Arnold Schwarzenegger
Governor

END-USE EFFICIENT, ENVIRONMENTALLY FRIENDLY WATER-SOFTENING DEVICE

INDEPENDENT ASSESSMENT REPORT

Prepared For:
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Public Interest Energy Research Program
Energy Innovations Small Grants Program

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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.

PIER funding efforts focus on the following research, development, and demonstration (RD&D) program areas:

- 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
- Transportation
- Energy Innovations Small Grant Program

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

The EISG Program conducts up to six solicitations a year and awards grants for promising proof-of-concept energy research.

The EISG Program Administrator prepares an Independent Assessment Report (IAR) on all completed grant projects. The IAR provides a concise summary and independent assessment of the grant project to provide the California Energy Commission and the general public with information that would assist in making subsequent funding decisions. The IAR is organized into the following sections:

- Introduction
- Project Objectives
- Project Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology 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 IAR, please visit the EISG program page on the California Energy Commission's website at: http://www.energy.ca.gov/research/innovations or contact the EISG Program Administrator at (619) 594-1049, or e-mail at: eisgp@energy.state.ca.us.

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

Abstract

Today, brine regenerated, ion exchange (IE) water softeners threaten California's environment. Nano-filtration (NF) and reverse osmosis (RO) are candidate replacement salt-free-softening technologies. Replacing IE softeners with membrane (NF/RO) softening technology would waste one gallon for every gallon softened due to poor water use efficiency. Wasted water is wasted energy. This project built and tested water efficient, salt-less, Flow-Through-Capacitor (FTC) for water softening. New electrode technology, advanced reactor design and improved process control technique were incorporated in the device. Short term testing demonstrated that 90 percent hardness rejection at 90 percent recovery, with preferential rejection of divalent ions. Six month testing required de-rating recovery to 60 percent.

The FTC technology promises high water use efficiency as compared to similarly sized NF/RO. Although the FTC uses water more efficiently, it suffers from high electrical draw at the plug, and high maintenance costs. The economic driver for selecting the FTC over NF/RO does not warrant the risk inherent in new technology. The target performance for the FTC was 60 percent of the energy usage of membrane technology and a 54 percent of NF/RO life cycle cost. These advantages could save California 380 to 1,730 million kWh/yr electricity, or up to 1 percent of the urban electricity consumption, with a retail value of $38 to $173 million per year for consumers. Target energy performance and cost require additional engineering and scale-up. Target lifetime requires unforeseen technology breakthroughs. To achieve target performance, R&D is required to reduce production costs five fold, reduce energy draw at the plug by 40 percent, and increase the service interval ten fold.

Keywords: Brine regenerated, ion exchange, nano-filtration, reverse osmosis, salt-free softening, Flow-Through-Capacitor

Introduction

Future environmental considerations in California may require alternatives to the currently prevalent point-of-entry (POE) water softening technology. Today, 13 percent of California's urban water (approximately 1 billion gallons per day) is softened by an ion-exchange (IE) process. Ion exchange discharges excess salt (sodium chloride) into the sewage system during its regeneration cycle. This conflicts with a trend in California toward restricting brine discharge into municipal sewers. A new, environmentally friendly, water- and energy-efficient technology will be needed for end use if new regulations mandate IE phase-out or replacement. Today's alternatives do not fully meet these criteria. Environmentally friendly reverse osmosis/ nanofiltration (RO/NF) technology presently is available, but it is not end-use efficient.

IE technology sets the benchmark for system cost and end-use efficiency[1] with a recovery percentage between 95 percent, and 98 percent. Since the largest energy cost in water softening processes is the energy associated with the wasted water, highly efficient replacement technologies are preferable. RO/NF has a water end-use efficiency of 40 percent. An alternative technology with a 90 percent recovery rate could save 1,730 million kWh/yr in California (retail value equals $173 million/year). In a state with perennial water shortages and increasing demand, any improvement in efficiency would be a welcome conservation tool.

The researcher proposed the development and evaluation of an advanced, flow-through-capacitor-based (FTC) reactor with new ionic charge barriers (ICBs) in a prototype device that would efficiently soften up to 140 Gal/day of tap water (figure 1). Modifications to small devices now on the market sought to improve both recovery and rejection to greater than 90 percent through new electrode technology, advanced reactor design, and improved techniques of process control. A proprietary, nano-structured carbon electrode was incorporated into the FTC reactor to enhance performance by significantly increasing the active surface areas for ion adsorption and removal. The flow-through reactor was designed to minimize flow resistance and reduce power consumption. Improved process-control techniques for modulation of the applied DC voltage were incorporated in an effort to ensure smooth functioning of the FTC reactor with a long service life and reduced maintenance.

The device consists mainly of two carbon electrodes, two ion-exchange membranes, and a DC power source. As water flows through the narrow gap, an applied electric field removes salts and other species through adsorption onto the electrodes.

[1] The terms "water end use efficiency" and "recovery" are used interchangeably in this report.

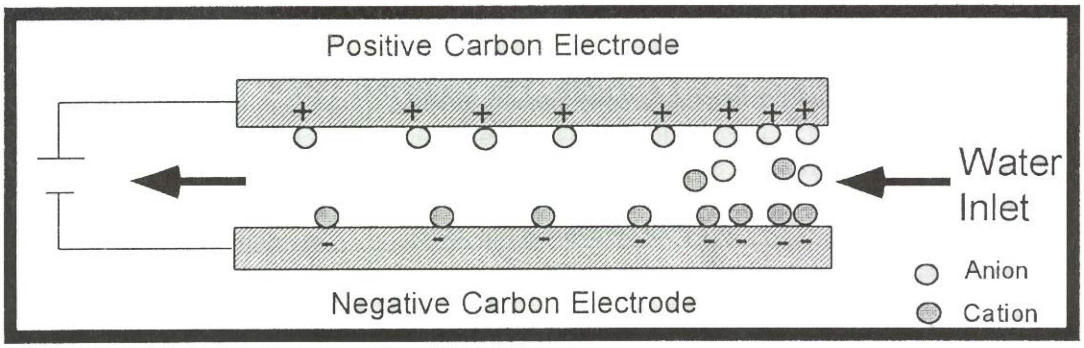

Figure 1: Illustrative Diagram of FTC with Charge Barriers

Objectives

This project was to determine the feasibility of using an advanced, flow-through-capacitor-based (FTC) reactor with new ionic charge barriers (ICBs) to soften water while maintaining low energy usage and 100 percent compliance with mandated levels of salt discharge. The researchers established the following project objectives:

1. Design and fabricate system prototypes
   - Design high-recovery FTC prototypes.
   - Build high-recovery FTC prototypes.
2. Evaluate rejection efficiency
   - Measure hardness rejection for tap water of > 90 percent using fabricated prototypes.
   - Measure repeatability and reproducibility to demonstrate >80 percent confidence.
3. Evaluate energy usage
   - Measure water use efficiency of > 90 percent using fabricated prototypes.
   - Measure device energy input of <3 W-Hr/gallon of purified water.
4. Assess competitiveness
   - Determine life-cycle cost of ownership for POE softening, from the perspective of the homeowner, and compare against both NF and RO.
   - Calculate energy costs and compare against NF and RO.

