ENERGY-EFFICIENT PROCESS FOR USING MEMBRANE TECHNOLOGY TO TREAT AND RECYCLE AGRICULTURAL DRAINAGE WATER

FEASIBILITY ANALYSIS AND FINAL EISG REPORT

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FEASIBILITY ANALYSIS REPORT (FAR)

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which $2.4 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)
    - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

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For more information on the overall PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/research/index.html.

Energy-Efficient Process For Using Membrane Technology To Treat And Recycle Agricultural Drainage Water

EISG Grant # 00-23

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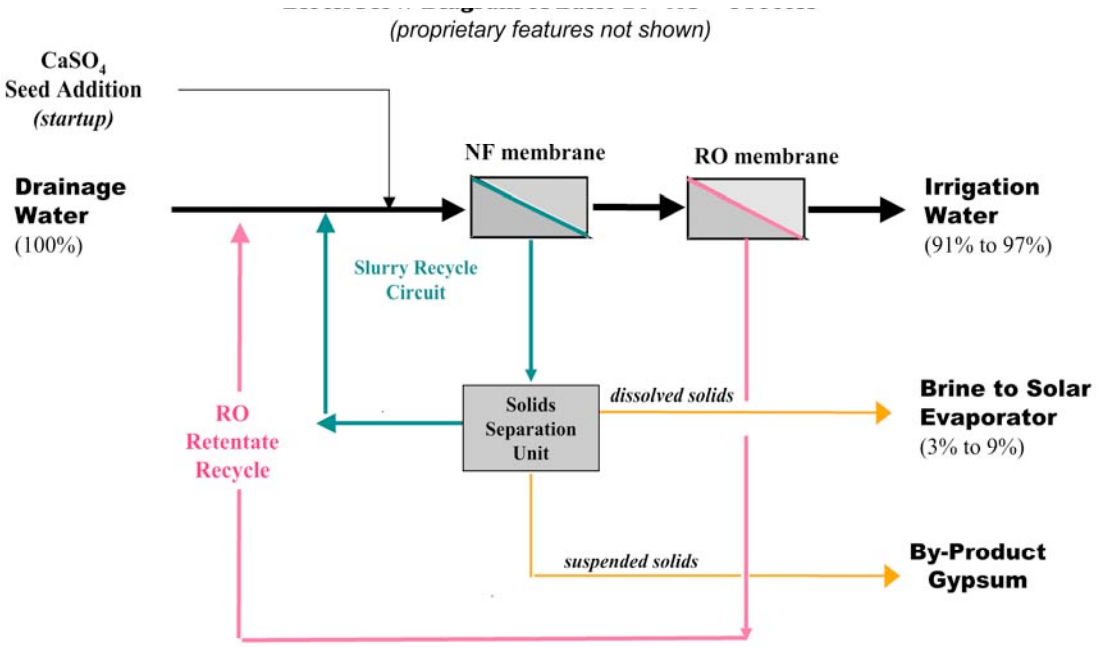
Introduction

U.S. Environmental Protection Agency has identified agricultural drainage/runoff as a significant contributor to surface water pollution. Pollutants that result from drainage/runoff are sediment, nutrients, pathogens, pesticides, and salts. The sources of these pollutants are confined animal facilities, grazing, plowing, pesticide spraying, irrigation, fertilizing, planting, and harvesting. In California, the viability of farming on 861,423 acres of prime farmland in western San Joaquin Valley is threatened by unresolved drainage problems. Drainage cleanup and reuse (recycling) are not being considered as a solution because a viable technology does not exist to recover 99% water content of agricultural drainage in a reliable, energy efficient, and cost-effective manner. Membrane technology has potential as a recycling solution for the agricultural drainage problem. It is extensively used for seawater desalination, but fouling problems have limited its ability to treat agricultural drainage. Although seawater total dissolve solids (TDS) are 35,000 mg/L versus 3,000 to 12,000 mg/L TDS for agricultural drainage, high $CaSO_4$ saturation in drainage has limited recovery by reverse osmosis to < 50%.

The estimated public funds required to implement the U.S. Bureau of Reclamation disposal plan is $716 million, projected to be $425/acre-foot (AF). The utilization of an improved membrane technology to recycle 80,000 AF of agricultural drainage for irrigation would avoid significant public fund expenditures and reduce processing energy consumption from 3,200 kWh/AF (based on best seawater desalination) to 2,400 kWh/AF.

WaterTech Partners proposed to improve the reverse osmosis recovery and reduce energy consumption by developing a two-pass membrane process utilizing preferential precipitation of dissolved $CaSO_4$ (see Figure below). In this arrangement, the precipitated $CaSO_4$ (as well as other salts) would be removed from the drainwater feed in the 1st pass nanofiltration (NF) membrane. The 2nd pass reverse osmosis unit would continue the clean-up of the water to meet irrigation requirements (<500 mg/L TDS with a sodium adsorption ratio <4.0).

Block Diagram of the Basic Process



Objectives

The goal of this project was to demonstrate the feasibility of the proposed two-pass membrane system as a viable technology solution for agricultural drainage water recycling. The researchers established the following project objectives:

1. Prove that "preferred precipitation" nanofiltration will lower agricultural drainage hardness from 2,000 mg/L to less than 50 mg/L.
2. Demonstrate the pilot-scale operation of a two-stage membrane filtration in which the total energy consumption is less than 2,400 kWh/AF (25% less than most efficient commercial reverse osmosis desalination process).
3. Demonstrate the pilot-scale operation of a two-stage membrane filtration whose total cost is 25% below the least costly commercially available seawater desalination process.

Outcomes

1. The researchers identified, through performance testing, a preferred nanofiltration membrane. They tested the nanofilter with "preferred precipitation" and were able to operate, on agricultural drainage, with less fouling than without "preferred precipitation."
2. The simulated specific energy consumption for a two-stage membrane system using "preferred precipitation" was lower (2,163 kWh/AF) than 2,400 kWh/AF (as proposed) for only one case: feed that is solar pre-heated (95°F) and with a TDS levels of 6,450 mg/L. The researchers calculated the membrane energy consumption from feed pressure and flow for the simulated two-stage system.
3. The estimated costs for a water plant using the technology developed in this project are $564/AF to $845/AF depending on feed TDS and use of solar energy for feed preheating. This compares to $850/AF for seawater desalination.

Project Conclusions

The researchers successfully proved the feasibility of "preferred precipitation" combined with nanofiltration as a method to process agricultural drainage water without fouling.

1. The use of "preferred precipitation" provides a method to process and recycle agricultural drainage using membrane technology without fouling problems. This was proved feasible by processing 1,500 gallons of Panoche tile-drain water over a 150 hour test period.
2. The amount of electric power for a simulated two-stage membrane water treatment plant did not meet the proposed goals of the project (<2,400 kWh/AF), but it is less than state-of-the-art seawater desalination reverse osmosis plants.
3. The water production cost of the two-stage membrane water treatment plant is less than a typical seawater desalination reverse osmosis plant, but it is difficult to conclude that this is a level field comparison. Note that seawater desalination reverse osmosis plants process feedwater with higher inlet TDS than the water from agricultural drainage.

Benefits to California

The project demonstrated that "preferred precipitation" combined with nanofiltration is a legitimate method for processing agricultural drainage. The research has significant value for the processing of agricultural drainage and recycling irrigation water. It is an environmentally attractive method of drainage processing compared to the proposed evaporation ponds.

It is unclear if this technology saves electric energy. The researchers derived an estimate of electric consumption by calculation based on feed pressure and flow, instead of measuring it. Since feed pressure and flow vary over time, this calculation can be complicated when considering real-world pump-motor systems.

The researchers also cite that this system could save 418 million kWh/yr, but they compared this system to a seawater desalination plant. Not all of the irrigation water used is from seawater desalination plants. They did not include the pumping energy to deliver irrigation water or the potential to use this in power plants to reduce imported water.

The researchers identified optimization methods that may be explored to further reduce energy consumption and energy cost of the two-stage water treatment plant. These may include off-peak operation, use of solar pre-heating of feedwater, and use of single-stage membrane systems.

Recommendations

The PA makes the following recommendations for this project:

1. Future development and testing should include energy optimized pilot system operation where energy consumption and clean water production are measured.
2. The researcher should compare energy and cost of this technology with the primary drainage treatment method: evaporation ponds or other methods that treat brackish water, not seawater.
3. The researcher is encouraged to identify electric energy savings other than seawater desalination such as avoided irrigation water pumping.
4. The researcher should pursue ways to further reduce the energy consumption of the two-stage water treatment plant.

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market

The targeted market will be individual water/irrigation districts in the drainage-impacted areas (e.g., Panoche and Westlands) and the state and federal agencies charged with solving the drainage problems in the San Joaquin Valley. The researchers should identify energy savings other than seawater desalination.

Engineering/Technical

This project proved the feasibility for membrane separation processing of agricultural drainage using a "preferred precipitation" with nanofiltration. The researchers should augment their electric energy calculations with actual measurements of pump-motor performance. They should also detail designs and controls to further reduce energy consumption of the system. The researchers should complete this activity before scaling up the system.

Legal/Contractual

The researchers have prepared an Invention Disclosure on certain proprietary aspects of the DP^3RO^{TM} process. They expect to complete and file a patent application. The developers conceived or reduced to practice certain aspects of these proprietary features of the DP^3RO^{TM} process in the work performed under the EISG project. Therefore, the State of California will have license rights in such inventions in accordance with the terms of the Grant Agreement. The

filing of a patent application on the proprietary features of the DP^3RO^{TM} process is the remaining uncompleted Stage 3 Legal/Contractual task.

Environmental, Safety, Risk Assessments/ Quality Plans

Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental. The current brine-disposal plan involves the construction and operation of a dedicated solar evaporator facility adjacent to each on-farm DP^3RO^{TM} plant to concentrate brine. Before proceeding with the pilot plant project, the researchers should obtain information on the design and operation of the demonstration solar evaporator at Red Rock Ranch near Mendota. The DWR personnel who will be involved in the DP^3RO^{TM} pilot plant project are also involved in this solar evaporator demonstration project. All other Stage 4-level environmental safety and risk issues related to the DP^3RO^{TM} pilot plant are resolved.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere.

Production Readiness/Commercialization

The researcher has identified membrane suppliers and membrane system designers/constructors who appear interested in working with them for the pilot project. These companies could also assist in the marketing and promoting of the technology to the targeted markets.

A successful scaled-up pilot plant demonstration will be necessary before the system could be deemed commercially viable.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the rate payer from this research is energy savings, but the project savings are in question. The researcher cites a potential to save 418 million kWh/yr. However, the energy savings benefits result from a comparison to seawater desalination, but it is unclear how much of the irrigation water comes from seawater desalination.

Program Administrator Assessment

After taking into consideration (a) research findings in the grant project, (b) overall development status as determined by Stages and Gates, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow-on funding within the PIER program.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

Appendix A to FAR 01-23

ENERGY INNOVATION SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

ENERGY-EFFICIENT PROCESS FOR USING MEMBRANE TECHNOLOGY TO TREAT AND RECYCLE AGRICULTURAL DRAINAGE WATER

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Inquires related to this report should be directed to the Awardee (see contact information on the cover page) or to the EISG Program Administrator at (916) 594-1049 or email at eisgp@energy.state.ca.us .

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Abstract

This project demonstrated the conceptual and technical feasibility of using preferential precipitation in the first-pass of a two-pass membrane process to eliminate fouling when desalinating agricultural drainwater saturated with calcium sulfate. All previous attempts at using membrane technology to reclaim agricultural drainwater have failed or have been limited to low recovery (<50%) because of calcium sulfate fouling. This novel double-pass, preferential precipitation, reverse-osmosis process (DP^3RO™) permits the simultaneous achievement of high water recovery (92-96%), high quality permeate (<500 mg/L of total dissolved solids [TDS] with a sodium adsorption ratio <4.0) and low energy use (2,163 to 2,970 kWh/acre-foot [AF] of product water) for agricultural drainwater with 3,625 to 10,500 mg/L of TDS. Water costs are $564/AF to $801/AF. In comparison, "best case" seawater desalination requires 4,000 kWh/AF and costs $850/AF. Thus, DP^3RO™ can provide a win/win/win outcome for the drainage problems affecting 861,423 acres of prime farmland in western San Joaquin Valley: 1) the farmers' drainage problems can be solved at no cost with <2% of their land taken out of production by having urban water users buy and pay the costs for desalinating the farmers' drainwater with on-farm DP^3RO™ plants; 2) urban water users would obtain this "new water" – possibly 180,000 AF/yr -- via exchange at less cost than seawater desalination; and 3) the adverse environmental impacts caused by off-farm drainage flows and operation of large evaporation ponds would be eliminated. This plan provides statewide power savings of 50 megawatts (MW) with an additional 60 MW shifted to off-peak.

Keywords: desalination, agricultural drainage, preferential precipitation, seeded reverse osmosis, nanofiltration, water recycling, water reclamation, tubular membranes, membrane fouling, mineral scale

Executive Summary

The viability of farming on 861,423 acres of prime farmland in western San Joaquin Valley in California is threatened by unresolved drainage problems. In response to a December 2000 court order, the U.S. Bureau of Reclamation (USBR) is developing a drainage service plan for the northern 379,000 acres of land in the drainage problem area. The costs to farmers for drainage service under this "disposal" plan, which would involve spending $716 million in public funds, are projected to be $425/acre-foot (AF). This plan would involve constructing over 5,000 acres of evaporation ponds. Because drainwater contains selenium, these ponds would be a hazard for wildlife and have other adverse environmental impacts. The reason a "recycling" plan – in which the value of the reclaimed water would pay for the cost of treatment -- is not being considered is because a viable technology does not exist to permit recovery of the 99% water content of agricultural drainage in a reliable, energy-efficient, and cost-effective manner.

Membrane technology has long been recognized as offering the best prospects for providing a recycling solution to the agricultural drainage problem. Indeed, agricultural drainwater is relatively low in total dissolved solids (TDS) compared to seawater (typical drainage has 3,000 to 12,000 mg/L of TDS while Pacific Ocean water has about 35,000 mg/L of TDS). This fact should make drainwater less costly to desalinate than seawater. However, typical drainwater is saturated with calcium sulfate ($CaSO_4$). Thus, as pure water is produced on the permeate side of the membrane, $CaSO_4$ precipitates out of solution on the feed side and fouls the membrane. Prior attempts to use membrane technology to desalinate agricultural drainage have failed entirely or have been limited to low recovery (<50%) because of $CaSO_4$ fouling problems.

WaterTech Partners (WaterTech), a private contract R&D and consulting firm, along with PCI Membrane Systems, Inc. (PCI), an international membrane technology company, has conceived and is developing a novel two-pass membrane process for solving the $CaSO_4$ fouling problem encountered when desalinating agricultural drainage. This new process, named "DP^{3}RO™," uses preferential precipitation (also called seeding) in a 1st-pass tubular-membrane nanofiltration (NF) unit to remove dissolved $CaSO_4$ from the drainwater feed. The softened NF permeate is then fed to a 2nd-pass reverse osmosis (RO) unit in which high quality irrigation water (<500 mg/L TDS with a sodium adsorption ratio <4.0) is produced in low-pressure spiral-wound RO membranes.[1] Drainwater recovery rates of up to 97% are possible with this novel two-pass design.

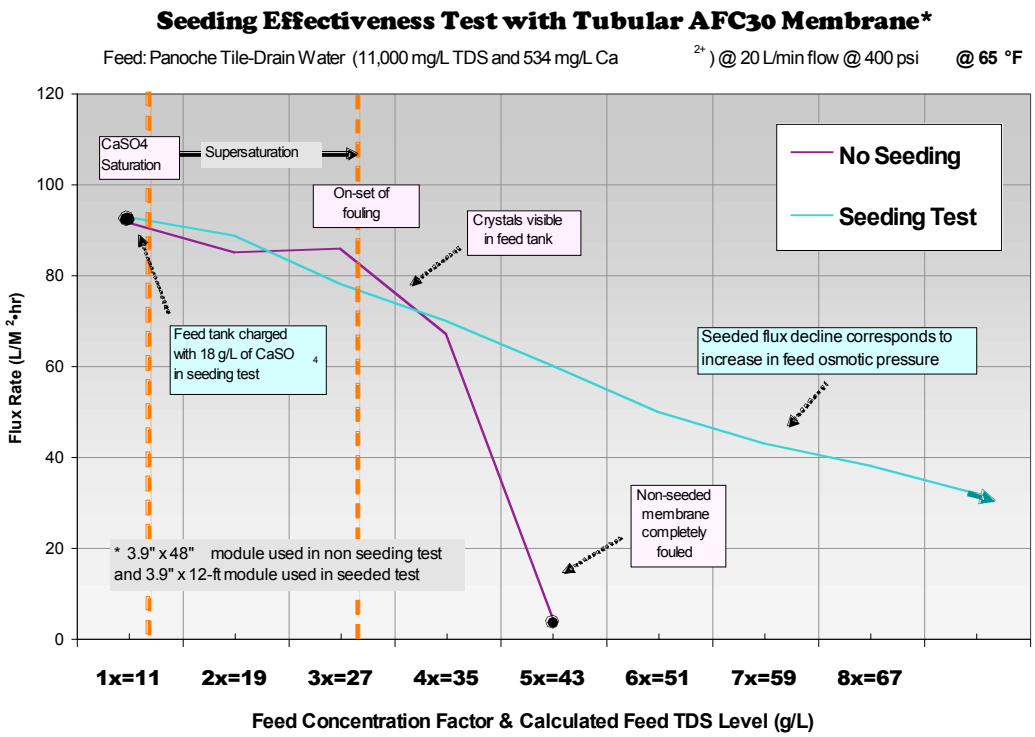
The purpose of this Stage 3-4 PIER project was to: 1) demonstrate the conceptual feasibility of using preferential precipitation to solve the fouling problem; 2) evaluate the performance of various commercially available membranes for use in the NF and RO units of a DP^{3}RO™ pilot plant; and 3) develop designs and cost projections for a high recovery (<90%) 15-gpm pilot plant and a 250-gpm DP^{3}RO™ commercial plant. The Membrane Test Program was conducted at an R&D facility in Walnut Creek, CA, using a pilot system rented from PCI. Actual drainage water was obtained for the tests from Panoche Drainage District. Five different commercial tubular membranes (four NF and

[1] Certain details and features of the DP^{3}RO™ process are proprietary and therefore are not disclosed in the body of this report. Proprietary process-design drawings for the 15-gpm DP^{3}RO™ pilot plant are presented in confidential Appendix V.

one RO) were purchased for testing from PCI; and four commercial low-pressure spiral-wound RO membranes were purchased for testing from Koch Membrane Systems (Koch HF and Koch ULP), Desalination Systems (Desal AG), and Hydranautics (ESPA1).

The initial screening tests showed that PCI's AFC30 membrane, which exhibited an 87% TDS rejection rate, had the best properties for use in the NF section. To determine the effectiveness of seeding for preventing $CaSO_4$ fouling, concentration tests were performed with the AFC30 using Panoche drainwater *with* and *without* seeding. As shown in Fig. ES-1, the non-seeded membrane began fouling at a 3x concentration factor and was completed fouled at 5x. In the seeded case, no evidence of fouling was observed all the way through the 8x concentration reached at the end of the test.

Figure ES-1

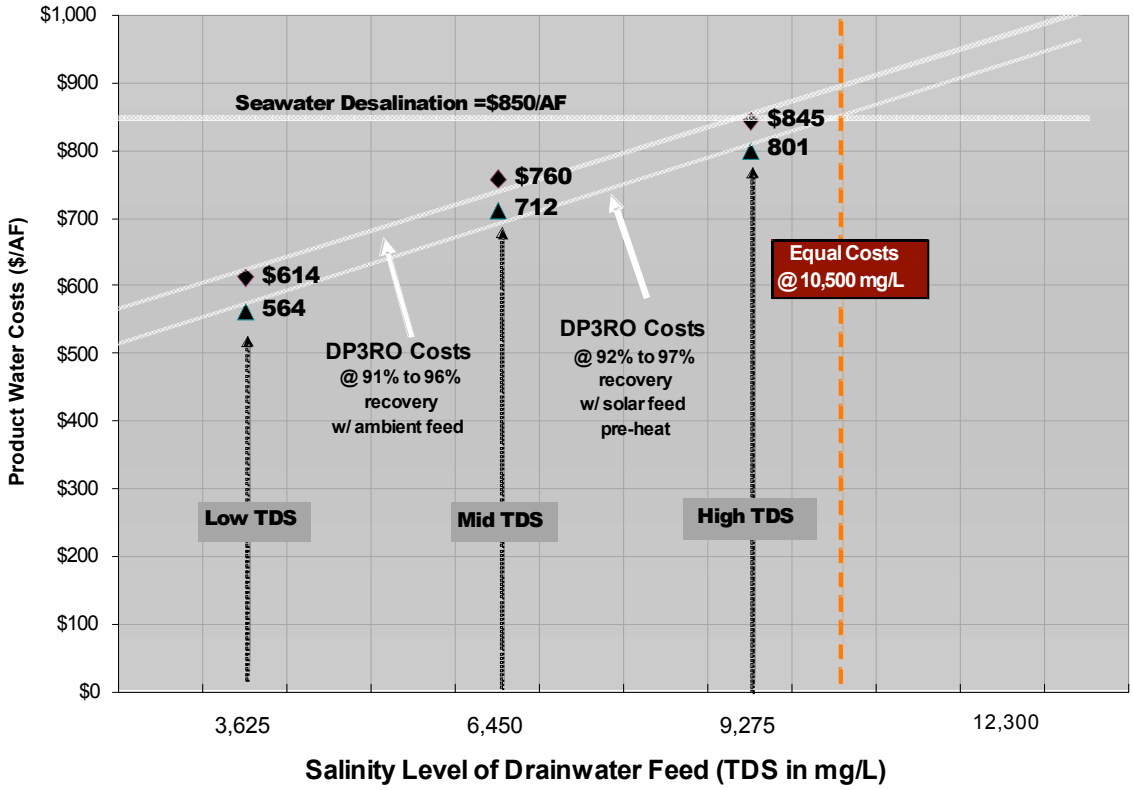


Additional tests were performed with AFC30 membranes using the Panoche drainwater to obtain design and cost data for the pilot plant. After the NF testing was completed, the RO membranes were tested using the collected NF permeate as feed. The key factor in comparing the performance of the RO membranes was their boron rejection rates at the natural 7.6 to 7.8 pH of the NF permeate. At this pH level, the Koch HF (79%) and the Hydranautics ESPA1 (69%) had the highest boron rejection rates. WaterTech recommends both of these RO membranes be used in the next stage pilot-plant project.

Using a DP^{3}RO™ computer process-design model and data from the Membrane Test Program, preliminary design drawings for a 15-gpm pilot plant were produced. This plant was "operated" at three different feed TDS levels to determine specific power use and operating costs. This design was then scaled by a factor of 16 to obtain performance data and capital and operating cost estimates for a 250-gpm commercial DP^{3}RO™ plant. Projected DP^{3}RO™ product water costs ($/AF) as a function of the TDS level of the

agricultural drainwater feed are presented in Fig. ES-2. The "with solar feed pre-heat" cost line shows that solar energy can be used to reduce costs by $44/AF to $50/AF.

Figure ES-2
Ag Drainage DP ^{3}RO™ vs. Seawater RO
Product Water Cost ($/AF) without and with Solar Pre-Heating



As shown in Fig. ES-2, the DP^{3}RO™ process can produce high quality irrigation water from agricultural drainage at >90% recovery at less cost than "best case" seawater desalination for drainwater with up to 10,500 mg/L of TDS. Approximately 200,000 AF/yr of the 252,800 AF/yr in drainage flows in western San Joaquin Valley has less than 10,500 mg/L of TDS. At 90% recovery, this represents 180,000 AF/yr of "new water."

In conclusion, this project has shown that DP^{3}RO™ can serve as an enabling technology for simultaneously providing 1) a "no cost" solution to the agricultural drainage problems in western San Joaquin Valley and 2) a significant source of "new water" for California at less cost and less environmental impacts than seawater desalination. This plan for using on-farm DP^{3}RO™ plant to desalinate drainage in the San Joaquin Valley will provide statewide power savings of 50 MW with an additional 60 MW shifted to off-peak.

Give the success of this Stage 3 (proof-of-concept) and Stage 4 (bench-scale testing) PIER project, WaterTech is attempting to secure $1,000,000 in grant funding for a 15-gpm pilot-plant project at a field location in Panoche. This Stage 5 (field testing) project will be performed by the same team that performed this EISG project. CALFED has already committed $216,090 for this project; and a pre- proposal requesting $270,000 in co-funding from USBR was submitted in January 2003. WaterTech requests $500,000 in follow-on PIER funding to complete the financing for this proposed 18-month pilot-plant project.

Introduction

Overview of Agricultural Drainage Problems in Western San Joaquin Valley

The production of agricultural drainage water is a necessary part of irrigated farming. This is because irrigation water contains dissolved salts that are brought onto the farmland along with the irrigation water. Water in excess of crop evapotranspiration requirements must be applied to flush ("leach") these imported salts away from the crop root zone which can extend to 5 feet below the surface. The leaching of imported salts away from the root zone is necessary for maintaining the long-term arability of the soil. Without leaching, the accumulation of salts would make the land non-farmable. As salts leach out the soil in the crop root zone, they dissolve into the leaching component of the applied irrigation water. This water, which typically contains about 1% salt with traces amount of contaminants (e.g., selenium, boron, heavy metals and possibly synthetic organics) becomes drainwater.[2]

Most of the 9.1 million acres of irrigated farmland in California has natural drainage. Natural drainage occurs when the excess applied irrigation water either 1) flows to the low end of the field and then moves in aboveground or underground water courses to a natural waterbody or 2) percolates into a useable groundwater basin underlying the field. In these situations, the 99% water component of agricultural drainage is put to beneficial use since this water is a "return flow" to a river system or useable groundwater basin. Although concerns are growing about the *quality* of natural agricultural drainage return-flow streams, no special collection or treatment systems are presently used or needed to deal with agricultural drainwater produced by fields with natural drainage.[3]

About 1.5 million acres of highly productive irrigated agricultural lands along the western side of the San Joaquin Valley does not have natural drainage.[4] This ancient seabed area, shown in Fig. 1, is characterized by the presence of an impermeable clay layer 300 to 500 feet below the surface. Because there are few natural water courses in this arid region and because the clay layer traps the leaching component of the applied irrigation water near the surface, saline water accumulates ("perches") at relatively shallow depths. Based on 1998 data collected and reported by the California Department of Water Resources (DWR), perched groundwater has risen to less than 5 feet from the surface – the "present problem" category – on 861,423 acres of farmland in the problem drainage area. This presence of saline groundwater this close to the surface poses an imminent threat to the arability of this land. Fig. 2 shows the most recent 8-year trend of changes in groundwater depth in the 1.5 million acre problem area. This analysis shows the "present problem" category (i.e., less than 5 feet) has increased notably since 1994.

