

ICR Treatment Study Summary Report

Evaluation of Membrane Technology Using the Pilot-Scale Test For Compliance of the Information Collection Rule's; Grandfather of A Previously Conducted Study

Conducted during the period of July 19, 1989 through April 4, 1991

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For:
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Keller Plant 1, ICR # - 317

Attachments: 1 diskette containing the *Data Collection Spreadsheets and Summary Report*

Section I: Conclusions and Recommendations

Conclusions

1. Silt density indexes of groundwater from the Eldridge-Wilde well field were found to be less than three.
2. Four of ten spiral wound membranes tested in a single element membrane selection study reduced the THMFP below 50 µg/L as the species. Membranes with molecular weight cutoffs (MWC) below 400 and greater than 100 reduced the product stream hardness to less than 100 mg/L as CaCO₃ and more than 50 mg/L as CaCO₃. Consequently, several membranes met the membrane selection criteria. The FilmTec N-70 nanofilter was found to have the highest mass transfer coefficient (MTC) for water of any membrane that met the water quality criteria. TH and THMFP reduction was observed when the MWC of the membrane tested was 2000 or less. Membranes that had MWCs greater than 100 and less than 400 met all selection criteria.
3. The rate of MTC decline during preproduction studies using a single unit operated over an approximately one month period was predicted to be less than 15% over three months using conventional pretreatment. Consequently, acid addition and five micron prefiltration, which is conventional pretreatment, was determined to be adequate pretreatment for nanofiltration using groundwater from the Eldridge-Wilde well field.
4. A two stage membrane pilot plant was operated at the Keller 1 water treatment plant using water from the Eldridge-Wilde well field and conventional pretreatment for a total of 4031 hours with 127 hours of downtime. The pilot unit was productive 97% of the time available for operation.
5. Excessive per stage recovery caused a high rate of MTC decline during the operation of the two stage pilot plant. The stage permeate stream flow was not restricted therefore, stage 1 flux operated at approximately 20 gsf/d and stage 2 operated at approximately 12 gsf/d. The predicted rate of membrane cleaning to maintain no more than a 15% MTC loss from an initial point of 0.35 gsf/d-psi was approximately 1.75 months under these conditions.
6. A black material was found on the prefilter cartridges and on the surface of an autopsied membrane. It was thought to be the major fouling material and indications were that it was ferric sulfide. The addition of oxygen into the source water by intermittent use of different wells could cause a reaction between hydrogen sulfide and iron that would foul the membranes. Elimination of this black material would very likely result in a lower rate of MTC decline.
7. For the five sample periods conducted during operation using the source water to Keller Plant 1. The average THM4 and HAA5 formation potential for the source water was 142 µg/L and 75 µg/L as the species, respectively. The combined permeate stream

concentrations averaged 22 µg/L for THM4 and 7 µg/L for HAA5, resulting in a respective 84 and 90 % reduction. All permeate sample concentrations were below the proposed phase 2 DBP rule 40 and 30 µg/L concentrations. These results were determined from formation potential testing conditions of 96 hour incubation, 20 °C temperature, pH of 7.6 and chlorine doses of 12.5 mg/L for the source and 5 mg/L for the permeate. The formation potential concentrations produced in the source water samples resulted in higher THMs than were normally recorded in the Pinellas County distribution system. Since the source water and distribution system represent similarly treated waters, the results from the membrane process monitoring would be expected to equal or be less than the actual DBPs found in a Pinellas County distribution system receiving a nanofiltered finished water.

8. The inorganic water quality produced by the membrane process using the Keller 1 source water averaged a total hardness of approximately 70 mg/L CaCO₃, an alkalinity of approximately 60 mg/L and a total dissolved solids of approximately 100 mg/L. The sodium concentration would be no more than 10 mg/L depending on whether lime or sodium hydroxide is used for alkalinity recovery. The remaining individual inorganic solutes will be less than 15 mg/L.

Recommendations

1. Any decision regarding the pursuit of a membrane process at Pinellas County should consider all benefits of the process. A nanofiltration process will produce high quality potable water in Pinellas County. The DBPFP will be low and is predicted to meet the proposed phase 1 and 2 DBP Rule MCLs for THMs and HAAs using a free chlorine residual for disinfection in the distribution system. The reduction in TDS concentration in the finished water should provide a less corrosive water. The reduction in non-purgeable dissolved organic carbon will not only form fewer DBPs but will provide less chlorine demand and less nutrients for regrowth in the distribution system. Consequently the DBPs and the bacterial quality in the distribution system will be improved and the corrosiveness will be reduced.
2. Concentrate disposal options should be investigated thoroughly before a membrane process is chosen for water treatment. The cost of concentrate disposal is effected significantly by option. There are five basic options and many combinations of these options for concentrate disposal. The five options are sewer discharge, surface water discharge, land application or irrigation, rapid infiltration basins and deep well injection. The cost of these options generally varies from \$0.02/Kgal to \$0.10/Kgal and is generally less than the cost of membrane replacement. Consequently the cost although significant is not prohibitive; however the permitting process is far from standard. Currently concentrates are classified as industrial wastes and significantly scrutinized by FDEP. There has not been a proposed membrane process stopped for lack of a permit for concentrate disposal to the author's knowledge. However the attainment of a permit can and will probably be an arduous path. A method of concentrate disposal should be attained before any detail design is initiated.

Section II: Background Information

Treatment plant description

The following section will describe the existing treatment process used by the Pinellas County Utilities Keller 1 water treatment plant (WTP). Figure 1 presents the process schematic of the Keller 1 WTP.

The membrane studies were conducted at the S. K. Keller Water Treatment Facility located in the northeast corner of Pinellas County near Tarpon Springs, Florida. The water used for the pilot studies was the raw groundwater source to the Keller Plant 1 (ICR-ID No. 317) and the Keller Plant 2 (ICR-ID No. 717). Both of the Keller Plants use the Eldridge-Wilde well field which pumps water from the Floridan aquifer. Though the two plants have a separate well and source water collection system, the wells for each plant are located adjacent to each other and have similar water quality. The water treatment process for the two plants consists of aeration, free chlorine disinfection, pH stabilization using sodium hydroxide and additional corrosion control using an ortho/poly-phosphate blend. The two Keller Plants are located adjacent to each other and are essentially the same except for age and the mode of aeration. The Keller Plant 1 uses induced draft and the Keller Plant 2 uses cascade aeration.