Outcomes

1. A plate-and-frame electrochemical design was built and incorporated into the prototype. This prototype softener contains power electronics, a controller, pre- and post-filters, and the flow-through capacitor. Prior FTC research and synergistic programs enabled this task. The prototype was capable of purifying 140 gallons per day.

2. A range of operating conditions was identified that satisfy the criterion of greater than 90 percent hardness rejection. High recovery is possible with high rejection, as shown in Figure 2. These data were repeated with both short and long intervals between repeats.

This performance came at a cost in terms of limited life for the device. It operated less than a week at 90 percent recovery before performance dropped significantly. Reducing recovery well below the target criterion to 60 percent extended device life to roughly six months.

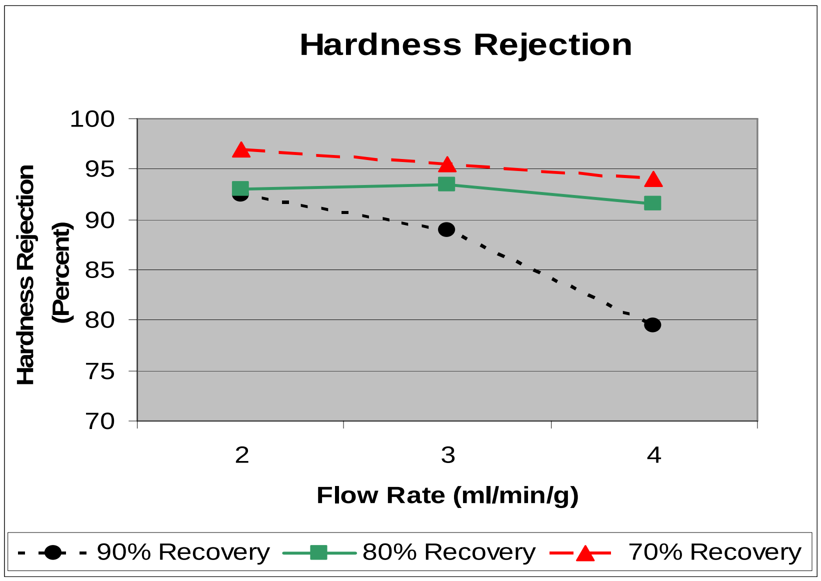

Figure 2: Hardness rejection for the FTC

3. Water use efficiencies of greater than 90 percent were measured over a range of flow rates, as shown in Figure 2. Measured cell energy was 2.92 Whr/gal. Total device energy used for purification was 5.7 Whr/gallon purified, measured at the wall plug. This figure includes the FTC cell energy consumption, plus energy to run the solenoid valves, controller, and power supply. These ancillary components use approximately the same amount of energy as purification.

4.   The life-cycle and total energy cost (including energy to deliver water) of the prototype FTC are similar to NF/RO.[2] The life-cycle cost of the FTC, based on actual performance, is \$9.49/1000 gallon purified[3], while NF/RO life-cycle cost is \$10.52/1000 gallon purified. While the FTC has higher maintenance costs, NF/RO has higher water costs due to lower water-use efficiency.

[2] Here researchers consider NF/RO systems suitable for POE water softening. POE systems have lower salt rejection and higher water use efficiency (recovery) than the popular, 30 gpd, under-the-counter RO systems.
[3] This figure depends on achieving a fivefold reduction from the prototype's \$10,000/gpm production cost to \$2000/gpm for a commercial unit through volume production and additional engineering of \$2 million over two years.

The total energy of the FTC, based on actual performance, is 13.0 Wh/Gal purified, while NF/RO is 14.4 Wh/gal purified. While the FTC has higher purification energy at the plug than NF/RO, its more efficient use of water reduces the energy required for delivery.

Conclusions

1. The goal of designing and building a high-recovery FTC prototype was met, and the device performed successfully in conducting the research for this project.

2. The prototype device met the hardness-rejection goal over a range of operating conditions, demonstrating that high rejection is possible with high recovery. However, the prototype experienced a very short life at 90 percent recovery before performance declined significantly. Reducing operation to 60 percent efficiency increased life to roughly six months, but it compromised the project goal of high efficiency in exchange for a still-short lifetime.

3. When device life was not used as a controlling factor, the prototype displayed high rejection at high efficiencies. Energy efficiency of the cell was within the project's goal of < 3 Whr/gal, but the ancillary load of the remaining hardware (solenoid valves, controller, and power supply) added nearly an identical amount, resulting in a total wall plug usage of almost double the project goal. This result does not necessarily suggest that a production-scale unit would not meet the design goal. The ratio of ancillary load to cell load is unusually high in the small prototype because it was not designed to minimize ancillary loads. In contrast, these loads would not increase much in a larger-size production unit, and the design for such a unit would include optimizing its power consumption. Taking these factors into consideration, the PI estimated that a unit of commercial size could be built with a 3.3 Wh/gal rating.

4. The FTC device with the operating parameters of the prototype would not be commercially viable in competition with NF/RO technology for POE softening. Although it has similar life cycle costs and lower total energy consumption and water usage, its very short lifetime would hinder customer acceptance. A service interval of six months at a cost approaching $1000 would not be acceptable.

The most likely improvement with commercialization would be reduced energy consumption for the device, as described in Conclusion 3 above. The path to solving the tradeoff between device life and efficiency is not as clear; it would depend on future engineering advances that allowed substantially longer life at high efficiencies. The researcher indicates that only limited lifetime studies have been performed. Preliminary indications are that the charge barriers (ion-exchange membranes) are the weak link.

In conclusion, the FTC device developed could meet (or come close to meeting) the original goals set for rejection, water-use efficiency, plug-energy consumption (at commercial scale), and life-cycle costs (at commercial scale, assuming a five-fold reduction in production cost from prototype). However, the study discovered a currently "fatal flaw" in the extremely limited life of the prototype in continuous purification service. Until a significantly longer life (five years compared to the prototype's six months at reduced recovery) is obtained, without offsetting compromises in the other performance parameters, the technology is not commercially viable in competition with available NF/RO technologies for POE softening.