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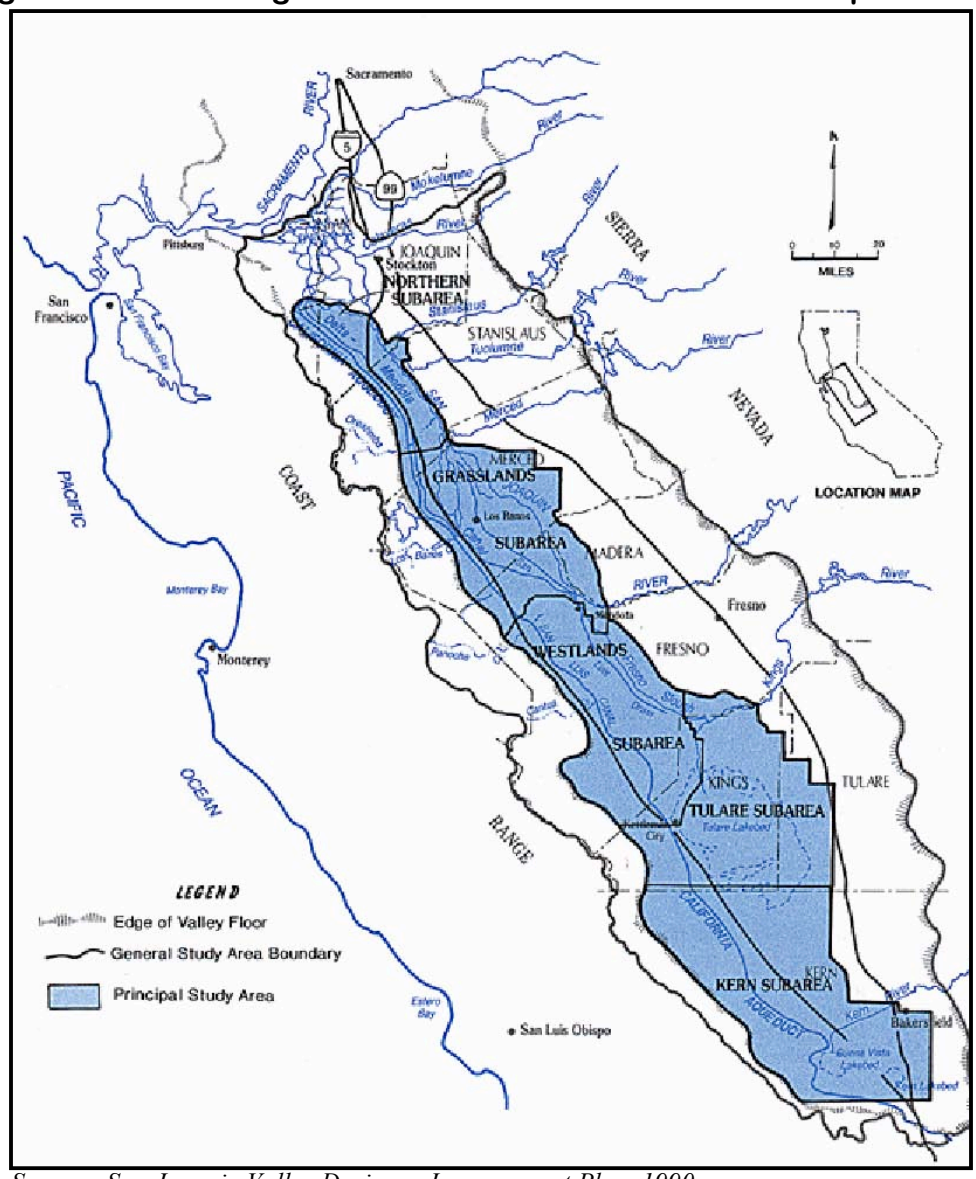
[2] Typical subsurface agricultural drainage has from 3,000 to 12,000 mg/L of total dissolved solids (TDS) (0.3 to 1.2% salts). In comparison, Pacific Ocean water has about 35,000 mg/L of TDS (3.5% salts).

[3] In most cases, farm runoff is considered a "non-point" source discharge and is therefore statutorily exempted from the federal Clean Water Act. Under state law (the Porter-Cologne Water Quality Control Act of 1982), farm run-off was initially granted a 20-year exemption from regulation. However, when this exemption expired on 12/31/02, it was renewed for only a 3-year period while the regional water quality control boards consider some form of regulations, controls, or treatment requirements for farm runoff.

[4] In addition to the 1.5 million acres in the San Joaquin Valley, agricultural drainage is an issue for the 645,000 aces of irrigated cropland in Imperial Valley. However, because agricultural drainage from Imperial Valley farms is beneficially used as makeup water for the Salton Sea, use of a conventional one-pass, 40%-recovery RO process – as recently proposed by US Filter -- is feasible for reclaiming a portion of Imperial Valley drainwater. This fact makes it unlikely the more expensive, two-pass, >90% recovery DP^3RO™ process being developed under this PIER project will have application in the Imperial Valley.

Figure 1
Agricultural Drainage Problem Area in Western San Joaquin Valley



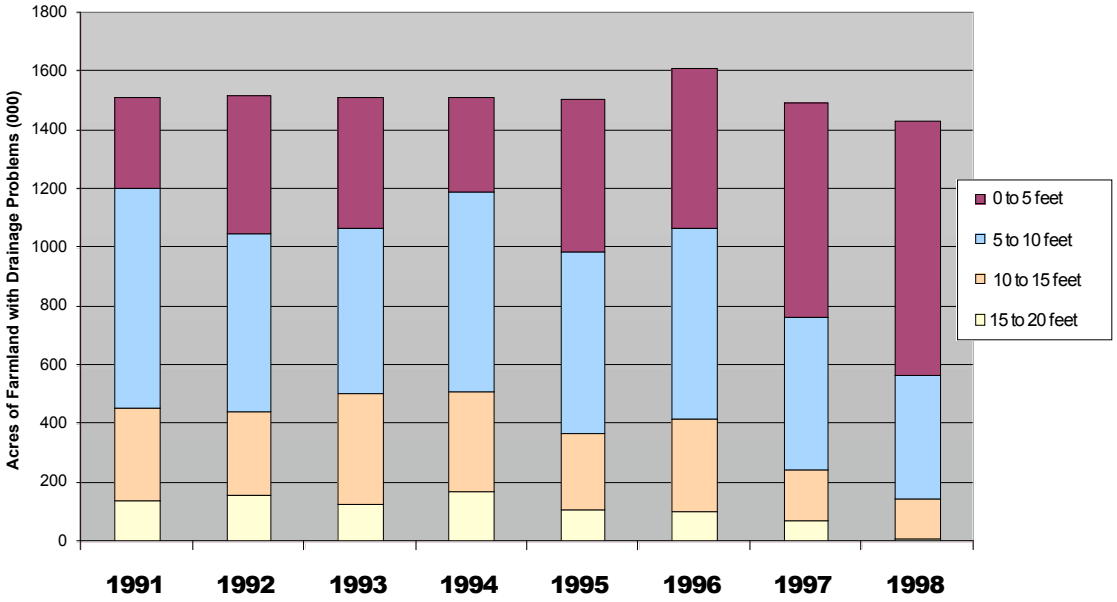
Source: San Joaquin Valley Drainage Improvement Plan, 1990

On 48,000 acres of farmland in the Grasslands subarea, the drainage problem has been alleviated by the installation and operation of a system of subsurface tile drains. These buried pipes provide artificial drainage to the fields. The approximate 30,000 AF/year of drainwater from the Grasslands subarea is currently discharged into water courses which flow into the San Joaquin River. This discharge, permitted under a special arrangement that expires in 2009, contains selenium and other contaminants thought to be harmful to aquatic life in the Bay-Delta. The salinity and boron in this drainage water degrade the drinking-water quality of Bay-Delta water. For these reasons, Grasslands area farmers are under pressure to eliminate their drainage flows into the San Joaquin River. USBR estimates a total of 54,000 acres in the Northern and Grassland subareas will require drainage in the future and will produce 47,800 AF/yr of drainage, including infiltration.[5]

[5] Table 3.1-1 in USBR *Plan Formulation Report* (December 2002)

Figure 2

Depth-to-Groundwater Trend in Agricultural Drainage Problem Area in Western San Joaquin Valley



Source: San Joaquin Valley Drainage Monitoring Program, 1998 DWR Report

In the middle and southern portions of the drainage problem area (i.e., Westlands, Tulare and Kern subareas in Fig. 1), drainage is either retained as perched groundwater below the fields (which explains the dramatic growth in the "0 to 5 feet" category); or the drainage is sent to large evaporation ponds. Retaining the drainage on-site as perched groundwater is only a temporary solution. Recently, 33,000 acres of prime farmland in the Westlands subarea was permanently retired because of soil salination problems.[6] Large evaporation ponds create an "attractive nuisance" for wildlife. Consequently, their viability as a method agricultural drainage disposal is highly suspect. Current regulatory requirements and mitigation measures make it almost impossible to obtain the requisite permits and approvals for building and operating evaporation ponds larger than 10 acres.[7]

The agricultural drainage "problem" in the western San Joaquin Valley is viewed in a different light by the CALFED Bay-Delta Program. Table 1 is reproduced from the 2000 CALFED Water Use Efficiency (WUE) Program Plan. The purpose of the CALFED WUE program is to identify and obtain funding for implementing water conservation and recycling projects which, from a statewide perspective, are more cost effective than new traditional water supply projects. Of the 385,000 AF/year of identified "irrecoverable losses" in the agricultural sector in the CALFED WUE program, over 50% of this

[6] The U.S. government reached a tentative settlement in December 2002 to pay $107 million to farmers of 33,000 acres in the Mendota area who sued the U.S. government (USBR) for not providing drainage service as required in the farmers' original water supply contracts signed with USBR in the 1960s. The farmers successfully made the case that their land was ruined because no drainage service was provided.

[7] "Evaporation Ponds: A Fish and Wildlife Service Perspective," presentation by Joe Skorupa, U.S. Fish & Wildlife Service, at UC/DWR Salinity/Drainage Annual Meeting in Sacramento, CA on March 26, 2002

amount – 205,000 AF/year – is potential recovery of lost drainage flows in the western San Joaquin Valley.[8] This figure represents about 8% of the 2.6 million AF/year in total potential irrecoverable losses in the entire state. Thus, rather than being a problem, agricultural drainage flows in western San Joaquin Valley are viewed by the CALFED program as a potential cost-effective "new water" source for California.

Table 1

Summary of Estimated Conservation and Recycling Potential (Thousand AF/yr)

USE	NO ACTION ALTERNATIVE[1] (IN ABSENCE OF CALFED)			POTENTIAL CALFED INCREMENT			TOTAL CONSERVATION POTENTIAL		
	Recoverable Losses with Potential for Rerouting Flows	Potential for Recovering Currently Irrevocable Losses	TOTAL Potential Reduction of Application	Recoverable Losses with Potential for Rerouting Flows	Potential for Recovering Currently Irrevocable Losses	TOTAL Potential Reduction of Application	Recoverable Losses with Potential for Rerouting Flows	Potential for Recovering Currently Irrevocable Losses	TOTAL Potential Reduction of Application
	(A=C-B)	(B)	(C)	(A=C-B)	(B)	(C)	(A=C-B)	(B)	(C)
Urban	379	530	927	355	680	1035	752	1210	1,962
Agricultural	2,235	**220**	2,457	1,676	**165**	1841	3,911	**385**	4,299
Urban Recycling	55	455	510	188	567	755	243	1022	1,265
TOTAL	2,687	1,205	3,894	2,219	1,412	3,631	4,906	**2,617**	7,536

Notes: Representative values shown are midpoints in value ranges shown in Tables 1-2, 1-3 and 1-4. See Sections 4, 5, and 6.
[1]No Action Alternative recycling values do not include existing recycling level of 485 TAF (the March 1998 Water use Efficiency Technical Appendix inadvertently included the existing values).

Source: Table 1.1 from page 1-7 of CALFED Bay-Delta Water Use Efficiency Program Plan, July 2000

In conclusion, an urgent need exists in California for a cost-effective technology that can enable a high percentage of the 252,800 AF/year of the agricultural drainage flows in the western San Joaquin Valley to be reclaimed and put to beneficial use.[9]

PIER Industrial/Agricultural/Water End-Use Efficiency Program Area

Elsewhere in the state, seawater desalination – an electric-energy-intensive process – is becoming a viable "new water" source. If a new technology for desalinating agricultural drainwater that required *less electrical energy* and produced "new water*" at less cost* than seawater desalination existed, substantial public benefits for California electricity ratepayers and citizens would be gained. Thus, the development of a new energy-efficient technology for recycling agricultural drainwater falls within the scope of the Industrial/Agricultural/Water End-Use Efficiency program area of the Commission's Public Interest Energy Research (PIER) program. In PIER terminology, the goal of this EISG project is to demonstrate the conceptual feasibility (Stage 3) and advance technical

[8] This figure *excludes* the 47,800 AF/yr of drainage flows in the Northern and Grasslands subareas that flow into the San Joaquin River and therefore are not considered irrecoverable losses by CALFED.

[9] In December 2002, USBR released its *Plan Formulation Report* for providing drainage to San Luis Unit water users in the Grasslands and Westlands subareas as required by federal law. This plan was constrained by available technology. Thus, instead of maximizing water reclamation and salt impoundment, the USBR plan is based on *salt movement* (reusing saline drainwater for irrigation) and *evaporation*. Under USBR's plan, farmers would *pay* $425/AF for drainage service. See Conclusions section for discussion of the USBR plan.

development of a new energy-efficient agricultural drainwater desalination process (Stage 4) to the point that a field pilot-plant project (Stage 5) is feasible as the next step.

The main technical objective of this Stage 3-4 PIER project is to develop the conceptual design of a high recovery (<90%) agricultural drainwater desalination process that 1) requires *25% less electricity per acre-foot* of product water than the most energy-efficient seawater desalination process and 2) produces high quality irrigation water at *less cost* than the "best case" for seawater desalination. Since the most energy-efficient seawater desalination process would have a specific power use of 4,000 kWh/AF (= 12.3 kWh per 1,000 gallons) with water costs of about $850/AF, the target specific power requirement for the new high-recovery agricultural drainwater desalination process being developed under this PIER project is 3,000 kWhr/AF with maximum water costs of $850/AF.[10]

The rationale behind these project goals is that, to pay the costs for converting the farmers' drainwater into high quality reusable irrigation water using the new membrane process being developed by WaterTech under this PIER project, the farmers will have to sell an equivalent amount of their potable-quality Central Valley Project (CVP) or State Water Project (SWP) water to urban users. Since urban water users are willing to pay a price of $850/AF for "new water" produced by desalinating seawater, they should be willing to pay an equivalent amount for "new water" produced by desalinating agricultural drainwater which otherwise is an irrecoverable loss or harms the environment. Under this proposed drainage recycling/water exchange plan made possible by the new membrane process, the drainage and soil salination problems in western San Joaquin Valley can be permanently solved at *no cost* to the farmers or the U.S. government with less than 2% of farmland being taken out of production. (See Public Benefits to California section for further explanation of these public benefits.)

Prior Attempts to Develop Agricultural Drainage Treatment Processes

Many previous attempts have been made to develop a cost-effective technology for treating and possibly recycling agricultural drainage flows. Over $50 million in public funds has been spent since the mid 1980s in studying and attempting to develop a viable method for providing drainage service to farmers in the western San Joaquin Valley.[11] A record of the various proposed biological, chemical and physical treatment processes for selenium removal and/or water reclamation that have been studied or pilot tested over the last 20 years – include several attempts to apply membrane technology – is presented in Appendix I. As this history shows, the unique advantages afforded by membrane technology as the basis for achieving a recycling solution to the agricultural drainage problems in western San Joaquin Valley are well known and documented.[12]

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[10] These figures are based on the new 25 million gallon/day desalination plant in Tampa, FL. See footnotes in Project Outcomes section for determination of the 4,000 kWh/AF specific power requirement and the projected $850/AF cost for seawater desalination in California.

[11] The $50 million figure was cited in the U.S. Appellate Court decision issued in April 2000 directing the USBR to proceed without delay in developing and implementing a drainage service plan for CVP water users in western San Joaquin Valley. Other references use a figure of $100 million.

[12] *San Joaquin Valley Drainage Implementation Program Ad Hoc Committee Report* (January 2000); and the underlying *Technical Committed Report on Drainage Water Treatment* (February 1999)

Problems in Using Membrane Technology to Treat Agricultural Drainage

Although agricultural drainage is relatively low in salinity compared to seawater (typical drainage ranges from 3,000 to 12,000 mg/L of TDS compared to about 35,000 mg/L for Pacific Ocean water),[13] the *chemical composition* of the salinity in agricultural drainwater presents a formidable problem for the effective use of membrane technology. Drainage from farms overlying the ancient seabed in western San Joaquin Valley contain extremely high levels of non-carbonate hardness (calcium sulfate [$CaSO_4$] and magnesium sulfate [$MgSO_4$]). The non-carbonate hardness of tile-drain water and perched groundwater is this area typically ranges from 1,400 to 2,400 mg/L. In most cases, the dissolved ionic concentration of calcium (Ca^{2+}) is from 400 to 600 mg/L which is at or near the saturation point for $CaSO_4$.[14] As product water is produced on the permeate side of a membrane, the concentration of $CaSO_4$ remaining on the feed side quickly exceeds the saturation level. When this occurs, $CaSO_4$ crystals (gypsum) precipitate out and adhere to the membrane surface. These deposits on the membrane surface (called mineral scale) block the passage of water through the membrane (called fouling). Thus, the problem of $CaSO_4$ fouling must be overcome before membrane technology can be used effectively for treating agricultural drainage. Researchers have attempted to solve this well known problem for over 30 years.

The two conventional approaches for overcoming $CaSO_4$ fouling in membrane processes are: 1) removing the $CaSO_4$ in a pretreatment step ahead of the membrane process; or 2) adding special chemicals (called scale inhibitors or sequestering agents) to the membrane feed stream so the $CaSO_4$ particles remain in solution beyond their normal saturation point. The problem with conventional pretreatment methods (lime-soda softening and ion exchange) is the large quantity of water-laden sludge that is generated due to the high levels of dissolved $CaSO_4$ and Mg SO_4 in the water. In lime-soda softening, these sulfate salts must be converted to carbonate salts and precipitated out of the water.[15] In ion exchange, Ca^{2+} and Mg^{2+} are replaced with Na^+. Both these processes involve *adding* sodium ($NaCO_3$ or NaCl) to the feed stream. This sodium must be subsequently removed so that irrigation water with <500 mg/L of TDS and an acceptable sodium adsorption ratio (SAR) is produced.[16] Even with these sludge and chemistry problems, the maximum recovery (i.e., % ratio of product water to feed water) obtainable with pretreatment softening or ion exchange is about 75% because not all $CaSO_4$ can be removed (rate limiting factors stop the conversion reactions at around 80% removal).

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[13] Because of the wide range in TDS values for agricultural drainage in western San Joaquin Valley, three representative values were used in this project: Low TDS (3,625 mg/L); Mid-Range TDS (6,450 mg/L); and High TDS (9,250 mg/L). Essentially all drainwater in the Northern, Grasslands and Westlands subareas and an estimated 60% in the Tulare and Kern subareas fall within this range (DWR 2000).

[14] *San Joaquin Valley Drainage Monitoring Report - 1998*, DWR 2000

[15] Removing of 80% of 2,000 mg/L of non-carbonate hardness from 1.0 AF/day of drainwater requires adding 5 tons/day of hydrated lime $Ca(OH_2)$ and soda ash ($NaCO_3$) and would create 20 tons/day of 20% solids $CaCO_3$ and $Mg(OH)_2$ sludge. This sludge must be settled out, dewatered, and hauled to a disposal site.

[16] A special concern for irrigation water is the ability of the water to penetrate into the soil after it is applied. Water that has substantially more sodium ions than calcium and magnesium ions (see formula in Glossary) has a poor sodium adsorption ratio (SAR) and will not infiltrate at an acceptable rate. Since RO membranes preferentially remove Ca^{2+} and Mg^{2+} ions over Na^+ ions, RO permeate water has a SAR deficiency. Introducing *additional* sodium into the RO feed – as occurs in lime-soda and ion-exchange pretreatment – exacerbates the SAR problem that must be corrected before the product water can be used for irrigation (A proprietary method for solving this SAR problem is part of the DP^3RO™ process.)

Scale inhibitors can sequester the formed $CaSO_4$ crystals so they remain in solution up to maximum 230% concentration above the normal $CaSO_4$ saturation point.[17] Assuming the drainwater is already at or near $CaSO_4$ saturation, only about 50% can be recovered as irrigation water in a membrane system with scale inhibitors. Even so, anti-scalants are expensive and their effectiveness in maintaining high levels of $CaSO_4$ in supersaturation depends on careful control of pH, temperature, and other process variables; otherwise, precipitation will occur. Maintaining precise process control is difficult to do in practice with agricultural drainwater since the chemistry and conditions of drainage flows are constantly changing. Mistakes are costly. Once spiral-wound RO elements are severely fouled with $CaSO_4$ scale, they usually cannot be cleaned and reused.

New Membrane Process for Treating Agricultural Drainage Water

WaterTech Partners (a private consulting and contract R&D firm) together with PCI Membrane Systems, Inc. (and international membrane technology company) has conceived and is developing a novel membrane process, termed **D**ouble **P**ass **P**referential **P**recipitation **R**everse **O**smosis ("DP^3RO™") for overcoming the $CaSO_4$ fouling problem that is encountered when desalinating high-hardness feed water like agricultural drainage.

A conceptual process flow block diagram of the DP^3RO™ is shown in Fig. 3. Compared to other membrane-based agricultural drainage treatment processes that have not worked, the DP^3RO™ process has two unique and distinguishing features: 1) the use of "preferential precipitation" to remove the $CaSO_4$ dissolved in the feed water; and 2) the use of two separate membrane processes (NF and RO) connected in a "double pass" arrangement so that permeate from the 1st-pass NF becomes the feed to the 2nd-pass RO.

The first unique feature of the DP^3RO™ process is preferential precipitation (also called seeding) for removing the dissolved $CaSO_4$ in the feed water. Preferential precipitation is a thermodynamic phenomenon explained as follows: when the saturation point of an ionic salt in solution is reach, the crystalline precipitate will preferentially form by adding to an *existing crystal* in the solution rather than by forming a *new crystal*.[18] Thus, if a high enough level of $CaSO_4$ nucleation sites (also called seed crystals) are maintained in suspension on the feed side of the first-pass NF membrane (around 20 g/L is the optimum level), the new $CaSO_4$ crystals that form as more permeate is produced will attach to the seed crystals in suspension in the feed stream; rather than forming mineral scale on the membrane surface and thus fouling the membrane.

Because 20 g/L of $CaSO_4$ seed crystals are intentionally maintained in suspension on the feed side of the NF membrane, the concentration of dissolved $CaSO_4$ in the NF feed is always at 100% saturation or higher (supersaturation). *Thus, there are no limits or concerns on how much dissolved $CaSO_4$ is present in the feed to the system.* The new $CaSO_4$ that comes into the system with the TDS in the drainwater simply precipitates out and adds to the 20 g/L of suspended solids in suspension in the NF slurry-recycle circuit.

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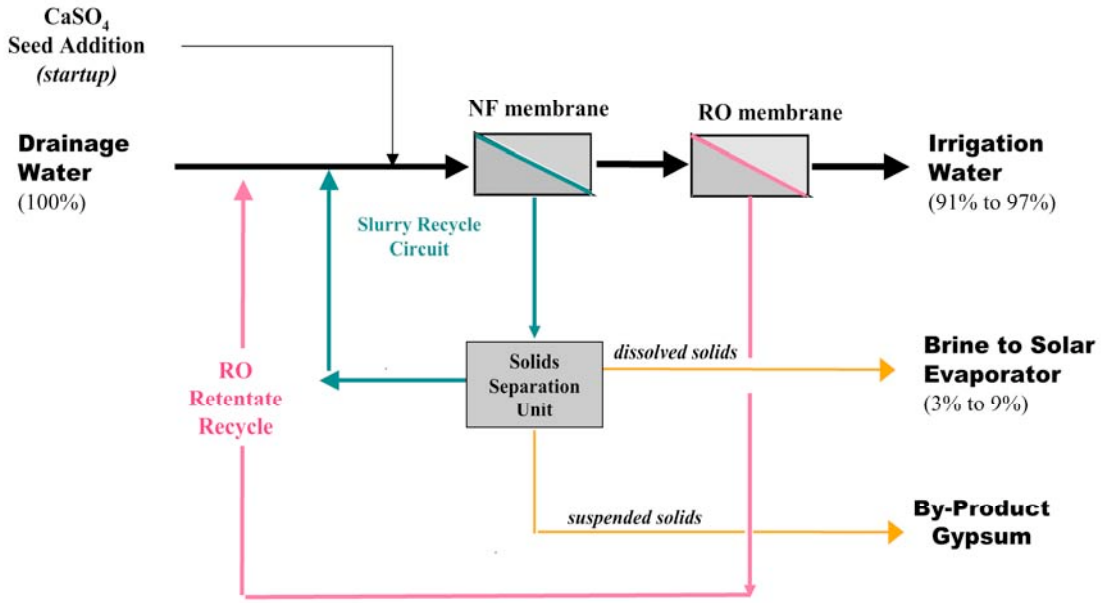
[17] Hydranautics' RO system design guidelines in the IMSDesign program set this limit for $CaSO_4$.

[18] The basic thermodynamic principles underlying preferential precipitation are two-fold: 1) the latent heat of crystallization (i.e., the enthalpy required to convert dissolved ions into a crystalline state) is *lower* for a precipitate to add to the mass of an existing crystal (growth) than for the precipitate to form a new crystal (nucleation); and 2) reactions requiring lower enthalpy will proceed before those requiring higher enthalpy.

Figure 3
Block Flow Diagram of Basic DP³RO™ Process
(proprietary features not shown)



A shown in the conceptual DP^{3}RO™ process flow block diagram in Fig. 3, a solids separation device is used in the NF slurry recycle circuit so that suspended solids can be continuously *removed* from the system. To maintain a material balance, the amount of Ca^{2+} removed from the system as $CaSO_4$ (gypsum) must equal: (i) the amount of dissolved Ca^{2+} that comes into the system as part of the TDS of the feed water; (ii) less the dissolved Ca^{2+} in the exported product water and brine streams. Thus, rather than continuously *adding* solids to the system and creating sludge as occurs in the conventional pretreatment approaches, solids (gypsum) are continuously *produced* from the TDS in the feed water in the DP^{3}RO™ process. The only solids added in the DP^{3}RO™ process is the initial charge of $CaSO_4$ seed crystals. Typically, 15% to 30% of the dissolved solids in the feed stream (depending on the ratio of Ca^{2+} to TDS) are converted to high-purity gypsum as part of the DP^{3}RO™ process.

The application of the preferential precipitation principle to the treatment of high-hardness waters in a RO process (called seeded RO) was first reduced to practiced and patented by Howard Herrigel of the Resources Conservation Company (RCC) in 1980. (This U.S. patent, No. 4,207,183, has now expired.) After seeded RO was conceived and patented by Herrigel, RCC conducted a number of pilot-system field trials (including USBR-funded work at the Yuma Desalting Test Site in 1980-81). However, after Ionics, Inc. acquired RCC in 1991, development work on seeded RO was halted because Ionics was not interested in the technology. Nonetheless, the existence of the Herrigel patent discouraged other parties in the U.S. (including WaterTech) from undertaking R&D projects aimed at developing commercial applications for seeded RO.