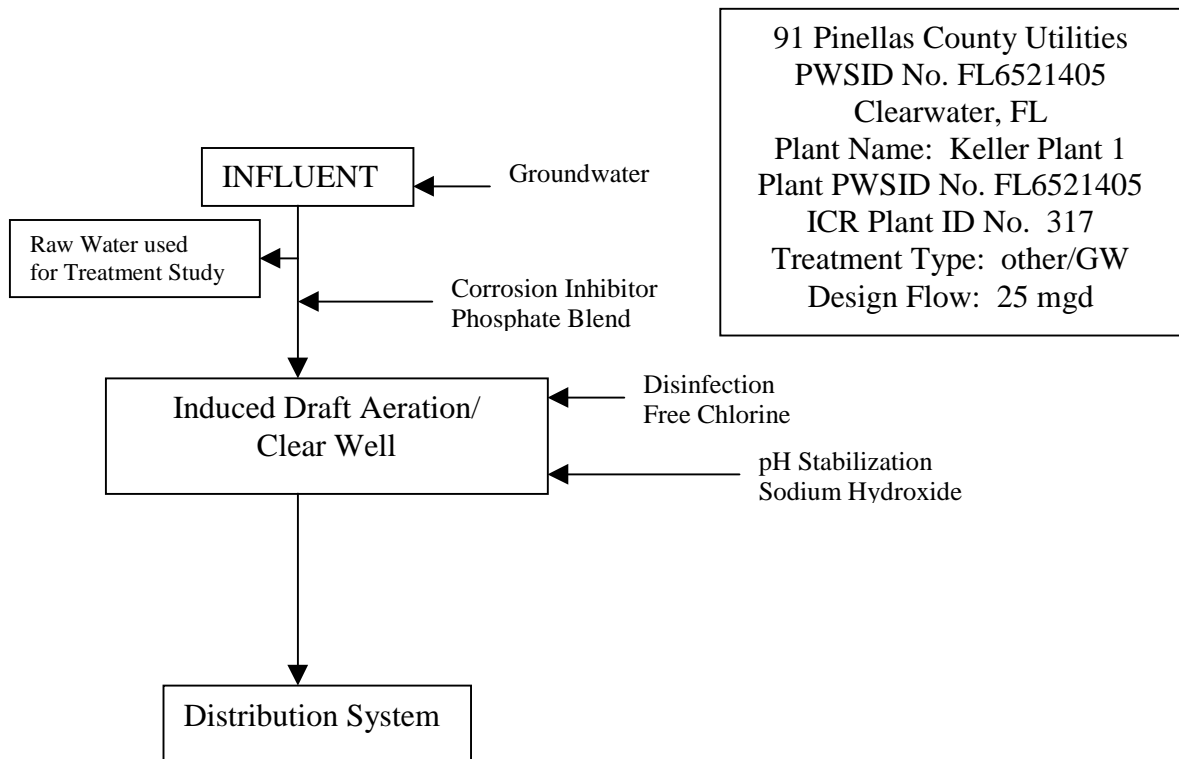


Figure 1: Process Schematic For Keller Plant 1

Table 2 presents the Keller Plant 1 process design and chemical addition parameters which were also documented in report forms A2 and A3 from the *ICR Sampling Manual* and submitted for the *ICR Water Utility Database System*. The major challenge facing the utility

will be meeting the proposed phase 1 and phase 2 DBP Rules using free chlorine. The Utility's water source and treatment facilities are located in the northern end of the county and it must distribute finished water through a very long system. Transmission of water through the entire length of the system requires numerous storage, repump and rechlorination facilities. In addition, approximately half of the water the county distributes is supplied by the West Coast Regional Water Supply Authority (WCRWSA). This Authority supplies chlorinated groundwater from well fields located in Pasco County, FL. This facility is north of Pinellas County and increases the length of time in the distribution system. To meet the proposed DBP Rules the Utility will have to use advanced treatment to remove DBP precursors and/or switch to an alternative disinfectant such as chloramines. To accomplish these alternatives coordination with the WCRWSA and their client utilities will have to be obtained.

Table 1: Keller Plant 1 Process Design and Chemical Addition Parameters

Unit Process	Process Description	Quantity
Plant Information		
	Treatment Plant Name	Keller Plant 1
	ICR Treatment Plant ID	317
	Treatment Plant PWS ID	FL6521405
	Treatment Plant Category	Other/GW
	State Approved Plant Capacity	15 MGD
	Historical Min. Water Temp.	24 deg. C
	Installed Sludge Handling Cap.	0.00
	Blending Indicator	N
Water Source		
	Water Source Name	Eldridge-Wilde Wellfield
	Water Resource Type	Groundwater
	Intake Name	Keller Plant 1 Influent
	Wellhead Protection	Yes
	Hydrologic Unit Code	Lat. +28°9'8" (deg.,min.,sec.)
		Long. -82°40'23" (deg.,min.,sec.)
Clear Well		
	Aeration	Induced Draft
	Surface Area	1,288 ft ²
	Liquid Volume	125,245 gal.
	Baffling Type	AV
	Short Circuiting Factor	N/A
Disinfection		
	Chlorine Gas	18 mg/L as Cl ₂
Corrosion Control		
	pH Stabilization	22 mg/L as NaOH
	Corrosion Inhibitor	1 mg/L as Product (ortho/poly phosphate)

Summary of source and finished water quality

The following section will present in tabular form the source and finished water quality of the Keller Plant 1. Table 2 presents the source water and Table 3 presents the finished

water. The water quality analysis represents the monthly sample monitoring from January 1997 through September 1997. A monthly average DBP concentration was determined from the results of four monitoring sites. The monthly averages were used to develop the DBP results shown in Table 3. The DBPs analyzed using USEPA methods 551.1 and 552.2. The monitoring period represents the most recent and complete parameter list and corresponds to sampling required by the ICR. Notification to monitor source water for bromides and uv-254 for one year was received in February of 1997.

Table 2: Source Water Quality Summary For Keller Plant 1

Water Quality Parameter	Average Yearly Concentration	Standard Deviation	Maximum Yearly Average	Minimum Yearly Average
Temperature (°C)	24.7	0.6	25.5	23.9
pH	7.47	0.05	7.54	7.40
Turbidity (ntu)	0.02	0.07	0.35	0.13
Alkalinity (mg/L CaCO ₃)	200	8	215	189
Calcium Hardness (mg/L CaCO ₃)	197	7	211	188
Total Hardness (mg/L CaCO ₃)	211	11	230	195
TOC (mg/L C)	4.9	0.7	5.9	3.8
UV-254 (cm ⁻¹)	0.161	.017	0.188	0.138
Bromide (mg/L)	0.053	0.010	0.071	0.044

Table 3: Finished Water Quality Summary For Keller Plant 1

Water Quality Parameter	Average Yearly Concentration	Standard Deviation	Maximum Yearly Average	Minimum Yearly Average
Temperature (°C)	24.9	0.7	25.6	23.0
pH	7.74	0.11	7.88	7.50
Turbidity (ntu)	0.87	0.40	1.73	0.32
Alkalinity (mg/L CaCO ₃)	209	8	225	199
Calcium Hardness (mg/L CaCO ₃)	194	6	203	183
Total Hardness (mg/L CaCO ₃)	210	7	220	195
UV-254 (cm ⁻¹)	0.118	0.021	0.142	0.090
TOC (mg/L C)	4.6	0.9	6.0	3.2
TOX (mg/L Cl)	0.24	0.04	0.28	0.20
Distribution System THM4 (µg/L)	88	9	101	78
Distribution System HAA5 (µg/L)	62	18	84	32

Section III: Methods and Materials

Pretreatment Processes to the Advanced Treatment Process

The membrane treatment study was conducted using the raw groundwater supplied to Keller Plant 1. From a tap in the raw water collection main, prior to entry into the plant the water was pumped to the membrane pilot unit trailer. This raw water pump was used to maintain a pressure of approximately 30 psi to the membrane pilot unit prefilter. The raw water was pretreated with sulfuric acid addition and prefiltration using two parallel cartridge filters with a nominal pore size of 5 microns. Figure 2 in the following Advanced Treatment Section presents a process diagram that shows the location of acid addition and prefiltration. Table 4 presents the pretreatment processes and design parameters.