Recommendations

Although today's ion exchange technology is a current winner in terms of cost and performance, at some point it may be prohibited or heavily restricted due to the environmental impact of its brine regeneration process. California needs diverse replacement technologies available to fill the gap as old technology is phased out. Now is the time to do the necessary research and development to make this possible. The limited life of the prototype device poses a significant barrier to its commercialization at this point, and the researcher indicates that there are no plans to continue FTC development. However, the following additional research would help determine whether solutions can be developed that would allow FTC technology to become a viable IE replacement candidate for POE softening:

1. Conduct in-depth studies of FTC lifetime to better understand causes of performance degradation.

2. Conduct analysis and engineering to reduce the causes of FTC performance degradation with a target of five-year service life, while preserving a 90 percent rejection at 90 percent efficiency.

3. Conduct engineering to identify a path to a commercial device with energy usage of greater than 3.5 Wh/gal.

4. Confirm that production costs can be reduced by four-fifths from a prototype to a commercial unit.

5. Identify cost-reduction strategies for charge barriers with a target of a 10-fold reduction.

After taking into consideration (a) research findings in the grant project, (b) overall development status, 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-up funding within the PIER program.

Receiving follow-up 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.

Benefits to California

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

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefits to the ratepayer from this research are increased affordability of electricity in California.

Energy-cost savings occur only if California mandates a phase-out of the current ion-exchange water softeners due to their brine-regeneration process. Once this takes place, the only presently known alternative technologies are NF/RO and, potentially, FTC. Assuming successful commercialization of an FTC device for POE softening, its superior water usage efficiency (90 percent) as compared with RO (40 percent) would provide energy savings through reduced water pumping and wastewater services, as well as conserving California's limited water supply.

Available figures for California's per capita water usage and percentage of electricity consumption used for water pumping and wastewater services yield an electricity consumption of 4.4 Wh/gal. Available estimates show that about 30 percent of residential water customers use softening at a per capita rate of 75 gallons per day, or an estimated total urban water softening usage of 1×10^9 gallons per day. A comparison of water usage between the prototype FTC device and current NF/RO technology shows that the replacement of existing IE with FTC, vs. replacement with NF/RO devices could result in a saving of about 380[4] to 1,730[5] million kWh/yr electricity (up to 1 percent of urban electricity consumption), with a retail value of $38[6] to $173[7] million per year for California.

Overall Technology Transition Assessment

As the basis for this assessment, the program administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated research effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The key driver for commercialization of alternatives to the present ion-exchange technology for POE residential and commercial water softening is potential future legislation curtailing or limiting use of ion exchange due to its brine-regeneration process. A market for alternatives does not exist at present and may not, absent such legislation or a substantial technological breakthrough in the cost of these alternative technologies (which is judged unlikely). A demonstration of successful alternative technologies such as FTC could hasten the transition away from ion exchange.

Engineering/Technical

While the technical feasibility of FTC water softening was demonstrated, the study identified a very short life span of the device as a limitation to commercial adoption. Further research into the causes and potential remedies of this limitation would be needed to move it toward commercialization. Confirmation also is needed of a substantial reduction in the device's energy usage and fabrication cost at commercial scale.

[4] Savings at 60% efficiency required to extend prototype life to six months.
[5] Savings assuming further research leads to operation at >90% efficiency with five-year life.
[6] Corresponds to 60% efficiency.
[7] Corresponds to 90% efficiency.

Legal/Contractual

The studied technology is based on an outside patent, and a license would be required for commercial development. The PI has not applied for any patents.

Environmental, Safety, Risk Assessments/ Quality Plans

See "Engineering/Technical" above.

Production Readiness/Commercialization

The researcher has identified a path to reduced cost and indicates a need for more data to establish a technical path to address lifetime and energy draw. He estimates that a decision to proceed would require three years to complete engineering development and demonstration. A commercialization plan was prepared three years ago, but it has not been updated. At present, the researcher has no plans to proceed, and he was unable to identify a potential development partner among manufacturers of ion-exchange equipment. Present development uncertainties and the absence of forcing legislation create risks judged to exceed potential rewards.

Appendix A: Final Report (under separate cover)

Attachment A – Grantee Report

End-Use Efficient, Environmentally Friendly Water Softening Device

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Legal Notice

Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

Acknowledgement

Development and commercialization of Flow Through Capacitor technology continues to capture enthusiasm with a promise of efficient, environmentally friendly water desalting. Many entities and people have joined in. This Commission project is part of that history. Successful completion of this project is due to the intelligence and hard work, at Material Methods LLC, of Devant Xoai, Robert Porter, Michael Craft, Quang Duc Pham, King Jeng, Ben Craft, Mark Drzymkowski, and Anton Hoang. The champion and visionary for the Flow Through Capacitor is Marc Andelman of Biosource, Inc.

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Abstract

Today, brine regenerated, ion exchange (IE) water softeners threaten California's environment. Nanofiltration (NF) and reverse osmosis (RO) are candidate replacement saltfree-softening technologies. Replacing IE softeners with membrane (NF/RO) softening technology would waste one gallon for every gallon softened due to poor water use efficiency. Wasted water is wasted energy. This Commission project built and tested a water efficient, saltless, Flow-Through-Capacitor (FTC) for water softening. New electrode technology, advanced reactor design and improved process control technique were incorporated in the device. Short term testing demonstrated 90% hardness rejection at 90% recovery, with preferential rejection of divalent ions. Six month testing required derating recovery to 60%.

	End use efficiency (%)	Total Energy Use (Whr/gal purified)	Life time (months)	Life cycle Cost ($/1000 gal)
RO/NF	40	14.4	60	10.5
FTC Actual	60	13.0	6	9.5
FTC Target	90	8.2	60	5.2

Table 1. Comparison of RO/NF (incumbent) and FTC saltless softening technologies for point of entry softening (300 gpd). Conditions are 90% rejection of 20 grains hardness. The FTC unit size is 140 gpd.

The FTC technology promises high water use efficiency as compared to similarly sized NF/RO. Table 1 summarizes the actual results of this program. The table also includes projections for the FTC at its high performance target. Actual performance of the FTC vs. NF/RO is comparable. Although the FTC uses water more efficiently, it suffers from high electrical draw at the plug, and high maintenance costs. The economic driver for selecting the FTC over NF/RO does not warrant the risk inherent in new technology. The target performance for the FTC was 60% of the energy usage of membrane technology and a 54% of NF/RO life cycle cost. These advantages could save California 380 to 1,730 million kWh/yr electricity, or up to 1% of the urban electricity consumption, with a retail value of $38 to $173 million per year for consumers. Target energy performance and cost require additional engineering and scale-up. Target lifetime requires unforeseen technology breakthroughs. To achieve target performance, R&D is required to reduce production costs five fold, reduce energy draw at the plug by 40%, and increase the service interval ten fold.

