DESIGN REFINEMENT AND DEMONSTRATION OF A MARKET-OPTIMIZED HEAT-PUMP WATER HEATER

CONSULTANT REPORT

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These three utilities provided match funds for the project and also helped to secure field-test sites within their respective service territories. Most importantly, their close involvement in the project facilitated information transfer to California utilities, which are a key stakeholder group.

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 (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

What follows is the final report for the Design Refinement and Demonstration of a Market-Optimized Heat-Pump Water Heater, Contract No. 500-98-028, conducted by TIAX LLC (formerly the Technology & Innovation Business of Arthur D. Little, Inc.). The report is entitled *Design Refinement and Demonstration of a Market-Optimized Residential Heat-Pump Water Heater*. This project contributes to the PIER Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Table of Contents

Preface iv

Abstract x

Executive Summary 1

1.0 Introduction 7

1.1 Background and Overview 7
1.2 Project Objectives 8
1.3 Report Organization 9

2.0 Project Approach 11

2.1 Refine Design 11
2.1.1 Refine Component Design and Selection Subtask 11
2.1.2 Fabricate Third-Generation Prototype and Conduct Laboratory Test Subtask 11
2.2 Fabricate and Deliver Field Test Units 12
2.3 Laboratory Testing 12
2.3.1 Prepare Laboratory Test Plan Subtask 12
2.3.2 Conduct Laboratory Testing Subtask 12
2.4 Field Testing 12
2.4.1 Prepare Field Test Plan Subtask 12
2.4.2 Conduct Field Testing Subtask 12
2.5 Evaluate Lessons Learned and Information Dissemination Plan 13
2.6 Production Readiness Plan 13

3.0 Project Outcomes 15

3.1 Refine Design 15
3.1.1 Compressor Selection 15
3.1.2 Condenser Design 16
3.1.3 Expansion Device Selection 16
3.1.4 Condensate Management System (CMS) (Factory Option) 17
3.1.5 Evaporator Fan Selection 17
3.1.6 Control System 18
3.2 Prototype Fabrication and Laboratory Testing 18
3.2.1 Summary of Prototype Fabrication 18
3.2.2 Summary of Laboratory Test Results 21
3.3 Laboratory-Based Durability Testing 22
3.4 Field Testing 24
3.4.1 Site Selection 24
3.4.2 Installation of Field-Test Units 32
3.4.3 Energy Savings 37
3.4.4 Economics 46
3.4.5 Hot-Water Deficits 47
3.4.6 Field Failures and Reliability 49
3.4.7 Participant Satisfaction 51
3.4.8 Pre- and Post-Field-Test Unit Evaluations 57
3.5 Information Dissemination Plan 58

3.6 Production Readiness Plan 59
3.6.1 Overview of Production Readiness Plan 59
3.6.2 Recommendations for Equipment Cost Reduction 60

4.0 Conclusions and Recommendations 61

4.1 Conclusions 61
4.2 Recommendations 62

5.0 Glossary 65

6.0 References 67

List of Attachments 69

Appendix I: Post-Field-Test Evaluations 1

Appendix II: Information Dissemination Plan 1

Appendix III: Production Readiness Plan 1

List of Tables

Table 1. Components Selected for Third-Generation Prototype 15
Table 2. Preliminary Specifications for the Market-Optimized HPWH (Production Version) 19
Table 3. Performance Summary for Third-Generation HPWH Prototype 21
Table 4. HPWH Performance Map 22
Table 5. Energy Factor Test Results (Measured Near the End of the Durability Test) 23
Table 6. Summary of Field-Test-Site Characteristics 26
Table 7. Instrumentation and Data-Acquisition Equipment for HPWH Field Test 28
Table 8. Key Weekly Data Analysis Inputs and Outputs 31
Table 9. Key Annual Data Analysis Inputs and Outputs 32
Table 10. Field-Test-Unit Installation Times (Excluding Instrumentation) 34
Table 11. Summary of Field-Test-Unit Energy Savings 38
Table 12. Unit 2—Comparison of Performance with and without Natural-Circulation, Recirculation Loop 40
Table 13. Summary of Reported Failures Resulting in Loss of Hot Water 49
Table 14. Target Customer Satisfaction Criteria for the HPWH 52
Table 15. Unit Disposition at End of Field Test 56
Table 16. Cold-Water Heat-Up Test Results—Before and After Field Test 58
Table 17. Recommended Design Enhancements for Ease of Installation 62
Table 18. Recommended Design Enhancements to Facilitate Maintenance and Failure Detection 62