Table 4: Membrane Pilot Unit Pretreatment Design Parameters

Unit Process	Process Description
Scale Control (Pilot-Scale)	Chemical Type: Sulfuric Acid
	Adjust pH: 5.9
	Dose Rate (mg/L): 110
Cartridge Filtration (Pilot-Scale)	
	Total Surface Area (ft ²): 2.2
	Nominal Pore Size (μm): 5
	Filter Material: Wrapped Polypropylene Yarn
	Filter Life (gal. of raw water): 10 ⁶

Advanced Treatment Process

The following section will present the membrane pilot plant design and the specification of the membrane elements. Figure 2 presents a flow diagram of the membrane pilot plant. Raw water was pumped from the Keller Plant 1 collection main to the membrane pilot plant trailer. Prior to passage through the prefilter, concentrated sulfuric acid was injected to reduce the pH and prevent calcium carbonate from precipitating. The acidified water then passed through (2)-20 inch long cartridge filters configured in parallel. The cartridge filters had an individual surface area of 1.1 ft², for a total surface area of 2.2 ft². These cartridge filters had a nominal pore size of 5 μm. After the prefilter the water passed through a high pressure feed pump which boosted the pressure to approximately 150 psi and passed the water through the membrane process.

The pilot plant utilized a 2-stage christmas tree configuration identical to the ICR pilot unit design described in the “*ICR Manual for Bench- and Pilot-Scale Treatment Studies*”. The first stage consisted of two pressure vessels in parallel, which in turn fed concentrate to a single pressure vessel in the second stage. It incorporated three 4040 elements per pressure vessel for a total of nine elements.

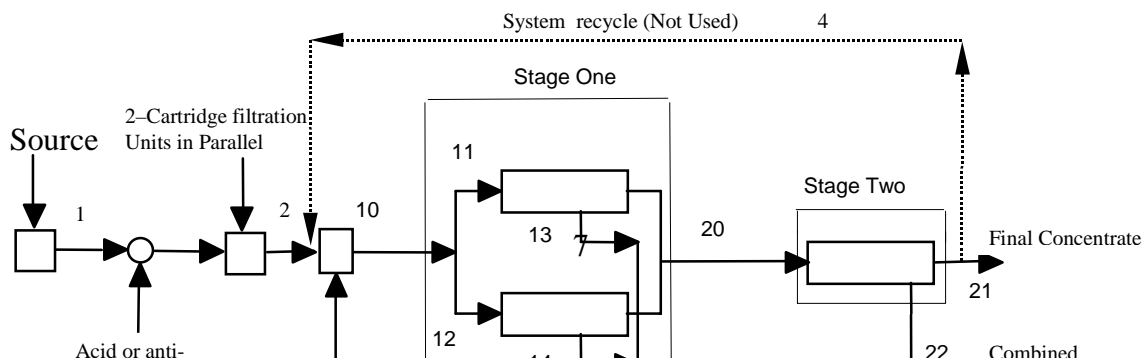


Figure 2: Membrane Pilot Unit Flow Diagram

Table 5 presents the information supplied by the manufacturer for the membrane elements used in the membrane pilot studies conducted at the Keller Plant 1. The initial single element testing was conducted using an element with approximately 70 ft² of membrane area. However, the elements used in the pilot study had an increased area of approximately 80 ft² due to a more efficient wrapping technique.

Table 5: Information Supplied by Membrane Manufacturer

Element	Dow U. S. A. (FilmTec)
Parameter	4040
Membrane	NF-70
Configuration	Spiral-Wound
Element Dia.	3.9"
Element Length	40"
Permeate Tube Dia.	0.75"
External Wrap	Fiberglass
Membrane Type	TFC
Active Layer	Cross Linked Aromatic Polyamide
Functional Group	Amide
Backing	Polyester
Molecular Weight Cut	200
Charge	Negative
Ks (gsfd)	15 (Na)
Active Membrane Area	80 ft ²
Recovery	15 %
Permeate Flow	1700
Max. Feed Flow	16 gpm
Minimum Feed Flow	4.0 gpm
Water Flux	15-25 gfd
Water MTC	0.35 gsfd/psi
Max. Pressure	250 psi
pH (Long Term)	3-9
pH (Short Term)	1-11 @ 25 ⁰ C
Max. SDI	5
Membrane Life	5 yr
Max feed Turbidity	1 ntu

Experimental Design

The studies conducted at the Keller Plant 1 scheduled operation of the membrane pilot for six months with collection of 5 sample sets on a monthly basis. Table 6 presents the experimental design of the membrane study. The unit was set to operate on a continuous basis after initiation with a system recovery of 75% and a system flux of approximately 15 gsf. Limiting salt calculations and computer projections determined that SiO_2 would be the limiting salt at approximately 85% recovery. However, pump capacity and hydraulic characteristics of the pilot unit limited recovery to between 75 and 80 %. The pretreatment consisted of acidification to control calcium carbonate precipitation and 5 μm prefiltration. Recycle was not used during the pilot studies conducted at Keller Plant 1. The permeate streams from each stage were not restricted during operation which produced higher flux in stage 1 than in stage 2, similar to how full scale plants are presently operated.

There were no cleaning operations conducted on the membranes during the studies conducted using the Keller Plant 1 source water.

Table 6: Experimental Design of Keller 1 Membrane Studies

Season	Membrane	Pretreatment	System Flux (gsf)	Recovery (%)
Summer	NF-70	Conventional/Acid	15	75
Fall	NF-70	Conventional/Acid	15	75
Winter	NF-70	Conventional/Acid	15	75

Analytical Methods

The following section presents a summary of the analytical methods used for the water quality analysis of samples collected during the membrane studies conducted for Pinellas County. Due to the broad scope of the water quality study conducted for the County in which the membrane study was one phase, analytical methods, material and quality control were included in a separate report. This report Titled “*Investigation And Analysis of Contaminants In The Potable Water Supply of Pinellas County: Laboratory Methods, Materials and Quality Control*” was forwarded to USEPA with the “*Request For Approval To Grandfather Data From A Previous Membrane Pilot Study To Meet The ICR Treatment Study Requirements For PWSID# FL6521405, Plant ICR # 717*”.

The DBP formation potential simulated the DBP formation in the distribution. The water is produced at the northeastern border of the county and is pumped, chlorinated and stored during distribution through the county. The distribution system is extensive and has a relatively long detention time. The conditions for DBP formation potential were selected to be a SDS formation for this system. These condition were set at an incubation pH of 7.6, temperature of 20⁰C, a reaction time of 96 hours at doses of 5 mg/L for the permeate samples and 12.5 mg/L for the feed stage 1. The free chlorine residuals after the 96 hours for the raw and total permeate samples were no less than 0.2 mg/L Cl_2 . For the total permeate samples residuals ranged from 0.2 to 2.1 and the raw water samples ranged from 1.3 to 4.5 mg/L Cl_2 . These formation conditions produced DBPs that were slightly higher than measured in the distribution system.

