with a standard deviation of 0.53.

6.1.2.2 *Performance degradation.* - Figures 15 and 16 present the average *NDP* (net driving pressure) and *NPF* (normalized permeate flow) for this test phase. Average *NDP* is the 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 feed and reject concentrations and dividing by 100)

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

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

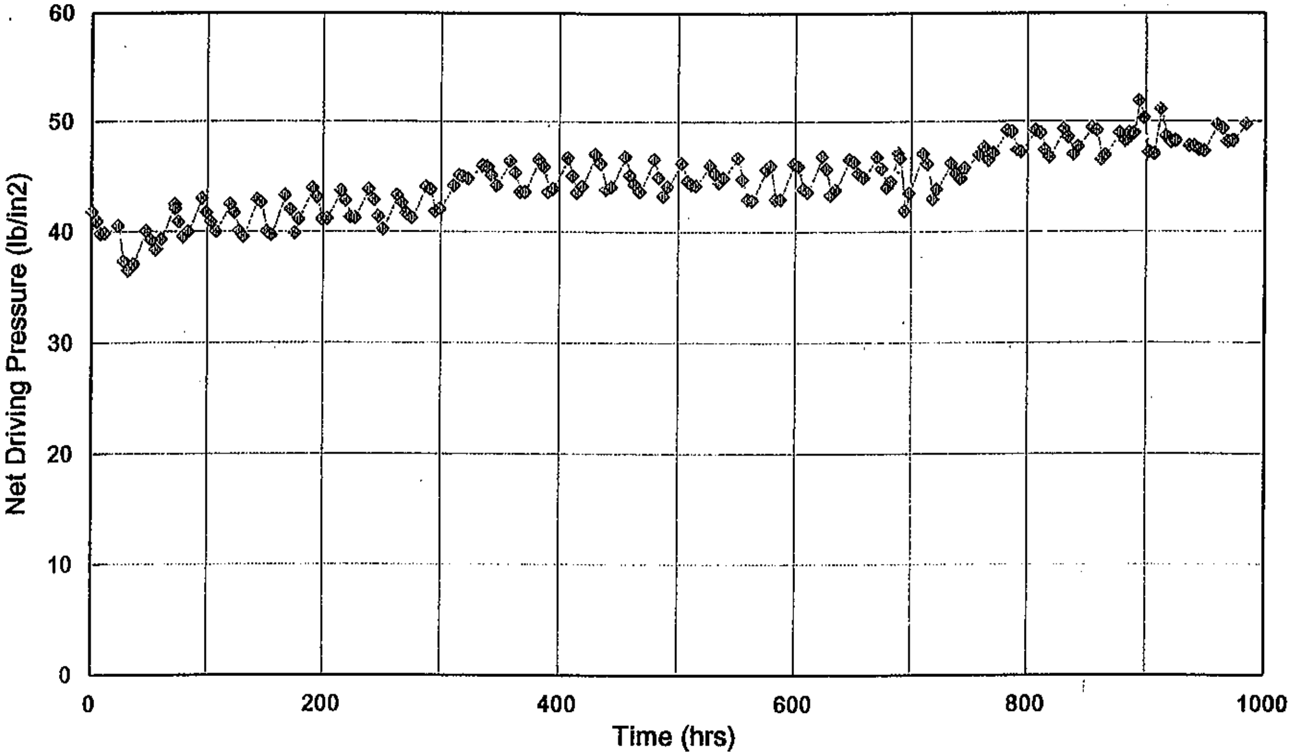


Figure 15. - Average net driving pressure.

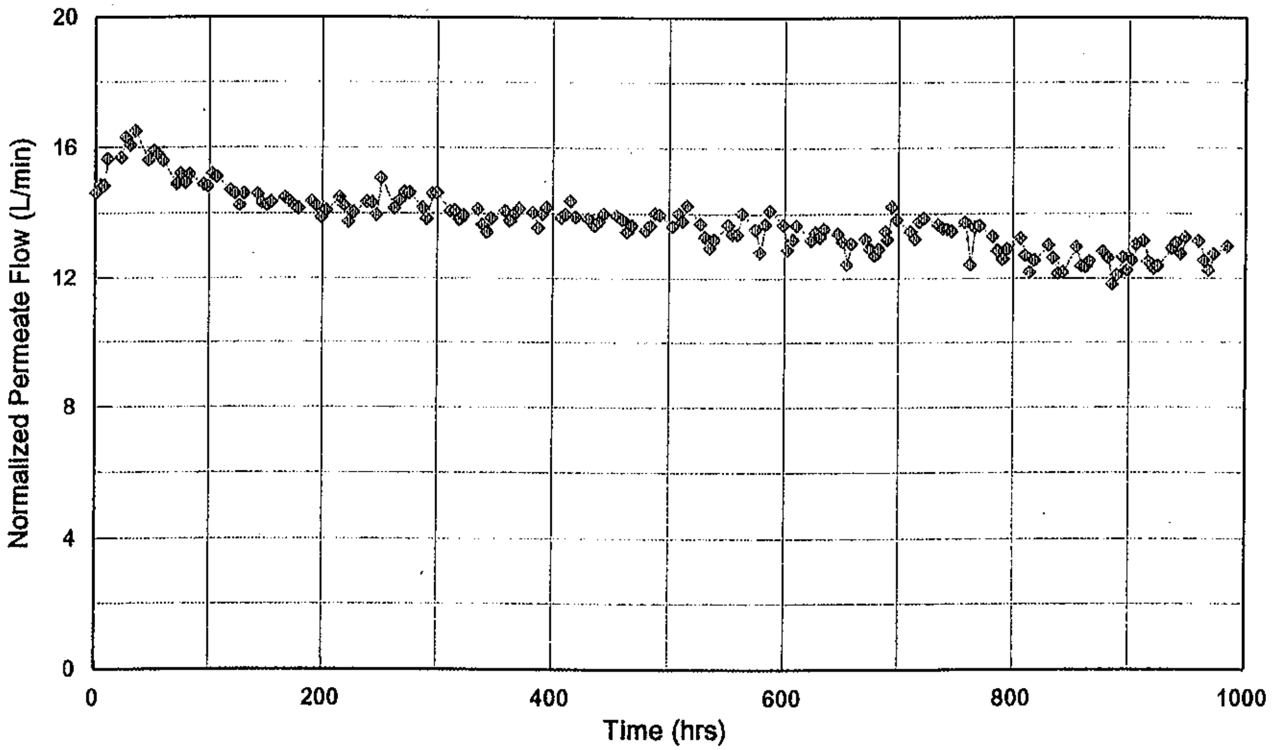


Figure 16. - Normalized permeate flow.

where:

TCF = temperature correction factor

F_p = permeate flow

The *NPF* graph (fig. 16) can be used to estimate the degree to which membranes are being fouled or if damage is occurring, and is commonly used to determine the time at which membranes should be chemically cleaned. Some drop in *NPF* with time is expected. For the TFC (thin-film composite) membranes used in this study, a 15- to 20-percent decline over a 3- to 5-year period would not be unusual. The roughly 16-percent drop in *NPF* experienced in this test program over a 1000-hour (6-week) test period is excessive by comparison.

One of two possible causes were considered for this decline in system performance: (1) the deposition of MnO_2 (oxidized manganese precipitates) on the membrane surface; and (2) biofouling.

6.1.2.3 *Membrane autopsy and SEM analysis.* - On November 11, 1994, autopsies were performed on 2 of the 18 NF elements, one of the lead elements in stage 1 (serial # A2282494; refer to appendix E) and the trailing element in stage 2 (serial # A2282495). Initial observations of the lead element membrane surface revealed no obvious fouling or scaling, perhaps only a slight and fairly uniform discoloration (darkening). Also, the vexar (plastic feed water-brine spacer located between membrane envelopes) showed no signs of any buildup. After measuring the dimensions of the active membrane area of the two leaves, one of the membrane surfaces was irrigated with deionized water and thoroughly squeegeed to collect any adhering deposits. Surprisingly, this operation yielded a significant amount of light brownish-colored material (the total quantity of material collected was later determined to have a dry mass of 0.32 grams; this material was collected from a membrane active surface area of 0.52 m^2). The uniformity of deposition, color, consistency, and strength of adherence was determined to be consistent with biofouling. Similar material was found in the trailing element of the second stage, but to a lesser degree (dry mass of 0.09 grams).

Two-inch-square membrane samples were cut from the second leaf of each element for SEM (scanning electron microscopy) imaging to determine if biological cell structure and morphology could be identified. Some of the samples were gold-coated to enhance the imaging resolution and detail. Several showed characteristic rod-shaped bacterial cell forms (refer to fig. 17 as a typical example). No attempt was made to classify specific bacterial types or strains.

The sample collected from the lead element squeegeeing operation (liquid with suspended material) was digested and analyzed for trace metals using ICP (inductively-coupled plasma) spectroscopy. Because the concentration of Mn^{+2} was high in the feed water, the presence of MnO_2 (manganic dioxide) was suspected. A total of 25 metals were identified. Table 4 lists the metals found with a total mass $\geq$ 0.030 mg. Remember, these metals were collected from a membrane surface area of about 0.50 m^2.

From these analyses, it appears unlikely that a problem exists with manganese. However, the presence of such a high level of iron is surprising. The concentration of iron (total) in the NF feed water was $\leq$ 0.05 mg/L, significantly less than the general RO/NF process limitation for Fe^{+2} of 0.3 mg/L. Two possible explanations were considered:

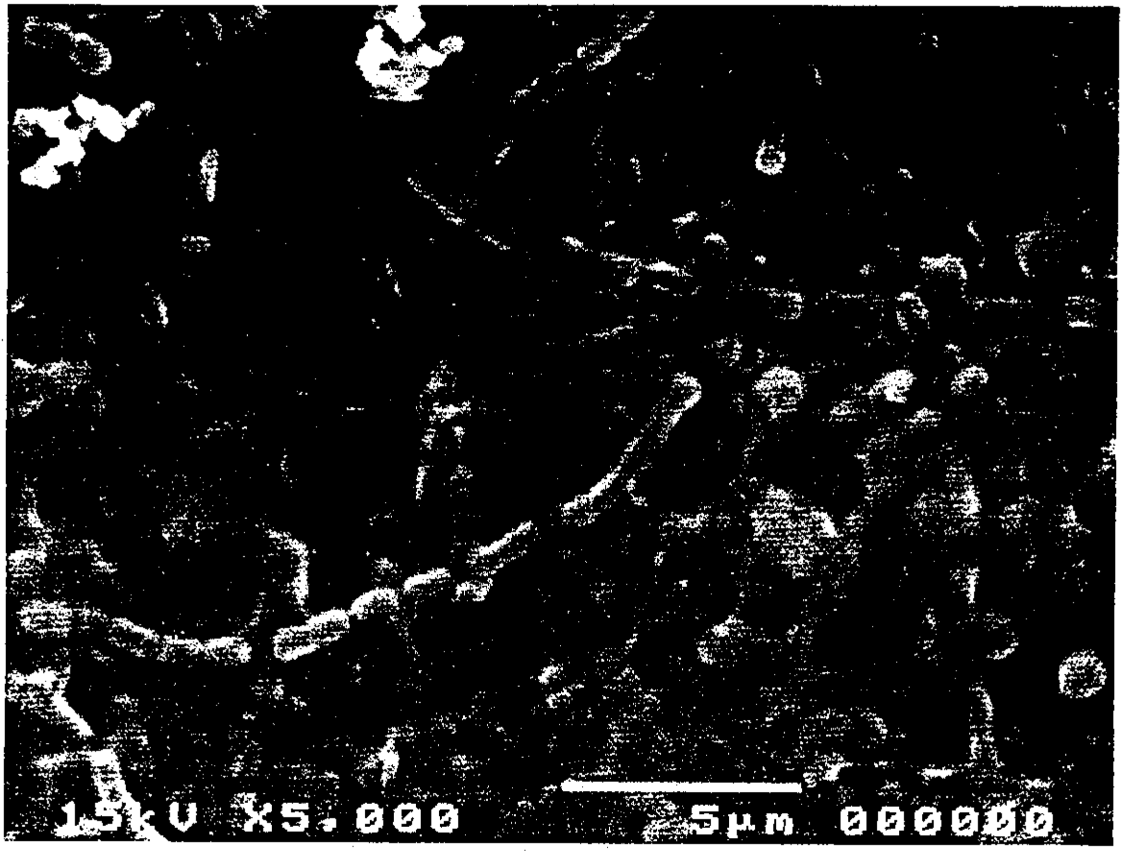


Figure 17. - SEM showing characteristic rod-shaped bacterial cell forms.

Table 4. - Metals found on autopsied membrane surface.

Metal	Mass (mg)
Iron, Fe	8.1
Sodium, Na	2.5
Calcium, Ca	0.89
Chromium, Cr	0.56
Silicon, Si	0.55
Arsenic, As	0.30
Aluminum, Al	0.19
Zinc, Zn	0.15
Magnesium, Mg	0.14
Barium, Ba	0.037
Manganese, Mn	0.030
Lead, Pb	0.030

- Iron-fixing bacteria may have oxidized the available Fe^{+2} to Fe^{+3} (ferric iron) which deposited on the membrane, or may have concentrated iron within the biomass of the fouling layer (Bess, 1994).

- Some corrosion of system components may have occurred (both Cr [chromium] and Ni [nickel] were found on the membrane surface, which are major components of 304 and 316 stainless steel); all wetted components of the NF system were specified to contain only 316 stainless.

A final test was performed on the membrane surfaces (both lead and trailing elements) to determine if any physical degradation had occurred during operation. Congo red dye was applied to a small area of the membrane's surface and then wiped away after a few moments. By doing this, surface penetrations (pin holes, cracks, etc.) can be readily identified by a residual dye stain. No physical degradation was observed.

6.2 Conclusions

6.2.1 $KMnO_4$ oxidation. - The following conclusions were reached based on this test phase:

- The combination of $KMnO_4$ oxidation and manganese-greensand filtration effectively reduced Mn^{+2} in the well S6 ground water to an average concentration of 0.05 mg/L (fig. 6), which is the secondary MCL.

- The optimum $KMnO_4$ dose was found to be about 1.1 mg/L (fig. 6). Considering the amount of Mn^{+2} removed (0.62 mg/L [average influent concentration] - 0.05 mg/L [average effluent concentration]), this dose is equivalent to 1.93 mg/L $KMnO_4$ per mg/L Mn^{+2}, which is essentially the same as the stoichiometric requirement (section 5.2.1).

- Greensand filtration was effective in controlling the over- and under-dosing of $KMnO_4$ (fig. 6).

- $KMnO_4$ oxidation could be used with conventional dual- or multi-media filtration, i.e., without greensand, if an effective control could be employed for chemical dosing. From figure 6, lower Mn^{+2} concentrations appear to be achievable without greensand (near the optimum $KMnO_4$ dose of 1.1 mg/L).

- The reaction is extremely fast (fig. 7). About 90 percent of the Mn^{+2} is oxidized within the first 1-1/2 minutes. The initial reaction rate was found to be second order dependent on both $[MnO_4^-]$ and $[Mn^{+2}]$ with a rate constant of -0.198/mol·sec.

- The greensand effluent turbidities were all $\leq$ 0.06 ntu for the 55-minute data and $\leq$ 0.09 ntu for the 12-minute data (appendix A), indicating efficient filtration.

- In jar testing for coagulating and settling MnO_2 precipitates, 20 to 40 mg/L alum was found to produce the best floc formation. However, the required settling time of 90 minutes was excessive and the floc produced was very fragile. It is therefore concluded that alum is not effective for this application.