List of Figures

Figure 1. First-, Second-, and Third-Generation HPWH Prototypes 8
Figure 2. Third-Generation HPWH Prototype 19
Figure 3. Map of Installation Locations (Unit Numbers in Parentheses) 25
Figure 4. Summary of Field-Test-Site Characteristics 27
Figure 5. Instrumentation Schematic for HPWH Field Test 29
Figure 6. Overview of the Weekly Data Analysis Program 31
Figure 7.Typical Closet Installation 36
Figure 8. Typical Garage/Laundry Installation 36
Figure 9. Simple T&P and Condensate Drain Plumbing 37
Figure 10. Average Hot-Water Consumption by Household Size 41
Figure 11. Average Heat-Pump Capacities 42
Figure 12. Average Heat-Pump COPs 43
Figure 13. Average Energy Savings by Ambient Temperature 43
Figure 14. Average Energy Savings by Installation Location 44
Figure 15. Comparisons of California (TIAX) and National (ORNL) Field Tests 45
Figure 16. Simple Payback Periods 47
Figure 17. Hot-Water Deficits 48
Figure 18. Frequency of High Compressor Discharge Temperatures 51
Figure 19. Participant Overall Satisfaction Rating 52
Figure 20. Summary of Participant Survey Results (Average for Three Surveys) 53
Figure 21. Unit 14 Installation 55
Figure 22. DOE Energy Factor Test Results—Before and After Field Test 57

Abstract

Under Contract No. 500-98-028 for the California Energy Commission Public Interest Energy Research Program, TIAX LLC (the prime contractor, and formerly the Technology & Innovation Business of Arthur D. Little, Inc.) and EnviroMaster International (EMI) (the key subcontractor, and subsidiary of ECR International) conducted a project called the *Design Refinement and Demonstration of a Market-Optimized, Residential Heat-Pump Water Heater*. "Market-optimized" means that cost and performance are balanced to meet market needs. Specifically, the market-optimized heat-pump water heater (HPWH) is less expensive and easier to install relative to other HPWHs on the market. Prior to this project, with support from the U.S. Department of Energy Oak Ridge National Laboratory (ORNL), TIAX and EMI developed and tested two generations of prototype market-optimized HPWHs. The overall scope of this project was to further refine the design of the market-optimized HPWH and then verify the third-generation design through both laboratory and field testing. Oak Ridge National Laboratory conducted laboratory-based durability tests on ten units, simulating the equivalent of ten years of heat-pump cycling under normal operation. We conducted a yearlong field test in California on 20 units. Key project outcomes are:

- The work accomplished under this project has allowed EMI to commercialize the market-optimized HPWH (which is sold under the trade name WATTER$AVER);
- We exceeded the project technical performance objective of a 2.0 Energy Factor. The prototype HPWH achieved a 2.48 Energy Factor. Two units tested before and after a yearlong field test achieved Energy Factors ranging from 2.21 to 2.57;
- We did not achieve the project economic performance objective of $875 installed cost. Estimated installed costs are $1450, which should drop to $1100 to $1200 in higher volume. The purchasing clout of a large manufacturer will likely be needed to achieve installed costs within the economic performance objective;
- Despite the relatively high installed cost, many Californians could achieve attractive economics with the WATTER$AVER product, given the relatively high cost of electricity in California ($0.12/kWh on average for residential applications);
- During the field test, the failure rate was higher than is likely to be acceptable in the general marketplace. Most failures were associated with the control system. EMI has addressed the failures in the design of their production units. Outside of this project, ORNL completed a second round of laboratory-based durability tests on five production units. While those test results have not yet been published, ORNL indicates that the units experienced no failures related to the durability test [ORNL 2004]; and
- The data collected during the field test has potential value beyond that which we have extracted for the purposes of this project. For example, a) additional analysis of the data could produce improved hot-water consumption profiles for use in modeling household energy consumption, and b) it may be possible to develop a better understanding of the diversified electric demand impacts of HPWHs through further analysis of the data.

Executive Summary

Introduction

Under Contract No. 500-98-028 for the California Energy Commission (Energy Commission) Public Interest Energy Research (PIER) program, TIAX LLC, Cambridge, MA and EnviroMaster International, LLC, Rome, NY (EMI) conducted a project called the *Design Refinement and Demonstration of a Market-Optimized, Residential Heat-Pump Water Heater*. TIAX, formerly known as the Technology & Innovation Business of Arthur D. Little, Inc., was the prime contractor, and EMI (a subsidiary of ECR International) was a key subcontractor and the manufacturer of the market-optimized Heat-Pump Water Heater (HPWH), called the WATTER$AVER™.