The DBPs for the long term membrane pilot studies were measured using the USEPA 551 and 552 methods which included the measurement of 26 different compounds. The

University of Central Florida was conducting membrane research for the USEPA titled “*Reduction of Disinfection By-Product precursors by Nanofiltration*”, (EPA/600/SR-92/023, April 1992) which required laboratory participation in the evaluation of the two analytical methods and the comparison of the THM4 methods EPA 501.2 and EPA 551. These studies were conducted in anticipation of the adoption of both EPA 551 and 552 methods. Included with the request for approval to grandfather information was a paper Titled “*Comparison of THM Analyses by EPA Method 501.2 and 551*”. This paper was presented during an AWWA WQTC conference, (Orlando, 1992) and summarizes the results of the comparison of THMs by EPA 501.2 and 551. In addition, during the Pinellas County Water Quality Studies an extensive evaluation of the source waters was conducted by varying the formation parameters to produce statistical predictive models for chlorine and chloramine demand as well as the 26 DBP compounds. The THMs for this study were analyzed by both EPA 501.2 and 551 methods. The study produced THM formation curves from 0 to 96 hours at two chlorine doses and two temperatures for the Keller Plant 1 and 2 source waters and the permeate using the EPA 501.2 method. This study report titled “*Investigation And Analysis of Contaminants In The Potable Water Supply of Pinellas County: Disinfectant Residual and By Product Modeling*” can be provided at the USEPA’s request.

The Pinellas County membrane study evaluated the water quality of the flow streams for more parameters than the ICR protocol requires. However there were 2 parameters that were not measured during this study that are required of a proposed ICR study, bromides and UV-254. In addition, instead of measuring total organic carbon (TOC) this study analyzed for non-purgeable dissolved organic carbon (NPDOC). Historical analysis on the Floridan aquifer has shown that the purgeable fraction of carbon is negligible and these water samples were not filtered before the analysis, therefore for this groundwater TOC and NPDOC are essentially the same.

The UCF ESEI Laboratory conducted all of the analysis associated with the membrane studies conducted at the Keller Plant 1. The UCF ESEI laboratory as described in the “*Investigation And Analysis of Contaminants In The Potable Water Supply of Pinellas County: Laboratory Methods, Materials and Quality Control*” was certified by the State of Florida and participated in USEPA performance evaluations during these studies. Pinellas County Utilities and Montgomery Laboratories are conducting the analysis associated with the ICR Monitoring requirements. Montgomery Labs are measuring TOX and Bromides. The sample analysis related to ICR monitoring was used to produce Tables 2 and 3, which present the most recent source and finished water quality for the Keller Plant 1.

A summary of the analytical methods and detection limits for the UCF ESEI Laboratory analysis associated with the membrane studies is presented in Table 7. The contact personnel and information for the three laboratories are presented in Table 8.

Table 7: Summary Of Analytical Procedures

Procedure	Description	Reference	Reporting Level
Alkalinity	Acid titration	SM 403	2 mg/L
Chloride	Argentometric	SM 407A	1 mg/L
Chlorine Residual	Amperometric titration DPD Ferrous titrimetric	SM 408C SM 408D	0.1 mg/L
Color	Spectrophotometric	SM 204B	0.5 cpu
Fluoride	SPADNS	SM 413C	0.05 mg/L
Hardness, Total Ca ⁺⁺	EDTA titration	SM 314B	2 mg/L
		SM 311C	2 mg/L
Metals, General	Plasma Emission	SM 305	Fe = 10 µg/L
PH	Meter	SM 429	N/A
Sulfate	Turbidimetric	SM 426C	1 mg/L
Total Dissolved Solids	Gravimetric	SM 209B	1 mg/L
Turbidity	Ratio turbidimeter	SM 214	0.05 NTU
Silica	Heteropoly Blue	SM ¹⁹ 4500-SiE	1 mg/L
Sodium	Plasma Emission	SM 305	1 mg/L
Non-purgeable dissolved Organic Carbon	Persulfate-Ultraviolet Oxidation	SM 505B	0.3 mg/L
Disinfection By-Products	Micro-extraction, GC-ECD	EPA551,552*	1 µg/L Individual
Trihalomethane	Liquid-Liquid extraction	EPA 501.2	1 µg/L Individual
Total Organic Halide	Adsorption-Pyrolysis, Titrimetric	SM 506	2 µg/L
Formation Potential	Chlorination followed by 501.2, 551, 552, and TOX Analysis	TEXT	N/A

*EPA 551 analyzed the base-neutral function, while EPA 552 analyzed the haloacetic fraction.

SM = 16th Edition of Standard Methods. SM¹⁹ = Referenced under 19 th edition of Standard Methods.

EPA = U.S. Environmental Protection Agency

Table 8: Laboratories Conducting Analysis For Report

Laboratory	ICR I.D.	Contact	Address	Phone
Pinellas County Utilities	FL-006	Robert M. Powell, Director	1620 Ridge Rd. Largo, FL 34648	Phone – (813)-582-2302 FAX – (813)-584-8623
Montgomery Watson	CA-013	James C. Hein	555 East Walnut St. Pasadena, CA 91101	Phone – (818)-568-6400 FAX – (818)-568-6324
UCF Environmental Systems Engineering Institute	N/A	Dr. James S. Taylor, Director	University of Central Florida CEE Department 4000 Central Florida Blvd. Orlando, FL 32816- 2450	Phone – (407)-823-2785 FAX – (407)-823 6562

Section IV: Results And Discussions

Operations Description

Time of operation is classified by the events that occurred during operation. Periods of operation are defined as the time increments between events, which for this study were mainly caused by modifications to the membrane pilot unit. This section will report these periods of operation numerically in order of their occurrence. Table 9 lists the three periods for Keller Plant 1. The effects of these system changes on water production and quality will be described in subsequent sections.

Table 9: Membrane Pilot Plant Periods Of Operation

Period	Date	Time (Hour)	Recovery (%)	Chem. Feed	Comments
KELLER 1	7/19/89-1/10/90	3904			
1	7/19/89-7/26/89	0-170	75	Acid	No inter-stage flow gages
2	7/26/89-9/29/89	170-1358	75	Acid	Inter-stage flow gages installed
3	9/29/89-1/10/90	1358-3904	75	Acid	Flow gages recalibrated.

There were three periods of operation while the membrane system was evaluated using the source waters of the Keller 1 WTP. The membrane pilot plant was operated for 3904 hours from 7/19/89 to 1/10/90. During this period the recovery was monitored and adjusted to between 75 % and 80 %. Initially only the total permeate and final concentrate flows were measure while meters were procured. Flow meters were added to measure permeate streams from each pressure vessel at the end of this period. The permeate flows from the individual pressure vessels were not recorded for the first 170 hours. of operation until 7/26/89 when they were delivered and installed.

During the second period between 170 hours and 1358 hours modifications were made to the discharge lines of the Keller 1 membrane pilot plant. These modifications were necessary because the discharge lines were broken several times during normal operation of the Keller 1 and 2 WTPs. These modifications caused fluctuations in the pressure measurements throughout membrane pilot plant. The flow meters were recalibrated at the end of this period.

During period three the combined permeate and concentrate stream flows were measured manually and recorded on a routine basis. The manual measurements were used to calibrate the flow readings from the inter-stage flow gages and adjust the pilot unit. On 1/10/90 the system was shut down and prepared for operation using the Keller 2 water source. This ended the third operational period using the Keller Plant 1 water supply.