6.2.2 Nanofiltration. - The following conclusions were reached based on this test phase:

- NF effectively reduced the concentrations of all contaminants of concern (see section 3.0) to below MCLs. The average TDS rejection for the 984-hour test was 90.9 percent. Specific ions of interest were removed as follows:

Constituent	% Rejection	Average Conc. Permeate (mg/L)
Ca^{+2} (hardness)	98.1	1.6
Mg^{+2} (hardness)	98.5	0.5
SO_4^{-2}	97.4	7.7
Mn^{+2}	$\geq$90.3	<0.05

- The average TDS (summation of ions [appendix D]) for the feed and permeate were 826 and 75 mg/L, respectively. By blending the NF permeate and filtered well water at an approximate ratio of 1:1.25, a net overall recovery of 90 percent (at 496 mg/L TDS) could be achieved. However, Mn^{+2} would have be to removed from the well water, prior to blending, to meet its secondary MCL of 0.05 mg/L.

- NPF dropped by about 16 percent during the 6 weeks of testing (fig. 15). During this same period, system feed pressure increased from about 75 to 89 lb/in^2 (fig. 13). The membrane autopsy, SEM analysis, and high heterotrophic plate counts (measured throughout the NF system) all point to biofouling as the cause.

- UV (ultraviolet) disinfection was not effective in controlling microbial contamination (biofouling) of the NF system. Chloramines or chlorination-dechlorination would provide more effective control; however, Mn^{+2} oxidized by these chemicals would have to be removed by media filtration prior to desalting. Also, because of the high microbial populations in the feed water, residual cell components of microorganisms killed during disinfection may have to be removed as well. These dead organisms can provide a food source for other live bacteria, and some evidence suggests that they may also deposit on and adhere to the membrane contributing directly to a biofouling layer (Ridgeway, 1984).

- The use of a food-grade oil (Unocal White Oil) as a well pump lubricant may have contributed to the biofouling. A plate count taken at the wellhead sample tap indicated 7900 cfu/mL (section 6.1.2.1). In addition, residues of the oil were found at the surface and along the walls of the detention tank.

- Very little manganese was found on the membrane surface of the autopsied first stage lead element (refer to section 6.1.2.3). However, a considerable quantity of iron was present. Because the feed-water concentration of iron was low (0.05 mg/L), it is suspected that iron-fixing bacteria may have oxidized or concentrated Fe^{+2} within the biomass of the fouling layer.

7. FULL SCALE TREATMENT

7.1 General

Lake Havasu City has several choices and decisions to make regarding the construction of a full-scale water treatment plant. Among these are plant location, level of treatment, and the amount of surface water versus ground water used to meet water demands. Full-scale treatment for Lake Havasu City is estimated to be accomplished over a phased expansion.. The city and their consultant, HDR Engineering Inc., have concluded that water demands for the city are projected according to table 5 below.

Table 5. - City average day water demands.

Year	Water Demand (acre-ft\yr)	Water Demand (Mgal/d)
1994-95	14,562	12.99
2004-05	19,180	17.12
2015	24,454	21.8

City officials have stated a size preference for a full-scale treatment plant, initially at 12 Mgal/d (million gallons per day), with a projected expansion of 12 Mgal/d, for a total plant capacity of 24 Mgal/d. This report addresses several treatment plant options available to the city at 12 Mgal/d capacity and, in section 8, presents construction cost estimates that the city can consider in final design.

It is important to note that the current and recent past water quality levels of LHC drinking water meet all EPA primary drinking water standards, which are designed to protect the public health (if the current action level for lead of 0.015 mg/L had been in place in 1991, then southern wells S4, S6, and S17 would have exceeded the standard).

Secondary drinking water standards are in effect to protect the public welfare by providing guidelines regarding the taste, odor, color, and other aesthetic aspects of the water. A review of the city's ground-water quality from wells in the north, central, and southern well fields indicates that several secondary standards have been exceeded in recent years and currently still exceed the manganese, TDS, and sulfate MCLs. HDR Engineering, Inc., addressed these secondary water quality levels in their Comprehensive Water Master Plan (HDR Engineering, 1992) with a discussion of treatment options for each constituent. Based on this information, Reclamation was asked to perform field pilot testing at well S6, which has historically contained high levels of manganese, TDS, and sulfates.

Full-scale treatment alternatives presented in this report fall into two levels of treatment. A significant cost increase occurs from one level to the next. These levels can be described as:

- Manganese removal using the piloted process of permanganate oxidation followed by filtration. This alternative will remove manganese but will not affect total dissolved solids.
- A higher level of treatment which would provide, or nearly provide, full compliance with all secondary standards of the Safe Drinking Water Act. These processes of NF and lime softening are included for complete and partial compliance, respectively.

7.2 Manganese Removal ($KMnO_4$ Oxidation)

The results of pilot testing on ground water indicate that manganese removal can be accomplished by a water treatment plant employing potassium permanganate ($KMnO_4$) oxidation followed by filtration. Full-scale ground-water treatment would consist of the following unit processes, as shown in the process flow diagram on figure 18: raw water pumping, permanganate feed system, 2-stage mixing, filtration, controls for monitoring and compensating for over- or under-dosing of $KMnO_4$, clearwell, post-disinfection, and booster pumping.

Formation of the precipitate MnO_2 (manganic dioxide), from the oxidation of Mn^{+2} (manganese), requires a rapid mix step followed by a slow mix, or flocculation step. The rapid mix step can be accomplished by an agitator-mixer designed to impart adequate energy for the size and shape of the rapid mix tank. A detention time of 1 minute is recommended for rapid mixing. From the piloting work, a detention time for flocculation of about 20 minutes is recommended.

The optimum amount of $KMnO_4$ required for the oxidation process was determined to be stoichiometric, based on the concentrations of soluble manganese and iron present (refer to section 6.1.1.1). Two control options could be considered for $KMnO_4$ addition: the use of greensand filtration for the compensation of over- and under-dosing; and the use of an effluent monitor and feedback loop to control the chemical feed pump. Test results indicated that although greensand filtration effectively controlled over- and under-dosing, the use of greensand apparently caused a slight increase in the soluble manganese level of the filter effluent at $KMnO_4$ doses that were determined to be near optimum (refer to section 6.1.1.1 and fig. 6).

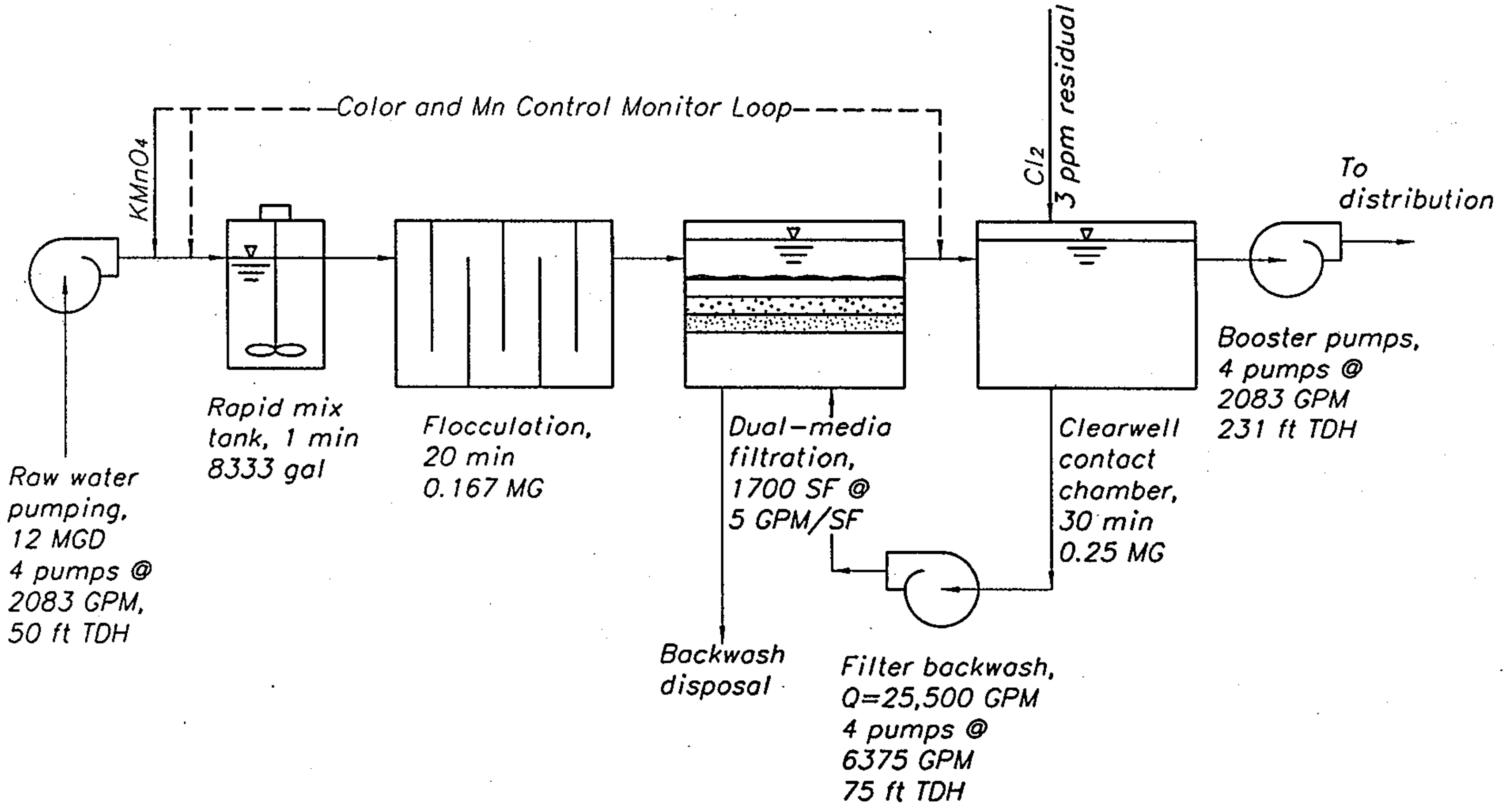


Figure 18. - Water treatment with potassium permanganate oxidation—Lake Havasu City water treatment study.

Because of this increase, and the higher cost of greensand filtration compared to conventional filtration, a multi-media (sand and anthracite) filter is recommended instead of greensand. This recommendation assumes that an effective $KMnO_4$ feed control system is commercially available for incorporation in the process design.

Following filtration, a post-disinfection step, consisting of chlorine addition, is recommended. The design includes a 30-minute chlorine contact basin, which also serves as a wetwell for the finished water booster pumping to the city's distribution system. Chlorine was selected because the final trihalomethane formation potential is low. Should this THMFP increase or more stringent limits be imposed for THMs, the city may have to use an alternate disinfectant, such as chloramine or ozone.

7.3 Full Compliance

7.3.1 General. - To achieve full compliance with secondary drinking water standards, contaminants which have repeatedly exceeded established MCLs in the city's ground water (manganese, sulfate, and TDS), must be reduced in concentration. Only a limited number of treatment methods can accomplish this reduction and, as shown in this report, the cost of treatment increases proportionately with levels of removal.

The nanofiltration option includes blending with partially treated ground water so that the volume of water treated by NF, and thus overall treatment costs, are reduced. The lime softening option does not remove all secondary drinking water contaminants to below the MCL, and therefore does not produce a product water that is in full compliance with all secondary MCLs. However, the lime softening option does have the potential to be blended with other higher quality waters, such as NF-treated ground water or surface water, to achieve full compliance.

7.3.2 Nanofiltration. - As discussed earlier in section 5.2.2, NF is a separation process that desalts water by the application of hydrostatic pressure to drive feed water through a semi-permeable membrane. A major portion of the water's impurity (dissolved salts) remains behind and is discharged as waste brine; relatively pure water emerges at near atmospheric pressure. Operating pressures for NF are in the range of 75 to 150 lb/in^2. Typical ion rejections are 90 to 95 percent for divalent ions (Ca^{+2}, Mg^{+2}, SO_4^{-2}), and 60 to 70 percent for monovalent ions (Na^+, K^+, Cl^-, HCO_3^-).

A proposed flow scheme for LHC using NF is presented on figure 19. As shown, the raw feed water is split, after pumping, with half of the flow directed to NF treatment, and the remaining half to $KMnO_4$ oxidation treatment for the removal of manganese. Because the NF product is of such high quality (far exceeds drinking water standards), the two product streams can be blended and still meet secondary MCLs. Also, by doing this blending, the overall treatment cost is lower than if the entire flow stream were to receive NF treatment.

Pretreatment is critical to protect membranes from scale deposits and colloidal and biological fouling. For LHC ground water, the following NF pretreatment is recommended: disinfection to destroy microorganisms; polymer addition and filtration to remove suspended colloidal materials; and the addition of an anti-scalant and acid to prevent scaling of the membranes.

Table 6 presents a summary of the anticipated ion concentrations in the proposed NF plant for the following flow streams: feed, reject brine, permeate (product), and blended (or final) product.

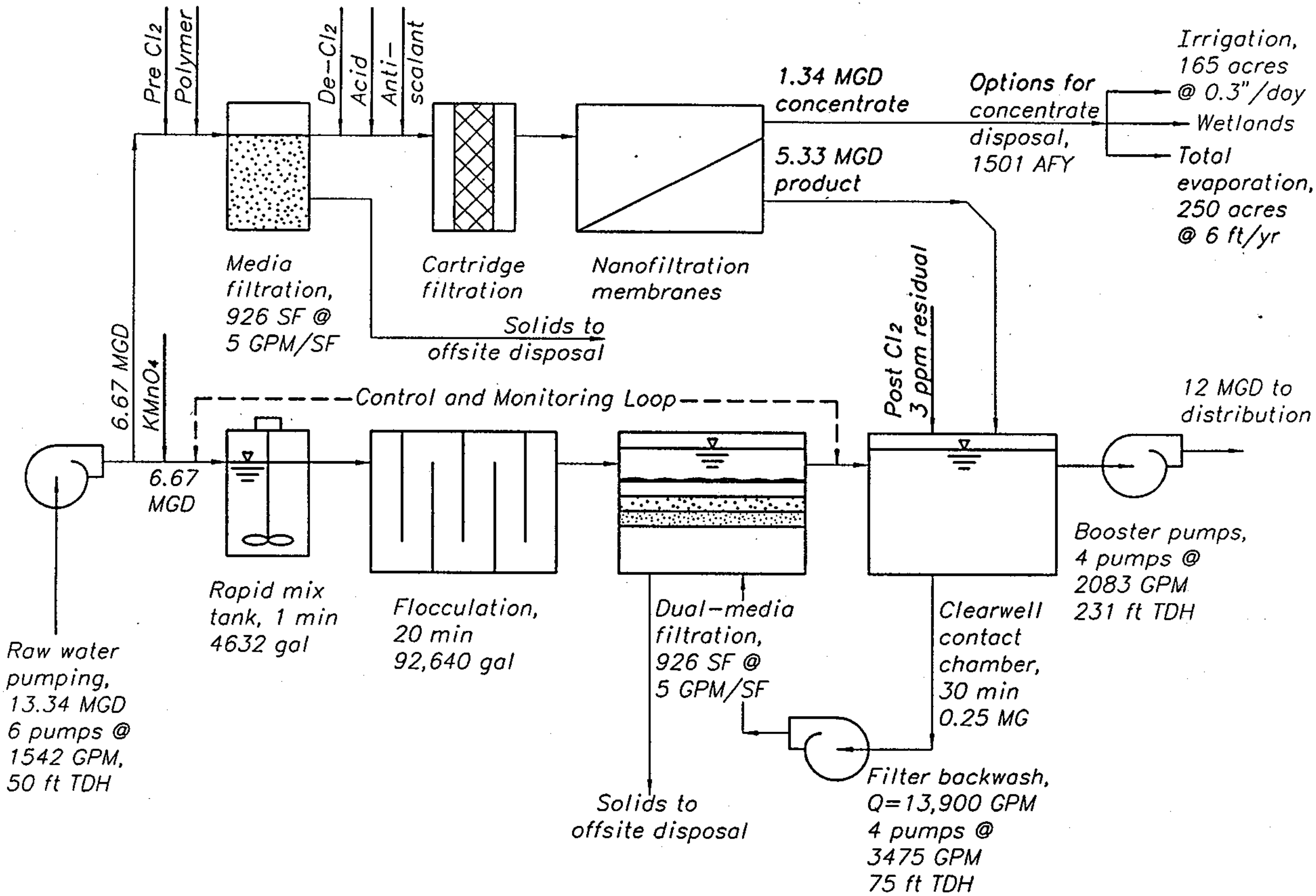


Figure 19. - Water treatment with nanofiltration—Lake Havasu City water treatment study.