A HPWH uses a refrigeration system to extract heat from the surrounding environment to heat water. A residential HPWH typically consumes less than half the energy relative to a conventional, electric-resistance water heater. Despite the substantial energy savings, a significant residential HPWH market has not yet developed, primarily due to the high equipment and installation costs associated with currently available HPWHs.

TIAX, in partnership with EMI and with support and assistance from the U.S. Department of Energy Oak Ridge National Laboratory (ORNL), developed a HPWH design that effectively addresses the market and technological barriers facing the current HPWH products. The key advantages of the market-optimized HPWH relative to existing HPWHs are significantly lower equipment cost with only a modest efficiency penalty; and a similar installation method to conventional electric-resistance water heaters. The market-optimized HPWH is designed to be a "drop-in replacement," with similar physical dimensions and no need to provide additional facilities.

Project Objectives

The primary goal of the project was to increase market penetration of the market-optimized HPWH by:

- Identifying and implementing design refinements to lower costs and increase performance;
- Performing laboratory test to demonstrate the durability/reliability of the design; and
- Demonstrating the performance, reliability and ease of installation through a California-based field test.
- The economic performance objective of the project was to achieve an estimated installed cost of $875 per unit.

The technical performance objective of the project was to achieve an Energy Factor of at least 2.0. Energy Factor is determined by a standardized test procedure prescribed by the U.S. Department of Energy. In addition, we anticipated replacing no more than one field-test unit due to failure during the one-year field test, with only very minor maintenance/repairs on all other units (exclusive of instrumentation-related maintenance/repairs).

Project Approach

Starting with previously developed prototype designs for the market-optimized HPWH, we refined the design of key components/subsystems including the compressor, condenser bond to the storage tank wall, expansion device, condensate management system, evaporator fan, and the control system. TIAX and EMI selected design approaches to these key components/subsystems to balance cost, performance, reliability, and ease of manufacture. With the concurrence of the Commission Contract Manager, we did not incorporate a condensate management system for this project, but instead incorporated condensate drains. However, EMI offers a condensate re-evaporation system as an option in their commercialized product.

EMI fabricated a third-generation prototype HPWH based on the refined design. The prototype maintained the same footprint as a conventional electric water heater, with a height increase of 10 to 12 inches. The U.S. Department of Energy, Oak Ridge National Laboratory (ORNL) conducted durability tests on ten prototype HPWHs. The 9.5-month HPWH test program approximated the equivalent of ten years of heat-pump cycling under normal use. The test program placed the ten units under increasingly demanding operating conditions that included elevated ambient temperatures and humidity levels as well as operation at reduced line voltage.

TIAX and EMI then conducted a yearlong field test in California of 20 market-optimized HPWH prototypes. Eighteen of the units were installed in residences, one in a commercial office building, and one in a public shower at a marina. EMI then conducted post-field-test evaluations of four field-test units, which included both laboratory performance testing and destructive inspections.

Project Outcomes

Energy Savings

The market-optimized HPWH achieved our technical performance objective of a 2.0 Energy Factor. Test results indicated that the third-generation prototype achieved an Energy Factor of 2.48—a 29 percent performance improvement relative to the 1.92 Energy Factor achieved by the second-generation prototype (which was built and tested prior to this project). The third-generation prototype also achieved a 30 percent increase in heat-pump heating capacity relative to the second-generation prototype (3500 Btuh versus 2700 Btuh). EMI also conducted Energy Factor tests on two of the prototypes fabricated for field testing, testing the units both before and after the field test. The results showed that the Energy Factor ranged from 2.21 to 2.57, which is reasonably consistent with the test results for the original third-generation prototype.

The results of the California field test showed that the prototype HPWHs effected average energy savings generally between 30 and 50 percent in residential applications (relative to the energy consumption of electric-resistance water heaters as determined by simulation). The units performed well even in tight enclosures such as utility closets.

Installed Cost

The market-optimized HPWH did not achieve the project's economic performance objective of $875 installed cost. EMI estimates the installed cost at $1450, which should drop to between $1100 and $1200 for production volumes of 10,000 units/year or more. The key contributing factor is that actual component costs are higher than originally estimated. There are potential

opportunities for component cost reduction, including the evaporator fans, expansion device, control system, and shroud. In addition, co-locating the fabrication of the HPWH with the fabrication of the tank assembly offers further potential cost savings. Even with its relatively high cost, EMI's production HPWH (the WATTER$AVER) is the only integrated HPWH (i.e., heat pump and tank packaged together) on the market. Given the relatively high electric rates in California (currently averaging about $0.12/kWh), the WATTER$AVER should be economically attractive for a significant number of California residents.