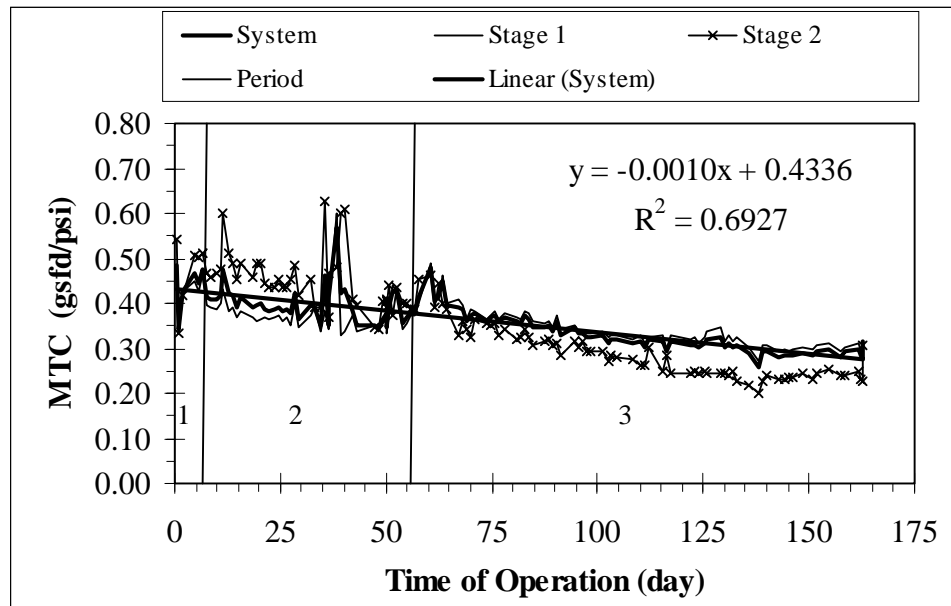
Water Production

The pilot plant was operated using the Keller Plant 1 source water and conventional pretreatment for a total of 4031 hours with 127 hours of downtime. The pilot unit was productive 97% of the time available for operation.

Figure 3 presents a plot of the MTCw(Tavg oC) generated from the *Data Collection Spreadsheets*. Using linear regression techniques on all the data presented in the graph a water production decline rate of 0.0011 gsfd/psi/day was determined. This rate of decline would indicate a cleaning frequency of once every 1.75 months using an initial manufacturer specification MTC of 0.35 gsfd and a 0.15 % decline. A cleaning frequency of 1.75 months is higher than would be expected for a Florida groundwater and is indicative of fouling from concentration polarization. Increasing the velocity across the membrane surface can reduce excessive concentration polarization. Lower recovery would result in a higher concentrate flow and cross membrane velocity. Subsequent studies conducted using Keller Plant 2 water, the same pretreatment conditions and a lower recovery of 60 % increased the cleaning frequency to approximately 6 to 8 months.

Figure 3 also indicates from the relatively steady rate in decline that there was minimal if any effect on water production by seasonal climate. The study was initiated in July 1989 and finished in January 1990.

Figure 3: Membrane Pilot Plant Water Production



Water Quality Data

The following section will present a summary of the water quality data collected from the membrane pilot studies conducted at the Keller Plant 1 WTP. Water quality samples were collected at the initiation of pilot plant operation in the summer (July 1989) and approximately once a month until completion in the winter (January 1990). There was a total of five water quality sample sets collected. There appeared to be no seasonal effect on the water quality of samples collected during this study.

Source Water Quality

Table 10 presents the source water quality of samples collected during operation of the membrane pilot unit at the Keller Plant 1WTP. The water samples were collected from a sample port located on the well field collection main at the tap for the pilot unit. These samples represent the raw water from the well field prior to any pretreatment.

Table 10: Source Water Quality For Keller Plant 1 Membrane Pilot Studies

Parameters	Units	High	Low	Avg.	Std. Dev.
PH		7.5	6.8	7.2	0.3
TDS	mg/L	300	264	276	15
Alkalinity	Mg/L CaCO ₃	218	191	205	11
Total Hardness	Mg/L CaCO ₃	230	212	221	6
Calcium Hardness	Mg/L CaCO ₃	210	194	202	7
Chlorides	mg/L Cl ⁻	20	8.8	14	4.2
Sulfates	mg/L SO ₄	16	0.6	4.7	6.4
Sodium	mg/L Na	10	7.7	8.4	0.9
Iron	µg/L Fe	58	35	43	10
Turbidity	NTU	0.4	0.1	0.3	0.1
Fluoride	mg/L F	0.24	0.17	0.21	0.03
Silica	mg/L SiO ₂	23.2	15	18.3	3.2
Color	CPU	20	12	16	3
NPDOC	mg/L C	4.1	3.3	3.7	0.3
SDS-THM	µg/L	246	94	142	62
SDS-HAA5	µg/L	108	39	75	29
SDS-TOX	µg/L Cl ⁻	600	444	541	69

Water Quality of Pretreated Influent

Table 11 presents the feed water quality of samples collected during operation of the membrane pilot unit at the Keller Plant 1 WTP. The water samples were collected from a sample port located on the pilot unit between the pretreatment processes and the high-pressure pump, which fed the membrane elements of stage 1. These samples represent the influent water to the membrane process after acidification with sulfuric acid and 5 micron filtration.

The major difference between the water quality of the source or raw water and the pretreated influent to the membrane process is the effects of the addition of sulfuric acid for scaling control. In general, the pH and alkalinity decreased while sulfates and TDS increased following acid addition. The source water had very low sulfates except for one sample at 16 mg/L SO₄. The acid raised the sulfate concentration average to 108 mg/L SO₄. The average fluoride concentration increased from 0.21 to 0.47 mg/L F following the addition of sulfuric acid. The DBP formation potentials were conducted on the source water and not the feed stream to the membrane pilot unit.

Table 11: Influent Water Quality For Keller Plant 1 Membrane Pilot Studies

Parameters	Units	High	Low	Avg.	Std. Dev.
PH		6.4	5.8	6	0.2
TDS	mg/L	347	300	324	20
Alkalinity	mg/L CaCO ₃	159	95	125	32
Total Hardness	mg/L CaCO ₃	238	218	227	8
Calcium Hardness	mg/L CaCO ₃	213	200	203	6
Chlorides	mg/L Cl ⁻	20	10.6	14.6	3.8
Sulfates	mg/L SO ₄	141	65	108	28
Sodium	mg/L Na	9.8	7.6	8.4	0.9
Iron	µg/L Fe	72	30	43	16
Turbidity	NTU	1	0.2	0.4	0.4
Fluoride	mg/L F	0.57	0.38	0.47	0.07
Silica	mg/L SiO ₂	19.3	15.4	16.8	1.7
Color	CPU	17	14	15	1
NPDOC	mg/L C	3.9	3.4	3.6	0.2

Finished Water Quality

Table 12 presents the combined permeate water quality of samples collected during operation of the membrane pilot unit at the Keller Plant 1WTP. The water samples were collected from a sample port located on the pilot unit after permeate from stage 1 was combined with permeate from stage 2. These samples represented the finished water from the membrane process. This data shows that the NPDOC was reduced to below 0.3 mg/L C and that the THM4 and HAA5 formation potentials were below the proposed phase 2 limits.