Executive Summary

1. Introduction

The goal of this project was to determine the feasibility of using an advanced Flow Through Capacitor (FTC)-based reactor with a new Ionic Charge Barriers (ICB) to soften water with low energy usage and 100% compliance with mandated salt discharge levels. Today, brine regenerated softeners threaten California's environment. Replacing salt regenerated softeners with existing membrane reverse osmosis/ nanofiltration (RO/NF) technology would avoid salt, but waste one gallon for every gallon softened. Wasted water is wasted energy. The FTC promises chemical free softening and high water use efficiency.

2. Project Objectives

- System Design and Fabrication
    - Design of high recovery FTC prototypes
    - Build high recovery FTC prototypes
- Evaluate Rejection Efficiency
    - Measure hardness rejection for tap water of > 90% using fabricated prototypes
    - Measure repeatability and reproducibility to demonstrate >80% confidence
- Evaluate energy usage
    - Measure water use efficiency of > 90% using fabricated prototypes
    - Measure device energy input of <3 W-Hr/gallon of purified water
- Competitive Comparison
    - Life cycle cost of ownership for POE softening, will be from the perspective of the homeowner and a comparison will be made against both NF and RO
    - Calculate energy costs compared to NF and RO

3. Project Outcomes

- A prototype system was designed and fabricated

A plate and frame electrochemical design was built and incorporated into the prototype device shown in Figure 1. This prototype softener contains power electronics, a controller, pre and post filters, and the flow through capacitor. Prior FTC research and synergistic programs enabled this task. The prototype unit was capable of purifying 140 gpd.

- Evaluate Rejection Efficiency

A range of operating conditions were identified that satisfy the criterion of > 90% hardness rejection. High recovery is possible with high rejection, which indicates that FTC performance can meet the project goals and market needs. These data were repeated with both short and long intervals between repeats.

- Evaluate energy usage

The device energy utilized for purification is 5.7 Whr/gallon purified. This energy is measured at the wall plug. It includes the FTC cell energy consumption plus energy consumed by the solenoid valves, controller, and power supply. The energy required for these ancillary components approximately equals the energy used for purification. TheFTC device did not meet the energy target of less than 3Whr/Gal, but this situation can be improved in a commercial device through selection of more energy efficient ancillary components. The FTC performance limit is estimated at 3.3 Whr/Gal purified. Combined with high water use efficiency, this performance provides significant energy savings compared to RO/NF.

- Competitive Comparison

The life cycle and total energy (including the water delivery energy) cost of the actual, prototype FTC are similar to NF/RO. Here we consider NF/RO systems suitable for POE water softening. POE systems have lower salt rejection and higher water use efficiency (recovery) than the popular 30 gpd POU, under the counter RO systems. The life cycle cost of the FTC, based on actual performance is $9.49/1000 gallon purified while NF/RO life cycle cost is $10.52/1000 gallon purified. While the FTC has higher maintenance costs, NF/RO has higher water costs due to lower water use efficiency. If the FTC operated at its projected performance target, it would be about half the cost of NF/RO, or $5.15/1000 gallon purified.
The total energy of the FTC, based on actual performance is 13.0 Wh/gal purified, while NF/RO is 14.4 Wh/Gal purified. While the FTC has higher purification energy at the plug than NF/RO, its better water use efficiency reduces the water delivery energy. If the FTC operated at its projected performance target, it would be about 60% the energy of NF/RO, or 8.2 Wh/gallon purified.

4. Conclusions

The prototype device suffered from a short lifetime. The lifetime was extended to 6 months by reducing the water use efficiency from 90% to 60%. Even with this derating, the FTC is not commercially viable. The consumer is not prepared to service a POE softener semiannually. In addition to the inconvenience, the FTC life cycle and energy costs are similar to NF/RO. There is no driver for adopting the novel FTC technology. On the other hand, strong economic drivers exist for the FTC operating in the performance limit. Therefore, FTC commercialization will depend on unpredictable engineering advances that will enable 90% water use efficiency, 3.3 Whr/gal device energy, and at least a 60-month service interval.

5. Recommendations

FTC technology is viable, and capable of high hardness rejection, and high water use efficiency. The major obstacle to commercialization (as a replacement for outlawed ion exchange) is limited device lifetime. The FTC performance, cost, and convenience all trade off with device lifetime. Only limited lifetime studies have been performed, more varied and more detailed studies are needed. Detailed analysis of lifetime failure is beyond the scope of this Commission project. These studies should be coupled with analytical efforts to determine the causes of performance decay with use. Initial analysis indicates that the weak link is in the charge barriers (ion exchange membranes.) Charges barriers are also a critical cost element. Commercialization cost projections assumed a ten-fold reduction in charge barrier cost. Lifetime investigation should be tied to charge barrier cost reduction strategies.

6. Public Benefits to California

The energy savings derives from the targeted end-use efficiency of the FTC (90%) as compared with RO (40%). The replacement of existing ion exchange softening with FTC, vs. replacement with NF/RO devices will result in a saving of about 380 to 1,730 million kWh/yr electricity, or up to 1% of the urban electricity consumption, with a retail value of $38 to $173 million per year for California. Both the State and consumers can benefit from these savings. In comparison to existing ion exchange softening, and without regard to environmental impact, the FTC represents significant increase in energy use and cost. The incumbent ion exchange technology will not be replaced without a legislative imperative.

Introduction

In the United States, the water and wastewater sector annually consumes 75 billion kWh—3 percent of the total consumption of electricity [1], in California this sector consumes 5% of total electricity consumption [2] or 12.7 billion kWh/year, with a retail value of about $1.65 billion. Energy costs constitute approximately half the wholesale cost of water supply and wastewater disposal; energy is about 4.4 Wh/gallon. This project addresses the PIER subject area of water end-use efficiency as an opportunity to increase California industrial competitiveness, and to reduce energy consumption. The residential, commercial, and industrial process of water softening, the reduction of hardness due to dissolved calcium and magnesium, presents a timely opportunity for energy and environmental conservation.

Approximately 1 billion gallons per day, or 13% of California's urban water is presently softened by an ion exchange (IE) process. Ion exchange discharges excess salt (sodium chloride) into the sewage system. The trend toward the restriction of brine discharge into municipal sewers has been brewing for a number of years in California-especially in Southern California. California is a big market for water softeners and has often set the standard for water treatment regulation[4]. Provisions in SB 1006 (Costa1999) that allow local communities to restrict automatic water softeners went into effect January 1, 2003 [5]. As ion exchange softeners are eliminated to protect the environment, end-use efficient, environmentally friendly replacement technology is needed. While reverse osmosis/ nanofiltration (RO/NF) technology is presently available as an environmentally friendly alternative, RO/NF is not end-use efficient.