Table 6. - Nanofiltration ion concentrations.

Constituent	Feed (mg/L)	NF Brine (mg/L)	NF Permeate (mg/L)	Blended Permeate (mg/L)
Calcium	84.4	400	1.39	48.1
Magnesium	29.5	120	0.46	16.7
Sodium	113	500	19	71.6
Potassium	3.33	11	≤1.0	≤2.3
Barium	<0.05	0.16	<0.05	
Strontium	1.35	7.4	<1.0	
Iron	<0.05	<0.05	<0.05	
Manganese	<0.05	2.3	<0.05	
Bicarbonate	173	780	19	105
Chloride	108	430	23.3	70.7
Sulfate	293	1600	7.7	167
Nitrate	<0.80	0.7	<0.50	
Fluoride	0.93	3	0.13	0.58
Silica (total)	18.3	77	3.88	12
Alkalinity	173	780	19	105
Hardness	333	1500	5.33	189
Total dissolved solids (TDS)	826	3932	75	496

7.3.2.1 *Brine production.* - Reject brine, or concentrate, is the waste stream resulting from the NF desalting process. It contains most of the impurities (dissolved salts) originally present in the feed water. The estimated ionic makeup of this reject stream for the proposed LHC plant is shown in the second column of table 6 (NF Brine). As shown on figure 19, about 1.34 Mgal/d of reject brine will be produced from the nanofiltration process.

7.3.2.2 *Brine disposal.* - Generally, brine disposal options include the following: surface water discharge, deep well injection, evaporation, spray irrigation, and constructed wetlands. However, for LHC, as with most other municipalities, brine disposal choices are restricted by State and Federal regulatory requirements.

By far, the least costly brine disposal option is discharge to a nearby surface water. Surface water discharges are regulated by the Clean Water Act and, as such, would be subject to permit restrictions. Arizona's permit program under the National Pollutant Discharge Elimination System program would probably not allow a high saline discharge to the Colorado River. Such cost-prohibitive treatment requirements make this option infeasible for the city.

Deep-well injection is possible in Arizona; however, an Aquifer Protection Permit is required with discharge limits which also are likely to make this option cost prohibitive. It would have to be shown that injection of the brine would not adversely impact sub-surface aquifers. This demonstration can be done with geohydraulic modeling of the aquifer, once the aquifer characteristics are known and understood.

The three remaining options for brine disposal are evaporation, spray irrigation, and the creation of a constructed wetlands. 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 city.

1. *Evaporation*: An evaporative pond system of about 250 surface acres would evaporate the 1.34 Mgal/d of brine, based on an estimated net evaporation rate of 6 ft/yr. This land area can be separated into several ponds to suit the desired goals and objectives of the disposal option. The liner for the ponds would be PVC, HDPE, or compacted clay if locally available. A force main system from the plant to the pond is assumed, which includes a storage tank, sized at 5 days production (6.7 Mgal), and a pump station operating at 4653 gal/min for 24 hours every 5th day. This disposal option was assumed for preparation of the cost estimate (section 8), primarily because of its popularity.

2. *Irrigation*: In a desert environment, a high priority must be placed on both water conservation and the reuse of waste waters to lessen water demands where possible. The city's "Comprehensive Master Water Plan" devotes an entire chapter to the scenario of developing areas around the city which can use reclaimed water for the irrigation of landscaped areas, thereby lowering water demands. Specifically identified in this Master Water Plan are nine potential reclaimed water sites that could use an average monthly rate of 1.3 Mgal/d and a peak monthly rate of 2.9 Mgal/d of reclaimed water for irrigating landscaped areas. The report concludes that because the city's three reclaimed water plants produce only 1.4 Mgal/d, any additional reclaimed water would lower the city's potable water demand. Therefore, disposal of NF brine by landscape irrigation is an attractive option serving a dual purpose, reducing water demands while increasing the city's landscaping. The ADEQ (Arizona Department of Environmental Quality) must approve such a plan.

Using appropriate salt-tolerant grasses and foliage, irrigation of landscaped areas can be applied at a rate of about 0.3 in/d and require 160 irrigable acres. Such areas can include open space, green belts, golf courses, highway medians, and resort complexes. An irrigation system would require a storage tank or lined holding pond sized for at least 2 days of storage (6.7 Mgal), a pump station that would operate at 1860 gal/min for 12 h/d, and a force main-distribution network.

3. *Wetlands*: The creation of a wetlands in a desert environment is aesthetically pleasing in that it creates an environment where selected brine-tolerant plants can proliferate. At a pilot saline wetlands in Hemet, California, alkali bulrush, cattails, arrow grass and spikerush plants have survived and flourished in the reject brine from a reverse osmosis demonstration plant (Boegli and Thullen, 1994). In addition, the wetlands will attract waterfowl and animals, i.e., ducks, geese, frogs, and insects. The ADEQ must approve such a brine disposal plan, and there would likely be a permitted discharge from a wetlands system to surface water or to the ground-water aquifer. Alternately, the discharge brine would be further concentrated in an evaporation pond.

   For the 12 Mgal/d water treatment facility being considered in this report, a wetlands area of 8.2 acres is required to dispose of 1.34 Mgal/d of brine produced. 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 LHC. The other main features of a wetland brine disposal system include a storage tank or lined holding pond sized at about 5 days of flow (6.7 Mgal), a pump station that can operate at 4653 gal/min for 24 hours every 5th day, and a force main.

7.3.3 Lime softening. - Lime softening is a widely used process for clarification, reduction of hardness and salinity, and heavy metals removal in natural waters. The process requires the presence of a significant concentration of HCO_3^- (bicarbonate ion) in the raw water.

$Ca(OH)_2$ (lime) is added to the water at ambient temperature. The following reactions occur:

$$Ca(OH)_2 + Ca^{+2} + 2HCO_3^- \rightarrow 2CaCO_3\downarrow + 2H_2O \qquad (1)$$

$$Ca(OH)_2 + Mg^{+2} \rightarrow Mg(OH)_2\downarrow + Ca^{+2} \qquad (2)$$

In water containing a reasonable amount of bicarbonate, a voluminous precipitate, consisting primarily of calcium bicarbonate, is formed. This precipitate entraps suspended particles of silica and other materials which cause turbidity in the raw water. To enhance flocculation, a small amount of coagulant, say 10 p/m of ferric chloride, is added.

In waters containing heavy metals like iron and manganese, these metals are precipitated as hydroxides or oxides, which are caught up in the precipitate. Reaction zone pH and residence time can be adjusted to ensure satisfactory removal of manganese.

A lime softening ground-water treatment plant for LHC would consist of rapid mixing, flocculation, settling, and filtration. Figure 20 illustrates these unit operations along with the raw and finished water pumping, a clearwell, and post-disinfection using chlorine.

Rapid mixing, flocculation, and settling occur in one unit, the solids contact reactor. These steps may be separated for greater system flexibility, but at a higher construction cost. A slurry of

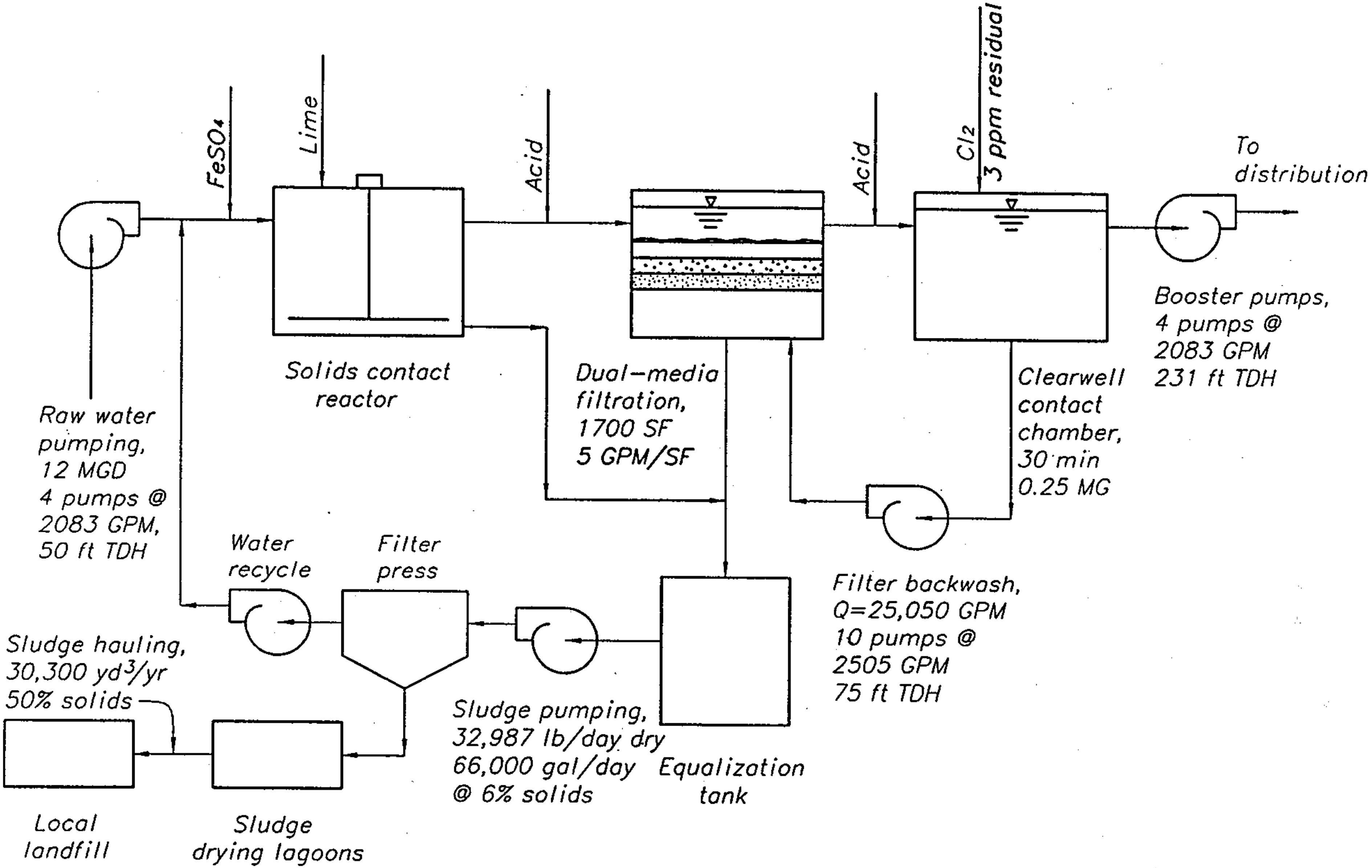


Figure 20. - Water treatment with lime softening—Lake Havasu City water treatment study.

lime in water is added to raw feed water in a high intensity mixing vessel or zone in which reactions (1) and (2) are carried out. Flocculation occurs under gentle agitation, and settling occurs in a zone with very low flow rates. The objective is to create large agglomerates of precipitate which will settle rapidly. Most of the solids are removed as a slurry from the bottom of the reactor. The clarified water is filtered, usually with a rapid sand and anthracite filter, to remove the balance of the solids and produce a clear, treated effluent. The filter is periodically backwashed with treated water to remove the solids. Backwash water is typically returned to the reactor.

The chemistry of this process is well understood. Sludge quantity and composition have been estimated, based on a process feed flow similar to well S6, and are included in appendix F.

7.3.3.1 *Sludge production.* - Sludge from lime softening results from the initial raw water solids, plus the precipitate formed from the introduction of lime. At 12 Mgal/d, this volume is estimated to be 66,000 gal/d of a slurry that contains about 6 percent solids by weight. If this sludge was dried, it would weigh about 33,000 lb/d. These solids collect in the bottom of the solids contact reactor and are periodically pumped to a sludge holding tank and filter press for thickening.

7.3.3.2 *Sludge disposal.* - It is recommended that the drying of thickened sludge at LHC be accomplished in a lined sludge drying bed. The final quantity of solids that would be hauled to a local landfill would be about 30,300 yd^3/yr, at a solids content of 50 percent. For cost estimation purposes, the hauling distance is estimated to be 5 miles.

7.4 Potential Alternatives Not Pilot-tested

Each summer, LHC experiences nationwide high temperatures and it struggles to provide enough water to its residents. To compound this problem, existing wells are declining in productivity as overall water levels in the vicinity recede. The quality of water found in Lake Havasu exceeds the quality of water in the wells. Both manganese and TDS in Lake Havasu are at levels that would not warrant the expense of their removal. Thus, a lower capital cost for treatment of surface water would be required than for ground water. To solve the city's imminent water shortage problem, a surface water treatment plant, sized to satisfy the city's critical summertime shortage, is recommended. The finished water quality data generated from such a plant would benefit the city in design of a larger ground-water treatment plant, both in terms of a lower capacity and for blending with ground water. By using the higher quality and less costly surface water, residents would pay less for their water because the volume of treated ground water would be lower.

Other ground-water treatment processes could not be tested during this pilot test, but they represent additional alternatives to the city to meet future water demands.

8. TREATMENT COSTS

8.1 General

Construction, annual O&M (operations and maintenance), and life cycle cost estimates for a 12-Mgal/d plant capacity are provided for the following three levels of ground-water treatment:

- Manganese removal using potassium permanganate oxidation.

- Full compliance with both primary and secondary drinking water standards using nanofiltration.

- Complete removal of manganese and partial removal of sulfates and TDS using lime softening.

Capital cost estimates are based on a combination of direct quotes from manufacturers, plus allowances for installation, and a newly-developed Reclamation software program that uses cost curves prepared by the EPA (Environmental Protection Agency). This program uses the raw water quality from the site and current indices of the ENR (*Engineering News Record*), along with the Producer Price Index, to calculate both construction and O&M cost estimates.

Capital construction costs are for individual treatment units, including all equipment, but do not include costs for land ownership, rights of way, special site-work, easements, or yard and offsite piping. Also not included are costs for an intake structure, grit removal equipment, or buildings (chemical feed, storage, administration, or 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 the cost estimates is the EPA's Research and Development manual numbered EPA-600/2-79-162a, titled "Estimating Water Treatment Costs." Each unit process is defined in terms of the following eight subcategories: excavation and site work, 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 December 1994 or the *Engineering News Record* construction cost index for January 1995. Each unit's estimate also includes the cost of a standby or spare unit plus a 15-percent allowance for miscellaneous and contingency items. For O&M costs, the EPA curves are also used with updates for electrical energy costs, maintenance materials, chemicals, and labor. Citizens Electric provided a value of nearly $0.06/kWh for plants under 1,000 kW. Chemical costs are estimated from recent contacts with chemical supply companies or from a chemical periodical. Labor has been estimated at $20.00/h.