However, an R&D team in South Africa led by Dr. Graham Juby developed, built and operated a 14-gallon-per-minute "Slurry Precipitation and Recycle Reverse Osmosis"

pilot plant for treating high-hardness mine drainage water in the mid-1990s.[19] This seeded RO plant was operated at 92% recovery for 8,000 hours without experiencing $CaSO_4$ scaling problems. However, because this pilot plant used a single-pass design and cellulose acetate (as opposed to polyamide) membranes, a 600 psi feed pressure was required to achieve 92% recovery and salt rejection was limited to 70%. Even at this low salt rejection rate (a salt rejection rate >99.5% is required to produce high quality irrigation water at >90% recovery in a single-pass design), specific power use was 5,800 kwh/AF at 3,000 mg/L TDS feed. This specific power value is more than twice the comparable value for the more energy-efficient double-pass DP^3RO™ process.

The second distinguishing feature of the DP^3RO™ process compared to the seeded RO systems developed by Herrigel and Juby and other previous attempts to use membrane technology for desalinating agricultural drainage is the use of two separate membrane processes connected so that the permeate from the first unit (NF) becomes the feed to the second unit (RO); hence, the term "double pass". The primary purpose of this novel two-pass design is to permit the separate NF and RO units to operate individually at *lower combined pressures* (e.g., 250 psi for NF unit and 175 psi for RO unit for Mid-Range TDS feed at 95°F) than the >750 psi operating pressure required in a single-pass RO system operating at >90% recovery and >99.5% salt rejection as necessary to produce on-spec irrigation water. In addition, higher boron rejection can be obtained, higher recovery rates achieved, and higher TDS drainwater can be treated with a two-pass NF-RO process compared to a single-pass RO process.[20]

The first-pass unit in the DP^3RO™ process uses NF membranes in tubular modules. NF is used because this type membrane has high rejection rates (85% to 95%) for divalent ions (like Ca^{2+}, Mg^{2+}, and SO_4^{2-}); but a lower rejection rate (75% to 85%) for monvalent ions (like Na^+ and $Cl^{-)}$. Thus, a NF membrane is good at removing the non-carbonate hardness that causes fouling; but, with a total TDS rejection of only 85%, NF membranes can operate at relatively low feed pressures (250 to 350 psi). A tubular configuration (½" diameter polystyrene tubes 12-ft. long with polyamide coating on the inside surface) is used in the NF unit because the ±20 g/L of $CaSO_4$ seed crystals that are maintained in suspension in the NF feed stream would clog a spiral-wound or hollow-fiber membrane.

The permeate leaving the NF unit, which has a relatively low Ca^{2+} concentration (70 to 110 mg/L using the PCI AFC30 membrane), becomes the feed to the second-pass RO unit. With $CaSO_4$ at <20% of saturation in the NF permeate, the RO unit can be operated safely at a 65% recovery rate *without scale inhibitors* without exceeding the saturation limit for $CaSO_4$ in the concentrate. Since mineral-scale fouling is not a concern in the RO unit, low-cost spiral-wound membrane elements (instead of tubular or hollow fiber modules) can be used in the RO unit. (Note: <u>one</u> standard 8" x 40" spiral-wound element with 35.2 M^2 of membrane area is equivalent to <u>three</u> 8" x 144" [12 ft.] tubular modules

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[19] After completing his work on this seeded RO process in South Africa in 1998, Dr. Juby moved the U.S. and is now a partner with Carollo Engineers in Santa Ana, CA. Dr. Juby served as a consultant on this PIER project.

[20] For drainwater with <6,000 mg/L TDS, computer modeling indicates that a single-pass system could be less expensive than a double-pass system at a 92% recovery rate. Based on test results from this project, PCI's AFC99 tubular RO membrane can achieve the >99.5% rejection rate needed for producing on-spec product water in a single-pass system. See Conclusions for further discussion on single-pass design.

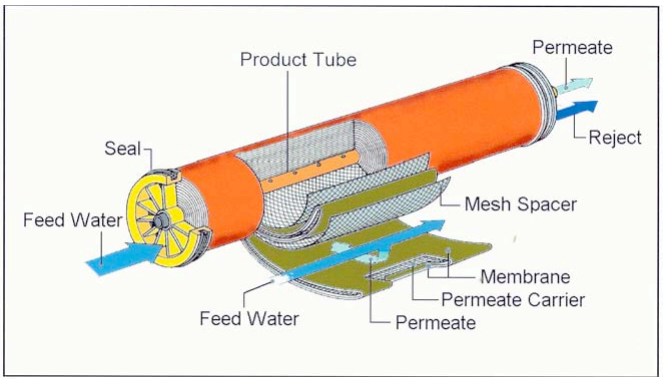
each with 10.4 M^2 of membrane area.) Exploded views of an 8" diameter PCI tubular membrane module, as used in the 1st-pass NF unit, and a typical 8" diameter spiral-wound membrane element, as used in the 2nd-pass RO unit, are shown in Figs. 4 and 5.

Figure 4

Tubular Membrane Module

Figure 5

Spiral-Wound Membrane Element



Source: PCI product literature

Project Objectives

WaterTech Partners conceived of the basic concept, design and operating principles for the DP^3RO™ process prior to submitting its proposal for this PIER project. The purpose of this Stage 3-4 project was to demonstrate the feasibility of the proposed process design by conducting a series of membrane pilot-system tests using actual agricultural drainage water. The specific Project Objectives for this project, as refined and expanded from the original objectives set forth in the EISG proposal, were as follows:

1. Prove the concept and efficacy of using preferential precipitation to eliminate $CaSO_4$ fouling problems for treating high-hardness agricultural drainage water in a high-recovery, high-salt-rejection, high-energy-efficient membrane process.
2. Demonstrate achievability of a specific power requirement of less than 3,000 kWh/AF so expected power use is less than 75% of the 4,000 kWh/AF required for "best case" seawater desalination in California.
3. Demonstrate the ability to produce high quality irrigation water, defined as follows:
   - 3.1 TDS <500 mg/L <u>after</u> adjustment of SAR to <4.0
   - 3.2 Boron <1.0 mg/L (ideal); or <5.0 mg/L (acceptable with blending)
   - 3.3 $7.0 \leq pH \leq 8.0$

4 Develop the conceptual design, projected performance parameters, and cost estimates for a 15-gpm pilot plant and a 250-gpm full-scale DP^3RO™ plant;

- 4.1 evaluate performance of four (4) different tubular NF membranes for possible use in the NF unit of a two-pass process design
- 4.2 evaluate performance of four (4) different low-pressure spiral-wound RO membranes for possible use in the RO unit of a two-pass process design

4.3 evaluate performance of the only commercially available tubular RO membrane (PCI's AFC99) for use in a single-pass process design

4.4 generate product-water cost curves based on feed TDS and temperature to indicate the range of feed conditions at which the cost objective of being lower than the cost of seawater desalination can be achieved

Project Objective 1 above is the same as proposal Objective 1; except that the possibility of using preferential precipitation in both a one-pass and two-pass process was considered in the project. Project Objectives 2 and 4 above are the same as proposal Objectives 2 and 3; except that the "operation" of a two-pass process was accomplished using a computer process-design model based on data obtained from the Membrane Test Program. The sub-objectives in Objective 4 were added to provide the basis upon which the conceptual pilot and commercial plant designs and cost estimates would be determined. Project Objective 3 was added after Panoche provided more precise specifications for high quality irrigation water based on crops grown in the Panoche service area; and the possibility of blending to reduce boron was reviewed by the District Engineer and determined to be feasible.

Project Approach

The following tasks were performed during the project performance period (September 2002 through January 2003) to complete the Scope of Work set out in the proposal and to achieve the revised Project Objectives set out above:

- *Meet with Agricultural Water Users to Ascertain Their Needs and Interests*

  The project manager (Mr. Enzweiler) established and maintained close contact with the staff of the Panoche Water & Drainage District, including District Engineer Joe McGahan of Summers Engineering, throughout the project performance period. On November 12, 2002, Mr. Enzweiler made a presentation to the Panoche board of directors on the status and objectives of the project. In September and December 2002, Dr. Strasser, the project engineer, rented a truck and obtained two 900-gallon batches of drainwater from Drain Pit #25 in Panoche. This actual drainwater was used for conducting the Membrane Test Program. Macros Hedrick, the Panoche Watermaster, visited the WCRC on November 1, 2002, and observed the testing.

- *Lease Facilities and Hire Personnel for Conducting Pilot-System Tests*

  WaterTech arranged with Del Monte Foods and PCI Membrane Systems (PCI) to use the facilities, equipment, and lab services at Del Monte's Walnut Creek Research Center (WCRC) for conducting the pilot-system tests. This location was chosen because PCI already had a membrane pilot system at the WCRC (see photographs in Appendix III), and the WCRC was a convenient location for the project team members. WaterTech rented the pilot system and engaged project team personnel on an hourly basis for performing the Membrane Test Program.

- *Identify and Involve Individuals and Companies with Relevant Expertise*

  In addition to PCI, which supplied the pilot system and tubular membranes that were tested, Dr. Strasser contacted and obtained test RO membranes from Koch Membrane Systems, Desalination Systems, and Hydranautics. Mr. Enzweiler contacted and engaged Dr. Graham Juby, a partner with Carollo Engineers in Santa

Anna, CA who has previous experience in the design and operation of seeded RO membrane systems. Dr. Juby visited WCRC on November 7, 2002.

- *Coordinate with Government Entities Involved in SJV Drainage Problems*

  Mr. Enzweiler established and maintained contact with Jose Faria at the DWR's San Joaquin District office in Fresno. Mr. Faria's branch conducts and produces the annual report on the San Joaquin Valley Drainage Monitoring Program. Mr. Faria, Kurt Kovac and David Lara from the DWR Fresno office visited the WCRC on December 11, 2002. Mr. Enzweiler also established and maintained contact with Mr. Scott Irvine at USBR's Technical Services Center in Denver. Mr. Irvine heads the USBR team that is conducting a Feasibility Study on the preferred In-Valley Disposal Alternative identified in the USBR *Plan Formulation Report* (December 2002) for providing drainage service to CVP water users in the Grasslands and Westlands subareas. Mr. Irvine and Saied Delagah from the USBR Technical Services Center in Denver, along with Alan Stroppini from USBR's Sacramento office, visited the test site at the WCRC on December 19, 2002.

- *Purchase NF and RO Elements for Conducting the Membrane Test Program*

  WaterTech purchased four (4) sets (AFC80, AFC30, CDA16 and ES404) of NF tubular membrane inserts (18 - ½" diameter tubes x 48" length) and fitted them into standard 3.9" x 48" tubular modules for testing for use in the NF section of a two-pass design. Since the AFC30 provided the best results in the initial tests, four (4) sets of 12-ft AFC30 membrane inserts (a total of 72 - ½" x 12-ft. tubes) for use in four (4) 3.9" x 12-ft modules were purchased and assembled in series to replicate the hydraulics and separation properties of a single commercial 8"x 12-ft tubular module. WaterTech also purchased a set of 18 - ½" x 48" tubular RO membrane inserts (AFC99) for testing for possible use in a single-pass process design.

  WaterTech also purchased the following four (4) 2.5" x 40" spiral RO elements for testing for use in the RO section of a two-stage design: Desal AF, Koch ULP, Koch HF and Hydranautics ESPA1. A representative of each supplier recommended these models for inclusion in the test program after being told the application and the desired performance requirements. (See photographs in Appendix IV.)

- *Develop Protocols for Conducting Membrane Test Program*

  The project team and PCI developed protocols for each phase of the testing. These protocols included both batch "volume concentration tests" and continuous feed "production tests." The protocols were designed and the tests were performed to provide performance data that could be used in the computer process-design model. For example, if the computer model indicated the average TDS in the first-stage of the NF unit in the Mid-Range TDS feed case was 30,000 mg/L, concentration tests were performed to obtain feed pressures, flux rates, and rejection rates for the NF membrane at a concentration factor equating to 30,000 mg/L TDS feed.

- *Perform Membrane Tests Using Pilot System*

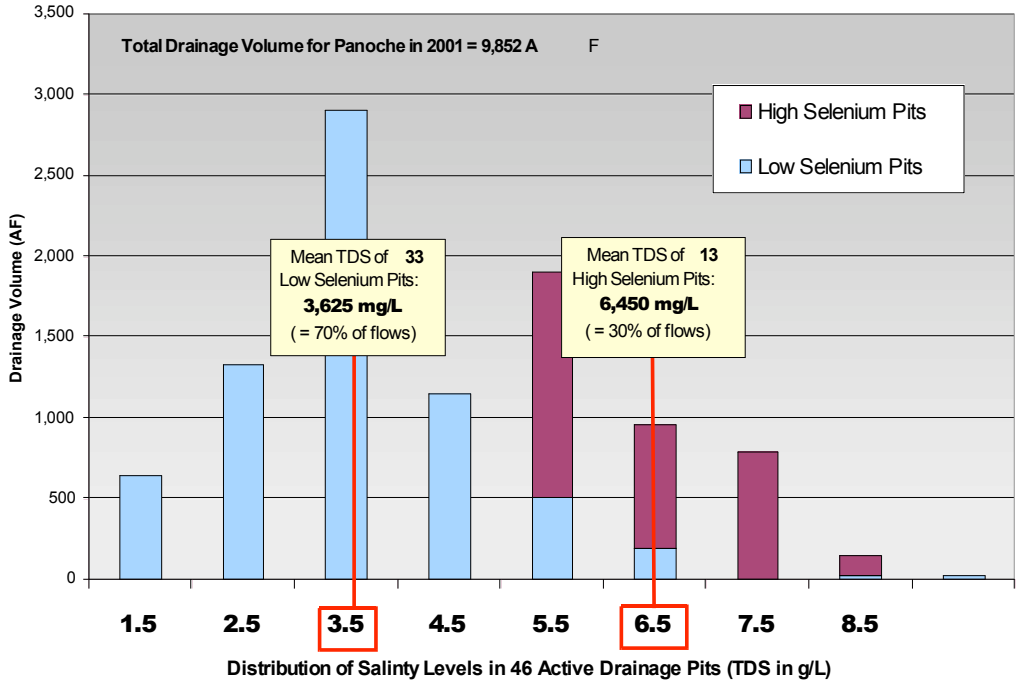
  Membrane performance tests were conducted at the WCRC using the PCI pilot system on 19 days beginning on October 10, 2002 and concluding on January 10, 2003. A summary of the test program is presented in Appendix II. In total, over

150 hours of testing was conducted by the six-person project team using all 1,800 gallons of specimen drainwater obtained from Drain Pit # 25 in Panoche.

- *Develop Computer Process-Design Model for15-gpm Pilot Plant & 250-gpm Commercial Plant and Run Model at Drainwater TDS Levels in Panoche*

  The immediate market potential for the DP^{3}RO™ process is to desalinate and recycle the tile-drain flows in Panoche. Like other Grasslands area dischargers, Panoche must meet mandated annual reductions in the amount selenium contained in Panoche's off-farm flows that reach the San Joaquin River.[21] As shown in Fig. 6, 14 drain pits with flows totaling 3,061 AF/yr (=30% of Panoche's total drainage flow of 9,801 AF/yr in 2001) accounted for 80% of Panoche's total annual selenium discharge load. The average TDS level of these 14 high selenium pits is 6,450 mg/L. The remaining 70% of Panoche's drainage had an average TDS level of 3,625 mg/L in 2001. These values are indicative of the low and high values for salinity for the 47,800 AF/yr of drainage produced in the Grassland subarea.

Figure 6
Salinty Distribution of Panoche Tile-Drain Water
(2001 data)



The USBR *Plan Formulation Report* issued in December 2002 provides the most up-to-date information on drainage salinity levels in the Westlands subarea. In this report, the average TDS level of the 91,100 AF/yr of drainage flows in Westlands is estimated range from 8,000 to 9,900 mg/L with an average of 8,800 mg/L. For the purposes this project, the following values were used to represent the range of TDS levels in the 141,700

[21] Under the terms of the renewed Grassland Bypass Agreement, signed on September 21, 2001, the Grasslands area dischargers are required to reduce their aggregate selenium discharges by over 50% from 2002 to 2009. Panoche accounts for about 70% of the selenium load of the Grassland area dischargers.

AF/yr of drainage flows in the Grasslands and Westlands subareas: Low (3,625 mg/L), Mid-Range (6,450 mg/L), and High (9,250 mg/L).[22] A computer process-design model was developed to evaluate performance and product-water costs for the DP^{3}RO™ process at these three TDS levels. This model was also used to evaluate and compare alternative designs and operating parameters in a preliminary attempt to optimize costs.

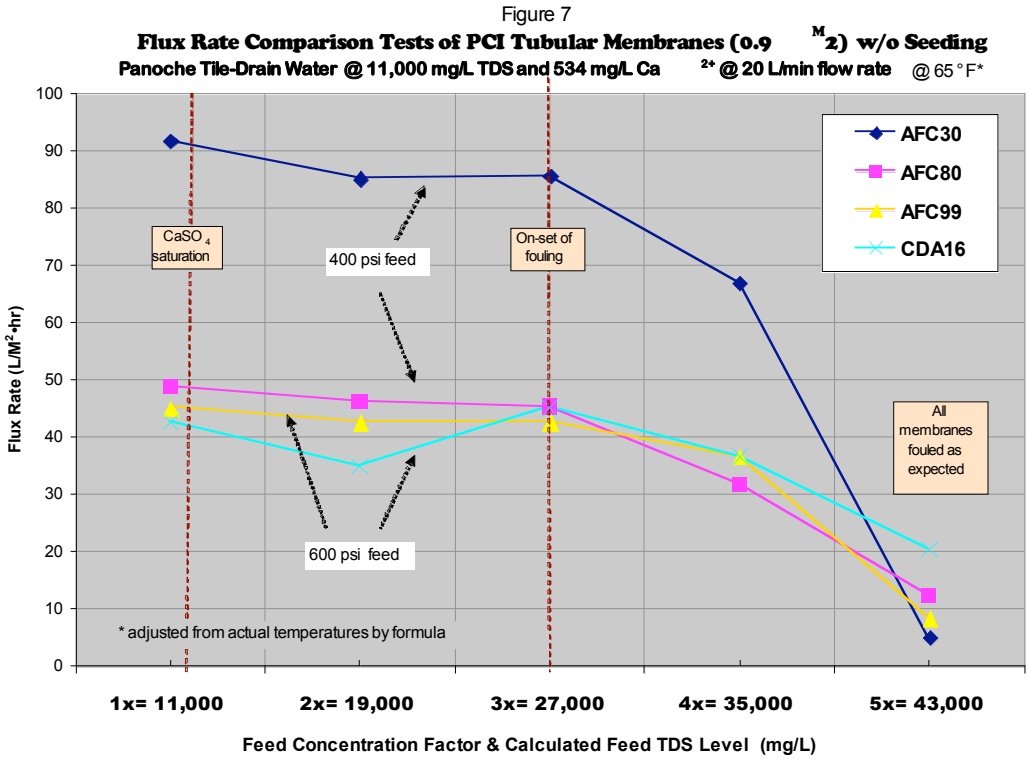
Project Outcomes

The Membrane Test Program was conducted in four phases. The results from each phase are summarized, discussed, and correlated with project objectives below. The test data on which the graphs in this section are based are shown in the tables in Appendix III.

Phase I Tests

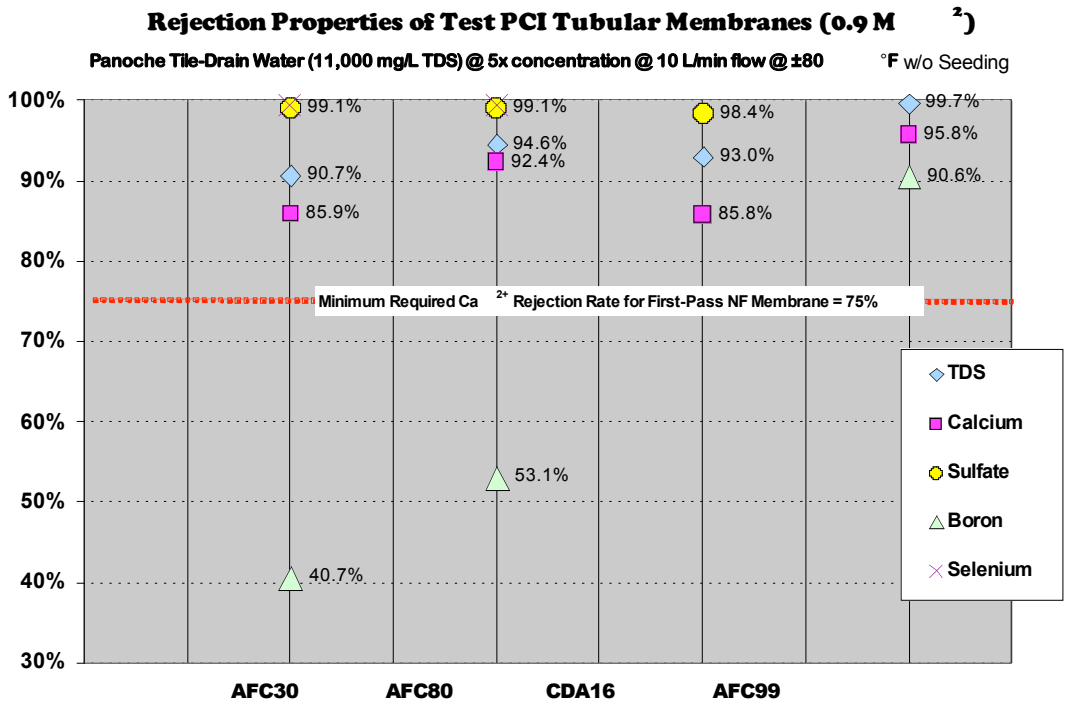
The purpose of the initial testing was to compare flux rates and rejection properties of the four candidate tubular membranes (ES404, AFC30, AFC80 and CDA16) for use in the 1st-pass NF section of a two-pass design. A tubular RO membrane (AFC99) was also tested for use in a single-pass design For these non-seeded concentration tests, the pilot system was operated in "batch mode" as follows: the 150 liter feed tank was filled with Panoche drainwater; concentrate was returned to the tank to buildup the TDS in the feed; and permeate was discharged. Comparative flux and rejection rates are shown in Figs. 7 and 8.

Figure 7



[22] Grasslands and Westlands are the only subareas for which USBR is required to provide drainage service. The mean TDS of drainage in the Tulare and Kern subareas is 9,682 mg/L with a range of 3,030 to 28,600 mg/L (*San Joaquin Valley Drainage Monitoring Program Report - 1998).* Thus, an estimated 60% of the drainage in the Tulare and Kern subareas has TDS <10,500 mg/L and therefore can be desalinated by DP^{3}RO™ at ≥90% recovery at less cost than seawater desalination. For the other 40%, the recovery would have to be reduced to <90% to produce on-spec irrigation water at below seawater desalination costs.

Figure 8



Notes: 1. No data are shown for ES404 in Figs. 7 and 8 since no TDS rejection was achieved with this ultrafiltration membrane (the ES404 was tested at the end of the program to confirm that a tubular membrane with higher flux than the AFC30 could not meet the required 75% Ca^{2+} rejection rate). 2. In subsequent tests, AFC30 exhibited >65% boron rejection .

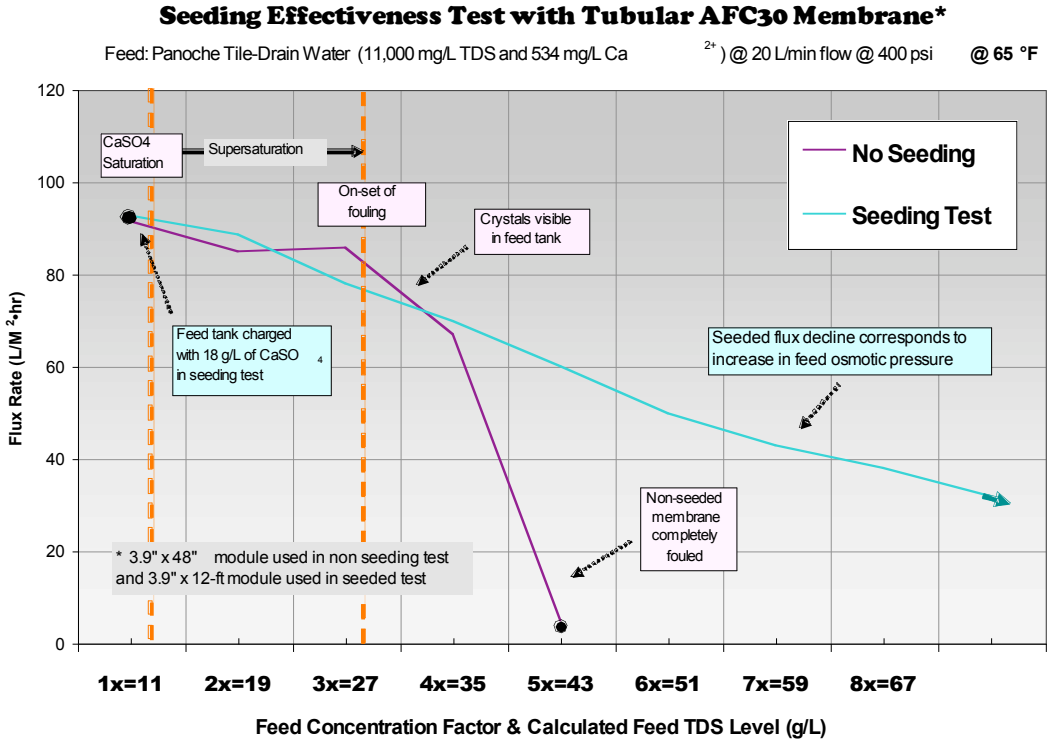
As shown in Figs. 7 and 8, the AFC30 has significantly higher flux rates than the other tested NF membranes. Since the Ca^{2+} rejection rate achieved with the AFC30 (85.9%) exceeded the 75% minimum needed for the first-pass NF membrane, the AFC30 was selected for further testing for determining pilot-plant design parameters. The 99.7% TDS rejection rate obtained by the AFC99 tubular RO membrane is also a significant finding from the Phase I tests. This >99.5% TDS rejection rate and the >90% boron rejection rate obtained by the AFC99 make it feasible to produce on-spec product water in a single-pass design for drainwater with up to about 6,000 mg/L of TDS.

As indicated in Fig. 7, the concentration tests were run until each membrane fouled. In each case, evidence of fouling was noticed when a 3x concentration was reached. All membranes ceased to produce permeate at 5x. This result was expected since the Panoche drainwater used as feed was nearly at the $CaSO_4$saturation limit. Hence, as permeate was produced, $CaSO_4$ first supersaturated in the feed tank; and then $CaSO_4$ precipitated out of solution (the feed-tank water turned milky) as concentration increased. When the crystals became visible in the feed tank, the membrane immediately fouled. After these tests, the membranes were washed with hot water and a high pH surfactant. This cleaning removed the $CaSO_4$ scale and restored the membrane's water flux to its original value.

To prove the efficacy of seeding as a means for preventing fouling (Objective 1), a second concentration test was performed with the AFC30 membrane with the only difference being that 2.6 kg of $CaSO_4$ (18 g/L) was added to the 150 liter feed tank before the test began. Fig. 9 below shows the flux rates obtained with the AFC30 as a

function of feed TDS in this *seeded test* plotted against the flux rates obtained in the *non-seeded test* as previously shown in Fig. 7.