The largest energy cost in water softening equipment is the energy associated with the wasted water. This Commission project investigated the capability of novel technology to provide high water end use efficiency and hence low energy water softening. The proposed FTC technology is expected to operate at 60% of the energy usage of state of the art technology, RO. This energy efficiency is won through 90% water end use efficiency vs. 40% end use efficiency for RO. Less energy consumption, less waste generation, more water conservation mean greater state competitiveness and state ability to accommodate growth.

The results from this Commission project are organized as project objectives (goals associated with the demonstration of FTC technology readiness,) project approach (detailed experimental procedures and data,) conclusions (interpretation of the data apropos of the objectives,) recommendations (a suggested course forward,) and benefits to the State (economic rewards of this technology.)

Project Objectives

The overall objective of the proposed project was the development of an energy efficient potable water device for residential and commercial applications. The specific objectives of the project were

- 1) System Design and Fabrication
    - Design of high recovery FTC prototypes
    - Build high recovery FTC prototypes
- 2) Evaluate Rejection Efficiency
    - Measure hardness rejection for tap water of > 90% using fabricated prototypes
    - Measure repeatability and reproducibility to demonstrate >80% confidence
- 3) Evaluate energy usage

- Measure water use efficiency of > 90% using fabricated prototypes
  - Measure device energy input of <3 W-Hr/gallon of purified water
- 4) Competitive Comparison
  - Life cycle cost of ownership for POE softening, will be from the perspective of the homeowner and a comparison will be made against both NF and RO
  - Calculate energy costs compared to NF and RO

Project Approach

Experiments were conducted on a small-scale, laboratory-sized FTC-based electrochemical device capable of treating 140 gal/day potable water. The principal focus of the technical approach during the six-month period was to perform fundamental studies on the removal of salts from tap water in an energy efficient manner.

The FTC is mainly composed of two carbon electrodes made of high-surface-area carbon powders. Between these two carbon electrodes, there is a small spacing for the flow of water containing arsenic and other dissolved species. A DC power source is then connected to the two electrodes making it an electrochemical capacitor with one positive and one negative electrode. In a practical design, a piece of porous, hydrophilic material, inserted between these two electrodes, serves as a separator as well as a water channel and distributor.

- 1) System Design and Fabrication

  Material Methods engineers designed a FTC water softener device complete with electrochemical cell, electronics, and plumbing. Previous experience in larger FTC research programs, informed these softener designs. Components were machined by outside vendors. Material Methods engineers performed assembly and test.
- 2) Evaluate Rejection Efficiency

Using the cell designed in Task # 1 we set up a test protocol to study hardness removal. Four flow rates and three recoveries (water use efficiencies) were used for a total of twelve test permutations. These 12 test combinations were tested over a period of 2 days.

Inlet flow rates ml/min of flow/gram of carbon	Recoveries (%)
1	70
2	80
3	90
4	—

Table 2. Test parameters for rejection efficiency tests.

The test procedure was to collect a fixed water supply for the experiment to avoid uncertainties associated with daily variations in the tap supply. Two fifty-gallon storage drums were filled with Newport Beach tap water. The conductivity was 650 microsiemens/cm and the hardness was 200ppm (12grains) of hardness as $CaCO_3$. Water hardness is classified as <5grains moderately soft, <10grains…. moderately hard & > 20grains very hard. Using the stored water as a stable feed source to the FTC cell, conductivity data was recorded on the computer during the entire test runs. Then, purified samples were taken after a stabilizing period (usually < 30 min) & the hardness was measured.

- 3) Evaluate energy usage

We used the FTC Demo Unit that was built from the Task #1 to measure for the total device energy consumption. Task #2 reported a range of 90% recovery rejection rate. The optimum flow rate was chosen at 2ml/min/g because this was the highest flow rate at which the FTC device could still could reject more than 90% hardness. The solution used for running the test was “tap” water at 500 ppm total dissolved solids (TDS) and 200 ppm hardness.
The energy input was measured at three different locations:

1. Energy input to the FTC electrochemical cell alone
2. Energy for electronics accessories (power supply inefficiency, solenoid valves)
3. Total energy input for the whole device

- 4) Competitive Comparison

FTC and incumbent technology costs are calculated with standard cost inputs, and representative performance inputs. Both life cycle cost (the consumer’s perspective,) and energy use (the State’s perspective) are calculated. The life cycle cost (dollar per gallon purified over the device lifetime) is calculated by the following formula:

$$\text{Life Cycle Cost} = \frac{\text{Device Cost}}{\text{Lifetime}} + \frac{\text{Water Cost}}{\text{r}} + \text{Electricity Cost} \bullet \text{Purification Energy} + \text{Maintenance Cost} \tag{1}$$

The energy use (watt-hour per gallon purified) is calculated by the following formula:

$$\text{Energy Use} = \frac{\text{Delivery Energy}}{\text{r}} + \text{Purification Energy} \tag{2}$$

In these calculations WaterCost ($/gal) is the retail cost of tap water; *r* is the dimensionless ratio of water purified to water input, i.e. end-use efficiency; ElectricityCost ($/kWH) is the retail cost of electricity, PurificationEnergy (WH/gal) is the energy used by the purification device to produce one gallon; MaintenanceCost ($/gal) is the cost of replacement components and reagents; DeliveryEnergy (WH/gal) is the energy cost of supplying and removing one gallon of water to and from the residence, i.e. State pumping and waste treatment energy expense.

Project Outcomes

- 1) A prototype system was designed and fabricated

A plate and frame electrochemical design was built and incorporated into the prototype device shown in Figure 1. This prototype softener contains power electronics, a controller, pre and post filters, and the flow through capacitor. This task was enabled by prior FTC research and synergistic programs.