Ease of Installation

The market-optimized HPWH design concept is intended to virtually eliminate installation barriers. However, installation of field test HPWHs generally averaged 1.0 to 1.5 hours longer than estimated for installation of an electric-resistance water heater and required an additional person, although additional experience might reduce the installation time requirements. Key installation issues that still need to be addressed include:

- Explore ways to reduce HPWH weight or otherwise permit installation by a single installer;
- Redesign the HPWH so that the shroud need not be removed during installation (i.e., allow electrical and plumbing connections to be made without removing the shroud);
- Use a common condensate drain line size for both the primary and back-up condensate drains;
- Develop guidelines for installers so that they can readily determine whether to recommend EMI's optional condensate re-evaporation system;
- Develop a procedure by which the installer does not have to wait for the heat pump to operate when first starting up the HPWH;
- Locate the removable air filter on the front (thermostat side) of the unit for ease of removal and cleaning; and
- Make status-indicating lights visible to the exterior of the unit without removal of the top shroud.

Most of the above installation issues could be addressed through straightforward design changes, although for installations not having ready access to a drain, condensate management will require additional cost and complexity for either a condensate pump or the optional condensate re-evaporation system.

Reliability/Life

In laboratory-based durability tests conducted by Oak Ridge National Laboratory (ORNL), the heat pumps of the test units were relatively reliable—the only failure being a single thermostatic expansion valve. However, the control system experienced multiple failures, most of which were associated with spliced joints in sensor lead wires. Also, compressor tear-downs uncovered wear on the crank pins and crank-pin bushings. Before fabricating units for the California field test, EMI incorporated design refinements to address the control-system failures. The compressor manufacturer also agreed to incorporate design changes to address the crank pin and crank-pin bushing wear.

During the 20-unit California field test, the control system continued to be the weak link in reliability of the prototype units. During the course of the field test, we replaced six failed control boards. We experienced one failed thermistor, one failed thermostat, and one refrigerant leak of undetermined origin. We also experienced one failed upper heating element, although this failure was technically after the completion of the field test. While the failure rate experienced is higher than would be acceptable in the residential water-heater market, EMI has made additional design changes in their production WATTER$AVER to address the deficiencies identified in the field test. Outside of this project, ORNL completed a second round of laboratory-based durability tests on five production WATTER$AVER units. While those test results have not yet been published, ORNL indicates that the units experienced no failures related to the durability test [ORNL 2004].

Post-field-test evaluations on four units showed no evidence of performance degradation during the field test. Destructive inspections showed that the anode rods in two of the units were heavily scaled, with no apparent correlation between the formation of anode scale and the mineral content of the water at the field-test sites. However, scale formation on anode rods is not unusual, and does not necessarily render the anode rod ineffective.

Post-field-test evaluations showed no significant scale build up on the inner walls of the storage tanks, which, if present, could interfere with the long-term performance of the HPWH.

User Acceptance

Field-test participants were generally satisfied with the performance of their HPWHs. While the measured hot-water deficits (hot-water run outs) ranged from 0 to 6.6 percent for the residential units (compared to 0 to 0.3 percent for simulated electric-resistance water heaters), participants in general reported no greater incidence of hot-water deficits. One area that may need further attention is noise reduction. In some installations, where the HPWH was near bedrooms and other frequently occupied areas, the noise level was sufficient to cause complaints.

Conclusions and Recommendations

Despite not achieving the project economic objective, the EMI WATTER$AVER should provide economically attractive energy savings for many California residents who use electric water heaters due to the high electric rates in the state. Additional cost reductions may be possible through a component cost reduction exercise.

Running condensate drain lines can significantly increase installation times in some situations. It would be helpful to develop guidelines for installers so that they can readily determine whether to recommend EMI's optional condensate re-evaporation system. Installation of the WATTER$AVER currently requires two people, primarily due to increased height and weight. Redesigning the unit for installation by one person is an important goal. Minor design refinements would permit installation of the WATTER$AVER without removing the shroud. Minor design refinements would also permit installation without having to wait for the heat pump to engage after filling the tank with cold water.

The commercialized WATTER$AVER should be more reliable than the pre-production units tested under this project. However, the reliability of the commercialized product has not yet

been demonstrated adequately. Further field testing of the production WATTER$AVER is needed to verify that adequate reliability has been achieved.

Under separate projects, TIAX has conducted development and testing work on a more advanced, patented condensate management system that thermally sterilizes the condensate and then injects it into the water storage tank [DOE Condensate 2001] [CRS 2002]. Should the HPWH begin to achieve market success, further development efforts (and regulatory acceptance efforts) may be warranted.