8.2 $KMnO_4$ Oxidation

A plant that uses potassium permanganate to oxidize manganese in the well S6 feed water is described in section 7.1, and is shown schematically on figure 18. Because little water is lost in this treatment scheme, the flow rate of 12 Mgal/d is used for all unit processes. This treatment plant will effectively remove manganese down to its MCL of 0.05 mg/L. However, other secondary drinking water parameters such as sulfates and TDS will remain above their maximum contaminant levels.

8.2.1 Construction cost. - The total estimated construction cost for a plant which removes manganese using potassium permanganate oxidation is $3,018,700, as shown in table 7. This cost is equivalent to about $0.25 per daily gallon.

8.2.2 Operations and maintenance costs. - The total estimated annual O&M cost for a plant which removes manganese using potassium permanganate oxidation is $301,500, as shown in table 7. This cost is equivalent to about $0.07 per thousand gallons treated.

Table 7. - Construction and annual operations and maintenance costs (12 Mgal/d).

Option 1: Potassium permanganate oxidation

	Construction Cost ($)	Annual O & M ($)
Raw Water Pumping[1]	145,200	44,600
Potassium Permanganate Addition[2]	74,200	62,500
Rapid Mix[3]	72,200	30,000
Flocculation[4]	247,000	8,000
Dual Media Filter[5]	1,422,100	83,100
Filter Backwash Pumping[6]	455,000	10,800
Chlorination[7]	74,000	33,400
Clearwell[8]	393,000	8,000
Booster Pumping[9]	136,000	21,100
Total	3,018,700	301,500

[1] Six pumps with intake screens, each rated at 2083 gal/min at 50 feet of TDH
[2] Concentration of 1.2 p/m potassium permanganate
[3] 1-minute detention time, G = 900/second
[4] 20-minute detention time
[5] 1700 ft^2 filter area, includes dual media and housing
[6] Four pumps, each rated at 6375 gal/min at 75 feet of TDH
[7] Residual concentration of 3 p/m chlorine
[8] 0.25-Mgal capacity
[9] Four pumps, each rated at 2083 gal/min at 231 feet of TDH

8.3 Full Compliance using Nanofiltration

If the residents of LHC decide they want drinking water that meets all primary and secondary drinking water standards, then an NF plant is recommended. NF produces water of such high quality that blending with available raw water sources will still produce a combined product meeting all secondary MCLs. Data gathered during pilot testing suggest that a full scale treatment plant producing 12 Mgal/d of full-compliance water could treat 6 Mgal/d for manganese alone, and 6 Mgal/d with NF.

8.3.1 Construction cost. - The water treatment plant discussed above, described in section 7.3.2 and shown schematically on figure 19, will cost about $16,910,100, as shown in table 8. This cost is equivalent to $1.41 per daily gallon. This cost estimate includes brine disposal using total evaporative drying beds for half of the brine and spray irrigation of greenbelts for the other 50 percent of the brine flow.

Table 8. - Construction and annual operations and maintenance costs (12 Mgal/d).

Option 2: Nanofiltration

	Construction Cost ($)	Annual O & M ($)
Raw Water Pumping[1]	217,100	66,700
Chlorination[2,3]	35,200	16,600
Polymer[2,4]	46,200	87,600
Dual Media Filter[2,5]	949,200	47,900
Filter Backwash Pumping[2,14]	269,300	8,300
Dechlorination[2,6]	46,200	87,600
Acid Addition[2,7]	778,100	11,200
Anti-Scalant[2,8]	87,900	285,900
Nanofiltration[2]	3,581,400	622,400
Brine Disposal[2]	8,735,000	436,800
Potassium Permanganate Addition[9,10]	46,200	61,400
Rapid Mix[9,11]	40,000	12,200
Flocculation[9,12]	186,000	5,600
Dual Media Filter[9,13]	949,200	47,900
Filter Backwash Pumping[9,14]	269,300	8,300
Chlorination[3]	78,500	35,700
Clearwell[15]	393,000	8,000
Booster Pumping[16]	202,300	31,500
Total	16,910,100	1,881,600

[1] 13.4 Mgal/d, 6 pumps with intake screens, each rated at 1542 gal/min at 50 feet of TDH
[2] Flow stream for nanofiltration process, 6.7 Mgal/d
[3] Concentration of 1 p/m chlorine
[4] Concentration of 2 p/m polymer
[5] 930 ft^2 filter area
[6] Concentration of 2 p/m sodium bisulfite
[7] Concentration of 25 p/m of 93% sulfuric acid
[8] Concentration of 7 p/m anti-scalant
[9] Flow stream for potassium permanganate oxidation process, 6.7 Mgal/d
[10] Concentration of 1.2 p/m potassium permanganate
[11] 1-minute detention time
[12] 20-minute detention time
[13] 930 ft^2 filter area
[14] Four pumps, each rated at 3475 gal/min at 75 feet of TDH
[15] 0.25-Mgal capacity
[16] Four pumps, each rated at 2083 gal/min at 231 feet of TDH
[17] Assumes half of brine is spray irrigated and half is evaporated

8.3.2 Operations and maintenance costs. - The total estimated annual O&M cost for a 12-Mgal/d ground-water treatment plant using NF is $1,881,600, as shown in table 8. This cost includes a membrane cleaning apparatus, and the cost of membrane replacement every 3 years. This cost is equivalent to $0.43 per thousand gallons treated.

8.4 Lime Softening

As described in section 7.3.3, lime softening of ground water will remove the manganese to levels below the MCL (as long as influent values do not differ much from well S6). Lime softening will not reduce TDS or sulfates to secondary drinking water standards. However, these standards could be achieved by blending with water of higher quality, such as surface or ground water that has been treated with NF.

8.4.1 Construction cost. - The 12-Mgal/d lime softening ground-water treatment plant, which is shown schematically on figure 20, will cost about $7,818,400, as shown in table 9. This cost is equivalent to about $0.65 per daily gallon.

Table 9. - Construction and annual operations and maintenance costs (12 Mgal/d).

Option 3: Lime Softening

	Construction Cost ($)	Annual O & M ($)
Raw Water Pumping[1]	145,200	44,600
Ferric Sulfate Addition[2]	488,900	723,100
Lime Feed Addition[3]	266,500	290,000
Solids Contact Reactor[4]	1,549,700	66,200
Dual Media Filter[5]	1,422,100	83,100
Acid Addition[6]	28,000	5,900
Filter Backwash Pumping[7]	455,000	10,800
Chlorination	74,000	33,400
Clearwell[8]	393,000	8,000
Sludge Disposal[9]	2,860,000	462,500
Booster Pumping[10]	136,000	21,100
Total	7,818,400	1,748,600

[1] Six pumps with intake screens, each rated at 1542 gal/min at 50 feet of TDH

[2] Concentration of 10 p/m ferric sulfate

[3] Concentration of 185 p/m of hydrated lime

[4] Four pumps, each rated at 2083 gal/min at 231 feet of TDH

[5] 1700 ft^2 filter area, includes dual media and housing

[6] Concentration of 2.5 p/m of 93% sulfuric acid

[7] Ten pumps, each rated at 2505 gal/min at 75 feet of TDH

[8] 0.25-Mgal capacity

[9] Includes sludge pumping, storage, filter press thickening, drying beds, and off-site hauling up to 5 miles

[10] Four pumps, each rated at 2083 gal/min at 231 feet of TDH

8.4.2 Operations and maintenance costs. - The total estimated O&M cost for a 12-Mgal/d lime softening plant is $1,748,600, as shown in table 9. This cost is equivalent to about $0.40 per thousand gallons treated.

8.5 Cost Analysis

Table 10 presents summarizes the ground-water treatment options presented in this study. It is important to note that these options are not equivalent in terms of the level of treatment each provides and that both construction and O&M costs increase with the increasing levels of treatment. These costs also do not represent final capital costs as explained in section 8.1. It is also important to note that final costs depend on the type of residual disposal option selected. For NF, the combined use of single-lined evaporation ponds and spray irrigation is assumed.

Table 10. - Cost summary of ground-water treatment options (12 Mgal/d).

	Option 1	Option 2	Option 3
Construction Cost ($)	3,018,700	16,910,100	7,818,400
Annual O&M ($)	301,500	1,881,600	1,748,600
Construction Cost ($)/Daily Gallon	0.25	1.41	0.65
O&M Cost ($)/1000 Gallons	0.07	0.43	0.40

A 20-year life cycle cost analysis is presented in table 11. The analysis is presented in terms of total present worth and total annual cost. A final cost/1000 gal of treated water is also shown.

8.6 Surface Water Treatment Costs

Assuming that lime or alum chemical treatment will remove suspended solids and the city can obtain all necessary water rights, a 12-Mgal/d water treatment plant for surface water would cost about $9,300,000 or $0.78/daily gallon to construct (HDR Master Plan, table 9-2, and figure 9-6). It would also cost about $4,190,000 to operate per year or $0.96/1000 gallons (interpolated from HDR Master Plan table A3-4).

9. CONCLUSIONS

This report concludes the following:

1. Water treatment costs to remove contaminants of concern to the residents of LHC vary proportionately with the level of treatment provided. For a 12-Mgal/d (product) treatment plant, these costs range from $0.25 to $1.41 per daily gallon for construction, and from $0.07 to $0.43 per 1000 gallons treated for annual O&M, as detailed below:

    a. For a 12-Mgal/d water treatment plant employing potassium permanganate oxidation and the unit operations displayed on figure 18, the construction cost estimate is $3,018,700 and the annual O&M costs are $301,500.

    b. For a 12-Mgal/d water treatment plant employing nanofiltration and the unit operations displayed on figure 19, the construction cost estimate is $16,910,100 and the annual O&M costs are $1,881,600.

Table 11. - Life cycle costs for ground-water treatment options.

	Basic Assumptions		
Study Period		20 years	
Annual Interest Rate		6.5%	
Capital Recovery Factor		0.0908	
Present Worth Factor		11.019	
	Potassium Permanganate	Nanofiltration	Lime Softening
Capital Cost	$3,018,700	$16,910,100	$7,818,600
Present Worth of Annual Operating Cost[1]	$3,322,200	$20,733,400	$19,267,800
Total Present Worth	$6,340,900	$37,643,500	$27,086,400
Annualized Capital Cost[2]	$274,100	$1,535,400	$709,900
Annual Operating Cost	$301,500	$1,881,600	$1,748,600
Total Annual Cost	$575,600	$3,417,000	$2,458,500
Cost/1000 Gal of Product[3]	$0.13	$0.78	$0.56

[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 annual cost/(365x12,000)

c. For a 12-Mgal/d water treatment plant employing lime softening and the unit operations displayed on figure 20, the construction cost estimate is $7,818,400, and the annual O&M costs are $1,748,600.

2. Based on the assumptions made in this report and the life cycle cost analysis assuming 20 years at an interest rate of 6.5 percent, the total annual cost of a 12-Mgal/d plant for the three alternatives studied are:

   1) Potassium permanganate oxidation - $575,600 or $0.13/1000 gal
   2) Nanofiltration - $3,417,000 or $0.78/1000 gal
   3) Lime softening - $2,458,500 or $0.56/1000 gal.

   Refer to section 8.1 for an explanation as to what these life cycle costs include.

3. For a 12-Mgal/d treatment plant employing nanofiltration and the unit operations displayed on figure 19, potential benefits might be realized by using about 1.34 Mgal/d of reject brine in either a reclaimed water capacity that could lower irrigation demands on the city's water system, or to create a wetland environment.

10. RECOMMENDATIONS

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

1. LHC is experiencing a severe problem with manganese in their drinking water. Although manganese is only a secondary drinking water standard, and the quality of the water served to the residents of the city meets all Federal and State primary drinking water standards, manganese-related problems such as discolored water, stained clothing, and clogged waterlines are a continuing concern. It is recommended that the city use the economic and treatment process conclusions contained in this report in their planning for future water treatment expansion, and that consideration be given to achieving full compliance with secondary drinking water standards.

2. If LHC considers nanofiltration an affordable water treatment option, it is recommended that meetings be arranged with the State of Arizona to determine specific requirements for the brine disposal options presented in this report.

3. From a water shortage standpoint, the city is urged to proceed with the construction of a temporary surface water treatment plant sized to provide enough water to meet the critical summertime demands.

11. REFERENCES

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APPENDIX A

$KMnO_4$ oxidation and greensand test data

KMnO4 Oxidation/Greensand Test Data

Date	Feed (L/min)	KMnO4 (mg/L)	Res. Time (min)	Sample	Mn (mg/L) Hach	Mn (mg/L) Westech	Sample	Mn (mg/L) Hach	Mn (mg/L) Westech	Sample	Mn (mg/L) Hach	Mn (mg/L) Westech	Avg Temp. (deg C)	-------- Turbidity (ntu) --------		
														Raw Feed	GS Influent	GS Effluent
9/11/94	22.7	0.54	55	GS1-1	0.613	0.57	GS1-2	0.252	0.21	GS1-3	0.033	<0.05	24.3	0.09	5.09	0.06
9/12/94	22.7	0.76	55	GS2-1	0.621	0.58	GS2-2	0.119	0.10	GS2-3	0.046	<0.05	23.8	0.15	7.84	0.05
9/13/94	22.7	0.99	55	GS3-1	0.621	0.57	GS3-2	0.021	<0.05	GS3-3	0.060	<0.05	23.5	0.10	11.70	0.06
9/14/94	22.7	1.16	55	GS4-1	0.633	0.52	GS4-2	0.017	<0.05	GS4-3	0.040	<0.05	23.7	0.09	16.40	0.06
9/15/94	22.7	1.30	55	GS5-1	0.630	0.53	GS5-2	0.064	<0.05	GS5-3	0.054	<0.05	23.7	0.09	18.70	0.06
9/16/94	22.7	1.57	55	GS6-1	0.647	0.57	GS6-2	0.125	0.10	GS6-3	0.062	<0.05	24.0	0.10	17.80	0.05
9/17/94	22.7	1.72	55	GS7-1	0.597	0.55	GS7-2	0.177	0.15	GS7-3	0.052	<0.05	24.0	0.12	19.20	0.06
9/19/94	15.1	0.81	12	GS8-1	0.621	0.56	GS8-2	0.011	<0.05	GS8-3	0.079	0.06	25.5	0.16	12.90	0.09
9/20/94	15.1	0.95	12	GS9-1	0.614	0.59	GS9-2	0.017	<0.05	GS9-3	0.088	0.06	24.5	0.12	12.00	0.07
9/21/94	15.1	0.95	12	GS10-1	0.618	0.59	GS10-2	0.017	<0.05	GS10-3	0.096	0.07	24.3	0.11	12.80	0.06
9/22/94	15.1	0.95	12	GS11-1	0.626	0.58	GS11-2	0.012	<0.05	GS11-3	0.100	0.08	24.4	0.10	13.30	0.07