Figure 9



In both cases, the initial feed was saturated with $CaSO_4$. The non-seed membrane started fouling at a 3x concentration factor (the limit of $CaSO_4$ supersaturation) and fouled completely by 5x. In contrast, non-fouled flux rates (30 to 50 L/M^2• hr) were sustained in the seeded case all the way to the 8x concentration reached at the end of the test. The steady flux-rate decline shown in the seeded case is normal; this decline is explained by the increase in feed osmotic pressure that was occurring as feed TDS levels increased.

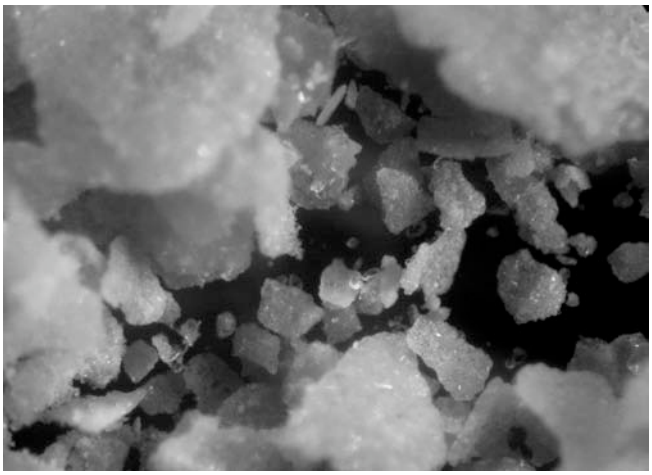
As further evidence that preferential precipitation was working in the seeded case and can explain the different flux rates shown in Fig. 9, microscopic observations were made of the $CaSO_4$ seed crystals used in a seeded 10x concentration test conducted with the four 12-ft. AFC30 modules in series (10.4 M^2 membrane area). "Before" and "after" photographs of crystals from this test at 50x magnification are shown in Fig. 10. The enlarged size of the "after" crystals is clear evidence that the $CaSO_4$ that came out of solution during the test did, in fact, add to the mass of the existing crystals (growth); rather than form new crystals (nucleation) as mineral scale on the membrane surface. In all seeded tests that were conducted, the $CaSO_4$ crystals were visibly darker in color and noticeably coarser in texture after the test than before.

Phase II Tests

Having determined in Phase I that AFC30 had the best properties for use in the 1st-pass NF unit, the next test was designed to demonstrate that, *with seeding*, the AFC30 could be operated on sustained basis on drainwater without fouling (i.e., not exhibiting a flux decline when operating at constant pressure and temperature with relatively constant TDS feed).

Figure 10

Microscopic (50x) Analysis of Calcium Sulfate from Membrane Seeding Tests Conducted with Agricultural Drainage Water



Above: "Before" pictures (50x magnification) of fine, powdery commercial $CaSO_4$ used in seeding test on with 4 x 12-ft AFC30 modules (10.4 M^2 membrane area). For this 10x concentration test, 2,600 grams of $CaSO_4$ was added to the recirculation tank as seed crystals. The test was performed using Panoche water with 7,344 mg/L TDS as feed. During the test, the 578 mg/L of Ca^{2+} in the drainwater (saturation point for Ca SO_4) was reduced to 76 mg/L in the composite permeate. A 28 L/M^2•hr flux rate and a 50% water recovery rate was achieved at 400 psi at the 10x concentration factor. *(Photo Credits: Nyoptics)*

For this Phase II test, the pilot system was equipped with a single 3.9" x 40" AFC30 module (0.9 M^2 membrane area); 2.64 kg of $CaSO_4$ was added to the 150 liter feed tank to achieve an 18 g/L seeding rate; and the system

was operated in steady-stage "production mode" (i.e., permeate was

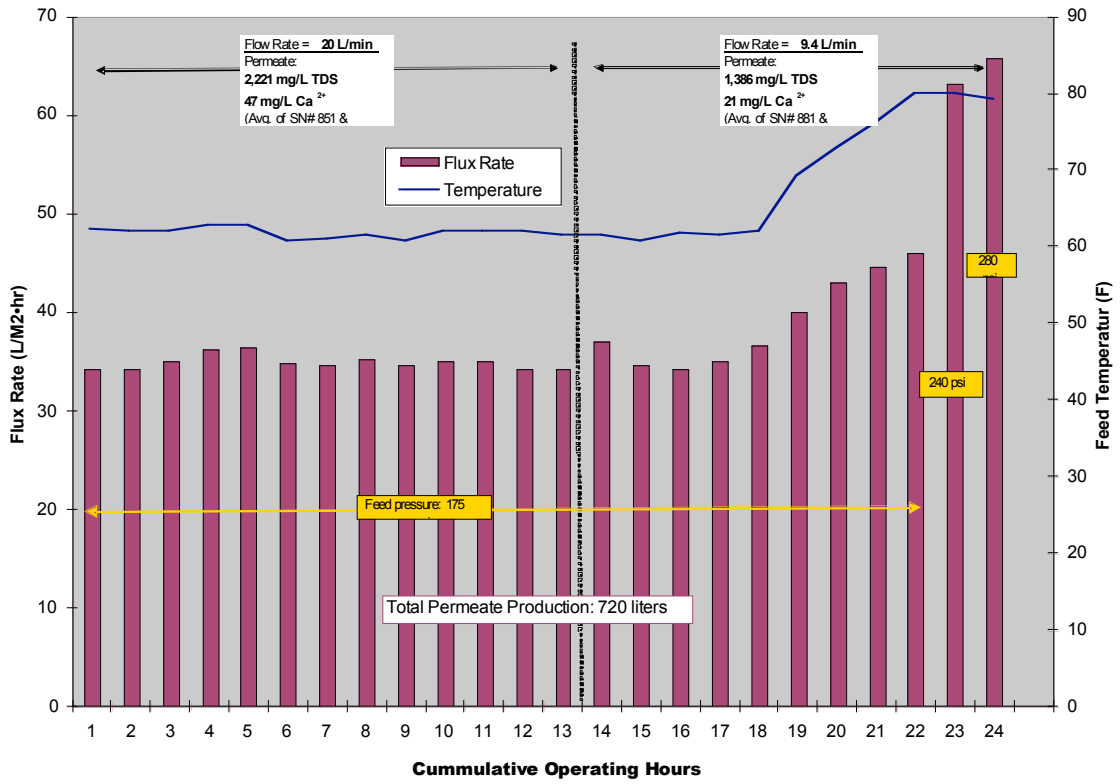
/e: "After" pictures (50x magnification) of the coarse, granular $CaSO_4$ particles recovered from the culation tank after the 10x concentration test. During this test, 750 liters of drainwater was reduced to 75 . Of the 433 grams of Ca^{2+} in the feed, 48 grams left with the 675 liters of permeate (= 70 mg/L avg. entration) and 28 grams remained in solution in the 75 liters of concentrate (= 375 mg/L, the saturation point aSO_4). The remaining 357 grams of Ca^{2+} precipitated out of solution as part of the 1,206 grams of alline $CaSO_4$ produced during the test. Rather than forming new crystals as scale on the membrane surface, ,206 grams of produced CaSO4 *preferentially* added to the 2,600 grams of seed crystals. The seed crystals' ged size and transformed appearance -- shown in these "before" and "after" pictures -- is evidence of the acy of seeding for preventing fouling when treating high-hardness drainwater. *(Photo Credits: Nyoptics)*

discharged; concentrate was recycled to the feed tank; and new Panoche drainwater was continuously added to the feed tank during test to maintain a constant system volume). This test was run for 24 hours over a 4-day period. The results of this Phase II sustained operation test are shown in Fig. 11.

Figure 11

Sustained Operation Test of Seeded AFC30 Membrane (0.9 M ^{2})

Panoche Drain Water @ 11,000 mg/L TDS and 534 mg/L Ca ^{2} with $CaSO_4$ Seeding @ 18 g/L



This test provided the following information related to Objective 1 (efficacy of seeding for preventing fouling) and Objective 4 (design of a pilot and commercial plant):

1. With 18 g/L of seeding, the system could be operated for an extended period on a steady-state basis. This indicates that no sedimentation (i.e., seed crystals falling out of suspension) occurred at the module exit (where cross-flow velocity is the lowest) at the 9.4 L/min per module flow rate used over last 10 hour of testing.
2. A seeding rate of 18 g/L (recommended by Dr. Juby from his South African pilot plant experience) provided a sufficient level of seed crystals in suspension in the feed stream to achieve preferential precipitation and thereby prevent fouling.
3. Permeate quality is a function of flow rate. Higher TDS and Ca^{2+} rejection rates were obtained at 9.4 L/min (87% and 96%) vs. 20 L/min (80% and 91%).

   Note: In this single 40" module test, it appears that flux rate does not change with flow rate. However in subsequent tests with the 4 x 12-ft AFC30 modules, flux rates obtained at 20 L/min were 30% higher than flux rates obtained at 10 L/min.

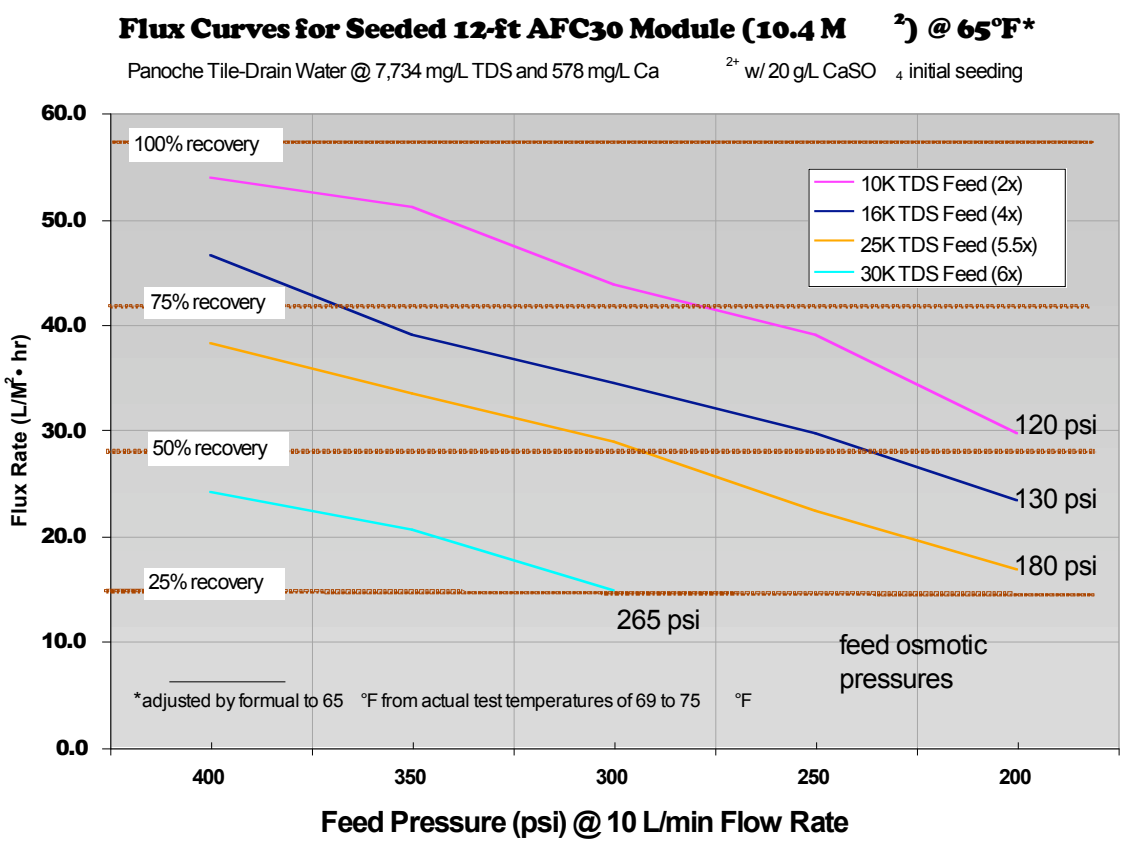
Phase III Tests

Given the excellent results obtained in Phase I and II testing with the AFC30, WaterTech decided to complete the NF membrane testing by scaling up to a full-size (8" x 12-ft)

commercial AFC30 module (72 – ½ diameter x 12-ft long tubes). Since only 3.9" x 12-ft modules were available at the WCRC, the equivalent membrane area and hydraulics of an 8" x 12-ft module was achieved by assembling four (4) 3.9" x 12-ft modules (each with 18 tubes) in series. This provided the same 864 linear feet of path length (=10.4 M^2 membrane area) as an 8" module. (See photographs of 4 x 12-ft test system in Appendix IV.) By using a test module the same size as the modules that will be used in commercial plants, actual (instead of calculated) performance data could be obtained.

By the time the Phase III tests were performed, the DP^3RO™ computer process-design program had been developed. Thus, it was possible to determine the feed TDS level and average concentration factors for both the first and second stage modules of the NF unit in the pilot-plant design under Low, Mid-Range and High TDS feed conditions. A series of seeded concentration tests were performed to establish the performance (i.e., flux and rejection rates as a function of feed pressure and temperature) of the full-size 10.4 M^2 module at the first and second stage feed TDS levels and recovery rates expected in the three different feed TDS design cases. The results of these seeded concentration tests are the flux rate vs. pressure curves for a commercial 12-ft AFC30 module shown in Fig. 12.

Figure 12



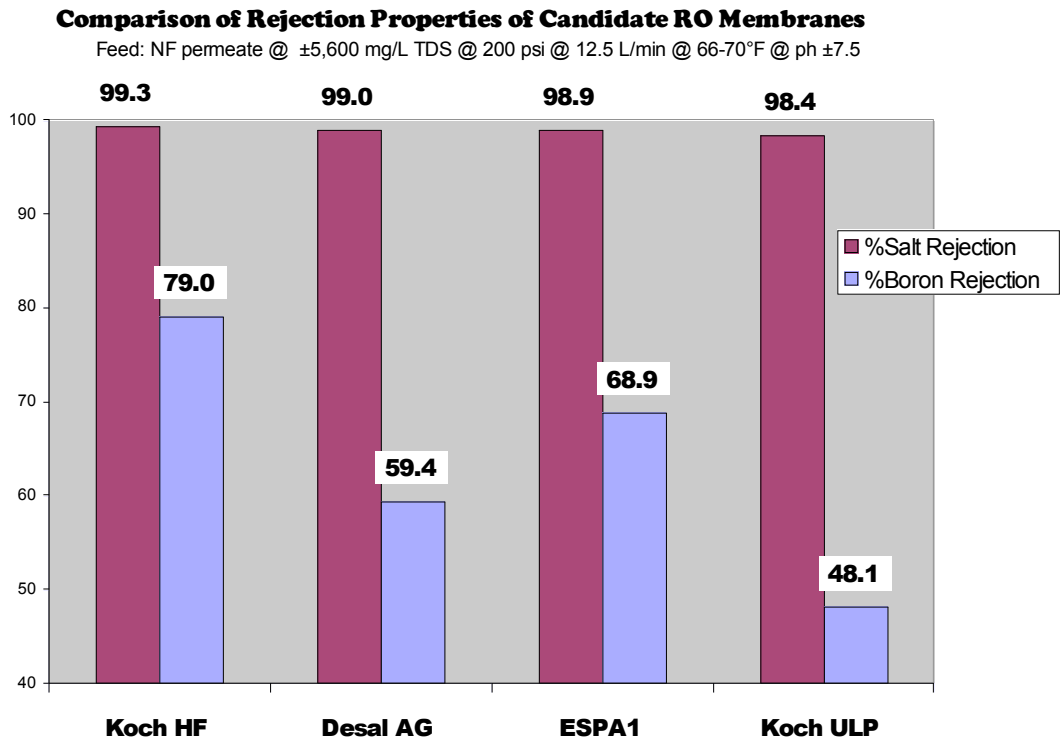
These test results directly relate to Objective 3 (specific power use) since power use is determined by the feed pressure required to achieve a given flux rate based on the feed TDS level, feed temperature, and average concentration factor across the module.

Phase IV Tests

The final series of tests involved evaluating the relative performance of the four (4) different 2.5" x 4" low-pressure RO elements for use on the second-pass RO unit of a

two-pass design. These tests relate to Objective 3 (meet specifications for high quality irrigation water) and Objective 4 (design and cost estimates for pilot and commercial system). These four industry standard "2540" elements each had 2.5 M^2 (27 ft^2) of membrane area; except the ESPA1 had 2.6 M^2 (28 ft^2). The DP^3RO™ computer process-design model indicated that optimal economics are obtained by operating the RO unit at 65% to 70% recovery (i.e., an average concentration factor of 1.6 to 1.7) and 150 to 250 psi feed pressure. The model also showed that the TDS of the NF permeate that becomes the RO feed ranges from 5,000 to 11,000 mg/L.[23] Thus, the RO element tests were conducted at a 2x concentration factor using the NF permeate produced in the Phase II and III tests (about 3,000 mg/L TDS) as feed. The comparative flux and rejection rates for the four candidate RO membranes that were tested are shown in Figs. 13 and 14.

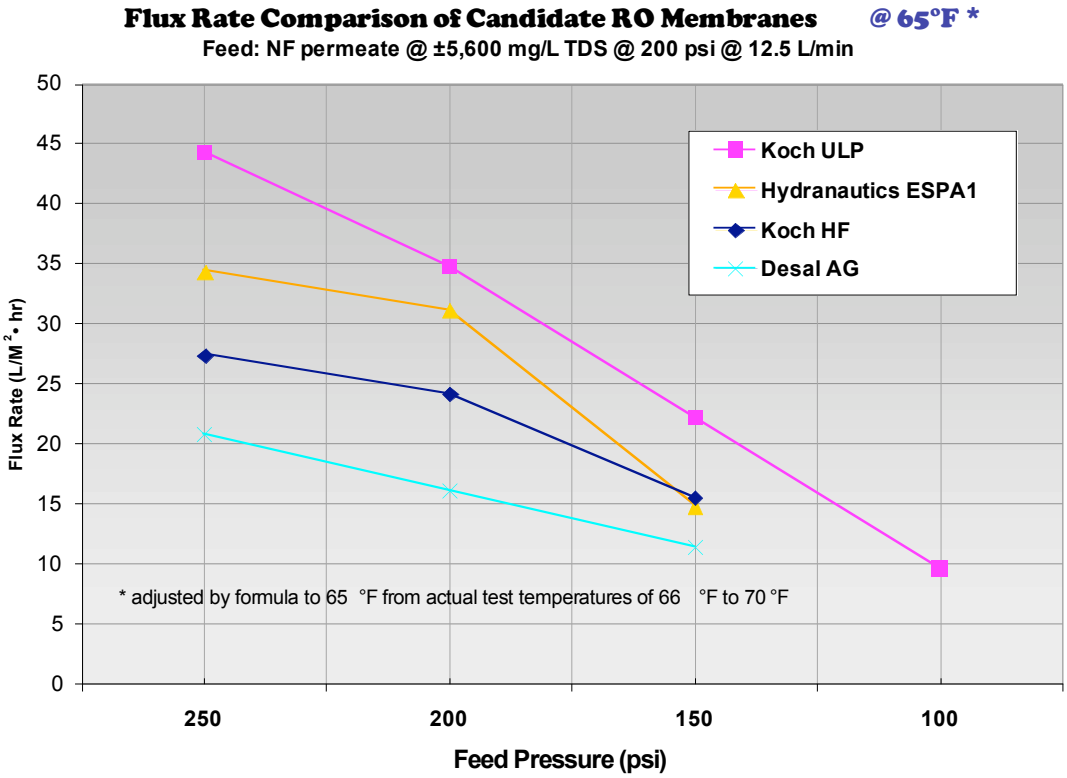
Figure 13



The model showed that to produce on-spec product water with High TDS feed, a RO salt rejection rate ≥98.9% is required. Three of the membranes (Koch HF, Desal AG and ESPA1) met this criterion. For drainwater with 12 mg/L boron (a typical level in Panoche), a RO boron rejection rate >98% is needed to meet the ideal specification of <1.0 mg/L; and >75% to meet the acceptable level of <5.0 mg/L. As expected, no membrane achieved the >98% rejection rate for the ideal boron specification at the natural 7.6-7.8 pH of the NF permeate. One membrane (Koch HF) achieved the >75% rejection rate required to meet the acceptable boron specification of <5.0 mg/L.

[23] The Hydranautics RO system-design program (IMSDesign, ver. 8.0; also called RODESIGN) was used to model the RO unit using NF permeate as feed. Results from the IMSDesign program were then input into the DP^3RO™ process-design model developed by WaterTech as part of this project.

Figure 14



As shown in Fig. 14, the Koch ULP had the best flux rates over the range of feed pressures expected to be used in the RO unit. However, since the Koch ULP did not exhibit a ≥98.8% salt rejection rate, it does not meet the criteria for the DP^{3}RO™ process. Based on these tests, either Koch HF or Hydranautics ESPA1 is the most suitable commercially available RO membrane for use in the DP^{3}RO™ process.[24]

Other notes regarding the Membrane Test Program:

- All analytical tests were performed by the Del Monte laboratory staff at the WCRC facility using acceptable methods published in the literature.
- The lab values for tank-feed TDS during seeded tests at high concentration factors were, in some cases, inconsistent with the electroconductivity readings and calculated TDS values. The high level of suspended solids and the unknown extent of $CaSO_4$ supersaturation are probable reasons inconsistent data were obtained. Thus, the flux rate vs. feed TDS curves for the AFC30 (Fig. 12) were not conclusively determined.
- The AFC30's maximum pH tolerance is 9.5. This limits cleaning agents to mild surfactants. Delamination occurred when a higher pH cleaner was used.

Using data from the test program, the computer model was used to design a two-pass DP^{3}RO™ pilot plant sized to process 15 gpm of Mid-Range TDS drainwater at an average ambient feed temperature of 65°F.[25] The NF unit in this nominal 15-gpm system

[24] Per the IMSDesign program, the Hydranautics ESPA2 appears to perform better than the ESPA1 in the DP^{3}RO™ process. However, the ESPA2 was not available in the 2540 size used in the test program.

[25] Almost all drainwater in the problem areas is (or will be) collected in perforated pipes installed 5 ft. to 15 ft. below the field and conveyed to drain pits at various on-farm locations. The temperature of the

contains 15 – 8" x 12-ft tubular modules (10.4 M^2 each) equipped with AFC30 membranes (total membrane area = 146 M^2) in a 2-stage design; and the RO unit contained 18 – 4" x 40" Koch HF spiral-wound membranes (8.8 M^2 each) in a 3 x 6 array (total membrane area = 157 M^2).[26] The flux rate of polymeric membranes can be increased by 40% to 60% by increasing the feed temperature from 65°F to 95°F.[27] Since **solar pre-heating of the feed** is possible at commercial on-farm DP^3RO™ plants, a second design case assuming the **feed is pre-heated to 95°F to reduce electric power use and lower costs** was considered in the performance and economic evaluation.

Once the 15-gpm DP^3RO™ pilot plant was designed at the two feed temperature conditions, each design was "operated" under the three feed TDS conditions to determine specific power use (Objective 2) and product water quality (Objective 3). To determine projected capital and operating costs for a 250-gpm commercial DP^3RO™ plant (Objective 4), the two pilot-plant designs were scaled up by a factor of 16. In these commercial-plant designs, 8" x 40" RO elements (35.2 M^2 each) were used instead of 4" x 40" elements (8.8 M^2). The results of these six case runs are summarized in Table 2.

Table 2
Projected Performance and Costs for 300 AF/yr Capacity On-Farm DP^3RO™ Plant

Design Case: (*feed temp.*)	**Ambient (65°F)**			**Solar Pre-Heat (95°F)**		
Operating Case:[1] (*feed TDS*)	Low	Mid-Range	High	Low	Mid-Range	High
Total Capital Costs:[2]	**$1.7 million**			**$1.9 million**		
Drainwater Treatment Capacity: *(AF/yr)*	413	323	299	479	329	312
Drainage Service Area @ 0.5 AF/acre: *(acres)*	**826**	**646**	**598**	**958**	**658**	**624**
Maximum Feed Rate: *(gpm)*	320	250	232	384	272	264
Recovery Rate *(% feed)*	**96.6%**	**92.5%**	**91.2%**	**96.7%**	**93.9%**	**91.6%**
Spec. Power Use: *(kWh/AF)*	2,632	2,667	3,124	2,529	2,163	2,970
Product Water Quality:[3]						
TDS *(mg/L)*	226	270	538	396	500	527
Boron *(mg/L)*	3.8	4.0	5.5	3.8	4.5	5.4
SAR	2.3	2.3	3.2	2.3	2.5	4.0
Product Water Cost *($/AF)*	**$614**	**$760**	**$845**	**$564**	**$712**	**$801**
Required Area for:						
• Solar Pond for Feed Pre-Heat	not applicable			4.4 acres		
• Solar Evaporator for Brine	6.6 acres			7.2 acres		

[1] TDS [boron] levels: Low = 3,625 [8.0] mg/L; Mid-Range = 6,450 [12.0] mg/L; High = 9,250 [16.0] mg/L
[2] Projected costs for the 10th plant built assuming improved, cost-optimized design; excludes land costs
[3] For reference, California Aqueduct water has 300 mg/L TDS, 0.15 mg/L boron, and a SAR of 2.3
Source: DP^3RO™ Projected Capital and Operating Costs, Tables III-F and III-G in Appendix III

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drainwater in these pits ranges from 60°F in the winter to 70°F in the summer. Hence, 65°F is used as the average ambient feed water temperature for the design and economic evaluation of the DP^3RO™ process.

[26] Certain details and features of the DP3RO™ process are proprietary. The drawings for the Mid-Range TDS at Ambient (65°F) Feed Case, marked "Proprietary and Confidential" are presented in Appendix V.

[27] Temperature conversion formulas for the NF and RO membranes are shown in Tables III-C and III-D.