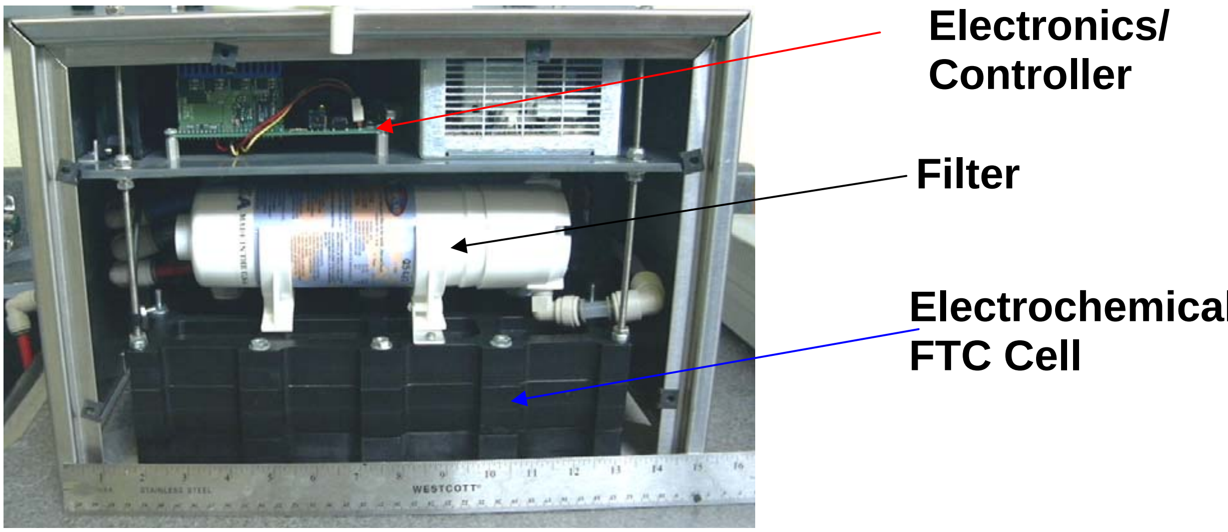

Figure 1. Prototype system. System throughput is about 0.1 gallon per minute for tap water softening.

- 2) Evaluate Rejection Efficiency

A range of operating conditions were identified that satisfy the criterion of > 90% hardness rejection. Figure 2 summarizes the data; here flow rates are normalized on the mass of carbon electrodes incorporated in the FTC. At a flow rate of 2 ml/min/g carbon, all data points showed > 90% hardness rejection for recoveries of 70% to 90%. At 3 and 4 ml/min/g carbon, >90% hardness rejection was shown at 70% & 80% recoveries. High recovery is possible with high rejection, which indicates that FTC performance can meet the project goals and market needs.

Flow Rate	Recovery	Hardness Removal	Conductivity Purification
(ml/min/g)	(%)	(%)	(%)
2	90	92.5	88
3	90	89.0	74
4	90	79.5	54

Table 3. Selective ion removal data.

Additionally, preferential divalent ion (over monovalent ion) rejection was observed under these conditions. Table 3 shows that hardness removal (divalent rejection) exceeds conductivity purification (predominantly monovalent rejection.) An ideal water softener only rejects the divalent ions, and allows the monovalent ions to pass. In this way, hardness is removed, but the ionic strength of the water is not altered.

Figure 2 show a trade off between recovery & flow rate while hardness rejection is at least 90%. If MAXIMUM RECOVERY (minimum energy cost) is required then operating at 90% recovery at approx. 2.75ml/min/g carbon (interpolated from the data) meets the 90% hardness rejection. If MAXIMUM FLOW (minimum device cost) is required then operating at 4 ml/min/gm at 80% recovery is optimal. These data were collected in short duration (one hour) laboratory runs. In the economic analysis, we will discuss tradeoffs between recovery and lifetime.

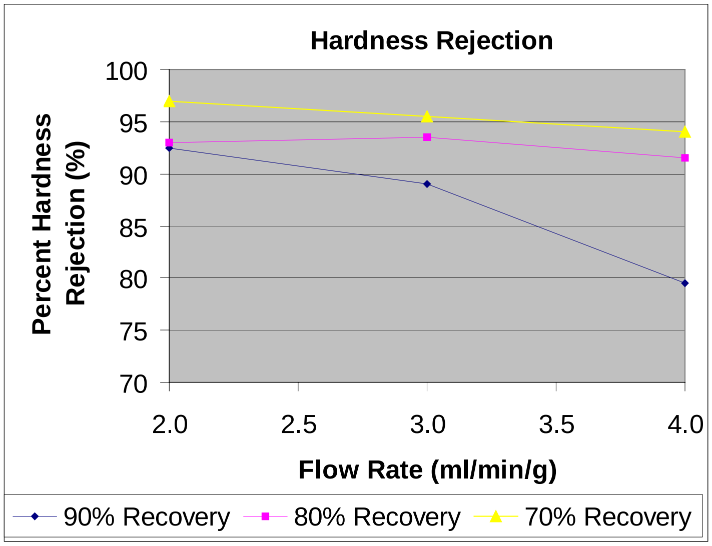

Figure 2. Hardness rejection for the FTC.

Repeatability variance of <+/- 1% was measured over short time periods, as shown in Figure 3. Reproducibility within +/- 5% was seen in comparison with conductivity data taken 1 year ago.

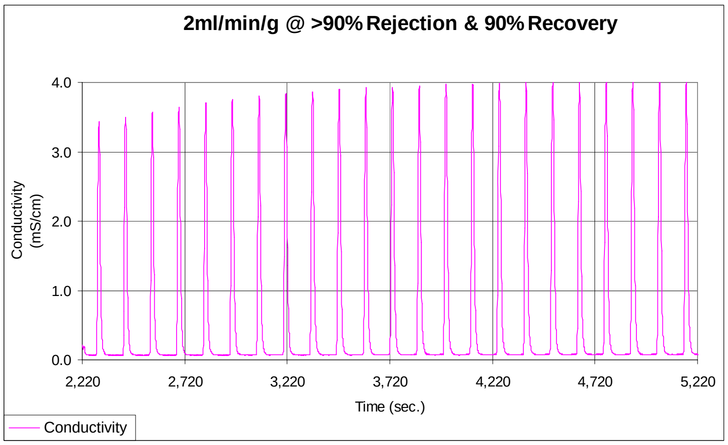

Figure 3. High recovery repeatability data. Conductivity of outlet stream.

3) Evaluate energy usage

Table 3 demonstrates the capability of the FTC softener to remove 90% of the hardness at 90% water use efficiency. Table 4 shows the direct energy consumption for the FTC. Theoretical cell energy is based on the ion current corresponding to the measured purification and the applied voltage. Measured cell energy is based on measured cell electronic current and cell voltage. Their ratio is the cell coulombic efficiency, 76%. The measured cell energy meets the project target value of 3 Whr/Gal.

The total device energy is measured at the wall plug. It includes the FTC cell energy consumption plus energy consumed by the solenoid valves, controller, and power supply. The energy required for these ancillary components approximately equals the energy used for purification. The FTC device did not meet the energy target of less than 3Whr/Gal. This situation can be improved in a commercial device. Ancillary component usage will be a smaller part of the device total in larger, commercial devices. A commercial device will have more engineering effort in the design of ancillary components and in the FTC cell efficiency. In a commercial device the estimated energy usage will be 3.3 Whr/gal.