APPENDIX B

Nanofiltration test data

Nanofiltration Test Data

Elapsed Time (hours)	Flowrates					Conductivity					Pressure			Temperature		Turbidity
	Feed (L/min)	Reject (L/min)	Permeate Stage 1/1 (L/min)	Permeate Stage 1/2 (L/min)	Permeate Stage 2 (L/min)	Feed (uS/cm)	Reject (uS/cm)	Permeate Stage 1/1 (uS/cm)	Permeate Stage 1/2 (uS/cm)	Permeate Stage 2 (uS/cm)	Feed (lb/in2)	Interstage (lb/in2)	Reject (lb/in2)	Feed (deg F)	Feed (deg C)	Feed - after cart. filter (ntu)
1.0	18.2	3.6	5.9	6.0	3.1	1170	5380				79	57	49	78.6	25.9	0.112
4.8	18.2	3.6	5.8	5.9	3.2	1170	5040				77	56	47	78.4	25.8	0.077
7.6	18.3	3.6	5.8	5.9	3.2	1170	4940	87	91	309	75	55	46	80.3	26.8	0.064
11.2	18.1	3.6	5.8	5.8	3.3	1170	5070	84	88	295	75	55	47	76.9	24.9	0.063
23.0	18.0	3.6	5.6	5.7	3.4	1170	4870	81	85	283	76	55	46	74.7	23.7	0.064
26.9	18.1	3.6	5.6	5.6	3.3	1170	4950	87	90	309	72	53	44	76.8	24.9	0.064
30.9	18.2	3.6	5.6	5.6	3.3	1170	4890	87	90	316	71	52	43	79.0	26.1	0.066
35.3	18.1	3.6	5.6	5.6	3.3	1170	5020	87	91	318	72	53	44	76.4	24.7	0.066
46.6	18.2	3.6	5.6	5.7	3.3	1170	5160	84	84	290	76	56	47	75.3	24.1	0.067
50.6	18.2	3.6	5.6	5.6	3.3	1170	5260	82	83	295	75	56	47	75.0	23.9	0.067
54.6	18.2	3.6	5.7	5.7	3.3	1170	5220	82	83	297	74	55	46	77.9	25.5	0.069
59.4	18.3	3.6	5.6	5.7	3.3	1170	5240	80	83	289	75	56	47	76.7	24.8	0.069
71.0	18.2	3.6	5.6	5.6	3.4	1170	5190	73	77	257	79	58	49	74.7	23.7	0.073
71.9	18.2	3.6	5.6	5.7	3.2	1190	5140	74	78	276	78	58	49	74.6	23.7	0.077
74.6	18.2	3.6	5.7	5.7	3.3	1190	5350	78	79	294	77	58	49	76.3	24.6	0.082
78.6	18.2	3.6	5.6	5.7	3.3	1190	4990	79	82	294	75	56	46	79.0	26.1	0.084
82.5	18.2	3.6	5.6	5.6	3.3	1190	5150	78	81	289	76	56	47	76.8	24.9	0.081
94.7	18.2	3.6	5.7	5.5	3.4	1190	5160	72	79	262	80	59	49	73.9	23.3	0.073
98.6	18.2	3.6	5.5	5.6	3.3	1190	5100	80	83	281	78	57	48	75.3	24.1	0.074
102.6	18.2	3.6	5.8	5.9	3.4	1190	5050	77	81	286	77	56	47	78.0	25.6	0.070
108.7	18.1	3.6	5.6	5.7	3.3	1190	5010	80	83	285	76	56	46	77.6	25.3	0.064
118.8	18.2	3.6	5.6	5.4	3.3	1190	5170	75	80	270	79	58	49	74.1	23.4	0.053
122.8	18.2	3.6	5.6	5.7	3.3	1190	5090	76	80	280	78	57	48	77.1	25.1	0.050
126.8	18.2	3.6	5.7	5.7	3.2	1200	4980	80	83	298	76	55	46	81.1	27.3	0.049
130.6	18.2	3.6	5.6	5.6	3.2	1200	5000	82	84	297	75	55	46	79.6	26.4	0.046
142.5	18.2	3.6	5.6	5.6	3.2	1190	5200	73	77	270	80	58	49	74.5	23.6	0.041
146.1	18.2	3.6	5.6	5.7	3.3	1190	5270	76	78	279	80	58	49	77.0	25.0	0.040
150.9	18.2	3.6	5.7	5.7	3.2	1200	5000	79	82	292	76	55	46	81.2	27.3	0.043
154.6	18.2	3.6	5.6	5.6	3.3	1200	4940	81	81	286	76	55	45	80.8	27.1	0.044
166.9	18.2	3.6	5.5	5.6	3.3	1190	5230	72	75	263	81	59	49	74.3	23.5	0.045
171.0	18.2	3.6	5.6	5.6	3.3	1190	5160	80	81	283	79	57	48	77.3	25.2	0.051
175.1	18.2	3.6	5.6	5.7	3.2	1200	5030	79	82	295	76	55	46	81.1	27.3	0.052
178.7	18.2	3.6	5.6	5.7	3.3	1200	5110	77	80	281	78	57	47	79.9	26.6	0.051
190.6	18.2	3.6	5.6	5.6	3.3	1190	5190	71	73	263	81	60	50	74.4	23.6	0.053
194.6	18.2	3.6	5.6	5.7	3.3	1190	5270	75	77	273	81	59	49	76.7	24.8	0.057
198.6	18.2	3.6	5.6	5.7	3.3	1200	5110	78	80	288	78	56	47	81.1	27.3	0.059
202.6	18.2	3.6	5.6	5.7	3.3	1190	5100	76	78	280	78	57	47	80.1	26.7	0.056
214.6	18.2	3.6	5.6	5.7	3.3	1190	5240	74	75	263	81	59	50	74.5	23.6	0.061
218.6	18.2	3.6	5.6	5.7	3.3	1190	5210	75	77	276	80	58	49	77.1	25.1	0.063
222.6	18.2	3.6	5.6	5.7	3.3	1200	5060	76	79	290	78	56	47	81.5	27.5	0.067
226.6	18.2	3.6	5.6	5.7	3.3	1190	5090	76	78	278	78	56	47	80.3	26.8	0.065
238.6	18.2	3.6	5.6	5.6	3.3	1190	5220	73	74	259	81	59	50	74.6	23.7	0.074
242.6	18.2	3.6	5.7	5.7	3.3	1200	5190	72	74	267	80	58	49	77.1	25.1	0.045
246.6	18.2	3.6	5.7	5.7	3.3	1200	5050	75	78	281	78	56	47	80.9	27.2	0.047
250.6	18.2	3.6	5.7	5.6	3.3	1200	5220	81	80	279	78	56	46	77.4	25.2	0.046
262.6	18.2	3.6	5.6	5.7	3.3	1190	5080	72	74	262	81	58	48	76.8	24.9	0.045
266.6	18.2	3.6	5.6	5.7	3.3	1200	5130	73	75	266	80	58	48	76.7	24.8	0.048
270.6	18.2	3.6	5.6	5.7	3.3	1200	5250	79	79	281	79	57	48	77.1	25.1	0.045
274.6	18.2	3.6	5.6	5.6	3.3	1200	5230	80	78	271	79	57	47	77.4	25.2	0.043
287.0	18.2	3.6	5.7	5.7	3.3	1190	5140	69	72	261	82	59	49	76.0	24.4	0.045
290.7	18.2	3.6	5.6	5.7	3.3	1190	5060	70	72	267	81	58	49	77.4	25.2	0.047
294.7	18.2	3.6	5.6	5.7	3.3	1200	5210	79	80	284	80	57	47	77.0	25.0	0.052

Nanofiltration Test Data - Continued

	Flowrates					Conductivity					Pressure			Temperature		Turbidity
Elapsed Time (hours)	Feed (L/min)	Reject (L/min)	Permeate Stage 1/1 (L/min)	Permeate Stage 1/2 (L/min)	Permeate Stage 2 (L/min)	Feed (uS/cm)	Reject (uS/cm)	Permeate Stage 1/1 (uS/cm)	Permeate Stage 1/2 (uS/cm)	Permeate Stage 2 (uS/cm)	Feed (lb/in2)	Interstage (lb/in2)	Reject (lb/in2)	Feed (deg F)	Feed (deg C)	Feed - after cart. filter (ntu)
298.7	18.2	3.6	5.6	5.7	3.3	1200	5280	79	79	280	80	57	48	76.5	24.7	0.053
310.6	18.2	3.6	5.6	5.7	3.3	1190	5110	67	71	257	82	59	49	75.8	24.3	0.054
314.6	18.2	3.6	5.6	5.7	3.3	1190	5130	67	70	249	83	60	50	74.3	23.5	0.060
318.6	18.2	3.6	5.6	5.7	3.3	1190	5160	71	71	255	83	60	50	75.8	24.3	0.065
322.6	18.2	3.6	5.6	5.7	3.3	1190	5210	70	71	261	83	60	50	75.4	24.1	0.064
334.6	18.2	3.6	5.6	5.7	3.3	1190	5310	68	70	241	85	61	51	72.8	22.7	0.076
338.6	18.2	3.6	5.6	5.6	3.3	1190	5200	69	69	248	84	61	51	74.8	23.8	0.074
342.6	18.2	3.6	5.6	5.7	3.3	1190	5130	67	71	220	83	60	50	77.5	25.3	0.077
346.6	18.2	3.6	5.6	5.7	3.3	1200	5100	67	71	252	82	59	49	76.8	24.9	0.045
358.5	18.2	3.6	5.6	5.7	3.4	1190	5330	71	72	250	85	62	52	72.9	22.7	0.045
362.6	18.2	3.6	5.6	5.7	3.4	1190	5210	70	70	249	84	60	50	75.9	24.4	0.044
366.6	18.2	3.6	5.6	5.7	3.3	1200	5270	69	71	264	82	59	49	77.0	25.0	0.043
370.6	18.2	3.6	5.6	5.7	3.3	1200	5270	69	72	259	82	59	49	76.3	24.6	0.043
382.7	18.2	3.6	5.6	5.7	3.4	1190	5310	67	68	242	85	62	52	73.0	22.8	0.042
386.7	18.2	3.6	5.6	5.7	3.4	1190	5200	68	70	253	84	61	51	76.2	24.6	0.043
390.6	18.2	3.6	5.6	5.7	3.3	1200	5270	68	72	264	82	59	49	77.1	25.1	0.043
394.5	18.2	3.6	5.6	5.7	3.4	1200	5340	72	75	260	83	59	49	76.2	24.6	0.044
406.6	18.2	3.6	5.6	5.6	3.4	1190	5260	66	68	242	86	62	51	73.1	22.8	0.065
410.6	18.2	3.6	5.6	5.6	3.4	1190	5300	70	71	252	84	60	50	75.0	23.9	0.049
414.5	18.2	3.6	5.8	5.8	3.4	1200	5290	70	75	213	82	59	49	77.1	25.1	0.049
418.7	18.2	3.6	5.6	5.6	3.4	1200	5270	75	77	267	83	59	49	76.8	24.9	0.052
430.2	18.2	3.6	5.6	5.7	3.4	1190	5290	66	69	236	86	62	52	73.1	22.8	0.060
434.5	18.2	3.6	5.6	5.7	3.4	1190	5260	68	70	244	85	61	51	75.4	24.1	0.061
438.6	18.2	3.6	5.7	5.7	3.3	1200	5200	74	76	266	82	58	49	78.2	25.7	0.060
442.9	18.2	3.6	5.6	5.7	3.4	1200	5290	75	74	264	83	60	49	76.9	24.9	0.056
454.6	18.2	3.6	5.6	5.7	3.3	1190	5360	71	70	241	86	63	52	72.6	22.6	0.076
458.6	18.2	3.6	5.6	5.6	3.3	1190	4830	64	68	227	84	59	47	75.1	23.9	0.047
462.6	18.2	3.6	5.7	5.7	3.3	1200	5220	71	73	262	83	59	49	79.0	26.1	0.056
466.6	18.2	3.6	5.6	5.7	3.3	1200	5260	73	71	272	82	58	49	78.6	25.9	0.056
479.2	18.2	3.6	5.6	5.6	3.4	1190	5130	63	68	237	85	61	51	75.1	23.9	0.052
482.6	18.2	3.6	5.6	5.6	3.4	1190	5030	66	70	247	83	60	49	76.7	24.8	0.052
486.7	18.2	3.6	5.6	5.6	3.4	1200	5230	70	74	260	82	58	48	77.5	25.3	0.052
490.6	18.2	3.6	5.6	5.6	3.4	1200	5270	73	75	261	83	59	49	76.4	24.7	0.049
502.7	18.2	3.6	5.5	5.6	3.4	1190	5240	69	70	242	85	61	51	74.5	23.6	0.056
507.7	18.2	3.6	5.6	5.6	3.4	1190	5280	72	74	257	83	60	50	75.4	24.1	0.060
510.7	18.2	3.6	5.6	5.6	3.4	1190	5230	73	75	264	83	59	49	77.1	25.1	0.070
514.7	18.2	3.6	5.6	5.6	3.4	1190	5260	73	74	260	83	60	49	75.0	23.9	0.073
526.6	18.2	3.6	5.6	5.7	3.3	1190	5170	66	69	243	85	61	50	74.9	23.8	0.067
530.6	18.2	3.6	5.6	5.6	3.3	1190	5070	67	71	212	84	60	49	77.5	25.3	0.064
534.6	18.2	3.6	5.6	5.7	3.4	1190	5030	69	73	264	83	59	48	81.0	27.2	0.059
538.6	18.2	3.6	5.6	5.7	3.3	1190	5350	70	74	263	84	60	50	78.8	26.0	0.054
526.6	18.2	3.6	5.6	5.7	3.3	1190	5170	66	69	243	85	61	50	74.9	23.8	0.067
530.6	18.2	3.6	5.6	5.6	3.3	1190	5070	67	71	212	84	60	49	77.5	25.3	0.064
534.6	18.2	3.6	5.6	5.7	3.4	1190	5030	69	73	264	83	59	48	81.0	27.2	0.059
538.6	18.2	3.6	5.6	5.7	3.3	1190	5350	70	74	263	84	60	50	78.8	26.0	0.054
550.6	18.2	3.6	5.6	5.7	3.3	1190	5540	67	70	251	86	62	53	74.0	23.3	0.050
554.3	18.2	3.6	5.6	5.5	3.4	1190	5230	70	72	264	83	59	50	77.7	25.4	0.053
558.6	18.2	3.6	5.6	5.6	3.4	1190	5330	72	75	281	81	58	49	80.8	27.1	0.051
562.6	18.2	3.6	5.6	5.6	3.4	1190	5510	78	78	274	81	58	50	78.1	25.6	0.054
574.6	18.2	3.6	5.6	5.6	3.4	1190	4980	67	69	235	84	60	49	76.3	24.6	0.057
578.6	18.2	3.6	5.6	5.6	3.4	1190	4860	65	69	244	84	59	49	79.1	26.2	0.064
582.6	18.2	3.6	5.6	5.6	3.4	1190	5040	71	60	256	81	57	47	79.4	26.3	0.074