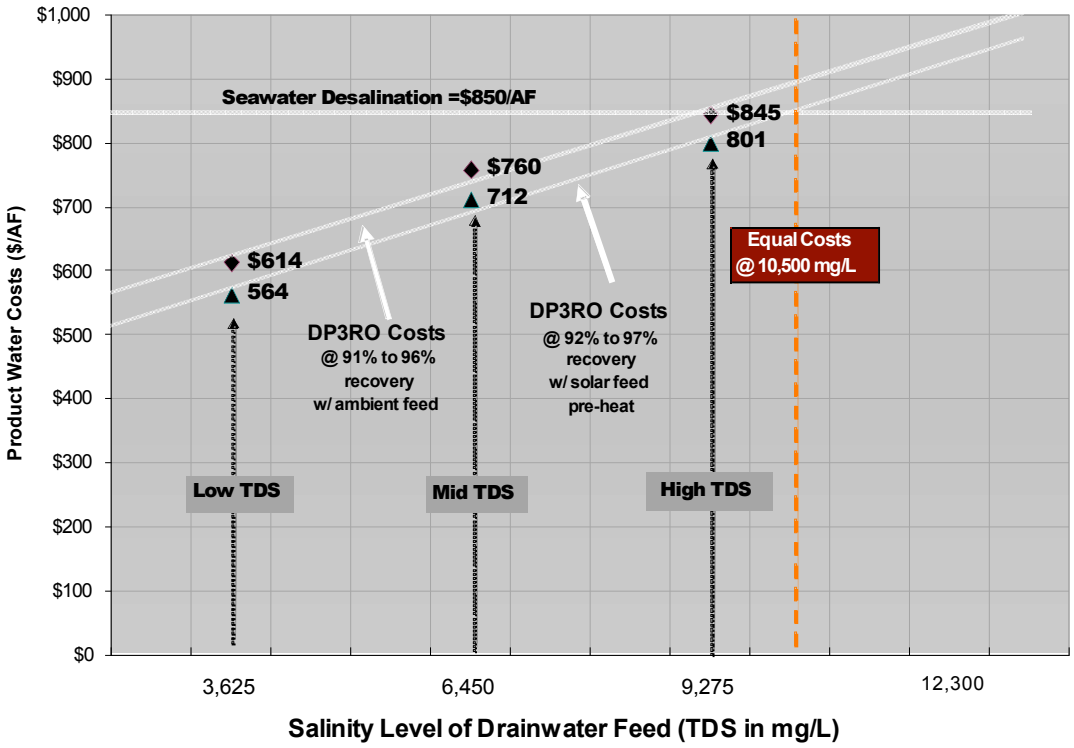
As shown in Table 2, **solar pre-heating can reduce costs by $44 to $50/AF**. The specific power requirement is reduced by about 10% with solar pre-heating to between 2,163 and 2,970 kWh/AF. The specific power use for a large-scale (25-to-50 million gallon/day) Pacific Ocean water desalination plant, sited adjacent to a power plant so the power plant's 95°F return-flow cooling water can be used as feed for the RO membranes, would be about 4,000 kWh/AF.[28] Thus, ***with solar feed pre-heat***, the DP^{3}RO™ agricultural drainwater desalination process can achieve the project objective of requiring less than 75% of the specific power required for desalinating Pacific Ocean water.

The range of agricultural drainwater TDS levels at which the DP^{3}RO™ process can produce high quality irrigation water at >90% recovery at *less costs* than seawater desalination (assumed to be $850/AF[29]) is shown for the two design cases in Fig. 15.

Figure 15

Ag Drainage DP ^{3}RO™ vs. Seawater RO

Product Water Cost ($/AF) without and with Solar Pre-Heating



Source: DP^{3}RO™ Projected Capital and Operating Costs, Tables III-F and III-G in Appendix III

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[28] This figure is based on the 25-million-gallon/day RO desalination plant recently commissioned in Tampa, FL. This new $110 million plant uses 92°F cooling water return-flow from an adjacent power plant as feed; however, the average feed TDS is only 26,000 mg/L since bay water is used. At 31,000 mg/L and 92°F, the specific power for the Tampa plant is specified to be 11.1 kWh per 1,000 gallons. (Source: Presentation by Ken Klinko of Hydranautics at 2002 ATMA Conference in Tampa, FL on Aug. 7, 2002). This equates to a power use of 12.3 kWh per 1,000 gallons (4,000 kWh/AF) at 35,000 mg/L TDS, which would be the "best case" power figure for a 35,000 mg/L TDS feed seawater RO plant in California

[29] The 30-year cost of water from Tampa's 25-million-gallon/day RO desalination plant is $1.88 per 1,000 gallons plus $85 million in state funds. (Source: "As Desalination Plant Readies for Day 1, Eyes Turn to Tampa," *Tampa Tribune,* Jan. 6, 2003). Assuming bond financing at 5% interest, this equates to $2.49 per 1,000 gallons (=$811/AF). Adjusting for the higher salinity of Pacific Ocean water and higher power costs in California, the "best case" cost for seawater desalination in California currently is about $850/AF.

Given the 99.6% salt rejection rate and the >90% boron rejection rate achieved with the AFC99 tubular RO membrane, a one-pass process design is technically feasible.[30] To determine the conditions under which a one-pass design could produce on-spec product at less costs than the DP^{3}RO™ double-pass design, a 15-gpm one-pass system with AFC99 membranes was modeled in both the DP^{3}RO™ program (modified to a single-pass) and the Hydranautics IMSDesign program[31]. Both programs showed that, to achieve >90% recovery and 99.6% salt rejection, a 750 psi operation pressure and a two-stage RO unit is required. This high feed pressure increases the specific power for ambient Mid-Range-TDS feed to 3,542 kWh/AF. Although this specific power requirement is 33% higher than the 2,667 kWh/AF required in a two-pass design, total costs are about the same: $751/AF for single-pass and $760/AF for double-pass. Though less energy-efficient than the DP^{3}RO™ process, a single-pass process design may afford lower costs in cases where drainwater TDS levels remains below 6,000 mg/L on year around basis.

Conclusions

By meeting all Project Objectives, this project has achieved its goal of establishing the conceptual feasibility of using the DP^{3}RO™ process to provide a cost-effective solution to the agricultural drainage problems in western San Joaquin Valley. The achievement of each objective and the market potential for the DP^{3}RO™ process are discussed below.

1. *Prove the concept and effectiveness for using preferential precipitation to eliminate $CaSO_4$ fouling problems for treating high-hardness agricultural drainage water*

   Because of the long record of failure in prior attempts to use membrane technology for treating agricultural drainage water, a great deal of skepticism existed at the beginning of the project as to whether a non-fouling, high-recovery membrane process for recycling agricultural drainage water was technically possible. The results of this project, in which over 1,500 gallons of actual Panoche tile-drain water were successfully processed in over 150 hours of pilot-system operation, has dispelled this skepticism The graph in Fig. 9 and the photographs in Fig. 10 provide clear scientific evidence that preferential precipitation worked to prevent fouling in accordance with the underlying thermodynamic principles. Moreover, these results are more credible because: (i) all testing was performed using commercially available membrane elements and modules and actual drainwater; (ii) the tests were performed at the same operating conditions as expected in a full-size DP^{3}RO™ plant, and (iii) key personnel from Panoche, DWR and USBR were able to observe the testing.

2. *Demonstrate achievability of a specific power use that is <3,000 kWh/AF so expected power use is less than 75% of the 4,000 kWh/AF required for seawater desalination.*

   The DP^{3}RO™ process is expected to require less than 3,000 kWh/AF of power and achieve >90% recovery for agricultural drainage water with less than 10,500 mg/L. Approximately 200,000 AF/yr of the drainwater from the drainage-impaired farmland in the San Joaquin Valley has TDS levels less than 10,500 mg/L. In the Mid-Range TDS case with feed pre-heat, the DP^{3}RO™ process requires only about 50% of the power required for seawater desalination. These project findings make agricultural drainage desalination using the DP^{3}RO™ process a significantly less energy-

[30] The possibility of a single-pass design was suggested by a reviewer of WaterTech's EISG proposal.

[31] A seawater RO membrane (SWC1) was used as a proxy for the AFC99 in the IMSDesign program.

intensive source of "new water" for California than the alternative of seawater desalination.

3. *Demonstrate the ability to produce high quality irrigation water*

   The viability of using the DP^{3}RO™ process as a "no cost" solution to the agricultural drainage problems in western San Joaquin Valley depends on the willingness of farmers to trade an equal amount of their high quality CVP or SWP water to urban water users in exchange for keeping and using as irrigation water the product water from on-farm DP^{3}RO™ plants. For this exchange to be commodities of equal value, the irrigation quality of DP^{3}RO™ product water must be the same or better than the CVP or SWP water that the farmers receive from the California Aqueduct. As shown in Table 2, DP^{3}RO™ water can meet or exceed aqueduct water quality for TDS and SAR. The boron level in DP^{3}RO™ product water will range from 3.8 to 5.5 mg/L compared to 0.15 mg/L for aqueduct water. Fortuitously, the extremely low value for boron in aqueduct water makes it feasible to mix 1 part DP^{3}RO™ water with 5 parts aqueduct water to achieve the ideal boron level of <1.0 mg/L In practice, a 1:5 mixing ratio is achievable since recycled drainwater will be used on average for only 17% of the irrigation water on any farm.[32] Since the TDS and SAR of DP^{3}RO™ water are as good as or better than aqueduct water, no degrading of TDS or SAR will result from a 1:5 blending of DP^{3}RO™ water with aqueduct water (see Sheet 3 in Appendix V). Thus, the DP^{3}RO™ process can meet or exceed all product water quality criteria.

4. *Develop the conceptual design, projected performance parameters, and cost estimates for a 15-gpm pilot plant and a 250-gpm full-scale DP^{3}RO™ plant.*

   The projected performance and costs for the DP^{3}RO™ process shown in Table 2 provide the basis for formulating an alternative approach to USBR's proposed drainage service plan for the 254,000 acres of drainage-impaired farmland in the Grasslands and Westlands subareas.[33] USBR's preferred In-Valley Disposal Alternative consists of: 1) on-farm drainage reduction measures; 2) mixing *untreated* drainwater with CVP water; 2) operating regional reuse sites where drainwater is "consumed" by growing salt-tolerant crops; and 4) building large evaporation ponds. A small amount of single-pass, 50% recovery RO desalination is included. The estimated costs for the USBR In-Valley Disposal Alternative are shown in Table 3.

Table 3
Cost for Drainage Service under USBR In-Valley Disposal Alternative

	On-Farm Measures (local actions)	**Regional Measures** (federal action)	**Total In-Valley**
Required Capital Investment ($million)	not given	**$716***	
Annual Equivalent Cost ($million/year)	$10.4	$48.6	$59.0
Volume of Drainwater (AF/year)	32,200	106,700	138,900
Cost to Farmers ($/AF of drainwater)	$323	$455	**$425**

[32] This calculation assumes average annual applied water use of 2.6 AF/acre and drainage volume of 0.5 AF/acre (USBR 2002); and 90% recovery and recycling of all drainwater with on-farm DP^{3}RO ™ plants.

[33] USBR's plan is articulated in the *Plan Formulation Report* (December 2002) that USBR has prepared to fulfill its contractual obligation to provide drainage service to CVP contractors in Grasslands and Westlands.

* This is about the same capital investment as required for a network of on-farm DP3RO plants totaling 106,700 AF/yr of drainage treatment capacity (e.g., 356 plants w/300 AF/yr capacity at $1.9 million each)

Source: USBR Plan Formulation Report (December 2002); derived from Tables ES-1 and ES-3

Because development of the USBR plan was constrained by available technology and no viable high-recovery agricultural drainwater desalination process presently exists, USBR had to devise a drainage service plan based on "disposal" instead of reclamation -- even though 99% of agricultural drainage is water. Thus, USBR's plan is based on *salt movement* (mixing drainage with CVP water and reusing drainwater on salt-tolerant crops) and *irrecoverable water loss* (evaporation ponds). The high cost to farmers and the adverse environmental impacts associated with this disposal plan will make its implementation problematic. In contrast, the recycling approach made possible by DP^{3}RO™ is based on *water reclamation* (<90% recovery as high quality irrigation water) and *salt impoundment and recovery* (solar evaporators). This recycling plan is more economically and environmentally sound approach for providing a sustainable solution to the drainage and soil salination problems in western San Joaquin Valley than USBR's disposal plan.[34]

In summary, this PIER project has shown that the projected cost to produce "new water" from agricultural drainage with the DP^{3}RO™ process is *less than* the cost of seawater desalination for drainage with up to 10,500 mg/L of TDS. An estimated 200,000 AF/yr of the 252,800 AF/yr of agricultural drainage flows in western San Joaquin Valley has less than 10,500 mg/L of TDS. These flows could be converted into 180,000 AF/yr of new urban water supplies. Thus, DP^{3}RO™ technology can provide a significant and cost-effective source of "new water" for the state. In doing so, DP^{3}RO™ would also provide a "no cost," solution to the agricultural drainage and salination problems in western San Joaquin Valley with less environmental impacts than the proposed USBR plan.

Recommendations

The results of this EISG project support the continued investment of public funds in development of the DP^{3}RO™ technology. Specifically, WaterTech is attempting to secure $1,000,000 in grant funding from multiple sources (e.g., CALFED, USBR, and PIER) for building a 15-gpm DP^{3}RO™ pilot plant in Panoche. The plant would be operated for a one-year performance evaluation and design improvement period. To achieve maximum benefits, WaterTech recommends this follow-on project include:

- a computer control system so **energy optimization** operating strategies and software can be developed; this should include the **ability to "idle" the plant during on-peak power-demand periods**
- sufficient **instrumentation and telemetry** so the plant can operate unattended and be supervised from a remote location (i.e., Panoche's office)
- the ability to **heat the feed to 95°F** so that the **electric power savings** that can be achieved by using **solar pre-heating** can be validated
- the flexibility to allow for operation in a **single-pass** mode so a single-pass desalination process using AFC99 membranes can be tested and evaluated
- the purchase and testing of both **Koch HG** and **Hydranautics ESPA1** (or ESPA2) membranes for the RO unit so their comparative performance can be evaluated

[34] The DPR^{3}RO™ recycling plan for the San Joaquin Valley is similar to US Filter's proposed $2 billion plan for using membrane technology to produce 500,000 AF/yr of potable water from the 1.2 million AF/yr of agricultural drainage flow in Imperial Valley. Both plans rely on urban water sales to pay for treatment costs.

Note: If WaterTech cannot raise the full $1,000,000 for the plant-pilot project, certain of these features will be eliminated and/or the size of the pilot plant reduced.

Public Benefits to California

These potential pubic benefits for electricity ratepayers and the citizens of California attributable to the DP^3RO™ process are discussed and quantified as follows.

- The U.S government has reached a tentative agreement to pay $107 million to settle a lawsuit claiming damages from the USBR's failure to provide drainage service to 33,000 acres of farmland in the Mendota area. This payment sets the precedent for making damage payments of $3,242 per acre. At this rate, it would cost taxpayers over $800 million to solve the drainage problem on the 254,000 acres of drainage-impaired land in the Grasslands and Westlands subareas. In lieu of this land retirement option, USBR has developed its preferred In-Valley Disposal Alternative which requires $716 million in public funding to implement. The farmers would presumably back these funds by paying $455/AF for drainage service for 50 years. Either of these solutions would be very expensive for the citizens of California.

- Many urban areas in California are in desperate need of new water supplies to support population and economic growth. Seawater desalination is coming into play as the most reliable and economical "new water" supply source in many areas of the state. However, only a few locations can offer the ideal scenario of co-location with a coastal power plant. Many issues must be overcome in building coastal desalination plants; including local opposition, power availability, and brine disposal. In addition to being less costly than seawater desalination, the alternative of building on-farm DP^3RO™ plant to produce "new water" by reclaiming agricultural drainage requires less energy and raises fewer siting, power supply, and permitting issues. Assuming Mid-Range TDS feed with pre-heating, DP^3RO™ technology can produce "new water" from agricultural drainage for only 2,163 kWh/AF compared to 4,000 kwh/AF for "best case" seawater desalination. Assuming 90% of the 252,800 AF/yr of potentially recoverable drainwater in the San Joaquin Valley is eventually recovered using the DP^3RO™ process, the electrical power savings in the state would be 418 million kWh/year. **This equates to a 50 MW power plant**. Equally important, the on-farm DP^3RO™ plant can designed and operated to use only off-peak and partial-peak power. Compared to coastal seawater RO plants operating around the clock, **another 60 MW of load would be shifted to off- and partial-peak periods by on-farm DP^3RO™ plants.** Transmission-grid benefits would also be gained by building new desalination plants in the San Joaquin Valley in close proximity to several new combined-cycle gas-turbine power plants; as opposed to coastal locations where relatively little new electrical-power generating capacity is being built.

- In the USBR's In-Valley Disposal Alternative, 5,000 acres of new evaporation ponds would be built to dispose of the 28,800 AF/yr of highly saline drainage from the 26,700 acres of regional reuse facilities. These ponds would have elevated levels of selenium which will make them "attractive nuisances" for waterfowl. Instead of evaporation ponds, solar evaporators would be build adjacent to each on-farm DP^3RO™ plant and used for brine disposal in the DP^3RO™ recycling plan. Properly operated solar evaporators do not endanger wildlife, and can provide

opportunities for salt recovery [35] The USBR disposal plan will take over 37,000 acres of farmland out of normal production. This equates to 14% of the farmland provided drainage service. In the DP^{3}RO™ recycling approach, the total areas required for a solar evaporator for brine disposal and a solar pond for feed pre-heating for a 300 AF/yr-capacity DP^{3}RO™ plant is only 11.6 acres. A DP^{3}RO™ plant this size can provide drainage service to between 624 and 958 acres of farmland depending on the salinity level of the drainwater (Table 2). Thus, *less than 2%* of the area provided drainage will be taken out of production under the DP^{3}RO™ recycling approach.

Development Stage Assessment

Substantial progress was achieved in the development of the DP^{3}RO™ process under this EISG-funded PIER project. As shown in Table 4, the status of development in all "gate" activities at the end of the project was at Stage 4 (Technology Development); except Legal/Contractual which remained in Stage 3. Details on the development status of the DP^{3}RO™ technology with respect to the PIER stage/gate matrix are discussed below.

Table 4
Development Assessment Matrix

Stages / Gates	1 Idea Generation	2 Technical & Market Analysis	3 Research & Bench Scale Testing	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Tranfor-mation	8 Commer-cialization
Marketing								
Engineering/ Technical								
Legal/ Contractual								
Risk Assessment/ Quality Plans								
Strategic								
Production Readiness								
Public Benefits Costs								

- **Marketing**

  The customers for the DP^{3}RO™ technology will be the individual water/irrigation districts in the drainage-impacted areas (e.g., Panoche and Westlands) and the state and federal agencies charged with solving the drainage problems in the San Joaquin Valley (i.e., DWR and USBR). Representatives from these customer entities visited the WCRC and observed the pilot tests. The initial skepticism these entities

[35] The use of solar evaporators instead of evaporation ponds for brine disposal is recognized and encouraged by state law. SB 1372, enacted in 2002, exempts on-farm solar evaporates that occupy *less than 2%* of the area of the farm from compliance with the Toxic Pits Act.

had about the technical viability of a non-fouling, high-recovery membrane process for agricultural drainage recycling was dispelled by these visits. The DP^{3}RO™ recycling approach for solving the drainage and soil salination problems in the western San Joaquin Valley offers clear economic and environmental advantages over competing plans (e.g., the USBR In-Valley Disposal Alternative). USBR has agreed to include the DP^{3}RO™ approach in the Feasibility Study that USBR is presently conducting as the next step in USBR's drainage implementation plan. The only uncompleted Stage 4-level marketing task is to contact and solicit interest from urban water users who are potential customers for buying via exchange DP^{3}RO™ product water. These contacts will be initiated during Stage 5.

- **Engineering/Technical**

  All Stage 4 engineering and technical task are essential completed. An on-farm test site has been identified for the pilot plant (Drain Pit # 25 in Panoche); and preliminary design drawings and specification for the pilot plant have been prepared (Appendix V). The only uncompleted Stage 4 engineering task is the completion of a detailed Field Test Plan. This plan will be developed and included as part of the proposal that WaterTech will submit within the next month to USBR, the PIER Industrial/Agriculture/Water program area manager, and other potential pilot-plant grant-funding sources.

- **Legal/Contractual**

  WaterTech has prepared an Invention Disclosure on certain proprietary aspects of the DP^{3}RO™ process and expects to complete and file a patent application within the next few months. Certain of these proprietary aspects or features of the DP^{3}RO™ process were conceived or reduced to practice in the work performed under the EISG project and therefore the State of California will have license rights in such inventions in accordance with the terms of the Grant Agreement; other proprietary aspects and features were not conceived or reduced to practice as part of the work performed under the EISG project and therefore the State of California will not have license rights in such inventions. The filing of a patent application on the proprietary features of the DP^{3}RO™ process is the remaining uncompleted Stage 3 Legal/Contractual task.

- **Risk Assessment/Quality Plans**

  The current brine-disposal plan involves the construction and operation of a dedicated solar evaporator facility adjacent to each on-farm DP^{3}RO™ plant. There is not way the viability of this brine disposal method can be tested and evaluated ahead of building and operating an on-farm pilot plant. Before proceeding with the pilot plant project, information will be obtained on the design and operation of the demonstration solar evaporator at Red Rock Ranch near Mendota. This facility has been in operation for several years. The DWR personnel who will be involved in the DP^{3}RO™ pilot plant project are also involved in this solar evaporator demonstration project. Transferring the know-how gained from Red Rock Ranch to this project will reduce the uncertainty on this matter and justify proceeding with the Stage 5 pilot plant. All other Stage 4-level environmental, safety and risk issue related to the DP^{3}RO™ process and proposed pilot-plant project are resolved.

- **Strategic**

  This development of the DP^3RO™ process is being coordinated with other public agencies involved with drainage issues in western San Joaquin Valley. WaterTech and Panoche submitted a proposal in October 2001 requesting $2.4 million in CALFED grant funding under the 2002 Ecosystem Restoration Program. This proposal outlined a 3-year plan for developing the DP^3RO™ process in a three phases. Due to CALFED funding constraints, only $216,390 of the requested $2.4 million was approved for 2003 as partial funding of a Phase I pilot-plant project. The contract for this $216,390 in Phase I CALFED grant is expected to be issued by June 2003. WaterTech also submitted a pre-proposal request for $270,000 in co-funding for the proposed pilot-plant project under the USBR's 2003 Desalination and Water Purification Research Program. WaterTech will be notified in mid-February if its pre-proposal is considered meritorious. Finally, the possibility of using a network of on-farm DP^3RO™ plants to solve the drainage problems in the impacted areas is being considered as part of the Feasibility Study that USBR is now conducting as the next step in USBR's drainage implementation plan for Grasslands and Westlands.

- **Production Readiness**

  PCI Membrane Systems, Inc., a leading international membrane technology company, was actively involved in the EISG project and already has provided WaterTech with a quotation for supplying the NF unit as part of the proposed 15-gpm pilot plant. WaterTech has also maintained contact with potential RO membrane suppliers, such as Koch Membrane Systems and Hydranautics. Dr. Juby of Carollo Engineers, who has expertise in seeded RO technology from his prior work in South Africa, was a consultant on the EISG project. Carollo Engineers, a major membrane systems engineering firm, is interested and willing to provide design and engineering services for the Stage 5 pilot plant, and the eventual Stage 6 commercial demonstration project. Joe McGahan of Summers Engineers, Panoche's District Engineer, is knowledgeable about the technology and is prepared to perform the required permitting and site-related engineering work for the pilot plant project. Thus, all Stage 4 Production Readiness tasks are completed.

- **Public Benefits/Costs**

  WaterTech requests an additional $500,000 in PIER funding as 50% co-funding for a $1,000,000 Stage 5 pilot-plant project. This $500,000 is expected to be the last PIER funding needed for commercializing the DP^3RO™ process since the $2.2 million needed for building a prototype commercial plant is expected to be available from CALFED. Proposition 50, the $3.4 billion water bond approved by voters in November 2002, allocated $850 million to CALFED. This includes $180 million specifically designated for the Ecosystem Restoration Program with the provision that "not less than **$20 million** shall be allocated for projects that assist farms in integrating agricultural activities with ecosystem restoration". Thus, when WaterTech and Panoche submit their request to CALFED in 2004 for $2.2 million in Phase II and III grant funding for their already proposed 250-gpm DP^3RO™ demonstration project, they stand a good chance of receiving funding. The remaining uncompleted task under Stage 4 Public Benefits/Costs is preparing the work plan and other documents required for obtaining follow-on PIER funding.

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Glossary of Technical Terms and Acronyms

Acre-Feet (AF) -- unit of measure of water volume used in agriculture; amount of water covering one acre of land one foot deep; 1 AF of water = 325,851 gallons = 1,233 M^3

Average Concentration Factor (ACF) -- term used in designing membrane systems; formula is: $ACF = \ln(1/(1-R)) \div R$ where: ln = natural log and R = Recovery Rate

CALFED -- consortium of federal and state agencies working together to address and solve water issues related to the San Francisco Bay-Delta estuary; as of January 1, 2003, CALFED became an official state authority with it own board of commissioners

Commission - abbreviation for California Energy Commission

Concentrate -- term applied in a membrane process to the remaining fraction of the feed stream that does not permeate through the membrane; contains elevated levels of salt and other rejected constituents of the feed water (e.g., selenium and boron); also called brine

Central Valley Project (CVP) -- federally built and operated water transfer project that supplies irrigation water to farmers in the Grasslands and Westlands subareas using the California Aqueduct and the Delta-Mendota Canal

Department of Water Resources (DWR) – state agency responsible for water issues in California; the San Joaquin Valley Drainage Improvement Program is managed by DWR

Energy Innovation Small Grant (EISG) – PIER program that funded this project

Flux rate – measure of permeate production characteristic of a particular membrane; units are liters per square meter of membrane area per hour ($L/M^2 \cdot hr$); flux rates vary depending on feed pressure, TDS level, flow rate (cross-flow velocity), and temperature

mg/L – milligrams per liter; unit of measure of the constituents in an aqueous stream

Nanofiltration (NF) – class of membranes that reject dissolved solids but do not have as high of salt rejection rates as RO membranes; also called "loose RO"; NF membranes typically exhibit higher rejection rates for divalent ion (e.g., Ca^{2+}, Mg^{2+} and SO_4^{2-}) compared to monvalent ions (e.g., Na^+ and Cl^-)

PCI – abbreviation for PCI Membrane Systems, Inc.; PCI is a wholly-owned subsidiary of ITT Corporation; PCI's home office is in the U.K. and its U.S. office is in Milford, OH

Permeate – the fraction of the feed stream in a membrane process that passes through the semi-permeable membrane barrier and become the product water

Preferential Precipitation – the thermodynamic principle by which dissolved calcium sulfate is removed from the drainwater in the first-pass NF membrane; before entering the NF membrane, the drainwater is "seeded" with $CaSO_4$ crystals so that, as permeate is produced and $CaSO_4$ precipitates out of solution, the precipitate adds to existing seed crystals (growth) and does not form new crystals (nucleation) on the membrane surface

Public Interest Energy Research (PIER) – R&D program conducted by the Commission; source of funding for the PIER program is the public goods charge paid by California electricity ratepayers

Osmotic Pressure - the natural resistance that must be overcome for the water content of a feed solution at a high TDS level to diffuse through a semi-permeable membrane into a permeate solution at a lower TDS level. Osmotic pressure increases as a function of the feed TDS; hence, power use increases as feed TDS increases in membrane processes

Recovery Rate – ratio of permeate flow rate to feed flow rate expressed as percent; the DP^3RO™ process is designed to operate at high recovery rates (92% to 97%) to maximize water yield and minimize brine volume; whereas seawater desalination plants operate at low recovery rates (45% to 55%) since water yield and brine volume are not cost factors

Salt Rejection Rate - measure of a membrane's ability to reject salt (or any ion); formula is**:** $SR = 1 - \left(Cp/(Cf * ACF)\right)$ where Cp = salt or ion concentration of permeate (mg/L); C_f = salt or ion concentration of feed (mg/L); and ACF = average concentration factor

Reverse Osmosis (RO) – class of membranes that reject a very high percentage (>99%) of dissolved solids**;** *high pressure* RO membranes (400 to 1,000 psi) are used for desalinating high TDS water like 35,000 mg/L TDS seawater; *low pressure* RO membranes (150 to 400 psi) are used for desalinating low-to-mid salinity waters like the 5,000 to 10,000 mg/L TDS feed to the 2nd-pass RO unit of the DP^3RO™ process

Sodium Adsorption Ratio (SAR) – agronomic term for measure of the ability of irrigation water to penetration into the soil after the water is applied; formula is:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

Where: Na = sodium ion concentration in meq/L
Ca = calcium ion concentration in meq/L
Mg = magnesium ion concentration in meq/L

Note: a more accurate measure is called Adjusted SAR; but at the low TDS levels of DP^3RO™ product water, there is little difference between SAR and Adjusted SAR values

State Water Project (SWP) – state built and operated water transfer project that supplies farmers in Kings and Kern Counties with irrigation water using the California Aqueduct

Total Dissolved Solids (TDS) – measure of the salinity level of an aqueous solution; units are mg/L; the amount of energy needed to desalinate a solution in a membrane process increases as the solution's salinity increases

U.S. Bureau of Reclamation (USBR) – federal agency responsible for providing drainage service to CVP water contractors in the Grasslands and Westlands subarea; the USBR's Technical Services Center in Denver is performing the Feasibility Study on the In-Valley Disposal Alternative

Walnut Creek Research Center (WCRC) – R&D facility in Walnut Creek, CA, at which WaterTech conducted the Membrane Test Program for this project. (Note: Del Monte Foods, owner of the WCRC, is not involved in this project and only rented space and provided lab services to WaterTech on a fee-basis.