Theoretical Energy, Cell (Whr/Gal)	Measured Energy, Cell (Whr/Gal)	Total Demo-Device Energy (Whr/Gal)	Energy for Device other than FTC cell (Whr/Gal)	Target (Whr/Gal)
2.25	2.92	5.66	2.74	3.00

Table 4 Energy consumption breakdown for individual component.

The sizes of the RO/NF and prototype FTC are 300 and 140 gpd. These sizes provide reasonable comparison to each other, but the RO/NF device and the FTC are only 10% the size (measured as peak flow rate) of existing ion exchange devices. The saltless technologies both require water storage tanks to average usage over the entire day.

- 4) Competitive Comparison

Table 5 gives system components and representative costs for point of entry, saltless softeners. A family of four requires about 300 gallons per day of softened water. Peak demand is about 10 gallons/minute. To meet peak demand economically, saltless softeners are sized for average usage (0.25 to 0.5 gpm) and fitted with a storage tank. The RO/NF system requires a booster and repressurization pump. The FTC has low pressure drop, and it can operate off city pressure and still pressurize a storage tank.

The FTC (electrochemical cell, controls, and power supply) retail costs were extrapolated from prototype costs of $10,000/gpm down to production costs of $2000/gpm. This cost point requires volume production and additional engineering. The additional investment required to reach this point is about $2 million and two years. The system costs for RO, NF and the FTC are all similar. Most of the cost is in the balance of system, not the purification component.

Component	RO/NF	FTC
(2) 2.5x40 membranes	$549.00	$1,000.00
re-pressurization pump	$650.00	NA
re-pressurization tank	$1,000.00	$1,000.00
1/3 HP motor and pre-pressure pump	$300.00	NA
pre-filtration	$300.00	$300.00
(2) membrane housings	$300.00	$300.00
ozonation	$600.00	$600.00
pressure gages, rotameter, misc	$150.00	$150.00
skid	$400.00	$400.00
labor, assy, margin, warranty	$500.00	$500.00
Total	**$4,749.00**	**$4,250.00**

Table 5. Retail costs of saltless, softener systems, 0.5 gpm.

Equation (1) describes the life cycle cost. The system cost input to (1) is in $/gpm, or double the total costs shown in Table 5 for a 0.5 gpm system. The lifetime in equation (1) refers to the replacement interval for the entire system. The market expects a water softener appliance to last the duration of a typical home mortgage or about 15 years. During that time, the RO/NF system will have to replace membranes about every five years. The prototype FTC was tested for continuous purification at 90% recovery, and it only lasted less than a week before performance dropped 20%. Figure 4 shows FTC performance at 60% recovery. Performance is stable for 6 months. Longer lifetime may be possible, but a 6-month replacement interval, charge barriers and electrodes would have to be replaced. These items represent about half the FTC cost, or $1,000/gpm.

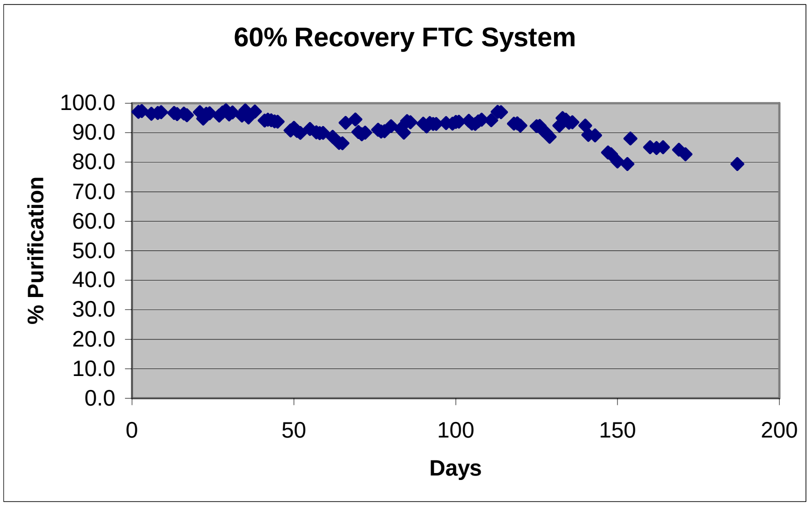

Figure 4. FTC life time performance at 60% recovery.

While the mechanisms of FTC failure are not understood, initial data suggest that the charge barriers become fouled or scaled. These data include: brief performance recovery after washing the membranes in dilute hydrochloric acid, increased membrane resistance with use, and increased life with lower brine reject concentration. Other lifetime factors may be corrosion of electrical contacts or corrosion of the carbon electrode surface.

The FTC device can be characterized by actual performance and by estimated limiting performance. Table 6 summarizes this range. Actual performance has been demonstrated on the prototype FTC in this Commission project. Target performance is estimated. For example the device energy was measured on the prototype at 5.7 Wh/gal purified. In a commercial device, this value could be 3.3 Wh/gal purified. This target performance estimate is based on a coulombic efficiency of 76% and a device energy efficiency of 90%.

	Recovery	Service Interval (months)	Device Energy (Wh/gal)
Actual	0.6	6	5.7
Target	0.9	60	3.3

Table 6. Range of FTC performance.

Table 7 lists the inputs to equation (1) and the resulting life cycle costs. Device costs are similar, water costs differ due to the higher recovery of the FTC. While membrane replacement costs are similar for the two devices, the replacement interval is a factor of 10 shorter for the FTC. The higher maintenance cost for the FTC is matched by a higher water cost in RO associated with lower recovery. The actual FTC and NF/RO life cycle costs are similar. In the limit of FTC performance, FTC cost of ownership can be about half NF/RO cost.

	FTC Actual	NF/RO	FTC Target
Device Cost ($/GPM)	8500	9500	8500
Water Cost ($/Gal)	0.003	0.003	0.003
Electricity Cost ($/Whr)	0.0001	0.0001	0.0001
Membrane Replacement Cost ($/GPM)	1000	1100	1000
Operation & Maintenance Cost ($/GPM)	N/A	0.29	N/A
Water Treatment Cost ($/GPM)	N/A	0.58	N/A
Recovery	0.60	0.40	0.90
Life Time (months)	180	180	180
Membrane Replacement Interval (months)	6	60	60
Power Consumption (Whr/Gal produced)	5.7	3.4	3.3
Life Cycle Cost ($/ 1000 Gal)	10.52	9.49	5.15

Table 7. Life Cycle Cost comparison.