Nanofiltration Test Data - Continued

Elapsed Time (hours)	Flowrates					Conductivity					Pressure			Temperature		Turbidity
	Feed (L/min)	Reject (L/min)	Permeate Stage 1/1 (L/min)	Permeate Stage 1/2 (L/min)	Permeate Stage 2 (L/min)	Feed (uS/cm)	Reject (uS/cm)	Permeate Stage 1/1 (uS/cm)	Permeate Stage 1/2 (uS/cm)	Permeate Stage 2 (uS/cm)	Feed (lb/in2)	Interstage (lb/in2)	Reject (lb/in2)	Feed (deg F)	Feed (deg C)	Feed - after cart. filter (ntu)
586.6	18.2	3.6	5.6	5.6	3.4	1190	5040	77	77	256	82	57	46	77.6	25.3	0.063
598.6	18.2	3.6	5.6	5.6	3.4	1190	5250	54	70	241	86	61	50	74.8	23.8	0.055
602.6	18.2	3.6	5.6	5.6	3.4	1190	5030	67	72	252	85	60	49	78.8	26.0	0.055
606.6	18.2	3.6	5.6	5.6	3.4	1190	5200	73	77	269	83	59	48	80.2	26.8	0.054
610.6	18.2	3.6	5.6	5.6	3.4	1190	5280	77	77	258	83	59	48	78.6	25.9	0.055
623.0	18.2	3.6	5.6	5.6	3.4	1190	5070	66	71	238	86	61	50	76.2	24.6	0.053
626.6	18.2	3.6	5.6	5.6	3.4	1190	5110	71	74	248	85	60	49	76.7	24.8	0.056
630.6	18.2	3.6	5.5	5.6	3.4	1190	5070	77	80	272	82	57	47	80.2	26.8	0.062
634.6	18.2	3.6	5.6	5.5	3.4	1190	5080	77	79	267	83	58	47	78.4	25.8	0.066
646.6	18.2	3.6	5.6	5.6	3.4	1190	5160	71	73	246	86	61	50	75.7	24.3	0.067
650.6	18.2	3.6	5.6	5.6	3.4	1190	5220	62	75	254	86	61	50	77.2	25.1	0.057
654.6	18.2	3.6	5.6	5.6	3.4	1190	5100	71	76	274	84	59	49	82.0	27.8	0.056
658.6	18.2	3.6	5.6	5.6	3.4	1190	5490	74	78	271	85	60	50	79.3	26.3	0.055
670.6	18.2	3.6	5.6	5.6	3.4	1190	5080	66	71	240	86	61	50	76.1	24.5	0.052
674.6	18.2	3.6	5.6	5.6	3.4	1190	4960	69	74	254	84	59	49	79.1	26.2	0.052
678.6	18.2	3.6	5.6	5.6	3.4	1190	4860	70	74	213	82	58	47	82.3	27.9	0.052
682.1	18.2	3.6	5.6	5.6	3.4	1190	5000	74	77	265	83	59	48	80.6	27.0	0.057
688.3	18.2	3.6	5.7	5.6	3.4	1190	5130	70	73	244	86	62	51	74.9	23.8	0.058
690.1	18.2	3.6	5.6	5.7	3.5	1190	4980	71	74	251	85	61	50	77.3	25.2	0.057
694.2	18.2	3.6	5.6	5.6	3.4	1190	5050	80	81	267	80	57	46	78.6	25.9	0.052
698.1	18.2	3.6	5.5	5.5	3.4	1200	5013	79	81	269	81	58	48	77.2	25.1	0.053
710.1	18.2	3.6	5.6	5.6	3.4	1190	5150	71	73	240	86	62	51	74.6	23.7	0.073
714.1	18.2	3.6	5.6	5.7	3.4	1190	5130	74	76	255	85	61	50	77.5	25.3	0.078
718.1	18.2	3.6	5.6	5.6	3.4	1190	5170	79	81	271	82	58	47	79.0	26.1	0.096
722.0	18.2	3.6	5.6	5.6	3.4	1200	5210	81	80	265	83	59	48	77.4	25.2	0.081
734.2	18.2	3.6	5.6	5.6	3.4	1190	5250	71	73	243	86	61	50	74.8	23.8	0.079
738.2	18.2	3.6	5.5	5.6	3.4	1190	5240	77	78	254	85	60	49	76.3	24.6	0.072
742.2	18.2	3.6	5.5	5.6	3.4	1200	5220	74	77	253	84	60	49	77.1	25.1	0.090
746.2	18.2	3.6	5.5	5.6	3.4	1190	5240	76	76	252	85	60	50	76.0	24.4	0.083
757.9	18.2	3.6	5.6	5.6	3.3	1190	5340	71	73	240	87	62	51	72.9	22.7	0.081
762.5	18.2	3.6	5.4	5.4	3.3	1190	5120	69	74	245	87	62	51	76.7	24.8	0.088
766.4	18.2	3.6	5.6	5.6	3.4	1190	5180	74	76	248	86	62	50	74.8	23.8	0.090
770.2	18.2	3.6	5.6	5.5	3.4	1190	5280	75	76	242	87	62	51	73.2	22.9	0.101
782.1	18.2	3.6	5.6	5.6	3.4	1190	5260	72	73	231	90	64	52	72.4	22.4	0.122
786.1	18.2	3.6	5.6	5.6	3.4	1190	5150	57	74	240	89	63	52	74.8	23.8	0.077
790.1	18.2	3.6	5.6	5.6	3.4	1190	5050	73	73	250	87	61	50	78.4	25.8	0.076
794.1	18.2	3.6	5.6	5.6	3.4	1190	5090	70	73	239	86	62	51	77.1	25.1	0.077
806.1	18.2	3.6	5.6	5.6	3.4	1190	5260	59	75	238	90	64	52	72.7	22.6	0.072
810.1	18.2	3.6	5.6	5.6	3.4	1190	5180	72	75	245	90	63	51	75.7	24.3	0.070
814.1	18.2	3.6	5.6	5.6	3.4	1190	5040	72	75	255	87	61	50	80.4	26.9	0.069
818.1	18.2	3.6	5.6	5.6	3.4	1190	4950	69	73	251	86	61	49	79.4	26.3	0.070
830.1	18.2	3.6	5.6	5.6	3.4	1190	5230	72	62	231	90	64	52	73.6	23.1	0.072
834.1	18.2	3.6	5.6	5.6	3.4	1190	5140	72	74	205	89	63	51	76.6	24.8	0.077
838.1	18.2	3.6	5.6	5.6	3.4	1200	5010	71	74	218	87	60	49	81.1	27.3	0.080
842.1	18.2	3.6	5.6	5.6	3.4	1190	4950	67	72	206	87	61	50	80.0	26.7	0.087
830.1	18.2	3.6	5.6	5.6	3.4	1190	5230	72	62	231	90	64	52	73.6	23.1	0.072
834.1	18.2	3.6	5.6	5.6	3.4	1190	5140	72	74	205	89	63	51	76.6	24.8	0.077
838.1	18.2	3.6	5.6	5.6	3.4	1200	5010	71	74	218	87	60	49	81.1	27.3	0.080
842.1	18.2	3.6	5.6	5.6	3.4	1190	4950	67	72	206	87	61	50	80.0	26.7	0.087
854.1	18.2	3.6	5.6	5.6	3.4	1190	5200	68	71	227	90	63	52	73.8	23.2	0.092
858.1	18.2	3.6	5.6	5.6	3.4	1190	5110	72	74	241	90	63	51	77.2	25.1	0.077
861.6	18.2	3.6	5.6	5.6	3.4	1190	4710	69	73	235	85	59	48	80.6	27.0	0.093

Nanofiltration Test Data - Continued

	Flowrates					Conductivity					Pressure			Temperature		Turbidity
Elapsed Time (hours)	Feed (L/min)	Reject (L/min)	Permeate Stage 1/1 (L/min)	Permeate Stage 1/2 (L/min)	Permeate Stage 2 (L/min)	Feed (uS/cm)	Reject (uS/cm)	Permeate Stage 1/1 (uS/cm)	Permeate Stage 1/2 (uS/cm)	Permeate Stage 2 (uS/cm)	Feed (lb/in2)	Interstage (lb/in2)	Reject (lb/in2)	Feed (deg F)	Feed (deg C)	Feed - after cart. filter (ntu)
865.6	18.2	3.6	5.6	5.6	3.4	1190	4730	67	71	227	86	60	48	79.2	26.2	0.079
877.6	18.2	3.6	5.6	5.6	3.4	1190	5040	68	71	225	89	63	51	75.1	23.9	0.156
881.6	18.2	3.6	5.6	5.6	3.4	1190	5100	69	72	239	88	63	51	77.1	25.1	0.103
885.2	18.2	3.6	5.6	5.6	3.4	1190	5040	66	68	238	88	63	52	80.4	26.9	0.135
889.2	18.2	3.6	5.6	5.6	3.4	1190	5060	64	67	232	88	63	52	79.0	26.1	0.090
893.9	18.2	3.6	5.6	5.6	3.4	1190	5500	60	70	229	93	68	56	72.2	22.3	0.084
897.9	18.2	3.6	5.6	5.6	3.4	1190	5090	66	68	227	90	64	53	76.5	24.7	0.078
901.9	18.2	3.6	5.6	5.6	3.4	1190	5110	70	72	239	86	61	51	78.8	26.0	0.065
905.9	18.2	3.6	5.6	5.6	3.4	1190	5150	76	76	242	87	61	50	76.6	24.8	0.064
912.3	18.2	3.6	5.6	5.6	3.4	1180	5300	73	68	189	92	66	54	70.6	21.4	0.071
916.3	18.2	3.6	5.6	5.6	3.4	1190	5120	70	72	236	88	63	52	77.1	25.1	0.063
920.3	18.2	3.6	5.6	5.6	3.4	1180	4990	67	70	233	87	62	51	78.9	26.1	0.057
924.3	18.2	3.6	5.6	5.6	3.4	1180	4960	66	69	230	87	62	51	78.4	25.8	0.058
936.3	18.2	3.6	5.6	5.6	3.4	1180	5090	67	70	227	87	62	51	76.2	24.6	0.073
940.2	18.2	3.6	5.7	5.7	3.5	1190	5230	69	72	240	87	63	52	76.7	24.8	0.085
944.2	18.2	3.6	5.7	5.7	3.5	1190	5190	69	72	246	86	62	52	78.8	26.0	0.092
948.2	18.2	3.6	5.6	5.6	3.4	1180	5240	73	74	239	87	62	51	75.2	24.0	0.104
960.1	18.2	3.6	5.6	5.6	3.5	1190	5400	73	73	234	90	65	54	72.9	22.7	0.127
964.5	18.2	3.6	5.6	5.6	3.5	1180	5230	72	73	240	89	64	53	76.5	24.7	0.069
968.5	18.2	3.6	5.6	5.6	3.5	1190	5110	68	71	241	87	62	52	79.5	26.4	0.068
972.5	18.2	3.6	5.6	5.6	3.5	1180	5250	71	73	240	88	63	52	76.9	24.9	0.068
984.2	18.2	3.6	5.6	5.6	3.4	1180	5390	74	75	237	90	65	54	73.2	22.9	0.063

Nanofiltration Calculated Values

Elapsed Time (hours)	--- Delta	P ------	Temperature Correction Factor (TCF)	Inverse Temp. Correction Factor (1/TCF)	Average Feed Pressure (lb/in2)	-------	Concentration	--------	Average Osmosis Pressure (lb/in2)	Average Net Driving Pressure (lb/in2)	Normalized Permeate Flow (L/min)
	Stage 1 (lb/in2)	Stage 2 (lb/in2)				Feed Cf (mg/L)	Reject Cr (mg/L)	Average (Cf+Cr)/2 (mg/L)			
1.0	22	8	1.027	0.974	64.0	787	3649	2218	22.2	41.8	14.6
4.8	21	9	1.023	0.977	62.0	787	3418	2103	21.0	41.0	14.9
7.6	20	9	1.056	0.947	60.5	787	3351	2069	20.7	39.8	14.8
11.2	20	8	0.999	1.001	61.0	787	3439	2113	21.1	39.9	15.7
23.0	21	9	0.967	1.034	61.0	787	3303	2045	20.5	40.5	15.7
26.9	19	9	0.997	1.003	58.0	787	3357	2072	20.7	37.3	16.3
30.9	19	9	1.033	0.968	57.0	787	3317	2052	20.5	36.5	16.1
35.3	19	9	0.991	1.009	58.0	787	3405	2096	21.0	37.0	16.5
46.6	20	9	0.975	1.025	61.5	787	3500	2143	21.4	40.1	15.6
50.6	19	9	0.971	1.030	61.0	787	3568	2177	21.8	39.2	15.9
54.6	19	9	1.015	0.985	60.0	787	3541	2164	21.6	38.4	15.8
59.4	19	9	0.996	1.004	61.0	787	3554	2171	21.7	39.3	15.6
71.0	21	9	0.967	1.034	64.0	787	3520	2154	21.5	42.5	14.9
71.9	20	9	0.965	1.036	63.5	801	3486	2143	21.4	42.1	14.9
74.6	19	9	0.990	1.010	63.0	801	3629	2215	22.1	40.9	15.2
78.6	19	10	1.033	0.968	60.5	801	3385	2093	20.9	39.6	14.9
82.5	20	9	0.997	1.003	61.5	801	3493	2147	21.5	40.0	15.2
94.7	21	10	0.955	1.047	64.5	801	3500	2150	21.5	43.0	14.9
98.6	21	9	0.975	1.025	63.0	801	3459	2130	21.3	41.7	14.8
102.6	21	9	1.017	0.984	62.0	801	3425	2113	21.1	40.9	15.2
106.7	20	10	1.010	0.990	61.0	801	3398	2099	21.0	40.0	15.1
118.8	21	9	0.958	1.044	64.0	801	3507	2154	21.5	42.5	14.7
122.8	21	9	1.002	0.998	63.0	801	3452	2126	21.3	41.7	14.6
126.8	21	9	1.070	0.935	61.0	807	3378	2093	20.9	40.1	14.2
130.6	20	9	1.044	0.958	60.5	807	3391	2099	21.0	39.5	14.6
142.5	22	9	0.964	1.037	64.5	801	3527	2164	21.6	42.9	14.6
146.1	22	9	1.000	1.000	64.5	801	3574	2187	21.9	42.6	14.3
150.9	21	9	1.071	0.933	61.0	807	3391	2099	21.0	40.0	14.2
154.6	21	10	1.064	0.940	60.5	807	3351	2079	20.8	39.7	14.3
166.9	22	10	0.961	1.041	65.0	801	3547	2174	21.7	43.3	14.5
171.0	22	9	1.005	0.995	63.5	801	3500	2150	21.5	42.0	14.4
175.1	21	9	1.070	0.935	61.0	807	3412	2109	21.1	39.9	14.2
178.7	21	10	1.049	0.953	62.5	807	3466	2137	21.4	41.1	14.2
190.6	21	10	0.962	1.039	65.5	801	3520	2160	21.6	43.9	14.4
194.6	22	10	0.996	1.004	65.0	801	3574	2187	21.9	43.1	14.2
198.6	22	9	1.070	0.935	62.5	807	3466	2137	21.4	41.1	13.9
202.6	21	10	1.052	0.950	62.5	801	3459	2130	21.3	41.2	14.1
214.6	22	9	0.964	1.037	65.5	801	3554	2177	21.8	43.7	14.5
218.6	22	9	1.002	0.998	64.5	801	3534	2167	21.7	42.8	14.2
222.6	22	9	1.076	0.929	62.5	807	3432	2120	21.2	41.3	13.7
226.6	22	9	1.056	0.947	62.5	801	3452	2126	21.3	41.2	14.0
238.6	22	9	0.965	1.036	65.5	801	3541	2171	21.7	43.8	14.3
242.6	22	9	1.002	0.998	64.5	807	3520	2164	21.6	42.9	14.3
246.6	22	9	1.066	0.938	62.5	807	3425	2116	21.2	41.3	14.0
250.6	22	10	1.007	0.993	62.0	807	3541	2174	21.7	40.3	15.1
262.6	23	10	0.997	1.003	64.5	801	3446	2123	21.2	43.3	14.2
266.6	22	10	0.996	1.004	64.0	807	3479	2143	21.4	42.6	14.4
270.6	22	9	1.002	0.998	63.5	807	3561	2184	21.8	41.7	14.6
274.6	22	10	1.007	0.993	63.0	807	3547	2177	21.8	41.2	14.6
287.0	23	10	0.986	1.015	65.5	801	3486	2143	21.4	44.1	14.2
290.7	23	9	1.007	0.993	65.0	801	3432	2116	21.2	43.8	13.8
294.7	23	10	1.000	1.000	63.5	807	3534	2171	21.7	41.8	14.6