EISG FINAL REPORT

Energy-Efficient Process for Using Membrane Technology to Treat and Recycle Agricultural Drainage Water

Grant # : 52735A/01-23

Appendices

I. History of Laboratory Tests, Field Trials, Pilot System and Full-Scale Demonstration of Selenium Removal and Water Reclamation Processes in the San Joaquin Valley (1985-Present)

II. Summary of Membrane Test Program

III. Data Tables from Test Program and Economic Analyses

IV. Photographs of Pilot System & Membranes Used in Test Program

V. PROPRIETARY & CONFIDENTIAL

Proprietary Design Drawings for 15-gpm DP^3RO™ Pilot Plant with Mid-Level TDS Feed @ 65°F (Rev. 6)

Appendix I

HISTORY OF LABORATORY TESTS, FIELD TRIALS, PILOT SYSTEMS AND FULL-SCALE DEMONSTRATIONS OF SELEMIUM REMOVAL TREATMENT PROCESSSES IN THE SAN JOAQUIN VALLEY SINCE 1985*

Proponents/ Contractor	Dates	Location	Funding	Technology	Project Scope	Results/Projected Costs	Reference
Biological							
1.a EPOC Agricultural Corp. (aka Binnie California Inc). United Kingdom	1987 – 1988	Murietta Farms, Westland Water District, near Mendota, CA	USBR, DWR, and Westlands Water District	Anaerobic bacterial reduction (ABR) using methanol as bacterial food source, followed by crossflow microfiltration (or dissolved air flotation) to remove Se-laden sludge	Pilot Plant: 24,000 gal/day two-stage system; upflow anaerobic sludge blanket (UASBR) reactor followed by fluid bed reactor (FBR)	$CaCO_3$ precipitation clogged reactors; 90% Se removal achieved (300 to 30 µg/L) in some tests; hazardous waste disposal required; projected cost of **$244/AF** for 3 AF/day (= 1.0 MGD) plant	Chapter 25 (Owens) in *Environmental Chemistry of Selenium* (1998: Marcel Dekker, Inc.);Frankenberger & Engberg, editors
1.b U.C. Davis (Dr. Joan Macy)	1992-1995	U.C. Davis;: Panoche Drainage District		ABR using selenate-respirating bacterium (*Thauera selenatis*) and acetate as food source	Lab Test: one liter UASBR followed by one liter FBR; Field Tests : 2 gpm at Panoche in 1995	Advantage of *T. selenatis* is reduction of selenate occurs independent of nitrate; acetate costly	*Ibid.*
1.c Engineering Research Institute at Cal State Fresno (L. P. Owens)	1991-1995	Adams Ave. Agricultural Drainage Research Center (near Tranquility, CA)	USBR, DWR, and Westlands Water District	ABR (continued development of process initially tested by EPOC)	Pilot-Scale Tests: seven types reactors operated at AADRC over 4-year period; test flow rate was about 2,500 gal/day	90% Se removal generally achieved; sludge carryover, temperature control and equipment breakdowns hampered operations; cost same as reported in 1.a	*Ibid.*
2. U.C. Riverside (Dr. Frankenberger and Dr. Hanna)	1994 - 1995	Adams Ave. Agricultural Drainage Research Center (near Tranquility, CA) & Sumner Peck Ranch	USBR, DWR, and Westlands Water District	Flash Evaporation (i.e., volatilization by aerial spraying selenium contaminated water over microbial enriched soil)	Field Test: 7-acre site at AAADRC and 10-acre site at Peck Ranch using cattle manure from Harris Ranch	Effective for low concentration water (< 150 µg/L Se); projected cost reported by Quinn to be **$267/AF** at 100 µg/L with income loss of $50/acre	Chapter 28 (Frankenerger & Hanna) in *Environmental Chemistry of Selenium, ob cit.*
3.a U.C. Berkeley Algal Research Laboratory (Dr. Oswald)	1986 - 1989	Murietta Farms, Westlands Water District Mendota, CA	San Joaquin Valley Drainage	Algal biomas used as carbon source to produce native bacteria to reduce nitrate and selenate	Field Test: 760 gal/day system on 0.05 acre site	Total selenium reduced from 400 µg/L to less than 10 µg/L; cost for 3 AF/day system projected to be	http://www-esd.lbl.gov/quinn/Grassland_Bypass/RESEARCH/Pancohe.html

* adopted, expanded and updated from similar chart by Quinn, *et al.* in *California Agriculture*, Vol. 54, No. 6 (Nov/Dec 200), p. 52. In addition to the references cited, the "Drainage Water Treatment" Final Report, dated February 1999, by the Drainage Water Treatment Technical Committee of the SJVDIP and the U.C. Salinity/Drainage Program was also used.

Appendix I (cont'd)

HISTORY OF LABORATORY TESTS, FIELD TRIALS, PILOT SYSTEMS AND FULL-SCALE DEMONSTRATION OF SELEMIUM REMOVAL TREATMENT PROCESSSES IN THE SAN JOAQUIN VALLEY SINCE 1985

Proponents/ Contractor	Dates	Location	Funding	Technology	Project Scope	Results/Projected Costs	Reference
			Program			**$272/AF** (`1988 estimate)	
3.b Lawrence Berkeley Laboratory and U.C. Berkeley Algal Research Laboratory (Drs. Oswald, Leighton & Quinn)	1997 - present	Panoche Drainage District DP-25	USBR Drainage Challenge Grant; PDD; U.C. Berkeley; CALFED	Algal-Bacteria Selenium Removal (ABSR) using Advanced Integrated Wastewater Pond Systems (AIWPS); may need to add carbon source (e.g. molasses)	Pilot System: two parallel 10,000 gpd systems consisting of Reduction Ponds, Paddle-Wheel Mixed Algal High Rate Pond; and Algae Settling Pond	Must deplete dissolved O_2 and reduce nitrate before reducing selenate; high sulfate (4,000 mg/L) not problem; residual biomass potential soil amendment; projected costs is **$200/AF** for 10 AF/day unit	http://www-esd.lbl/gov/quinn/Grassland_Bypass/RESEARCH/Panoche.html; and *California Agriculture*, Vol. 54, No. 6 (Nov/Dec-00), pp. 50-56
Chemical							
4. Hazra Engineering Inc. Fresno, CA	1985-1988	Panoche Drainage District		Reduction using Iron Filings (zero-valence Iron); iron acts as both catalyst and reductant	Pilot Scale Tests	Only 50% to 70% removal; problems with bed clogging (precipitates) and channeling due to poor pH control; projected cost of **$120/AF** at 70% removal, plus sludge disposal costs	Reported by Quinn, et al. in *California Agriculture*, Vol. 54, No. 6 (Nov/Dec-00), p. 52
5. U.S. Bureau of Reclamation – Engineering and Research Center Denver, CO	1985 - 1989	Murietta Farms in Westlands Water District near Mendota, CA	USBR (internal project)	Ferrous Hydroxide Precipitation (U.S. patents 4,806,264 and 5,089,141)	Laboratory test in Denver followed by field tests of micro-plant at Murietta Farms	Se reduced from 90 µg/L to < 1 µg/L in lab tests; nitrate interference and slow reaction rates are problems; hazardous sludge produced; projected cost of **$200 to $250/AF** plus sludge disposal	http://www.usbr.gov/water/content/c_tech.htm
6. HDRO-Solutions and Purifications, LLC Fairbanks, AK	1998 - 1999	Panoche Drainage District DP-25	$70,0000 EPA Phase I SBIR # 68D98150	Enhanced Iron Co-Precipitation	• Lab tests in Univ. of Alaska – Fairanks • Field trials at Panoche	98% reduction achieved in lab (500 to 10 µg/L), but only 90% in field; sulfate interference required adding $BaCl_2$; lab work continuing	www.epa.gov/ncerqa/progress/sbir/water
7. Boyle Engineering Bakersfield, CA	1985-1986	Panoche Drainage District	USBR Drainage Challenge Grant	Ion Exchange (alone or as polishing step after biological treatment)	Laboratory Tests	Fouling is problem; further testing needed to improve efficiency and determine costs	www.mp.usbr.gov/mp400/irrdrn/drangrnt.html

Appendix I (cont'd)

HISTORY OF LABORATORY TESTS, FIELD TRIALS, PILOT SYSTEMS AND FULL-SCALE DEMONSTRATION OF SELEMIUM REMOVAL TREATMENT PROCESSSES IN THE SAN JOAQUIN VALLEY SINCE 1985

Proponents/ Contractor	Dates	Location	Funding	Technology	Project Scope	Results/Projected Costs	Reference
8. Lawrence Livermore National Laboratory Livermore, CA	1998 -	Panoche Drainage District (C. Hurley)		Composite Carbon Aerogel Electrodes for Electrochemical Metal Removal	Laboratory Tests	Unknown (paper not obtained prior to proposal due date)	http://www-cms.llnl.gov/sci_tech/waterbrochure.pdf and http://www.electrochem.org/meetings/193/pic1.html
Physical							
9.a Department of Water Resources and CH2M Hill	1983 - 1987	Los Banos Desalting Facility Los Banos, CA	DWR	Membrane Reverse Osmosis with various conventional pretreatment steps	Pilot-plant testing over six year period, including operation of solar ponds for brine disposal	95% Se removal achieved (150-200 µg/L to 10-20 µg/L), but low boron removal; projected cost in 1986 of **$1,090/AF** for 30 AF/day (= 10 MDG plant), plus brine disposal costs	Reported by Quinn, et al. in *California Agriculture*, Vol. 54, No. 6 (Nov/Dec-00), p. 52
9. b Eco-Water Technologies Corp.	2000 - present	Panoche Drainage District DP-25	Private Investors	Membrane Reverse Osmosis with experimental pretreatment processes	Prototype Full-Scale Plant designed to operated at 250 gpm (= 1 AF/day)	TDS reduction from 500 to 70 mg/L, including over 95% Se (300 µg/L to < 5 µg/L); but poor boron rejection; ***shut-down in Aug-01 due to irreversible fouling of membranes***	Personal communications with Eco-Water and PDD in Aug-01; site visits in Sept-01
10. DWR, U.C. Los Angeles, Kern County Water Agency, Boyle Engineering , et al.	1999 – present	Bloemhof Land & Farming in Buena Vista Water Storage District, near Buttonwillow, CA	DWR	Membrane Nanofiltration ***(Note: treatment objective is desalination of tile-drain water, not Se removal)***	±10 gpm pilot system consisting: two-stage multimedia pretreatment followed by two-stage membrane filtration	TDS successfully reduced from over 6,000 mg/L to 215 mg/L in first-year trials; objective now is to increase recovery to >90%, sustain operations, and develop cost data	Personal visit and communications with Boyle Engineering; site visit in Nov-00

Note: In addition to above biological, chemical and physical processes, other studies and demonstration projects for selenium removal from agricultural drainage water have included: 1) deep well injection, 2) desalination as part of cogeneration power plants; 3) various phytoremediation possibilities, including agroforestry; 4) assimilation in biomass in natural and/or constructed wetlands; and 5) desiccation in solar and/or evaporation ponds.

Appendix II
Summary of Membrane Test Program

	Test Dates/ Personnel*	Activities	Data Reports	Lab Reports
Phase I a) Initial screening tests with five (5) candidate tubular membrane elements (0.9 M^2) to determine Ca^{2+} rejection and flux rates without seeding using Bach #1 Panoche Water (11,000 mg/L TDS with $CaSO_4$ at saturation) b) 5x concentration test (30,000 mg/L TDS feed) of seeded AFC30 module (0.9 M^2) for comparison w/ above unseeded tests, using Panoche Batch #2 water (7,400 mg/L TDS)	**Oct 10** JS, TS, KN, JR **Oct 22** KN, JR, JS, PA **Oct 23** JS, JR, TS, PA, KN **Oct. 24** JS, KN, TS, JR, **Oct. 31** JS,KN, JR, RE **Nov. 1** JS, KN, RE & **MH** **Jan. 6** JS, KN & RE **Jan. 9** JS, KN & RE	Initial operation; leakage problems Integrity test, CIP & sanitizing AFC30 & AFC 80 concentration tests AFC99 & CDA16 concentration test Repeat tests with AFC99 & CDA16 Repeat tests with AFC30 &AFC80 ES404 rejection test 5x concentration test w/seeded AFC30	"Evaluation of NF Membranes with Panoche Tile Drain Water Bach #1" Test on Oct. 23 Test on Oct. 24 Test on Nov. 1 (JS – 1/1/03)	SN# 784 Panoche B#1 SN# 810-812 AFC 30/80 data 10/23 tests SN# 519-525 permeates from 11/1 tests SN# 816-817-921 CDA16 & AFC99 permeates 10/24 SN# 923 AFC99 permeate 10/31 SN#922 ES404 permeate 1/6
Phase II Seeding and "sustained operation" tests on selected NF membrane (AFC30) to verify efficacy of seeding for fouling prevention using Batch #1 Panoche Water	**Nov. 5** JS, KN, RE **Nov. 6** JS, KN **Nov 7** JS, KN, PA, RE & **GJ** **Nov. 11** JS, KN	Seeded production test of AFC30 w/ 2.64 kg of $CaSO_4$ continuation continuation 4-ft AFC30; ▲p, ▲t, and hydrocyclone	"Four Day Seeded Test Run with Panoche Tile Drain Water" (JS – 11/14/02)	SN# 818 SiO2 Panoche B#1 SN# 850-852 TDS, TSS, Ca^{2+} 11/6 and 11/7 SN# 880-883 permeates from 11/11 tests
Phase III Concentration tests on full-size AFC30 module (10.4 M^2) to determine flux rates and Ca^{2+} and TDS rejection properties over range of feed TDS levels and pressures expected for commercial plant w/Batch #2 Panoche Water (7,400 mg/L TDS with $CaSO_4$ at saturation)	**Dec 9** JS, KN **Dec. 11** JS, KN, RE, PA, & **DWR visit** **Dec. 19** JS, RE, & **USBR visit** **Jan. 10** JS, KN & RE	100-gallon 6x NF test w/ 3.8 kg seeding 100-gallon 6x NF test w/2.0 kg seeding repeat 12/11 tests 200-gal 10x test w/2.6 kg seeding	"Seeded Test with Panoche Drain Water Batch #2" Dec. 9 Dec. 11 (JS-12/22/02)	SN# 885 – Ca^{2+} Panoche B#2 SN# 898-904 Panoche B#2 TDS & Ca^{2+} from 12/9 tests SN# 909-910 "tank feed" TDS on 12/11 tests SN#919-920 boron on 12/9
Phase IV Screening tests with four (4) candidate spiral-wound RO membranes (2.5 M^2) to determine flux-rate curves and boron and TDS rejection properties using NF permeate from Phase II & III tests as initial feed	**Dec. 3** JS, KN **Dec. 12** JS, KN, RE **Dec. 20** JS, KN	15x concentration test with Koch HF 2x tests: Koch HF and Desal AG 2x tests: Koch ULP & Hydranautics ESPN1	"Koch RO Membrane Dec 3 Test"; "RO Membrane Comparison"; and reports on Koch HF, Desal AG, Koch ULP and ESPNA1 (JS – 12/22/02)	SN# 886-887 Koch HF permeate 12/3 SN# 905-916 boron & TDS: Koch HF Desal AG Koch ULP ESPA1

* JS = Jurgen Strasser; KN = Karim Nafisi; PA = Peter Allan; TS = Tom Svanoe; JR = Joe Remonda; RE = Ron Enzweiler

Appendix III
Data Tables & Economic Analyses

Data from Screening Tests with 48" Membrane Modules

- Table III-A Comparative Rejection Properties of PCI Membranes (0.9 M^2) on Panoche Tile-Drain Water

Data from 4 x 12-ft. AFC3O Membrane Tests

- Table III-B Rejection Properties of 12-Ft. AFC30 Module (10.4 M^2) on Panoche Tile-Drain Water

- Table III-C Flux Rates for 12-Ft. AFC30 Module (10.4 M^2) Used in DP^3RO™ Process Design

Comparative Performance Tests of Candidate RO Membranes

- Table III-D Comparative Flux & Rejection Rates for Candidate RO Membranes for DP^3RO™ Process

- Table III-E Computation of Rejection Rates for Candidate RO Membranes

Design and Cost Calculations for Pilot and Commercial Plant

- Table III-F Plant Design Parameters and Projected Capital & Operation Costs for Nominal 300 AF/yr Capacity DP^3RO™ Plant at Ambient Feed Conditions

- Table III-G Plant Design Parameters and Projected Capital & Operation Costs for Nominal 300 AF/yr Capacity DP^3RO™ Plant w/ Feed Pre-Heat to 95°F

Table III - A

Rejection Properties of Tested PCI Tubular Membranes (0.9M²)

Panoche Tile-Drain Water (11,000 mg/L TDS) @ 5x concentration @ 10 L/min flow rate @ 69-72°F w/o Seeding

Lab Values in Bold

	AFC30 @ 400 psi[c]										
	Flow	TDS		Calcium		Sulfate		Boron		Selenium	
	L/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min
Feed @ 5x:[a]	**20.0**	42,786	855,710	474	9,475	23,869	477,383	31.9	639	3,879	77,573
Avg. Feed:		42,904		475		23,935		32.0		3,889	
Concentrate:a	**19.9**	**43,000**	855,270	**476**	9,468	**24,000**	477,360	**32**	636	**3,900**	77,571
Permeate:	**0.11**	**4,000**	440	**67**	7	**212**	23	**19**	2	**21**	2
Total:			855,710		9,475		477,383		639		77,573
Recovery	0.6%										
ACF	1.00										
%Salt Rejection:[b]		**90.7%**		**85.9%**		**99.1%**		**40.7%**		**99.5%**	

	AFC80 @ 400 psi										
	Flow	TDS		Calcium		Sulfate		Boron		Selenium	
	L/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min
Feed @ 5x:[a]	**20.0**	42,491	849,825	471	9,410	23,703	474,053	31.8	636	3,852	77,031
Avg. Feed:		42,759		473		23,852		32.0		3,876	
Concentrate:[a]	**19.8**	**43,000**	849,250	**476**	9,401	**24,000**	474,000	**32**	632	**3,900**	77,025
Permeate:	**0.25**	**2,300**	575	**36**	9	**213**	53	**15**	4	**22**	6
Total:			849,825		9,410		474,053		636		77,031
Recovery	1.3%										
ACF	1.01										
%Salt Rejection:[b]		**94.6%**		**92.4%**		**99.1%**		**53.1%**		**99.4%**	

	CDA16 @ 600 psi										
	Flow	TDS		Calcium		Sulfate		Boron		Selenium	
	L/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min
Feed @ 5x:[a]	**20.0**	42,280	845,600	469	9,373	20,628	412,559				
Avg. Feed:		42,665		473		20,816					
Concentrate:[a]	**19.6**	**43,000**	844,520	476	9,349	21,000	412,440	**Not Tested**		**Not Tested**	
Permeate:*	**0.36**	**3,000**	1,080	**67**	24	**330**	119				
Total:			845,600		9,373		412,559				
Recovery	1.8%										
ACF	1.01										
%Salt Rejection:[b]		**93.0%**		**85.8%**		**98.4%**					

* TDS of 3,000 mg/L estimated from Na^+ 882 mg/L and Ca^{2+} and SO_4^{2-} values as shown

	AFC99 @ 600 psi										
	Flow	TDS		Calcium		Sulfate		Boron		Selenium	
	L/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min	mg/L	mg/min
Feed @ 5x:[a]	**20.0**	42,679	853,571	473	9,452	23,820	476,406	31.5	630		
Avg. Feed:		42,839		474		23,910		31.8			
Concentrate:[a]	**19.9**	**43,000**	853,550	**476**	9,449	**24,000**	476,400	**32**	628	**Not Tested**	
Permeate:	**0.15**	**140**	21	**20**	3	**40**	6	**3**	1		
Total:			853,571		9,452		476,406		630		
Recovery	0.8%								631		
ACF	**1.0**										
%Salt Rejection:[b]		**99.7%**		**95.8%**		**99.8%**		**90.6%**			

[a] The 5x feed and retentate TDS values are calculated from mass balance (lab value of 64,000 mg/L TDS in retentate considered too high to be valid

[b] Computed as: $1 - [C_P / (C_F * ACF)]$ where C_F = feed concentration, C_P = permeate concentration, and ACF = average concentration factor

[c] TDS and Ca^{2+} rejections rates for the AFC30 were approximately 10% lower when the feed rate was increased to 20 L/min in the 11/1 test

[d] Re-test (SN#923) was performed on AFC99 permeate from 10/31 test; second values were: <10 mg/L TDS and 5 gm/l boron; electroconductivity readings correlate with initial 140 mg/L TDS value which is why this valued was used in chart

Data Sources: SN# 810-812 (10/23); SN# 816-817and SN#921 (10/24); SN#923-24 (10/31); and data sheets 10/23 and 10/24 tests (JR & JS)

Table III - B

Rejection Properties of 12-Ft. AFC30 Module (10.4 M^2) on Panoche Tile-Drain Water

Analysis of Results of Membrane Pilot-System Tests Conducted on December 9 and 11, 2002

Test Conditions: 10 L/min feed rate @ 300 psi @ 69°F ; Panoche #2 drainwater (7,344 mg/L TDS and 578 mg/L Ca^{2+})

1. Salinity Rejection

BOLD Figures are Actual Lab Data

1		2	3	4	5	6	7	8	9	10	11	12
		Permeate Production			CaSO4 Precipitation	Remaining Feed Tank Conditions					% Salt Rejection	
		Volume	TDS	Removed Salt		Salt Load	Volume	TDS of "Tank Feed" to Membrane[1]				
		Liters	mg/L	mg	mg	mg	Liters	mg/L	mg/L	mg/L		
Volume Concentration Factor								Calculated TDS				
						w/o supersat		w/o supersat	w/ supersat	Actual TDS	without supersat[2]	with supersat[3]
Total Feed:	ACF					2,783,376	**379**			**7,344**		
2.0	1.80	189.8	2,000	379,500	343,282	2,060,594	189.3	10,888	12,702		89.8%	91.3%
2.5	1.70	37.9	**2,536**	95,988	78,469	1,886,137	151.4	12,458	15,244		88.0%	90.2%
3.0	1.70	26.5	2,565	67,951	54,199	1,763,987	124.9	14,123	17,933		89.3%	91.6%
4.0	1.50	30.3	**2,622**	79,394	58,372	1,626,221	94.6	17,186	22,833	**18,846**	89.8%	92.3%
5.0	1.45	18.9	2,638	49,924	32,706	1,543,591	75.7	20,391	27,881		91.1%	93.5%
6.0	1.40	12.9	**2,670**	34,360	29,035	1,480,195	62.8	23,558	33,045	**30,202**	91.9%	94.2%
TOTALS / AVG:	1.59	316.2	2,237	707,117	596,064	1,480,195		16,434	21,606		91.4%	93.5%

Values used in the computer process-design model for %Salt Rejection in the 1st-stage NF

[1] actual TDS (col. 10) was higher than the calculated value (col. 8) because most of the produced CaSO4 (col. 5) remained in solution as supersaturate

[2] Formula = 1 - [Column 3 / (Column 1 * Column 8)] [3] Formula = 1 - [Column 3 / (Column 1 * Column 9)]

2. Calcium Rejection

	1	2	3	4	5	6	7	8	9	10	11
	Permeate Production			Remaining Tank Conditions				% Ca^{2+} Rejection	Precipitation		
	Volume	Ca^{2+}	Removed Ca^{2+}	Ca^{2+} Mass Load**	Volume	Dissolved Ca^{2+}			Suspended Ca^{2+}		CaSO4
	Liters	mg/L	mg	mg	Liters	mg/L	mg/L	1- (col.2/col. 7)	mg/L	mg	mg
Volume Concentration Factor						Total in Tank	100% Saturation				
Total Feed:				219,062	**379**	**578**	**578**				
2.0	189.8	**70**	13,283	205,780	189.3	1087	**551**	**87.3%**	536	101,503	343,282
2.5	37.9	**42**	1,590	102,687	151.4	678	525	92.0%	153	23,202	78,469
3.0	26.5	38	1,007	78,478	124.9	628	500	92.4%	128	16,026	54,199
4.0	30.3	**30**	908	61,544	94.6	650	**468**	**93.6%**	182	17,260	58,372
5.0	18.9	29	549	43,736	75.7	578	450	93.6%	128	9,671	32,706
6.0	12.9	**27**	347	33,718	62.8	537	**400**	**93.3%**	137	8,585	29,035
TOTALS / AVG:	316.2	56	17,684	25,132			496	88.7%		176,246	596,064

Computed on stoichiometric basis based on amount of Ca^{2+} in excess of saturation point

Values used in the computer process-design model for %Ca^{2+} Rejection in the 1st-stage NF

Aabout 20% of initial TDS in drainage feed water

** refers only to dissolved calcium originally in drainage feed water; excludes calcium seed crystals added to system

Data Source: SN#85 (Panoche Batch #2); SN#898-904 (Panoche Batch #2 and TDS & Ca^{2+} in permeates on 12/9 tests); SN#909-910 ("tank feed" TDS on 12/11 tests)

Table III - C

Flux Rates for 12-ft AFC30 Module (10.4 M^2) Used in DP^{3}RO™ Process Design*

Test Conditions: Panoche Tile-Drain Water @ 7,344 mg/L TDS with 20 g/L of $CaSO_4$ seeding @ 10 L/min flow rate

Note: Actual Flux Rates Recorded at 69°F (Col. 1) are converted by formula to design conditions of 65°F for **No Preheat** case (Col. 2) and 92°Ffor **Preheat with Solar Pond** case (Col. 3)