Table 8 compares RO technology at 40% water use efficiency to the FTC. Energy usage is calculated with equation (2). The RO device energy is based on a booster and re-pressurization pump supplying a cumulative pressure rise of 120 psi to the feed water. The actual FTC device uses more energy at the wall than RO, but the overall impact on California energy usage is comparable to RO technology because the FTC wastes less water. In the performance limit, the FTC total energy is less than 60% of NF/RO.

	NF/RO	FTC Actual	FTC Target
Electricity Basic Cost ($/kWhr)	0.10	0.10	0.10
Water Delivery Energy (Whr/Gal feed)	4.4	4.4	4.4
Device Energy (Whr/Gal purified)	3.4	5.66	3.3
Recovery	0.40	0.60	0.90
Total Energy (Wh/Gal purified)	14.4	13.0	8.2
Total Energy ($/1000 Gal purified)	$1.44	$1.30	$0.82

Table 8. Energy cost comparison, including water delivery.

Conclusions

- A prototype system was designed and fabricated

A FTC prototype device was design and build for this Commission project. The device, pictured in figure 1, was used to demonstrate the performance and calculate the costs of a commercial, saltless softener. The FTC is a working, viable technology.

- Evaluate Rejection Efficiency

The prototype FTC demonstrated hardness rejection for tap water of greater than 90%. This result shows the FTC capable of meeting a market dictated performance requirement. Confidence in this datum is high based on recent and year old comparisons.

- Evaluate energy usage

The prototype FTC demonstrated water use efficiency of 90% while maintaining 90% hardness rejection. The incumbent, saltless, membrane softener (NF/RO) has a water use efficiency of 40%. The superior FTC performance will benefit the State and the consumer with less water waste and lower water delivery energy expenditure. The prototype FTC did not meet the project goal of plug energy consumption <3 WHr/gal. NF/RO softeners use 3.4 WHr/gal, while the prototype FTC used 5.7 WHr/gal. About 3.3 WHr/gal is estimated for a commercial FTC. The FTC has greater electricity consumption at the wall than NF/RO. This performance deficit can be overcome by superior water use efficiency and the resulting lower water delivery costs.

- Competitive Comparison

The life cycle cost of ownership for POE softening was estimated based on projected retail costs for the residential FTC. The life cycle cost for the FTC based on actual performance is similar to NF/RO. A significant cost advantage for the FTC is projected for limiting performance. Similarly, the actual FTC energy cost is very close to the NF/RO value. In the performance limit, the FTC could use 40% less energy.

- FTC Commercialization

The prototype device suffered from a short lifetime. The lifetime was extended to 6 months by reducing the water use efficiency from 90% to 60%. Even with this derating, the FTC is not commercially viable. The consumer is not prepared to service a POE softener semiannually. In addition to the inconvenience, the FTC life cycle and energy costs are similar to NF/RO. There is no driver for adopting the novel FTC technology. On the other hand, strong economic drivers exist for the FTC operating in the target performance limit. Therefore, FTC commercialization will depend on unpredictable engineering advances that will enable 90% water use efficiency, 3.3 Whr/gal device energy, and at least a 60-month service interval. This comparison is subject to revision as NF/RO technology is improved.

Commercialization ultimately depends on consumer choice. Presently, the POE softening market is served by ion exchange. Ion exchange has performance and cost far superior to either the best FTC or NF/RO technologies. Environmental legislation may force ion exchange off the market. That legislation is the first requisite for FTC commercialization; the second requisite is recalibration of consumer expectations.

Recommendations

FTC technology is viable, and capable of high hardness rejection, and high water use efficiency. The major obstacle to commercialization (as a replacement for outlawed ion exchange) is limited device lifetime. The FTC performance, cost, and convenience all trade off with device lifetime. Only limited lifetime studies have been performed, more varied and more detailed studies are needed. These studies should be coupled with analytical efforts to determine the causes of performance decay with use. Initial analysis indicates that the weak link is in the charge barriers (ion exchange membranes.) Charges barriers are also a critical cost element. Commercialization cost projections assumed a ten-fold reduction in charge barrier cost. Lifetime investigation should be tied to charge barrier cost reduction strategies.

The critical issue for FTC commercialization is lifetime. Lifetime testing is typically time consuming and costly. The existing data indicates a problem exists, but the solution will require more understanding. Possible solutions include 1) modify the charge barrier surface chemistry or pore size, 2) eliminate the charge barrier with a higher pressure drop, packed bed design, 3) integrate radio frequency electronic descaling technology, 4) integrate periodic electrochemical descaling through electrolysis. In principle we seek to replace the conversion of one form of chemical energy to another (brine regenerated ion exchange) with conversion of electrical energy to chemical energy (FTC, RO/NF.) The most efficient conversion routes may not involve the large ion currents of the FTC or the high pressures of RO/NF. The solution may be an "active" ion adsorbing resin.

Public Benefits to California

The energy saving derives from the limiting end-use efficiency of the FTC (90%) as compared with RO (40%). California's electricity consumption was 2.54 x 10^{11} kWh/yr in 2001 [2]. Its water usage was 229 gallons/day/capita or 2.87 x 10^{12} gallons/yr [16]. PIER states that 5% of the electricity goes to water pumping and wastewater services. These figures ratio to an electricity cost of 4.4 Wh/gal in addition to water purification costs.

This efficiency difference will impact the state significantly if environmental concerns drive existing water softening applications to FTC technology instead of RO technology. Existing water softening is used by about 30% of residential users at per capita rate of 75 gallons per day [17]. California's 34 million residents represent about 70% of the urban water usage [18]. Total urban softening usage is therefore about 1 x 10^9 gallons per day or 13% of total urban usage. Table 9 shows the replacement of existing IE with FTC, vs. replacement with NF/RO devices will result in a saving of about 380 to 1,730 million kWh/yr electricity, or up to 1% of the urban electricity consumption, with a retail value of $38 to $173 million per year for California.

	NF/RO	FTC Actual	FTC Limit
Electricity Basic Cost ($/kWhr)	0.10	0.10	0.10
Water Delivery Energy (Whr/Gal feed)	4.4	4.4	4.4
Device Energy (Whr/Gal purified)	3.4	5.7	3.3
Recovery	0.40	0.60	0.90
Total Energy (Wh/Gal purified)	14.4	13.0	8.2
Total Energy ($/1000 Gal purified)	$1.44	$1.30	$0.82
kWh/yr	4.02E+09	3.64E+09	2.29E+09
Savings kWh/yr	$0.00E+00	$3.82E+08	$1.73E+09
Savings $/yr	$0.00E+00	$3.82E+07	$1.73E+08

Table 9. Public Benefits.

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Appendix I: FTC Business Plan (2002)

Please contact the awardee for a copy of this appendix.