Table 13 presents the average percent rejection of solutes from the finished water during the membrane studies. The reference concentration was the pretreated influent water quality. In general the organic parameters were reduced by 84 to 94 %.

Table 12: Keller Plant 1 Membrane Pilot Plant Finished Water Quality

Parameters	Units	High	Low	Avg.	Std. Dev.
PH		5.8	5.2	5.5	0.3
TDS	mg/L	130	70	97	24
Alkalinity	mg/L CaCO ₃	89	40	60	21
Total Hardness	mg/L CaCO ₃	81	50	67	16
Calcium Hardness	mg/L CaCO ₃	72	38	52	15
Chlorides	mg/L Cl ⁻	12.3	8.8	10.5	1.3
Sulfates	mg/L SO ₄	8.4	3.2	5.9	2.2
Sodium	mg/L Na	6.3	4.6	5.1	0.7
Iron	µg/L Fe	30	10	19	9
Turbidity	NTU	0.9	0.1	0.3	0.3
Fluoride	mg/L F	0.16	0.09	0.13	0.03
Silica	mg/L SiO ₂	17	8.6	12.3	3.3
Color	CPU	3	1	2	1
NPDOC	mg/L C	0.3	0.2	0.1	0.1
SDS-THM	µg/L	30	14	22	7
SDS-HAA5	µg/L	15	1	7	6
SDS-TOX	µg/L Cl ⁻	45	26	35	9

Table 13: Rejection of Solutes For Keller Plant 1 Membrane Studies

Parameter	Rejection (%)
TDS	70
Alkalinity	52
Total Hardness	70
Calcium Hardness	74
Chlorides	23
Sulfates	95
Sodium	38
Iron	55
Fluoride	72
Silica	34
Color	88
NPDOC	94
SDS-THM	84
SDS-HAA5	90
SDS-TOX	94

Impact of Seasonal Variability

The water quality and production data indicates that there are no impacts associated with the season of the year on the membrane process. Because the source to the Keller Plant 1 comes from a relatively deep aquifer the source water quality remains relatively constant. Relatively small changes in the source water quality are associated with the individual water quality of each well and the combination of wells that are operated at a given time.

Cost Information

This section outlines cost estimates for building and operating a membrane softening system for a 10 and 50 mgd groundwater nanofiltration plant at Pinellas County. The cost estimates are not exact and should be used for comparative purposes only. A much more exact estimate would have to be completed for actual cost estimates for financing. The cost estimate is adequate for general cursory cost comparisons to other water treatment processes. The groundwater cost estimate details cost for building and operating a membrane softening plant with conventional pretreatment of acid feed and prefiltration at 85 % recovery and 150 psi. The estimated capital cost for a 10 and 50 million gallon per day (MGD) membrane softening operation using a groundwater source at Pinellas County is shown in Table 14. The operation-maintenance (O & M) costs for the membrane softening operation are also summarized in Table 14. References for both O & M costs and capital costs were taken from several different sources (EPA 1979, Taylor 1989, Goigel 1990) and updated by the Engineering News Record Construction Cost Index to 1991.

The capital cost estimated consisted of land, site work, buildings, process equipment, process piping, instrumentation, high service pumps and capital costs associated with deep well injection. No cost for on site finished water storage tanks was estimated as these costs are common to all treatment processes and should be separated from the costs used for comparison of different processes. Using the references mentioned above, the capital cost of a 10 MGD and 50 MGD membrane softening plant was estimated as \$15,874,250 and \$65,040,500 respectively. The amortized cost over 20 years at 10% is \$0.51/Kgal for the 10 MGD plant and \$0.42/Kgal for the 50 MGD plant for finished water. The total O & M cost for the 10 and 50 mgd plant was estimated to be \$2,102,700 and \$9,348,500 or \$0.58/Kgal and \$0.51/Kgal respectively.

Both the 10 and 50 mgd plants were sized on a array basis. A three stage array with 4 pressure vessels in stage one, 2 pressure vessels in stage two and one pressure vessel in stage three was assumed. Each pressure vessel contained six membrane elements which had an 8" diameter and 350 sf. A system flux of 15 gsf/d was assumed at a system pressure and recovery of 150 psi and 85 %. Each array contained 42 membrane elements and would produce 220,500 gpd and 46 arrays would be required to produce 10 mgd. Increasing the number of arrays to 230 would supply 50 mgd and was the basis for developing the 50 mgd cost estimate.

The building for the 10 mgd plant was estimated to have 20,000 sf of area and was priced at \$70/sf for a total estimated cost of \$1,400,000. The estimated building cost for the 50 mgd plant was \$6,500,000. Since the building costs was only for the membrane facility very little economy of scale was realized. The control room area was only doubled for the 50 mgd plant from that of the 10 mgd plant, so a savings of \$500,000 was realized.

Table 14: Cost Estimate For Pinellas County Nanofiltration Plant

Category	Cost	Cost
	10 MGD	50 MGD
<u>Capital</u>		
Land	\$35,000	150,000
Site work	\$300,000	500,000
Buildings		
Membrane	\$1,400,000	6,500,000
Chemical Feed	\$224,000	560,000
Bulk Chemical Storage	\$168,000	630,000
Chlorine Feed	\$168,000	785,000
Clearwell and pumps	\$244,000	1,220,000
Administration and Lab	\$140,000	420,000
Power Vault	\$15,000	75,000
Process Equipment		
Membranes and pumps	\$6,000,000	\$27,000,000
Chemical Feed	\$115,000	\$517,500
Chlorination	\$100,000	\$160,000
Aerator	\$400,000	\$1,200,000
Process Piping	\$1,323,000	\$6,600,000
Instrumentation and electrical	\$992,250	\$3,473,000
High Service Pumps	\$200,000	\$1,000,000
Deep Well		
Injection Well	\$3,000,000	\$11,250,000
Unlined Lagoon Back-up System	\$200,000	not required
Transport Pipeline	<u>\$850,000</u>	<u>\$3,000,000</u>
Total:	\$15,874,250	\$65,040,500
\$/Kgal (20yrs at 10%)	\$0.51	\$0.42
<u>O & M (per year)</u>		
Wages	\$195,000	\$545,000
Power	\$600,000	\$2,850,000
Chemical Supplies	\$713,700	\$3,568,500
Maintenance	\$515,000	\$2,030,000
Telephone	\$12,000	\$30,000
Deep Well	\$15,000	\$75,000
Other	<u>\$52,000</u>	<u>\$250,000</u>
Total:	\$2,102,700	\$9,348,500
\$/Kgal	\$0.58	\$0.51
<u>Total Cost</u>		
\$/Kgal	\$1.09	\$0.93

The remaining building costs for the chemical feed and storage buildings, chlorine feed buildings, clearwell, administration and power vault buildings were taken from the EPA cost manuals and updated to 1991 costs using the ENR index.

Forty six membrane arrays were required for the 10 mgd plant. The arrays would be distributed among ten skids each of which would produce approximately 1.2 MGD. Membrane flux can be varied to suit actual needs so exact flux is not required for accurate cost estimates. There would always be one skid available for immediate utilization for the 10 mgd design. Five skids would be available for immediate use for the 50 mgd design. Each skid has an estimated capital cost of \$600,000 or \$6,000,000 for 10 skids in the 10 mgd plant. Some slight savings of scale were assumed for the 50 mgd design due to lower unit costs of materials. The capital cost for membrane process equipment was estimated at \$27,000,000.