Actual Data Points in Bold

	Feed TDS = ±10,000 mg/L			Feed TDS = ±16,000 mg/L			Feed TDS = ±21,000 mg/L			Feed TDS =±30,000 mg/L			Feed TDS = ±40,000 mg/L		
	2 x concentration factor from Dec 9 and 11 test runs			**4 x** concentration factor from Dec 9 and 11 test runs			**5.5 x** concentration factor during Dec 9 and 11 test runs			**6x** concentration w/supersaturation effect from Dec 11 test run			extrapolated from Dec 9 and 11 test results		
	Osmotic Pressure: ±120 psi			Osmotic Pressure: ±140 psi			Osmotic Pressure: ±180 psi			Osmotic Pressure: ±265 psi			Osmotic Pressure: ±325 psi		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
	Flux Rates (L/M^2•hr)			Flux Rates (L/M^2•hr)			Flux Rates (L/M^2•hr)			Flux Rates (L/M^2•hr)			Flux Rates (L/M^2•hr)		
Pressure	@ 69F	@ 65F	@92F	@ 69F	@ 65F	@92F	@ 69F	@ 65F	@92F	@ 69F	@ 65F	@92F	@ 69F	@ 65F	@92F
psi	Actual	0.948	1.433	Actual	0.948	1.433	Actual	0.948	1.433	Actual	0.948	1.433	Actual	0.948	1.433
450	N/A	N/A	N/A	N/A	N/A		N/A	N/A	N/A	N/A	N/A		17.0	**16.1**	**24.4**
400	58	**55.0**	N/A	50	**47.4**		**41**	**38.9**		26.0	**24.6**	**37.3**	13.8	**13.1**	**19.8**
350	**55**	**52.1**	N/A	42	**39.8**		**36**	**34.1**	**46.4**	22.0	**20.9**	**31.5**	10.0	**9.5**	**14.3**
300	**47**	**44.6**	N/A	**37**	**35.1**	**47.7**	**31**	**29.4**	**42.2**	**16.0**	**15.2**	**22.9**	N/A	N/A	
250	42	**39.8**	N/A	32	**30.3**	**43.6**	**24**	**22.8**	**34.4**	N/A	N/A	N/A	N/A	N/A	
200	32	**30.3**	**45.9**	25	**23.7**	**35.8**	**18**	**17.1**	**25.8**	N/A	N/A	N/A	N/A	N/A	N/A

* 4 (four) 2.5" x 12-ft modules each with 18 tubes (= 216 linear ft.) were connected in series to replicate the 72 tubes connected in series (= 864 linear ft.) in a commercial 8" x 12-ft module

Data Source: "Seed Test with Panoche Drain Water (Batch #2) -- Test on Dec. 9 and Test on Dec. 11" (JS-12/22/02)

Temperature Conversion Chart

Flux Rate Adjustment Factors:*

69F to 68F:	0.987
68F to 65F:	0.961
69F to 65F:	**0.948**
65F to 68F:	1.041
68F to 92F:	1.377
65F to 92F:	**1.433**

°F =	°C
65.0	18.33
68.0	20.00
69.0	20.56
70.0	21.11
77.0	25.00
80.0	26.67
92.0	33.33

*** Formula for temperature adjustment as supplied by PCI:**

$$TCF = e^{-0.024\,(T-20)}$$

where: **TCF = factor for converting flux rate at T (°C) to 20° C**
T = target temperature in °C

Table III - D

Comparative Flux & Rejection Rates from Candidate RO Membranes for DP³RO™ Process

Standardized Feed Condition: NF Permeate @ 200 psi feed pressure @ 10 L/min flow rate

Note: Actual Flux Rates Recorded at 67 to 70°F (Col. 1) are converted by formula to design conditions of 65°F for **no preheat** case (Col. 2) and 92°F for **preheat** case (Col. 3)

	Koch HF			Desal AG			Koch ULP			Hydranautics ESPA1		
Membrane Area (M^2):		2.5			2.5			2.5			2.6	
% Salt Rejection:*		99.3%			99.0%			98.4%			98.9%	
% Boron Rejection*:		79.0%			59.4%			48.1%			68.9%	
Avg. Conctn Factor:		106%			104%			108%			107%	
Feed/Permeate TDS:	4,790	38	mg/L	5,414	58	mg/L	6,158	108	mg/L	6,454	78	mg/L
Feed/Permeate Boron	18	4	mg/L	19	8	mg/L	16	9	mg/L	18	6	mg/L
Feed/Permeate pH:	7.8	6.5		7.3	6.0					7.8	6.8	
Actual Feed Temp:		68°F			70°F			67°F			69°F	
	1	2	3	1	2	3	1	2	3	1	2	3
	Flux Rates (L/M^2•hr)			Flux Rates (L/M^2•hr)			Flux Rates (L/M^2•hr)			Flux Rates (L/M^2•hr)		
Pressure	@68F	@ 65F	@92F	@70F	@ 65F	@92F	@67F	@ 65F	@92F	@69F	@ 65F	@92F
psi	Actual	0.947	1.597	Actual	0.914	1.597	Actual	0.964	1.597	Actual	0.930	1.597
250	22.0	**20.8**	**33.3**	30.0	**27.4**	**43.8**	46.0	**44.4**	**70.9**	37.0	**34.4**	**55.0**
200	17.0	**16.1**	**25.7**	26.5	**24.2**	**38.7**	36.0	**34.7**	**55.4**	33.5	**31.2**	**49.8**
150	12.0	**11.4**	**18.2**	17.0	**15.5**	**24.8**	23.0	**22.2**	**35.4**	16.0	**14.9**	**23.8**
100							10.0	**9.6**	**15.4**			

*Computed as: 1 - [C_P / (C_F * ACF)] where C_F = feed concentration, C_P = permeate concentration, and ACF = average concentration factor

Data Source: SN# 905-908 & 911-916 (TDS and boron in tank feed and permeate for Koch HF, Desal Ag, Koch ULP and ESPA1); Reports from Dec. 12 and Dec 20 test runs (JS - 12/22/02)

Temperature Conversion Chart

Flux Rate Adjustment Factors**		°F =	°C
65F to 77F:	1.2385	65.0	18.33
66F to 77F:	1.2162	66.0	18.89
67F to 77F:	1.1944	67.0	19.44
68F to 77F:	1.1730	68.0	20.00
69F to 77F:	1.1521	69.0	20.56
70F to 7F	1.1316	70.0	21.11
77F to 65F:	0.8074	75.0	23.89
77F to 92F:	1.2896	77.0	25.00
65F to 92F:	1.5972	92.0	33.33

**** Formula for temperature adjustment per Hydranautics technical information:**

$$\mathbf{TCF} = e^{\left(-2786 * \left[\frac{1}{(T+273)} - \frac{1}{298} \right]\right)}$$

where: **TCF** = factor for converting flux rate at T (°C) to 25° C

T = target temperature in °C

-2786 = constant applicable to polyamide membranes

Table III - E

Computation of Rejection Properties of Candidate RO Membranes

NF Permeate (2,500 mg/L TDS) @ 2x concentration @ 10 L/min flow rate @ 69-72°F

Koch HF-2540

	Flow	TDS		Boron	
	L/min	mg/L	mg/min	mg/L	mg/min
Feed @ 2x:	10.0	4,790	47,900	18	180
Avg. Feed:		5,075		19.1	
Concentrate:	8.9	5,377	47,858	476	176
Permeate:	1.1	38	42	4	4
Total:			47,900		180
Recovery	11.0%				
ACF	1.06				
%Salt Rejection:		99.3%		79.0%	
%Mass Flow Rejection:		99.9%		97.6%	

Desal AG-2540

	Flow	TDS		Boron	
	L/min	mg/L	mg/min	mg/L	mg/min
Feed @ 2x:	10.0	5,414	54,140	19	190
Avg. Feed:		5,613		19.7	
Concentrate:	9.3	5,817	54,099	476	184
Permeate:	0.7	58	41	8	6
Total:			54,140		190
Recovery	7.0%				
ACF	1.04				
%Salt Rejection:		99.0%		59.4%	
%Mass Flow Rejection:		99.9%		97.1%	

Koch ULP-2540

	Flow	TDS		Boron	
	L/min	mg/L	mg/min	mg/L	mg/min
Feed @ 2x:	10.0	6,158	61,580	16	160
Avg. Feed:		6,672		17.3	
Concentrate:	8.5	7,226	61,418	476	147
Permeate:	1.5	108	162	9	14
Total:			61,580		160
Recovery	15.0%				
ACF	1.08				
%Salt Rejection:		98.4%		48.1%	
%Mass Flow Rejection:		99.7%		91.6%	

Hydranautics ESPA1-2540

	Flow	TDS		Boron	
	L/min	mg/L	mg/min	mg/L	mg/min
Feed @ 2x:	10.0	6,454	64,540	18	180
Avg. Feed:		6,914		19.3	
Concentrate:	8.7	7,407	64,439	476	172
Permeate:	1.3	78	101	6	8
Total:			64,540		180
Recovery	13.0%				
ACF	1.07				
%Salt Rejection:		98.9%		68.9%	
%Mass Flow Rejection:		99.8%		95.7%	

Data Source: SN# 905-908 (12/6 tests) & SN# 911-916 (12/20 tests)

Table III - F

Drainage-Water Recycling Using DP³RO™ Membrane Process

Plant Design: Nominal 300 AFY Agricultural-Drainage Treatment Capacity

Projected Capital and Operating Costs @ Ambient Feed Conditions

Pilot-Plant Design Parameters:				Low TDS		Mid TDS		High TDS	
Design Basis:	Rev. 6	65°F	System Feed	20.0	gpm	15.0	gpm	14.5	gpm
# NF Modules:	14	8" x 12-ft	NF Feed:*	350	psi	350	psi	375	psi
			Flux:	32.2	L/M²/hr	26.1	L/M²/hr	15.3	L/M²/hr
# RO Modules:	18	4" x 40"	RO Feed:	225	psi	175	psi	300	psi
			Flux:	28.0	L/M²/hr	20.0	L/M²/hr	18.5	L/M²/hr
Scale-up Factor:	16		Specific Power	2632	kWhr/AF	2667	kWhr/AF	3124	kWhr/AF

* 1st stage; 2nd stage is 50 psi higher

Full-Size Facility Design & Capital Costs:					
1. NF Unit w/ pumps, instruments, controls & elec	224	8 in. x 12-ft. AFC30 membranes in modified C10 modules	$3,800	$851,200	51%
2. RO Unit w/ pumps, instruments, controls & elec	72	8" x 40" ESPA2 membranes in 12 x 6 array; 20ft PVC vesse	$5,000	360,000	22%
3. Solids handing equipment	2	x 300-gal reactors with mixers; and two (2) 10-gpm solids pumps		150,000	9%
4. Building, vessels and other equipment	3,600	sq .ft bldg; feed tank; cartridge filters; product, brine and solids tanks		100,000	6%
5. Salinity Gradient Solar Pond	0.0	acres @ $ 100,000		0	0%
5. Salt Evaporator (with catch basin & sprayers)	6.6	acres @ $30,000		199,000	12%
TOTAL ESTIMATED CAPITAL COSTS:				**$1,660,200**	**100%**

Plant Operating Modes:			Low-Salinity Feed TDS = 3,625 mg/L			Mid-Salinity Feed TDS = 6,450 mg/L			High-Salinity Feed TDS = 9,250 mg/L		
Operating Parameters:		Units									
Maximum Operating Rate (Feed Stream Flow)		gpm		320			250			232	
Average Feed Stream Flow Rate @ 95%		gpm		304			238			220	
Recovery Rate (water product as % feed)		% feed		96.6%			92.5%			91.2%	
Average Flow Rate - Product Stream		gpm		294			220			201	
Weeks per Year in Operation	hrs/wk wk/yr	weeks/year		50			50			50	
On-Peak Non-Operation	24 26	hours/year		624			624			624	
Annual In-Service Time (less 8 hrs/wk downtime)		hours/year		7,376			7,376			7,376	
Total Drain Water Processed		acre-feet/year		413			323			299	
Total Product Water Produced		acre-feet/year		399			298			273	
Total Brine Volume Generated		acre-feet/year		14.2			24.3			26.5	
Required Size of Dedicated SCF		acres		3.6			6.1			6.6	
Net Production of Gypsum	g/min	tons/year	909	443	22%	905	440	16%	749	365	10%
Other Salts	g/min	tons/year	3,217	1,566	78%	4,728	2,302	84%	6,943	3,380	90%
Total Solids	g/min	tons/year	4,126	2,009	100%	5,633	2,742	100%	7,692	3,744	100%
Operating Costs:			Units	Annual Amount	$ /AF Drainage	Units	Annual Amount	$ / AF Drainage	Units	Annual Amount	$ / AF Drainage
Electrical Power:*	$/kWhr $/kW	kW Load:		142.3			107.9			115.6	
Summer Off-Peak Rate	$0.07041 $6.55	Production AFY:	182	$34,755	$84	137	$26,346	$82	125	$28,234	$94
Winter Blended Rate	$0.06998 $4.40	Production AFY:	216	40,456	98	162	30,667	95	148	32,865	110
• **Sub-Total: Electrical Power**			399	$75,211	$182	298	$57,013	$177	273	$61,099	$204
Tubular NF Elements	Expected Life:	years	4.0			4.0			4.0		
112 sq. ft. per element	Replacement Cost:	$/ module	$400	22,400	54	$400	22,400	$69	$400	22,400	75
Spiral RO Elements	Expected Life:	years	7.0			7.0			7.0		
380 sq. ft. per element	Replacement Cost:	$/ module	$500	5,143	12	$500	5,143	$16	$500	5,143	17
• **Sub-Total: Replacement Membranes**				$27,543	$67		$27,543	$85		$27,543	$92
Cleaning Supplies	$200 per week	week/year	50	10,000	24	50	10,000	$31	50	10,000	33
Plant Operator@	$55,000 per year	no. of plants	4	13,750	33	4	13,750	$43	4	13,750	46
Other (lab, insurance, etc.)	$12,000 per year	lump sum		12,000	29		12,000	$37		12,000	40
• **Sub-Total: Other Costs**				$35,750	$87		$35,750	$111		$35,750	$119
Total O&M Costs:				$138,503	$237		$120,306	$278		$124,392	$306
Financing Costs											
100% bond financing from SWRCB as Water Recycling Project @ 50% of State of California interest rate[2]	Rate: 4.0%	term in years:	25	$106,273	$257	25	$106,273	$329	25	$106,273	$355
Total Costs for Drainage Treatment:				$244,776	$495		$226,579	$607		$230,665	$661
$ per acre-foot product water:					$614			$760			$845

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* service under Rate B (aggregrate load over 15 kW) of PG&E Schedule AG-5, LARGE TIME-OF-USE-AGRICULTURAL POWER

RJE- 1/28/2003

Table III - G

Drainage-Water Recycling Using DP³RO™ Membrane Process

Plant Design: Nominal 300 AFY Agricultural-Drainage Treatment Capacity

Projected Capital and Operating Costs with Feed Pre-Heat to 95°F

Pilot-Plant Design Parameters:				Low TDS		Mid TDS		High TDS	
Design Basis:	Rev. 6	92°F	System Feed	24.0	gpm	17.0	gpm	16.5	gpm
# NF Modules:	14	8" x 12-ft	NF Feed:*	375	psi	250	psi	350	psi
			Flux:	36.9	L/M²/hr	31.1	L/M²/hr	25.1	L/M²/hr
# RO Modules:	18	4" x 40"	RO Feed:	200	psi	175	psi	300	psi
Heat Load			Flux:	34.0	L/M²/hr	22.5	L/M²/hr	21.5	L/M²/hr
Heat Load	3.95	kW per gpm		94.8	kW	67.2	kW	65.2	kW
Scale-up Factor:	16		Specific Power	2529	kWhr/AF	2163	kWhr/AF	2970	kWhr/AF

Full-Size Facility Design & Capital Costs:		* 1st stage; 2nd stage 50 to 100 psi higher			
1. NF Unit w/ pumps, instruments, controls & elec	224	8 in. x 12-ft. AFC30 membranes in modified C10 modules	$3,800	$851,200	45%
2. RO Unit w/ pumps, instruments, controls & elec	72	8" x 40" ESPA2 membranes in 12 x 6 array; 20ft PVC vesse	$5,000	360,000	19%
3. Solids handing equipment	2	x 300-gal reactors with mixers; and two (2) 10-gpm solids pumps		150,000	8%
4. Building, vessels and other equipment	3,600	sq .ft bldg; feed tank; cartridge filters; product, brine and solids tanks		100,000	5%
5. Salinity Gradient Solar Pond	4.0	acres @ $ 50,000 per acre @ kW thermal per acre =	375	202,000	11%
5. Salt Evaporator (with catch basin & sprayers)	7.2	acres @ $30,000 per acre		215,000	11%
TOTAL ESTIMATED CAPITAL COSTS:				$1,878,200	100%

Plant Operating Modes:			Low-Salinity Feed TDS = 3,625 mg/L			Mid-Salinity Feed TDS = 6,454 mg/L			High-Salinity Feed TDS = 9,250 mg/L		
Operating Parameters:		Units									
Maximum Operating Rate (Feed Stream Flow)		gpm		384			272			264	
Average Feed Stream Flow Rate @ 95%		gpm		365			258			251	
Recovery Rate (water product as % feed)		% feed		96.7%			93.9%			91.6%	
Average Flow Rate - Product Stream		gpm		353			243			230	
Weeks per Year in Operation	hrs/wk wk/yr	weeks/year		50			50			50	
On-Peak Non-Operation	24 26	hours/year		624			624			624	
Annual In-Service Time (less 8 hrs/wk downtime)		hours/year		7,376			7,376			7,376	
Total Drain Water Processed		acre-feet/year		495			351			341	
Total Product Water Produced		acre-feet/year		479			329			312	
Total Brine Volume Generated		acre-feet/year		16.2			21.6			28.6	
Required Size of Dedicated SCF		acres		4.0			5.4			7.2	
Net Production of Gypsum	g/min	tons/year	216	105	23%	273	133	22%	222	108	10%
Other Salts	g/min	tons/year	948	461	100%	1,249	608	100%	1,940	944	90%
Total Solids	g/min	tons/year	4473	566	100%	1521	741	100%	2,163	1,053	100%
Operating Costs:			Units	Annual Amount	$ /AF Drainage	Units	Annual Amount	$ / AF Drainage	Units	Annual Amount	$ / AF Drainage
Electrical Power:*	$/kWhr	$/kW	kW Load:		164.3			96.6			125.7
Summer Off-Peak Rate	$0.07040	$6.55	Production AFY:	219	$40,137	$81	151	$23,591	$67	143	$30,690	$90
Winter Blended Rate	$0.06998	$4.40	Production AFY:	260	46,727	94	179	27,464	78	169	35,729	105
• Sub-Total: Electrical Power				479	$86,864	$175	329	$51,055	$145	312	$66,419	$195
Tubular NF Elements	Expected Life:		years	4.0			4.0			4.0	
112 sq. ft. per element	Replacement Cost:		$/ module	$400	22,400	45	$400	22,400	$64	$400	22,400	66
Spiral RO Elements	Expected Life:		years	7.0			7.0			7.0	
380 sq. ft. per element	Replacement Cost:		$/ module	$500	5,143	10	$500	5,143	$15	$500	5,143	15
• Sub-Total: Replacement Membranes					$27,543	$56		$27,543	$78		$27,543	$81
Cleaning Supplies	$200	per week	week/year	50	10,000	20	50	10,000	$28	50	10,000	29
Plant Operator@	$55,000	per year	no. of plants	4	13,750	28	4	13,750	$39	4	13,750	40
Other (lab, insurance, etc.)	$12,000	per year	lump sum		12,000	24		12,000	$34		12,000	35
• Sub-Total: Other Costs					$35,750	$72		$35,750	$102		$35,750	$105
Total O&M Costs:					$150,157	$209		$114,348	$248		$129,712	$276
Financing Costs											
100% bond financing from SWRCB as Water Recycling Project @ 50% of State of California interest rate²	Rate: 4.0%		term in years:	25	$120,227	$243	25	$120,227	$343	25	$120,227	$353
Total Costs for Drainage Treatment:					$270,384	$451		$234,575	$590		$249,939	$629
$ per acre-foot product water:						$564			$712			$801

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* Service under Rate B (aggregrate load over 15 kW) of PG&E Schedule AG-5 : LARGE TIME-OF-USE-AGRICULTURAL POWER

RJE- 1/28/2003

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Appendix VI

August 26, 2004

Hal Clark
EISG Program Administrator
San Diego State University Foundation
5250 Campanile Dr., MC 1858
San Diego, CA 92182-1858

Re: **Revised Responses to Reviewer Comments on Draft Final Report for EISG Project 01-23**

Ref: WaterTech Partners' EISG Project titled: "Energy-Efficient Process for Using Membrane Technology to Treat and Recycle Agricultural Drainage Water" (i.e., the **D**ouble **P**ass **P**referential **P**recipitation **R**everse **O**smosis or **DP^{3}RO™** Process)

Dear Mr. Clark:

I apologize for the delay in responding to the Review Comments (which I first received in July 2003) of the Draft Final Report (DFR), dated January 29, 2003, for Grant 01-23. However, by the time we had received the Reviewer Comments on the "proof of concept" bench-scale test work on the DP^{3}RO™ process that we conducted under the EISG Project in 4th quarter 2002 and January2003, WaterTech Partners had already been awarded a contract under the CALFED program for conducting pilot-system testing of the DP^{3}RO™ at a field location in Panoche Drainage District in the San Joaquin Valley. This CALFED-funded pilot-system testing of the DP^{3}RO™ process was conducted from December 2003 though May 2004. We felt your **Feasibility Analysis Report** on the DP^{3}RO™ process would be more accurate and useful if we also incorporated the result of this next-stage pilot-system test program in our responses to the Reviewer Comments on the DFR for the EISG Project.

Enclosed herewith for reference is the Draft Final Report, dated June 15, 2004, for the 2003 CALFED Ecosystem Restoration Program (ERP) project (Contract ERP-02-P44) under which the field pilot system testing of the DP^{3}RO™ process was conducted as a "next stage" project after the EISG Project was completed in January 2003. A mentioned in the ERP Project DFR, additional field pilot-system testing of the DP^{3}RO™ process will be conducted under a follow-on project sponsored by the U.S. Bureau of Reclamation (USBR) beginning in August 2004.

With respect to the specific comments made by the technical reviewer of the DFR for EISG Project, we hereby state our agreement or disagreement with such comments and/or provide clarification or additional information as follows:

CONTENT REVIEW CRITERIA

4. Was the research adequate to produce meaningful data? **NO**

We disagree. The purpose of the project was to show efficacy of the preferential precipitation concept and to evaluate different nanofiltration (NF) and reverse osmosis (RO) membranes for use in the subsequent DP^3RO™ process pilot-system tests. Data and graphs on both these matters are presented in the EISG Project DFR. The subsequent pilot system tests showed – just like Figs. ES-1 and 9 in the DFR – that the preferential precipitation effect does, in fact, work. The membranes selected for use in the pilot system based on the EISG Project results performed very well. As noted below, the DP^3RO™ pilot system used in the follow-on ERP Project was designed based on EISG Project data, it and worked very well.

5. Does the report clearly describe the outcome of each project objective? **NO**

We disagree. The Project Objectives are clearly stated on pp. 14-15 of the EISG Project DFR. In the Project Outcomes section (pp. 18-28), achievement of the Project Objectives is correlated with the test results on a point by point basis. Since some objectives refer to the expected/desired performance of commercial DP^3RO™ systems, they cannot be conclusively demonstrated by the single-element shop tests conducted under the EISG Project. In fact, since the NF section and RO section were operated separately in the EISG Project (not as an integrated system with RO retentate recycle, precipitated calcium sulfate extraction, etc.), the DP^3RO™ process itself was never actually reduced to practice in the EISG Project. But, to the extent possible for bench-scale testing, we contend the Project Objectives were met.

6. Are the conclusion drawn supported by the data? **NO**

We disagree. Based on data obtained from the EISG project single-element shop tests, we refined our computer program process model (i.e., the proprietary design drawings contained in Appendix V of the DFR.) We designed the pilot system and selected membranes based on the process model. The pilot system performed very close to the model predictions. Therefore, the data from the EISG Project single-element shop tests supported our conclusions as to how the DP^3RO™ process would work once it was fully configured.

7. Are the recommendations for future work logical and supported by the research findings? **NO**

We disagree. The recommendations (p. 30 of the DFR) refer to the pilot system project. These recommendations were scaled back since only $320,000 in funding (and not $600,000 as stated in the DFR) was obtained; but the fact that most these recommendations were implemented shows they were, in fact, logical and supported by the EISG Project findings.

8. Has adequate performance goals been established for the product? **NO**

We disagree. The performance goals for the DP^3RO™ process with respect to product quality, power consumption, and total water costs (i.e., lower than seawater desalination) are set out as Project Objectives (pp. 14-15). These goals – to the extent realized – will establish the market potential of the DP^3RO™ process. The pilot testing showed that some, but not all, these initial goals are achievable. Hence, some revisions to the DP^3RO™ process performance expectations and costs have been made (see Table 1 on page 6 of the ERP

project DFR). Nonetheless, as indicated in the subsequent ERP Project DFR for, the DP^3RO™ process still has significant market potential as a multi-benefit, cost-effective "new water" supply technology.

9. Has the product met the technical feasibility criteria/test? **NO**

We disagree. The results of the single-element EISG project bench-scale tests (as depicted in the graphs in Figs. 7-14) gave us confidence that the 5-gpm DP^3RO™ process system, as designed in accordance with the refined process design model, would work. In fact, the DP^3RO™ pilot system did work as designed in terms of technical feasibility (i.e., agricultural drainwater containing ~8,000 mg/L of TDS and 17 mg/L of boron was successfully processed into high quality irrigation water with <500 mg/L TDS and <0.50 mg/L boron at >90% water recovery.)

10. Will the field test plan adequately validate the system? **NO**

We disagree. The follow-on field test plan proposed in the EISG Project DFR was to design, install, and operate a 5-gpm DP^3RO™ pilot system on actual agricultural drainwater at a farm tile-sump location in the San Joaquin Valley. This is exactly what we did. The adequacy of this "field test plan" is evidenced by the fact that USBR's drainage treatment and membrane process technical experts, who visited the pilot system test site on several occasions, were impressed enough in the results and the potential of the DP^3RO™ process that they obtained $100,000 in internal USBR Science & Technology Program funding to undertake follow-on pilot testing on their own. The reviewer is correct in that pilot system testing alone will not "validate the system" for widespread commercial application. Only the successful operation of a full-scale prototype demonstration plant over a one-to-two year period will successfully "validate the system." However, since successful pilot system testing is a prerequisite for obtaining funding for a full-scale commercial demonstration project, we feel the proposed field test plan was adequate and achieved its intended purpose.

11. Will the quality plan adequately reduce the risk including those newly identified? **NO**

We disagree. As we defined it in the Development Stage Assessment section on page 33 of the EISG Project DFR, the risk assessment/quality issue for this "product" relates to brine disposal. In the DFR, we referenced the pilot-system test work that the California Dept. of Water Resources was doing on solar evaporators at Red Rock Ranch. In fact, the DWR personnel who are running the RRR facility visited the DP^3RO™ pilot system test site in Panoche on several occasions and engaged in "technology transfer" on the design and operation of solar evaporators for agricultural-drainage brine disposal. In July 2003, DWR got the State Water Resources Control Board (SWRCB) to issue new regulations that specifically exempted solar evaporators that are built and operated as part of an on-farm zero-discharge drainage management system from state toxic-waste laws for selenium. Thus, the reference to the use of on-farm solar evaporators in the EISG Project DFR as an environmentally acceptable method for brine disposal was prescient; and this risk has been removed from the commercialization path for the DP3RO™ process.