Nanofiltration Calculated Values - Continued

	--- Delta P ------					------- Concentration --------					
Elapsed Time (hours)	Stage 1 (lb/in2)	Stage 2 (lb/in2)	Temperature Correction Factor (TCF)	Inverse Temp. Correction Factor (1/TCF)	Average Feed Pressure (lb/in2)	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)
298.7	23	9	0.993	1.007	64.0	807	3581	2194	21.9	42.1	14.6
310.6	23	10	0.983	1.018	65.5	801	3466	2133	21.3	44.2	14.1
314.6	23	10	0.961	1.041	66.5	801	3479	2140	21.4	45.1	14.1
318.6	23	10	0.983	1.018	66.5	801	3500	2150	21.5	45.0	13.8
322.6	23	10	0.977	1.024	66.5	801	3534	2167	21.7	44.8	13.9
334.6	24	10	0.939	1.065	68.0	801	3602	2201	22.0	46.0	14.1
338.6	23	10	0.968	1.033	67.5	801	3527	2164	21.6	45.9	13.7
342.6	23	10	1.008	0.992	66.5	801	3479	2140	21.4	45.1	13.4
346.6	23	10	0.997	1.003	65.5	807	3459	2133	21.3	44.2	13.9
358.5	23	10	0.941	1.063	68.5	801	3615	2208	22.1	46.4	14.1
362.6	24	10	0.984	1.016	67.0	801	3534	2167	21.7	45.3	13.8
366.6	23	10	1.000	1.000	65.5	807	3574	2191	21.9	43.6	14.0
370.6	23	10	0.990	1.010	65.5	807	3574	2191	21.9	43.6	14.1
382.7	23	10	0.942	1.061	68.5	801	3602	2201	22.0	46.5	14.0
386.7	23	10	0.988	1.012	67.5	801	3527	2164	21.6	45.9	13.6
390.6	23	10	1.002	0.998	65.5	807	3574	2191	21.9	43.6	14.0
394.5	24	10	0.988	1.012	66.0	807	3622	2215	22.1	43.9	14.2
406.6	24	11	0.944	1.060	68.5	801	3568	2184	21.8	46.7	13.9
410.6	24	10	0.971	1.030	67.0	801	3595	2198	22.0	45.0	14.0
414.5	23	10	1.002	0.998	65.5	807	3588	2198	22.0	43.5	14.4
418.7	24	10	0.997	1.003	66.0	807	3574	2191	21.9	44.1	13.9
430.2	24	10	0.944	1.060	69.0	801	3588	2194	21.9	47.1	13.8
434.5	24	10	0.977	1.024	68.0	801	3568	2184	21.8	46.2	13.6
438.6	24	9	1.020	0.980	65.5	807	3527	2167	21.7	43.8	13.8
442.9	23	11	0.999	1.001	66.0	807	3588	2198	22.0	44.0	14.0
454.6	23	11	0.936	1.068	69.0	801	3635	2218	22.2	46.8	13.9
458.6	25	12	0.973	1.028	65.5	801	3276	2038	20.4	45.1	13.8
462.6	24	10	1.033	0.968	66.0	807	3541	2174	21.7	44.3	13.4
466.6	24	9	1.027	0.974	65.5	807	3568	2187	21.9	43.6	13.6
479.2	24	10	0.973	1.028	68.0	801	3479	2140	21.4	46.6	13.5
482.6	23	11	0.996	1.004	66.0	801	3412	2106	21.1	44.9	13.6
486.7	24	10	1.008	0.992	65.0	807	3547	2177	21.8	43.2	14.0
490.6	24	10	0.991	1.009	66.0	807	3574	2191	21.9	44.1	14.0
502.7	24	10	0.964	1.037	68.0	801	3554	2177	21.8	46.2	13.6
507.7	23	10	0.977	1.024	66.5	801	3581	2191	21.9	44.6	14.0
510.7	24	10	1.002	0.998	66.0	801	3547	2174	21.7	44.3	13.8
514.7	23	11	0.971	1.030	66.0	801	3568	2184	21.8	44.2	14.2
526.6	24	11	0.970	1.031	67.5	801	3507	2154	21.5	46.0	13.7
530.6	24	11	1.008	0.992	66.5	801	3439	2120	21.2	45.3	13.3
534.6	24	11	1.068	0.937	65.5	801	3412	2106	21.1	44.4	13.0
538.6	24	10	1.030	0.971	67.0	801	3629	2215	22.1	44.9	13.2
526.6	24	11	0.970	1.031	67.5	801	3507	2154	21.5	46.0	13.7
530.6	24	11	1.008	0.992	66.5	801	3439	2120	21.2	45.3	13.3
534.6	24	11	1.068	0.937	65.5	801	3412	2106	21.1	44.4	13.0
538.6	24	10	1.030	0.971	67.0	801	3629	2215	22.1	44.9	13.2
550.6	24	9	0.957	1.045	69.5	801	3758	2279	22.8	46.7	13.7
554.3	24	9	1.012	0.989	66.5	801	3547	2174	21.7	44.8	13.4
558.6	23	9	1.064	0.940	65.0	801	3615	2208	22.1	42.9	13.4
562.6	23	8	1.018	0.982	65.5	801	3737	2269	22.7	42.8	14.0
574.6	24	11	0.990	1.010	66.5	801	3378	2089	20.9	45.6	13.5
578.6	25	10	1.035	0.966	66.5	801	3296	2048	20.5	46.0	12.8
582.6	24	10	1.040	0.961	64.0	801	3418	2109	21.1	42.9	13.7

Nanofiltration Calculated Values - Continued

Elapsed Time (hours)	--- Delta	P ------	Temperature Correction Factor (TCF)	Inverse Temp. Correction Factor (1/TCF)	Average Feed Pressure (lb/in2)	-------	Concentration	--------	Average Osmosis Pressure (lb/in2)	Average Net Driving Pressure (lb/in2)	Normalized Permeate Flow (L/min)
	Stage 1 (lb/in2)	Stage 2 (lb/in2)				Feed Cf (mg/L)	Reject Cr (mg/L)	Average (Cf+Cr)/2 (mg/L)			
586.6	25	11	1.010	0.990	64.0	801	3418	2109	21.1	42.9	14.1
598.6	25	11	0.968	1.033	68.0	801	3561	2181	21.8	46.2	13.7
602.6	25	11	1.030	0.971	67.0	801	3412	2106	21.1	45.9	12.9
606.6	24	11	1.054	0.949	65.5	801	3527	2164	21.6	43.9	13.2
610.6	24	11	1.027	0.974	65.5	801	3581	2191	21.9	43.6	13.6
623.0	25	11	0.988	1.012	68.0	801	3439	2120	21.2	46.8	13.2
626.6	25	11	0.996	1.004	67.0	801	3466	2133	21.3	45.7	13.4
630.6	25	10	1.054	0.949	64.5	801	3439	2120	21.2	43.3	13.3
634.6	25	11	1.023	0.977	65.0	801	3446	2123	21.2	43.8	13.5
646.6	25	11	0.981	1.019	68.0	801	3500	2150	21.5	46.5	13.4
650.6	25	11	1.003	0.997	68.0	801	3541	2171	21.7	46.3	13.1
654.6	25	10	1.085	0.921	66.5	801	3459	2130	21.3	45.2	12.4
658.6	25	10	1.039	0.963	67.5	801	3724	2262	22.6	44.9	13.1
670.6	25	11	0.987	1.013	68.0	801	3446	2123	21.2	46.8	13.2
674.6	25	10	1.035	0.966	66.5	801	3364	2082	20.8	45.7	12.9
678.6	24	11	1.091	0.917	64.5	801	3296	2048	20.5	44.0	12.7
682.1	24	11	1.061	0.943	65.5	801	3391	2096	21.0	44.5	12.9
688.3	24	11	0.970	1.031	68.5	801	3479	2140	21.4	47.1	13.5
690.1	24	11	1.005	0.995	67.5	801	3378	2089	20.9	46.6	13.2
694.2	23	11	1.027	0.974	63.0	801	3425	2113	21.1	41.9	14.2
698.1	23	10	1.003	0.997	64.5	807	3400	2104	21.0	43.5	13.8
710.1	24	11	0.965	1.036	68.5	801	3493	2147	21.5	47.0	13.4
714.1	24	11	1.008	0.992	67.5	801	3479	2140	21.4	46.1	13.2
718.1	24	11	1.033	0.968	64.5	801	3507	2154	21.5	43.0	13.8
722.0	24	11	1.007	0.993	65.5	807	3534	2171	21.7	43.8	13.8
734.2	25	11	0.968	1.033	68.0	801	3561	2181	21.8	46.2	13.7
738.2	25	11	0.990	1.010	67.0	801	3554	2177	21.8	45.2	13.5
742.2	24	11	1.002	0.998	66.5	807	3541	2174	21.7	44.8	13.5
746.2	25	10	0.986	1.015	67.5	801	3554	2177	21.8	45.7	13.5
757.9	25	11	0.941	1.063	69.0	801	3622	2211	22.1	46.9	13.7
762.5	25	11	0.996	1.004	69.0	801	3473	2137	21.4	47.6	12.4
766.4	24	12	0.968	1.033	68.0	801	3513	2157	21.6	46.4	13.6
770.2	25	11	0.945	1.058	69.0	801	3581	2191	21.9	47.1	13.6
782.1	26	12	0.934	1.071	71.0	801	3568	2184	21.8	49.2	13.3
786.1	26	11	0.968	1.033	70.5	801	3493	2147	21.5	49.0	12.9
790.1	26	11	1.023	0.977	68.5	801	3425	2113	21.1	47.4	12.6
794.1	24	11	1.002	0.998	68.5	801	3452	2126	21.3	47.2	12.9
806.1	26	12	0.938	1.066	71.0	801	3568	2184	21.8	49.2	13.2
810.1	27	12	0.981	1.019	70.5	801	3513	2157	21.6	48.9	12.7
814.1	26	11	1.057	0.946	68.5	801	3418	2109	21.1	47.4	12.2
818.1	25	12	1.040	0.961	67.5	801	3357	2079	20.8	46.7	12.6
830.1	26	12	0.951	1.052	71.0	801	3547	2174	21.7	49.3	13.0
834.1	26	12	0.994	1.006	70.0	801	3486	2143	21.4	48.6	12.6
838.1	27	11	1.070	0.935	68.0	807	3398	2103	21.0	47.0	12.2
842.1	26	11	1.051	0.952	68.5	801	3357	2079	20.8	47.7	12.2
830.1	26	12	0.951	1.052	71.0	801	3547	2174	21.7	49.3	13.0
834.1	26	12	0.994	1.006	70.0	801	3486	2143	21.4	48.6	12.6
838.1	27	11	1.070	0.935	68.0	807	3398	2103	21.0	47.0	12.2
842.1	26	11	1.051	0.952	68.5	801	3357	2079	20.8	47.7	12.2
854.1	27	11	0.954	1.048	71.0	801	3527	2164	21.6	49.4	13.0
858.1	27	12	1.003	0.997	70.5	801	3466	2133	21.3	49.2	12.4
861.6	26	11	1.061	0.943	66.5	801	3195	1998	20.0	46.5	12.4

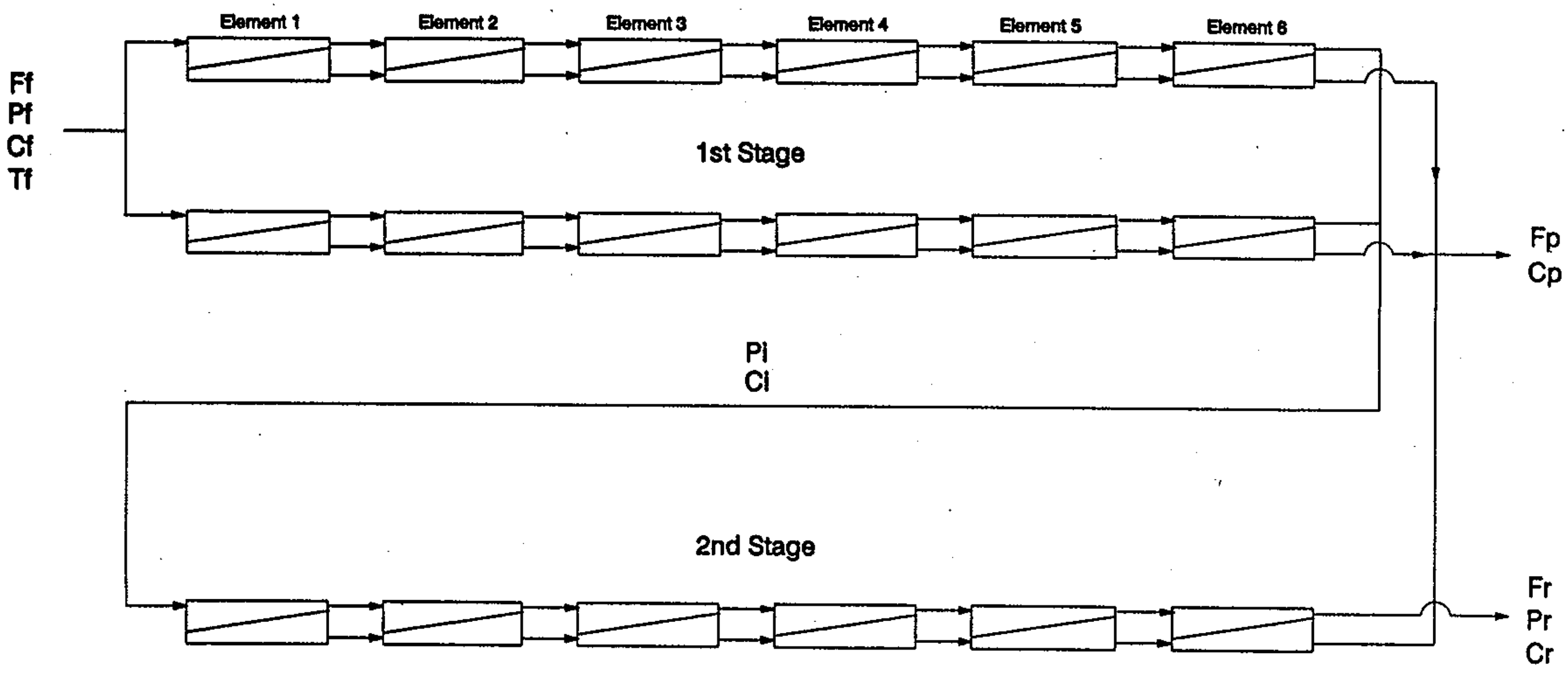
Nanofiltration Calculated Values - Continued