The remaining process equipment cost was estimated from EPA cost manuals and adjusted to 1991 cost using the ENI index. These costs are based on chemical dosing rates that are listed in the O&M cost section. There was very little economy of scale associated with the chemical feed equipment for the 50 mgd design. However, significant economy of scale was realized for the chlorination and aeration process equipment. The process piping is the interconnecting piping for each of the arrays, skids and system. Very little economy of scale was realized for the process piping or the high pressure pumps because the same amount of this type of equipment is required on a unit flow basis. Some electrical and instrumentation savings could be realized because of the reduction in unit cost of a central control facility for a 50 mgd plant.

Deep well injection was chosen as the method of concentrate disposal because it appears to be the current method of choice. However significant cost savings could be realized if surface discharge could be realized. The cost for deep well injection was estimated using a UCF master thesis (Goigel, 1991). This cost was developed by assuming one deep well with a 2 mgd capacity for the 10 mgd plant. The capacity for the 50 mgd plant is 9 mgd. Actually less than 2 mgd is required for disposal at 85 % recovery but the cost savings associated with a 1.76 vs a 2.0 mgd well are not significant. These costs include storage of 6 mgd in a unlined lagoon as a backup system.

Four deep wells were selected with a capacity of 3 mgd each in order to have a available well on stand by for the 50 mgd system. No unlined lagoon is required here because of the extra well. A 10" diameter ductile iron pipe was used for the ten mile transport pipeline. There is only one deep well included in the estimated cost for the 10 mgd facility. A ten mile distance from the membrane plant was assumed for transport of the concentrate to the injection well. A maximum velocity of 6 feet per second was used for transport and injection. The cost for all deep wells was estimated, per Florida regulations, as a Class I injection well for industrial and municipal waste. Construction includes a tubing and packer system, in addition to the conventional casing and cement.

The estimated annual operation and maintenance cost were estimated at \$2,102,700 per year or \$0.58/Kgal of finished water for the 10 mgd plant. The labor required for the membrane plant was estimated to be one supervisor at \$30,000/year, one head operator at \$25,000/year, and seven operators at \$20,000/year each. The operators worked in three shifts; three on the day shift, three evening and one night. The yearly salary for all above employees includes benefits. This labor cost was increased to include two supervisors, two head operators and 22 shift operators for the 50 mgd plant. The power cost for the membrane operation was developed using a feed pressure of 150 psi, 85% recovery, pump and motors both 85% efficient, a power cost of \$0.075/kwh, and a water flux of 15 gsfd. This power cost was calculated as \$445,300/year, which was increased to \$600,000 to cover other plant power for the 10 mgd plant. Some unit cost savings were assumed for the 50 mgd plant as the total power was estimated to cost \$2,850,000. The only power savings would have to be realized with other than the high pressure membrane pumps. High service pumping is not included in these costs. The total power costs account for 36% of the total O & M cost. The chemical supplies cost was calculated for doses of 143 mg/L H_2SO_4 , 68 mg/L NaOH, 7.5 mg/L Cl_2 , and 1 mg/L inhibitor at \$0.08/lb, \$0.10/lb, \$0.04/lb and \$1/lb, respectively. Cleaning chemicals were also added to this cost at \$3000/yr for quarterly cleaning.

The maintenance cost includes membrane replacement, professional controls and electrical maintenance contracts, prefilter replacement, and pump maintenance. Membrane replacement was estimated at \$445,300/yr for the 10 mgd plant based on a cost of

\$1000/membrane and a five year life. A \$50,000/yr professional contract was estimated for controls and electrical maintenance. Prefilters were estimated to be replaced monthly at a cost of \$7,800/year. Pump maintenance was estimated at \$10,000/year. The total maintenance cost estimated was increased to \$2,030,000 for the 50 mgd plant.

Section V: QA/QC Summary

The following section will present a summary of the quality assurance and quality control results compiled during the membrane pilot studies conducted at the Keller Plant 1.

Solute Mass Balances

Table 15 presents the solute mass balances for operation on the Keller Plant 1 source water. A mass balance was conducted around the membrane system for each sample period and the results summarized. The results show that the mass balances ranged from 92 to 112 % with the exception of fluoride, which had an average of 78 %. These mass balances indicate the accuracy of the measurements of flow and water.

The following equation presents the mass balance calculation.

$$X = \frac{M_P + M_C}{M_F} = K \left[\frac{C_P Q_P + C_C Q_C}{C_F Q_F} \right] 100$$

Where:

X = Percent mass recovery of solute

M = Mass (lb/day)

C = Concentration (mg/L)

Q = Flow (gpm)

_{F,P,C} = System Feed, Concentrate, Permeate locations

K = 0.012, conversion Factor

Table 15: System Mass Balance For Keller Plant 1 Membrane Pilot Study

Parameter	High	Low	Average	Std. Dev.
TDS	124	84	98	16
Alkalinity	100	73	93	11
Total Hardness	111	85	96	11
Calcium Hardness	109	72	92	14
Sulfate	135	82	101	20
Chloride	162	87	110	31
Sodium	141	95	106	20
Iron	145	70	112	28
Fluoride	105	56	78	20
Silica	112	88	99	10
NPDOC	120	74	94	17

Precision

Precision was the reproducibility observed between duplicate analyses. . Duplicates were two determinations of a given parameter for the same sample by repeating the analytical procedure. The precision was expressed as percent relative deviation for each pair of analyses and was calculated by the following formula:

$$\% \text{ RSD} = \left(\frac{S}{\bar{X}} \right) \times 100$$

where:

S = standard deviation

\bar{X} = mean (average for a pair)

The standard deviation (S) for a data pair was calculated using the following equation:

$$S = \sqrt{(X_1 - X_2)^2 / 0.89}$$

where: X_1 and X_2 were individual observations.

Precision of a given analytical method was continuously determined by using the mean range and variance determinations. The range was the difference between the two duplicates. The normalized mean range, \bar{R} , was calculated using the following equation:

$$\bar{R} = \frac{\sum_{n=1}^N R}{N}$$

where:

N

$\sum_{n=1}^N R$ = sum of the relative standard deviations

$n=1$

N = number of data pairs

The variance, S_R^2 , was calculated by:

$$S_R^2 = \frac{\sum_{n=1}^N R^2 - (N \bar{R}^2)}{(N-1)}$$

where:

N

$\sum_{n=1}^N R^2$ = sum of the relative standard deviations

$n=1$

\bar{R}^2 = square of the mean range

N = number of data pairs

The warning limits (WL) and control limits (CL) were calculated by the following equations:

$$WL = \bar{R} + 2S_R$$

$$CL = \bar{R} + 3S_R$$

where:

\bar{R} = mean range

S_R = square root of variance

Data was assessed by interpreting the mean range (also referred to as the central line), with regard to the warning and control limits. A graph of concentration versus sample occurrence or number was used to facilitate the interpretation. The mean range, WL and CL were shown as horizontal lines on the graph. The results of an individual paired duplicate analysis were entered on the graph and interpreted by where they fell within the boundaries on the graph. A minimum of twenty pairs of duplicate analyses were used to construct the graph.