14 Is there a commercialization partner commitment? **NO**

While this statement is technically true as of the conclusion of the EISG Project in January 2003, it is no longer true. PCI Membrane Systems, Inc. and ITT Corporation (PCI's parent company) were extensively involved in the CALFED-funded pilot system project and now are committed to pursuing the commercialization of the DP^3RO™ process. PCI/ITT is providing $50,000 in co-funding for the follow-on pilot system project with USBR. PCI has also agreed to provide $200,000 in co-funding for building and operating a 250-gpm DP^3RO™ commercial demonstration project at the test-site location in Panoche. A letter to this effect was included in a proposal that Panoche Drainage District (which also committed to provide $200,000 in co-funding) submitted to the SWRCB in October 2003 seeking $2.1 million in grant funding under Proposition 50 for a DP^3RO™ commercial demonstration project. Unfortunately, this October 2003 proposal was not accepted primarily because, at the time of its submission and review in January 2004, the results of the CALFED ERP pilot-system project, which was completed in July 2004, were not known. Now that the results of the pilot system testing are known, PCI and Panoche plan to apply for grant funding for a DP^3RO™ commercial demonstration project under a subsequent CALFED or SWRCB request for proposals.

SUPPORTING COMMENTS

"Seeding can be used to overcome fouling…. (but) it requires tubular membranes that are costly and energy intensive." This statement reflects a general bias throughout the reviewer's comments against the use of tubular membranes. State-of-art tubular membranes have improved energy-efficient levels compared to older versions, and they are less prone to fouling and can be cleaned easier than spiral or hollow fiber elements. We agree that tubular membranes are more expensive on a $/square foot of membrane area basis. Thus, the "genius" of the double-pass DP^3RO™ process is that tubular NF membranes are used only in the 1st pass unit to remove the hardness in the feedwater; and less expensive spiral RO membrane are used in the 2nd pass unit to completed the desalination of the water. We agree, if the entire DP^3RO™process relied upon the use of tubular membranes (like the "prior art" seeded RO systems built by Juby, et al.), the DP^3RO™ process would be too expensive to be commercially useful – but this is not the case.

"Two long term seeded RO operations are reported in the literature…. Lowering velocity will lower fluxes, decrease rejection and foul the membranes in the long-term operation and impede the successful operation of the membrane system." The reviewer's recitation of the crossflow velocity and power consumption figures from Harries' and Juby's "prior art" seeded RO pilot systems is correct. The reviewer was also correct in noting that the 0.5 m/s module exit velocities, as originally assumed in the design of the DP^3RO™ pilot system, proved be too low to avoid concentration polarization/caking. Because of this, the revised commercial system design (as presented in Appendix D of the ERP Project DFR) is based on maintaining a >1.0 m/s crossflow

velocity (similar to Juby's system) throughout the NF system in order to avoid concentration polarization/caking. However, in the 480 hours of pilot system operations, we did not experience any noticeable irreversible NF flux decline or any decrease in NF membrane rejection rates.*

"The assumptions used in this study to predict lower energy consumption and lower costs than seawater desalination … are not justified … the process will not be more energy efficient or more cost effective compared to seawater desalination."

In the EISG Project DFR, the claim about energy efficiency and cost effectiveness for the DP^{3}RO™ process compared to seawater desalination is ***qualified based on the salinity (TDS) level of the drainwater feed.*** This is why the cost graphs presented in Figs. ES-2 and 15 show DP^{3}RO™ product water costs as a function of the salinity of the drainwater feed. This cost analysis clearly shows that, for drainwater with >9,275 mg/L of TDS, DP^{3}RO™ product water is <u>not</u> projected to be cost competitive with seawater desalination. Thus, the reviewer's blanket statement that "the process will not be more energy or cost effective compared to seawater desalination" refutes a contention that was never made. We acknowledged this fact in EISG Project DFR for high TDS drainwater.

Because of the need to operate at higher NF module crossflow velocities (as mentioned above) and other design and operating limitations learned during the recently completed DP^{3}RO™ pilot-system test program, the range of drainwater TDS levels at which the DP^{3}RO™ is projected to operate with less specific power use and less total costs than seawater RO has been revised. We now project cost-competitiveness with seawater desalination for drainwater with ≤8,000 mg/L TDS. This range still includes about 70% of all farms in the 800,000 acre drainage impaired area in the western San Joaquin Valley. The new post-pilot system project "cost competitiveness" analysis is presented as Figures 15 and 16 in the ERP Project DFR. This updated cost analysis/comparison is based on a range of seawater RO and other potential CALFED project "new water" costs as stated in recent studies and reports. At these revised and updated cost figures, the DP^{3}RO™ is projected to have a $1.2 billion market potential in California as an agricultural drainage desalination technology.

Report in General: Review's comment on the lack of a detailed explanation on testing apparatus, procedures, and parameter is noted and accepted. However, in preparing the DFR, we felt it was more important to present the *results* of the EISG shop-test work in easy-to-understand graphs as they relate to the design and commercial viability of the DP^{3}RO™ process; and to discuss the application and market potential for the DP3RO™ process for agricultural drainwater desalination/recycling. Most people have no idea what agricultural drainage is, why it is a problem,

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*PCI performed autopsy testing on the tubular thin-film-composite AFC30 elements used in the NF unit during the field pilot tests at its Laverstoke, Hampshire, England membrane R&D and manufacturing facility. These sophisticated diagnostic tests indicated that abrasion had occurred to the inside thin-film coating on the AFC30 elements and that flux loss did occur. Consequently, additional field tests were performed with monolithic cellulose acetate membranes (PCI's CDA16) – which is the same type of membrane used by Harries and Juby in their successful "prior art" seeded-slurry RO pilot system work. The re-tests performed with the CDA16s were very successful. Consequently, CDA16 membranes will be used the USBR "expended operation" pilot system project that will commence in October 2004.

and why desalinating and recycling it makes economic sense and is good water policy for the state. We assumed most readers of the DFR would not be membrane process experts and would not understand or be interested in how single-element membrane tests are performed. We will prepare and present a separate technical paper on the details of the how the pilot-system test work was performed and elaborate on the technical results at a membrane technology conference.

Energy Efficiency: The reviewer's comments on crossflow velocity are understood and accepted. As mentioned above, they proved to be correct in the recent pilot system testing; and we have incorporated high crossflow velocities in the revised DP^{3}RO™ system commercial design. As shown in the revised commercial system design on Sheet 2 in Appendix D of the ERP Project DFR, for the desalination of drainwater feed with ~8,000 mg/L TDS at a ~90% water recovery rate, the DP^{3}RO™ process will require a projected 4,965 kwh/AF of electrical power use. This figure is in range of 4,800 to 5,200 kWh/AF for "best case" seawater RO in California – but not lower. Only in the case of drainwater feed at low salinity levels (~3,600 mg/L TDS) will the specific power use of the DP^{3}RO™ process (~3,725 kWh/AF) be >20% lower than seawater desalination – which was our original performance goal in the EISG Project. In fact, the range of specific power requirements for DP^{3}RO™ and seawater RO overlap, and each depends on a number of project-specific variables. Thus, the claim that desalinating agricultural drainwater using the DP^{3}RO™ process will be a more energy efficient technology than seawater RO can be made only on a case-by-case basis.

Flow Rate and Rejection: While we agree (and the pilot system testing showed) that higher NF flux rates are obtained at high crossflow velocities, we did not see any difference in the NF rejection or achievable recovery rates (higher or lower) based on crossflow velocities. We concur with the reviewer's general comment that better NF membrane system performance in terms flux and stability (i.e., avoiding concentration polarization) is obtained at higher crossflow velocities. However, higher crossflow velocities require more power consumption so a tradeoff has to be made.

Osmotic Pressure (Fig. 12) This graph may have been puzzling, but it was remarkably accurate. The light blue line on this graph (NF feed = 30,000 mg/L TDS = 265 psi osmotic pressure) shows that at a 450 psi NF feed pressure, 45% recovery rate, and 2.6 gpm feed flowrate, the expected flux rate of the NF system is 28 lmh (= 16.5 gfd). In Test #32 of the ERP Project pilot system test program (see Appendix A of the ERP Project DFR), NF unit was operated at a 450 psi feed pressure, a 37% recovery rate, and a 4.0 gpm feed flowrate, and we achieved a 26.0 lmh (=15.3 gfd) flux rate. Test No. 32 was run at a higher NF feed TDS level (35,000 vs. 30,000 mg/L) than the graph, which would lower the flux rate. Thus, considering that the higher feed EC level and the higher feed flowrate (4.0 vs. 26. gpm) in Test No. 32 vs. the blue line in Fig. 12 offset each other, the flux rates should be about the same. In fact, they were : 15.3 vs. 16.5 gfd. This comparison shows that, contrary to the reviewer's comments, the testing and data obtained from the EISG Project did provide technically accurate and reliable information for designing and predicting the operation of the DP^{3}RO™ pilot system In response to a specific reviewer question: The test runs in which the data for the Figure 12 graph were developed were conducted using a set of 4 x 12-ft AFC 30 modules connected in series as shown in the picture on page 4 (upper right) in Appendix IV.

Power and Feed Pressure (page 23): Let's see**:** In the example from ERP Project pilot-system Test No. 32 cited above**,** the osmotic pressure of the 35,000 mg/L TDS feed solution was ~300 psi. At a 66% salt rejection rate and 37% recovery, the NF permeate had about 20,000 mg/L TDS -- an osmotic pressure of ~220 psi. Thus, the osmotic pressure differential that had to be overcome in producing permeate was 80 psi. The applied pressure (NF feed pump discharge) was 450 psi and the retentate discharge pressure averaged about 290 psi (which is available to use in a 2nd stage). Thus, the net driving pressure was 160 psi. Give the osmotic pressure differential of 80 psi, the tubular membrane NF system had 80 psi in system hydraulic losses (i.e., energy required for maintaining crossflow velocities). This energy is 50% of the net driving pressure, i.e., the low end of the reviewer's estimate range of 50% to 60%. We acknowledge that tubular membranes are more energy intensive than spiral RO elements – which is why we only remove <30% of the osmotic pressure in the NF section.

Rejection Data: Rejection is not an issue in the design and operation of the NF system.

DP3RO Diagram: We acknowledge some errors in these drawings, including the mass rejection formula that the reviewer caught. These have been corrected in the Appendix D drawings in the ERP Project DFR. The input to this design model is the feed stream (left side of diagram) and the outputs are the product water, brine, boron regeneration stream and gypsum as shown in the right side of the diagram. The main purpose of this model is to (i) determine and show a material balance and (ii) approximate the chemistries of the various process steams. The recycle streams are necessary to achieve a high water recovery rate which is a key performance advantage of the DP^{3}RO™ process compared to other approaches for desalinating high hardness agricultural drainwater. The purpose of the bypass feed is to take advantage of the fact that the Ca^{2+} level in the NF permeate is low enough that some drainwater can be added directly to the RO feed tank.. This technique avoids having to process all the drainwater through the NF – which allows the NF system to be smaller and use less energy. It is more advantageous to do this and run the RO at 50% to 55% recovery than to run the RO at 65% to 70% recovery. Also, better quality RO permeate is produced since adding drainwater directly to the RO feed lowers the TDS of the RO feed. This technique was successfully tested with up to 40% bypass feed during the ERP Project pilot system tests.

Projected Performance (Table 2): Yes, we know that increasing feed stream temperature will lower the rejection rate. The evaluation of the cost/benefits of solar thermal pre-heating of the feed water has been deferred to a later stage in the development of the DP^{3}RO™ process.

Boron: The reviewer is absolutely correct about boron. It was a big problem. As reported and documented in Appendix B of the ERP Project DFR, we had to add a "third pass" boron-selective resin adsorption unit after the RO to get the boron in the DP^{3}RO™ product water down to the <0.7 mg/L specification that the farmers require. This boron adsorption system worked very well on the clean RO permeate, but this "third step" added about $175/AF to the product water costs.

Average Concentration Factor: The definitions and algorithms used in the DFR came from Hydranautics' technical literature available at the Hydranautics web site: www.membranes.com

Rejection Properties (Tables III A, B and D): Comments noted. The difference between VCF and ACF is not important in these tables since these tables are only meant to show the ***relative*** performance difference between different membranes under identical test conditions. Once we added the post-RO boron resin adsorption unit, the boron rejection rates achieved by the RO membrane became unimportant. Thus, any discrepancy in the boron rejection data in the DFR is a non-issue.
Plant Design (Table IIIF); The updated costs for the membrane system, membrane elements, and boron resin costs in the ERP Project DFR are all based on quotes from suppliers. These figures are higher than the figures used in the EISG Project DFR. Obviously, membrane life is not yet known, but PCI thinks its NF membranes should last for 2 to 3 years; and 5 years for RO membrane (especially as the second pass in a two-pass membrane system) is very typical in the industry.

Operating Costs: The reviewer is correct in that there was a formula error in the spreadsheet. The new spreadsheet (Table 4 in the ERP Project DFR) does **not** include unit costs figure on the basis of both drainwater feed and product water since this was too confusing. Only unit costs on the basis of product water are shown so that direct comparisons with seawater desalination and other "new water" supply options can be made.

Electrical Power: In the update spreadsheet, this anomaly does not occur. However, since the DP^3RO™ pilot system tests were run only on high TDS drainwater, the performance, power consumption and total water cost estimates for low and mid-range TDS drainwater are only computed estimates. They are not as accurate as the projections for high TDS drainwater which are based on actual test data.

I hope this information adequately addresses the concerns and issues cited by the technical reviewer and enable you to complete the **Feasibility Analysis Report** for this EISG Project.

At this point, we do not intend to apply for additional PIER funding to support the further development of the DP^3RO™ process as an energy-efficient desalination technology. As noted above, the DP^3RO™ process is currently projected to be only equal or marginally more energy efficient than seawater desalination. The most positive attributes of the DP^3RO™ process is its ability to provide the "environmentally preferred" solution to the agricultural drainage problem in the western San Joaquin Valley (USBR's interest) while simultaneously providing a cost-effective (but not substantially lower cost) source of "new water" compared to seawater desalination, urban wastewater recycling, and most other new water supply options (CALFED's interest). At some point, we may pursue additional PIER funding to evaluate whether adding solar thermal preheating of the drainwater feed would be cost effective and would reduce electrical power consumption.

Please get in touch if there is anything else I need to do to complete this EISG Project.

Sincerely,

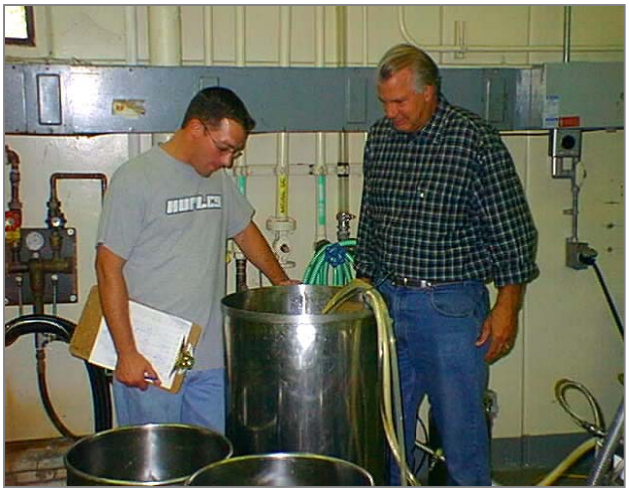
Ronald J. Enzweiler
Project Manager

Encl... Draft Final Report for CBDA Project No, ERP-02-P44

Appendix IV
Photographs of Water, Pilot-Test System, Membranes and Personnel Involved in Membrane Test Program

Above: Location (Drain Pit # 25) in Panoche Drainage District (near Firebaugh) where tile-drain water used in tests was obtained. (Note: Building in picture will be used for pilot plant.)

Above: 300-gallon stainless steel containers used to transport drainwater from Panoche and store it at test facility in Walnut Creek. White containers in back were used to hold NF permeate for use in RO tests.



Above: Dr. Jurgen Strasser and Dr. Karim Nafisi standing next to PCI's pilot-test system that was used in the test program.

Right top: Joe Remanda (system operator) checks feed tank as Ron Enzweiler (Project Manager) looks on.

Right bottom: Panoche drainwater in the 150-liter feed tank before start of a test. The "tinge" appearance is characteristic of agricultural drainwater.

Above: Drs. Strasser and Nafisi assist Mr. Remanda in setting up the pilot system for membrane test.

Above Right: Panoche drainwater (11,000 mg/ of TDS and saturated with $CaSO_4$) used for tests.

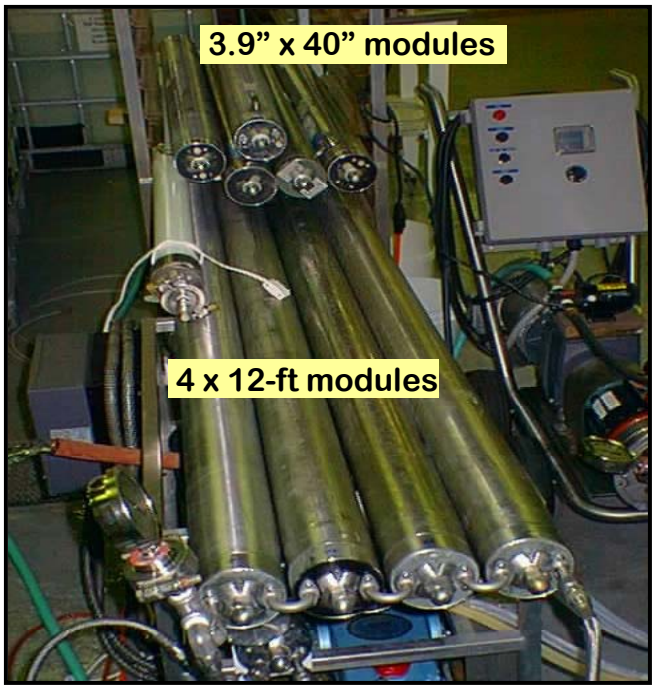
Right: Results of a *non-seeded* concentration test. The buckets on floor contain permeate. The $CaSO_4$ that precipitated out of feed at 4x concentration is visible in bottom of feed tank.

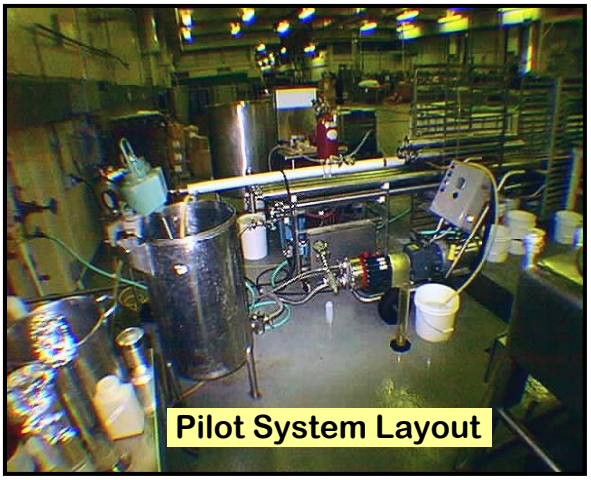
Below left: Dr. Nafisi adds $CaSO_4$ seed crystals to feed tank before starting seeding test. Pneumatic mixer was used to keep seed crystals in suspension in feed tank.

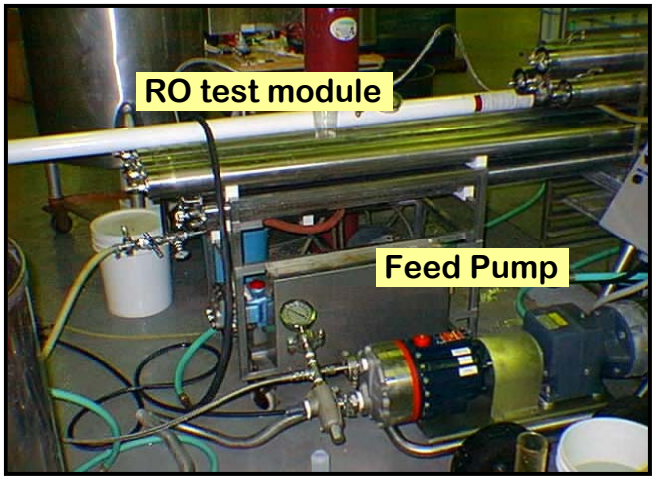
Below right: Feed tank before start of a seeded test.

Top: Appearance of feed tank at beginning of seeded concentration test (left) and after 5x concentration at end of test (right)

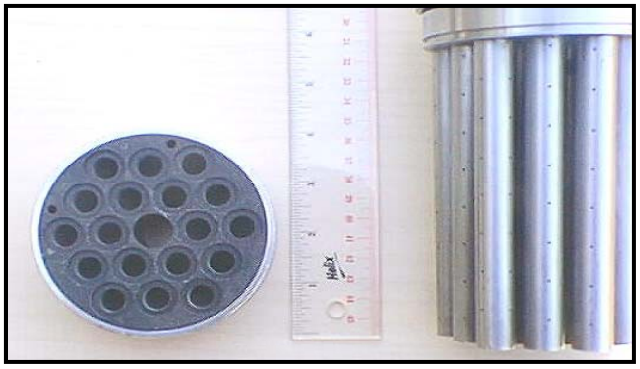
Right: Results from dye test performed to check integrity of 4 x 12-ft. AFC30 modules. The bucket on far left is the concentration. The four other buckets contain the permeate from each individual module. The dye is a proxy for TDS. **This test demonstrates how membranes work**. At a constant operating pressure, the rate of movement of *water* (flux rate*)* through the four modules in series *decreases* as the feed TDS level (and thus feed osmotic pressure) *increases*; however, dissolved *salts* pass at a constant rate through the membrane since salt passage is independent of pressure. Thus, the *permeate TDS level increases (*as shown by the progressively darker colors) from module #1 to module #4.

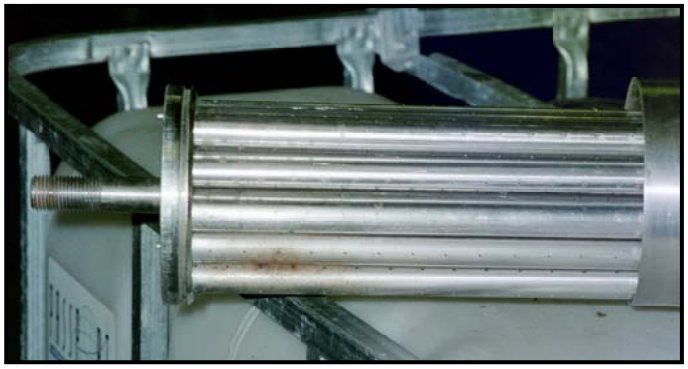


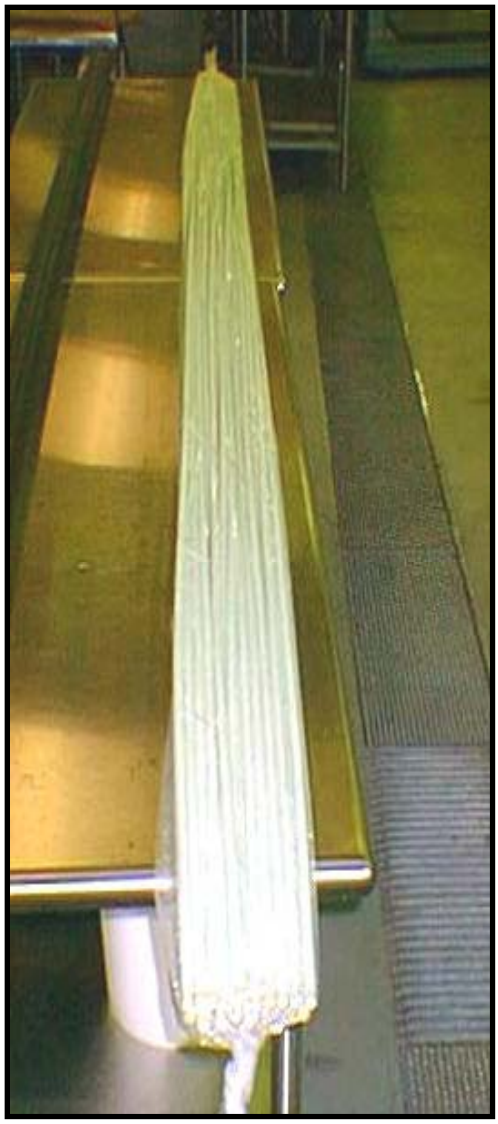




Below: Internal parts of PCI tubular membrane modules. Each 3.9” module contains 18 - ½” diameter tube-holders connected in series (connectors not shown). Replaceable membrane inserts (not shown) are placed inside the perforated tube-holders. The pressurized feed flows *inside* each tube. Permeate trickles out the holes in the tube-holders and collects in the module housing which has a discharge port. (Note: Plastic components [not stainless steel as shown] will be used in commercial DP^{3}RO™ plants.)

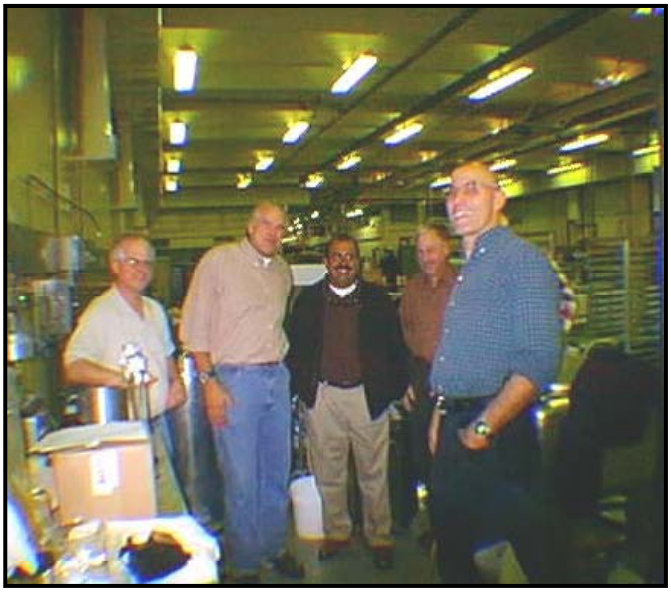






Top Left: Set of 18 – ½ inch diameter x 12 feet long AFC30 membrane elements for insertion into one (1) 3.9” x 12-ft module. All 18 of these 12-ft. tubes were connected in series in each module; and all four 12-ft. modules were connected in series. This provided the equivalent membrane tube length (864 ft.) as contained in one (1) 8” x 12-ft commercial module with 72 tubes. Close-up of end of membrane inserts is shown on left.

Top Right: The four (4) 2.5” x 40” spiral-wound RO membranes that were tested.



Above Left: (left to right) Peter Allan (PCI Membrane Systems), Ron Enzweiler (Project Manager) with David Lara, Kurt Kovac and Jose Faria from DWR at the WCRC on December 11, 2002

Above Right: (left to right) Saied Delagah, Alan Stroppini, and Scott Irvine from USBR at the WCRC on December 19, 2002. This visit was part of Reconnaissance Visit to San Joaquin Valley sites for USBR's In-Valley Alternative Feasibility Study

Below: Dr. Jurgen Strasser (left), Membrane Test Program Director, and Dr. Karim Nafisi (right) Research Chemist. Drs. Strasser and Nafisi provided over 100 in-kind service hours on the project.