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)
865.6	26	12	1.037	0.964	67.0	801	3208	2004	20.0	47.0	12.5
877.6	26	12	0.973	1.028	70.0	801	3418	2109	21.1	48.9	12.8
881.6	25	12	1.002	0.998	69.5	801	3459	2130	21.3	48.2	12.6
885.2	25	11	1.057	0.946	70.0	801	3418	2109	21.1	48.9	11.8
889.2	25	11	1.033	0.968	70.0	801	3432	2116	21.2	48.8	12.1
893.9	25	12	0.931	1.074	74.5	801	3730	2265	22.7	51.8	12.7
897.9	26	11	0.993	1.007	71.5	801	3452	2126	21.3	50.2	12.2
901.9	25	10	1.030	0.971	68.5	801	3466	2133	21.3	47.2	12.6
905.9	26	11	0.994	1.006	68.5	801	3493	2147	21.5	47.0	13.1
912.3	26	12	0.908	1.102	73.0	794	3595	2194	21.9	51.1	13.2
916.3	25	11	1.002	0.998	70.0	801	3473	2137	21.4	48.6	12.5
920.3	25	11	1.032	0.969	69.0	794	3385	2089	20.9	48.1	12.3
924.3	25	11	1.023	0.977	69.0	794	3364	2079	20.8	48.2	12.4
936.3	25	11	0.988	1.012	69.0	794	3452	2123	21.2	47.8	12.9
940.2	24	11	0.996	1.004	69.5	801	3547	2174	21.7	47.8	13.1
944.2	24	10	1.030	0.971	69.0	801	3520	2160	21.6	47.4	12.8
948.2	25	11	0.974	1.027	69.0	794	3554	2174	21.7	47.3	13.3
960.1	25	11	0.941	1.063	72.0	801	3663	2232	22.3	49.7	13.2
964.5	25	11	0.993	1.007	71.0	794	3547	2171	21.7	49.3	12.6
968.5	25	10	1.042	0.960	69.5	801	3466	2133	21.3	48.2	12.2
972.5	25	11	0.999	1.001	70.0	794	3561	2177	21.8	48.2	12.8
984.2	25	11	0.945	1.058	72.0	794	3656	2225	22.2	49.8	13.0

APPENDIX C

Generalized NF process diagram for checking data reduction

Generalized NF 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 nanofiltration testing

Analytical Data for Nanofiltration Testing

			5-Hour Data				362-Hour Data			
			Feed	Interstage	Permeate	Reject	Feed	Interstage	Permeate	Reject
CATIONS										
Calcium	Ca	mg/L	88	220	1.9	420	84	220	1.5	390
Magnesium	Mg	mg/L	30	72	0.69	130	29	65	0.34	120
Sodium	Na	mg/L	110	260	22	510	110	250	17	480
Potassium	K	mg/L	3.9	8	1	16	3.5	7.2	1.1	13
Aluminum	Al	mg/L	<0.05	<0.05	<0.05	0.08	<0.20	<0.20	<0.20	<0.20
Barium	Ba	mg/L	<0.05	0.09	<0.05	0.17	<0.05	0.07	<0.05	0.15
Strontium	Sr	mg/L	1.2	2.8	<1.0	5.1	1.3	3	<1.0	6.3
Iron	Fe	mg/L	<0.02	0.02	<0.02	0.03	<0.05	<0.05	<0.05	0.07
Manganese	Mn	mg/L	0.50	1.3	<0.05	2.5	0.50	1.2	<0.05	2.4
Phosphorus	P	mg/L	0.11	1.3	<0.10	0.58	<0.10	0.26	<0.10	<0.10
ANIONS										
Bicarbonate	HCO3	mg/L	170	400	28	770	170	410	14	790
Chloride	Cl	mg/L	94	250	28	280	130	250	22	390
Sulfate	SO4	mg/L	290	720	10	1112	290	730	7.2	1500
Nitrate (N)	NO3 (N)	mg/L	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Flouride	F	mg/L	1.6	1.4	0.2	3	0.66	1.6	0.1	3
Silica (total)	SiO2	mg/L	18	42	5.4	74	18	39	3.2	69
Total Organic Carbon	TOC	mg/L	1.7	-	-	-	1.8	-	-	-
Standard Plate Count	SPC	cfu	5700	-	-	-	4000	-	-	-
Alkalinity		mg/L	170	400	28	770	170	410	14	790
Hardness	as CaCO3	mg/L	340	850	7.6	1600	330	770	5.1	1500
Conductivity (lab)		uS/cm	1200	2600	160	4900	1200	2600	110	4700
Conductivity (ops)		uS/cm	1170	-	138	4900				
Total Dissolved Solids	TDS (sum)	mg/L	807	1979	97	3323	837	1977	66	3764
Anions (Ca,Mg,Na,K)		meq/L	11.74	28.42	1.13	54.25	11.45	27.39	0.87	50.55
Cations (HCO3,Cl,SO4)		meq/L	11.48	28.60	1.46	43.67	12.49	28.97	1.00	55.18
Ratio Anions:Cations		-	1.02	0.99	0.78	1.24	0.92	0.95	0.87	0.92

Analytical Data for Nanofiltration Testing - Continued

			693-Hour Data				984-Hour Data			
			Feed	Interstage	Permeate	Reject	Feed	Interstage	Permeate	Reject
CATIONS										
Calcium	Ca	mg/L	81	200	1.3	380	86	200	0.87	400
Magnesium	Mg	mg/L	30	69	0.46	130	29	63	0.33	120
Sodium	Na	mg/L	110	260	20	490	120	250	17	500
Potassium	K	mg/L	3.2	6.9	<1.0	13	2.7	5.6	<1.0	11
Aluminum	Al	mg/L	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Barium	Ba	mg/L	<0.05	0.08	<0.05	0.17	<0.05	0.08	<0.05	0.16
Strontium	Sr	mg/L	1.3	3.4	<1.0	7.1	1.6	3.7	<1.0	7.4
Iron	Fe	mg/L	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Manganese	Mn	mg/L	0.54	1.3	<0.05	2.6	0.53	1.2	<0.05	2.3
Phosphorus	P	mg/L	0.12	0.27	<0.10	<0.10	0.12	0.28	<0.10	<0.10
ANIONS										
Bicarbonate	HCO3	mg/L	180	400	19	820	170	390	15	780
Chloride	Cl	mg/L	120	220	23	380	95	230	20	430
Sulfate	SO4	mg/L	290	730	7	1500	300	720	6.4	1600
Nitrate (N)	NO3 (N)	mg/L	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	0.7
Flouride	F	mg/L	0.73	1.7	0.11	3	0.71	1.6	0.12	3
Silica (total)	SiO2	mg/L	18	40	3.6	69	19	42	3.3	77
Total Organic Carbon	TOC	mg/L	1.7	-	-	-	3	-	-	-
Standard Plate Count	SPC	cfu	1100	1200	790	1900				
Alkalinity		mg/L	180	400	19	820	170	390	15	780
Hardness	as CaCO3	mg/L	330	780	5.1	1500	330	760	3.5	1500
Conductivity (lab)		uS/cm	1000	2200	98	4000	1100	2300	91	4300
Conductivity (ops)		uS/cm								
Total Dissolved Solids	TDS (sum)	mg/L	835	1933	74	3795	825	1907	63	3932
Anions (Ca,Mg,Na,K)		meq/L	11.38	27.14	0.97	51.31	11.97	26.18	0.81	51.87
Cations (HCO3,Cl,SO4)		meq/L	12.37	27.96	1.11	55.39	11.71	27.87	0.94	58.22
Ratio Anions:Cations		-	0.92	0.97	0.88	0.93	1.02	0.94	0.86	0.89

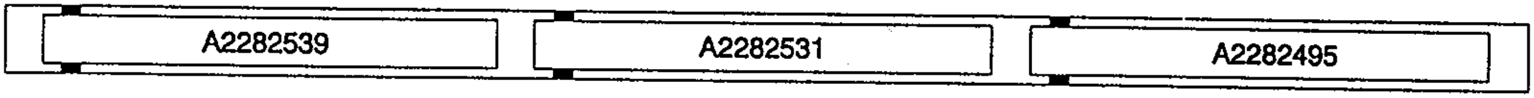
APPENDIX E

Nanofiltration element serial numbers as loaded in pressure vessels

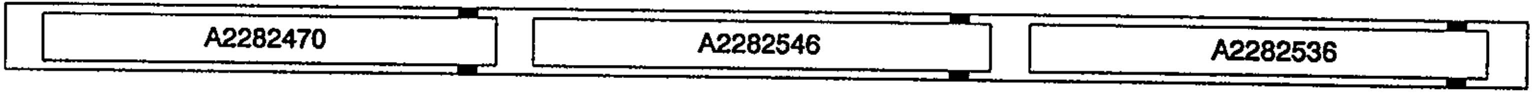
NF Element Serial Numbers as Loaded in Pressure Vessels

Manufacturer Filmtec ; Model NF70-2540 ; Date 9/30/94

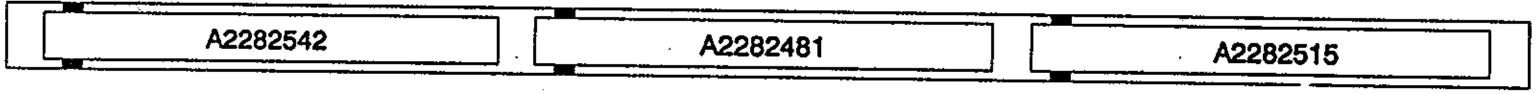
Stage 2, Vessel 1B, Elements 4-6 (top front)



Stage 2, Vessel 1A, Elements 1-3 (top rear)

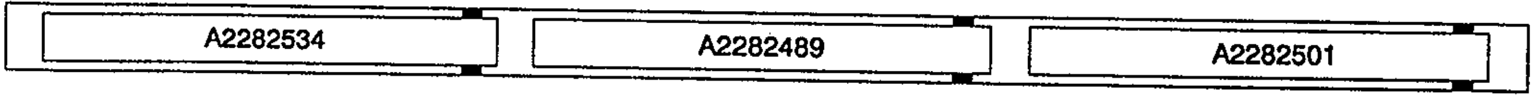


Stage 1, Vessel 2B, Elements 4-6 (2nd from top)

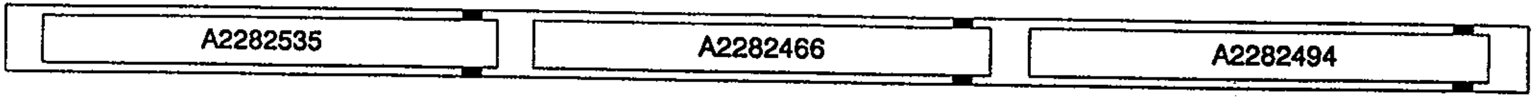


Stage 1, Vessel 1B, Elements 4-6 (2nd from bottom)

Stage 1, Vessel 2A, Elements 1-3 (bottom rear)



Stage 1, Vessel 1A, Elements 1-3 (bottom front)



APPENDIX F

Lime softening process calculations

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          COLD LIME PROCESS - Lake Havasu City - Well S6

   FEED WATER COMPOSITION

    Na+      110.00  mg/L   =     4.78  meq/L  =      239.45  mg/L (as CaCO3)
    K+         1.80  mg/L   =     0.05  meq/L  =        2.30  mg/L (as CaCO3)
    Ca++     100.00  mg/L   =     4.99  meq/L  =      249.72  mg/L (as CaCO3)
    Mg++      35.00  mg/L   =     2.88  meq/L  =      144.09  mg/L (as CaCO3)

 S cations                       12.70  meq/L  =      635.56  mg/L (as CaCO3)

    Cl-       95.00  mg/L   =     2.68  meq/L  =      134.10  mg/L (as CaCO3)
    HCO3-    232.00  mg/L   =     3.80  meq/L  =      190.29  mg/L (as CaCO3)
    SO4=     300.00  mg/L   =     6.25  meq/L  =      312.57  mg/L (as CaCO3)
    NO3-       4.42  mg/L   =     0.07  meq/L  =        3.57  mg/L (as CaCO3)
    CO3=       0.00  mg/L   =     0.00  meq/L  =        0.00  mg/L (as CaCO3)
    OH-        0.00  mg/L   =     0.00  meq/L  =        0.00  mg/L (as CaCO3)

 S anions                        12.80  meq/L  =      640.53  mg/L (as CaCO3)

   Cation/Anion Ratio       =     0.99  Balance is excellent.
   TDS =      878.22
   pH  =        7.62                    R      =      20.89
   CO2          9.11  mg/L (as CO2)
   Total Hardness (TH)  =                             393.81  mg/L (as CaCO3)
   Alkalinity (Alk)         =                         190.29  mg/L (as CaCO3)


   COAGULENT-CORRECTED COMPOSITION

   Coagulent:                  Aluminum Sulfate (20 ppm)
                               Ferrous Sulfate (20 ppm)
                             4 Ferric Sulfate (10 ppm)
                               Sodium Aluminate (10 ppm)


   Total Hardness (TH)  =                             393.81  mg/L (as CaCO3)
   Alkalinity (Alk)                                   184.29  mg/L (as CaCO3)
   Calcium Alkalinity (Ca Alk)  =                     184.29  mg/L (as CaCO3)
   Magnesium Alkalinity (Mg Alk)  =                     0.00  mg/L (as CaCO3)
   Sodium Alkalinity (Na Alk)  =                        0.00  mg/L (as CaCO3)
   Calcium Noncarbonate Hardness (NCH)  =              65.43  mg/L (as CaCO3)
   Magnesium Noncarbonate Hardness (MgNCH)  =         144.09  mg/L (as CaCO3)
   Total Noncarbonate Hardness (NCH)  =               209.53  mg/L (as CaCO3)
   Sulfate  =                                         318.57  mg/L (as CaCO3)
   Free Carbon Dioxide  =                              15.11  mg/L (as CO2)


   DOSAGE OF LIME REQUIRED

   Hyd. Lime - 93% Ca(OH)2  =     185    ppm  =        1.55  lbs/1000 gallons
   Chemical Lime - 90% CaO  =     145    ppm  =        1.21  lbs/1000 gallons
   Theor. Lime - 100% CaO  =      131    ppm  =        1.09  lbs/1000 gallons

          COLD LIME PROCESS - Lake Havasu City - Well S6   (continued)

   EFFLUENT COMPOSITION

   Calcium Hardness  =                                114.84  mg/L (as CaCO3)
   Magnesium Hardness  =                              129.68  mg/L (as CaCO3)
   Total Hardness  =                                  244.53  mg/L (as CaCO3)
   Alkalinity  =                                       35.00  mg/L (as CaCO3)
   pH  =        10.0  (estimated)       R      =     5011.87
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  CO2          0.01  mg/L (as CO2)

  DOSAGE OF ACID REQUIRED FOR pH ADJUSTMENT

       4 93% H2SO4  =           2.46    ppm  =       0.02  lbs/1000 gallons
         35% HCl  =             4.86    ppm  =       0.04  lbs/1000 gallons
  pH  =        7.5  (target)          R      =      15.85

  TREATED WATER COMPOSITION

   Na+       110.00  mg/L   =   4.78  meq/L  =     239.45  mg/L (as CaCO3)
   K+          1.80  mg/L   =   0.05  meq/L  =       2.30  mg/L (as CaCO3)
   Ca++       45.99  mg/L   =   2.29  meq/L  =     114.84  mg/L (as CaCO3)
   Mg++       31.50  mg/L   =   2.59  meq/L  =     129.68  mg/L (as CaCO3)

S cations                       9.72  meq/L  =     189.29  mg/L (as CaCO3)

   Cl-        95.00  mg/L   =   2.68  meq/L  =     134.10  mg/L (as CaCO3)
   HCO3-      39.82  mg/L   =   0.65  meq/L  =      32.66  mg/L (as CaCO3)
   SO4=      308.00  mg/L   =   6.41  meq/L  =     320.91  mg/L (as CaCO3)
   NO3-       4.42  mg/L    =   0.14  meq/L  =       3.57  mg/L (as CaCO3)
   CO3=        0.00  mg/L   =   0.00  meq/L  =       0.00  mg/L (as CaCO3)
   OH-         0.00  mg/L   =   0.00  meq/L  =       0.00  mg/L (as CaCO3)

S anions                        9.89  meq/L  =     447.25  mg/L (as CaCO3)

  Cation/Anion Ratio        =   0.98  Balance is good.
  TDS =      636.53
  CO2          2.06  mg/L (as CO2)
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Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.