Table 16 and 17 lists the compilation of the precision data obtained for the parameters monitored during the Pinellas County project and the percentage of the time that the data was within the ninety-five percent confidence interval.

Table 16: Precision For Organic Parameters

Parameter	Precision RSD	Std. Dev	Mean	UWL	UCL	%C.I.
Chloroform	0 - 23	6	4	12	18	98
Bromodichloromethane	0 - 16	5	3	9	14	100
Dibromochloromethane	0 - 44	10	4	20	30	93
Bromoform	0 - 16	4	3	8	12	80
Monochloroacetic acid	0 - 110	28	22	55	83	90
Monobromoacetic acid	0 - 95	24	18	49	73	98
Dichloroacetic acid	0 - 94	29	25	58	87	98
Dibromoacetic acid	0 - 48	15	14	29	44	93
Trichloroacetic acid	0 - 129	34	29	69	103	98
Color	0 - 9	3	2	6	9	100
NPDOC	0 - 14	4	4	8	12	98
TOX	0 - 15	4	6	9	13	98

Table 17: Precision For Inorganic Parameters

Parameter	RSD Precision	Std. Dev.	Mean	UWL	UCL	%C.I.
Alkalinity	0 - 4	1	1	2	4	100
Turbidity	0 - 17	4	6	9	13	93
TDS	0 - 13	4	4	8	12	98
Total Hardness	0 - 12	4	2	8	12	100
Ca Hardness	0 - 9	2	2	5	7	93
Chloride	0 - 11	3	2	7	10	93
Sulfate	0 - 75	20	8	41	61	93
Fluoride	0 - 16	5	4	11	16	100
Silica	0 - 8	3	1	5	8	100
Sodium	0 - 7	2	2	4	6	98
Iron	0 - 8	3	2	5	8	100

Accuracy

The data obtain through spike analyses was used as a measure of accuracy, the degree of difference between observed and known values. Known concentrations were added to samples and the following equation used to determine the recovery of the specific parameter:

$$\% \text{ Recovery} = \left(\frac{(Z - X)}{T} \right) \times 100$$

where:

Z = observed spike concentration

X = concentration of unspiked sample

T = True concentration of spike

The percent recovery, the mass of the spike, spiked and unspiked sample concentration were reported on quality control report forms. As with the duplicates, the mean, variance, warning and control limits were calculated using at least twenty data points. For the spikes, percent recovery was used instead of relative standard deviation; and as with the duplicates the mean, variance, warning and control limits were calculated using the previously cited equations. One additional difference between the presentation of the spike and duplicate data is that the warning and control limits were expressed in terms of plus or minus standard deviations. The upper limits were positive deviations. The lower limits were negative standard deviations. A graph of the data and the statistically calculated control were developed. This graph was used to access the acceptability of the data in the same manner as previously described for the duplicate analyses. Table 18 and list the compilation of accuracy data for the parameters monitored in this study and the percentage of time that the data was within the ninety-five percent confidence interval.

In addition to the duplicate and spike data, purchased reference check samples were also used to assess analytical quality. The samples came with preparation instructions, a true value, and a ninety-five percent confidence interval that was computed by the manufacturer. These samples were used for the inorganic analyses, since most of the samples could be

maintained and reanalyzed on a daily basis for three months if refrigerated. Sample analysis was not to take place if the results of the reference analysis were outside the given confidence interval. Additionally some analyses made use of a check sample that was prepared by the laboratory staff to monitor analytical performance.

Table 18 Accuracy For Organic Parameters

Parameter	Accuracy	Std. Dev.	Mean	Warning Limit	Control Limit	% C.I.
Chloroform	52 - 104	15	83	±31	±46	98
Bromodichloromethane	76 - 112	8	91	±16	±24	100
Dibromochloromethane	76 - 178	15	96	±30	±45	93
Bromoform	83 - 128	9	93	±18	±27	80
Monochloroacetic acid	16 - 190	39	63	±79	±118	93
Monobromoacetic acid	25 - 180	41	74	±83	±124	98
Dichloroacetic acid	20 - 196	44	77	±87	±131	100
Dibromoacetic acid	22 - 230	42	68	±85	±127	95
Trichloroacetic acid	6 - 74	20	33	±40	±60	98
NPOC	86 - 110	7	98	±14	±21	100
TOX	90 - 120	10	108	±20	±30	100

% C.I. refers to % of time analysis is within 95% confidence interval.

Table 19: Accuracy For Inorganic Parameters

Parameter	Accuracy	Std. Dev.	Mean	Warning Limit	Control Limit	% C.I.
Alkalinity	92 - 111	5	100	±11	±16	100
Total Hardness	88 - 106	6	99	±11	±17	100
Ca Hardness	89 - 105	5	99	±10	±15	100
Chloride	88 - 112	6	101	±11	±17	100
Sulfate	89 - 127	10	106	±21	±31	100
Fluoride	106 - 128	9	113	±18	±27	100
Silica	92 - 110	6	101	±11	±17	100
Sodium	86 - 115	9	98	±17	±26	100
Iron	93 - 110	6	100	±13	±19	100

USEPA Performance Evaluation

- Eight performance evaluation studies were performed during the course of the project. The results of the evaluations are summarized in Table 20.

Table 20: USEPA Performance Evaluation Summary

Parameter	Units	WS020	WS021	WS022	WS023	WS024	WS025	WS026	WS027
Chloroform	µg/l	19.6 56	13.1 76.6	44.9 24.3	37.5 45.1	9.9 67.8	83.8 28.7	6.7 51	87.3
Bromoform	µg/l	44 20.5+	67.1 27.8	56.7 25.7	70 15.9	11 60.8	49.4 10.2	16 92	25.5
Bromodichloromethane	µg/l	22.6 73	10.4 39.7	18.6 61.5	12 65.4	22.1 59.9	76.5 9.7	24 58	35.4
Dibromochloromethane	µg/l	63.7 30.2+	44.3 16.4	69 15.7	26.9 44.7	8.1 80.2	48.4 16.5	21 86	33.6
Total THM's	µg/l	149.9 179.7	134.9 160.5	189.2 127.2	146.8 171.1	51.1 268.7	258.1 65.1	67.7 287	181.8
Residual Free Chlorine	mg/l	0.64 1.42		0.31 1.13	0.35 1.26	0.7 1.18	0.54 1.47	0.89 0.27	0.36
Turbidity	NTU	4.4 0.7						5.83 1.28	0.99 0.7
Fluoride	mg/l			0.72 1.55	0.27+ 1.32	1.39 1.77	2.46 1.44	3.43 1.33	4.32
Calcium (as CaCO ₃)	mg/l	116		152				122	138
pH	Units	9.11						9.04	9.21
Alkalinity (as CaCO ₃)	mg/l	34.9		51.0+				40.6	37.9+
Sodium	mg/l							15.6	-15.3
Sulfate	mg/l							22.8 8.79	13.9
Dibromoacetic acid	µg/l								4.4
Dichloroacetic acid	µg/l								6.3
Monobromoacetic acid	µg/l								3.5
Monochloroacetic acid	µg/l								7.1
Trichloroacetic acid	µg/l								9.5

- = Value outside acceptable range on the low side

+ = Value outside acceptable range on the high side

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Appendix

Data Collection Spreadsheets