Additional energy savings (and other performance advantages) may be achievable by using carbon dioxide as a refrigerant in HPWHs. While we generally believe that there are more compelling design issues to address (namely, cost and reliability), ongoing carbon dioxide developments should be tracked. If successfully demonstrated in commercial-building applications, development of a carbon dioxide HPWH for the residential market should be considered.

Near-term promotional efforts should focus on major appliance manufacturers who have the resources to break open the HPWH market, such as a) brand recognition, b) extensive design and manufacturing expertise, c) component purchasing clout, and d) well developed distribution, sales, and service infrastructures. In addition, continued work with utilities and energy efficiency organizations will help refine product requirements and define the true nature of the HPWH market potential, which major manufacturers will need to understand before investing in such a technology. As products having proven reliability emerge, broader-scale promotional efforts will be warranted.

We accumulated extensive data during the field test that potentially has value beyond that which we have extracted under this project. For example, through additional analysis of the data, one could develop improved hot-water consumption profiles for use in modeling residential energy consumption. In addition, it may be possible to develop a better understanding of the diversified electric demand impacts of HPWHs through further analysis of the data.

1.0 Introduction

This section discusses the project background and overview, project objectives, and report organization.

1.1 Background and Overview

Under California Energy Commission Public Interest Energy Research Contract 500-98-028, TIAX LLC[1], the prime contractor, and EnviroMaster International (EMI), a key subcontractor, conducted a project to refine the design of and field test a market-optimized, residential heat-pump water heater (HPWH). EMI's commercialized version of the market-optimized HPWH is called the WATTER$AVER. The project technical tasks were:

- Task 2.1 Refine Design;
- Task 2.2 Fabricate and Deliver Field Test Units;
- Task 2.3 Laboratory Testing;
- Task 2.4 Field Testing;
- Task 2.5 Evaluate Lessons Learned and Information Dissemination Plan; and
- Task 2.6 Production Readiness Plan.

A HPWH uses a refrigeration system to extract heat from the surrounding environment to heat water. A residential HPWH typically consumes less than half the energy relative to a conventional, electric-resistance water heater. Despite the substantial energy savings, a significant residential HPWH market has not yet developed, primarily due to the high equipment and installation costs associated with currently available HPWHs.

TIAX, in partnership with EMI, has developed a HPWH design that effectively addresses the market and technological barriers facing the current HPWH products. The key advantages of the market-optimized HPWH relative to existing HPWHs are:

- Significantly lower equipment cost with only a modest efficiency penalty; and
- Same installation method as a conventional electric-resistance water heater ("drop-in replacement"), with no need to provide additional ventilation air or remove condensate (with optional condensate management system).[2]

The market-optimized HPWH will take advantage of emerging market and institutional drivers to realize broad market appeal enabling HPWHs to capture a significant portion of the electric-resistance water-heating market.

Figure 1 shows the first-, second-, and third-generation HPWH prototypes. The first-generation prototype has been operating since October 1996 in an employee's home (five-person household). It uses an oversized (80 gallon) storage tank and requires a condensate drain. Our second-generation prototype incorporated all the features of the market-optimized HPWH (including no requirement for a condensate drain and 50-gallon storage tank), and was

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[1] TIAX LLC was formerly known as the Technology & Innovation Business of Arthur D. Little, Inc. The contract was awarded to Arthur D. Little, and then reassigned to TIAX in late 2002.

[2] With the concurrence of the Energy Commission, the prototypes fabricated under this project did not include a condensate management system. Instead, they used a condensate drain.

successfully laboratory tested in simulated garage, basement, and utility closet installations (funded by the U.S. Department of Energy, Oak Ridge National Laboratory [ADL 1998].) The second-generation design served as the starting point for this project. This project resulted in the development and testing of a third-generation prototype, which is discussed in detail herein.

First-Generation HPWH Prototype ***Second-Generation HPWH Prototype*** ***Third-Generation HPWH Prototype***

Figure 1. First-, Second-, and Third-Generation HPWH Prototypes

1.2 Project Objectives

The primary goal of the project was to increase market penetration of the market-optimized HPWH by:

- Identifying and implementing design refinements to lower costs and increase performance;
- Performing laboratory test to demonstrate the durability/reliability of the design; and
- Demonstrating the performance, reliability and ease of installation through a California-based field test.
- The economic performance objective of the project was to achieve an estimated installed cost of $875 per unit.

The technical performance objective of the project was to achieve an Energy Factor of at least 2.0. Energy Factor is determined by a standardized test procedure prescribed by the U.S. Department of Energy. In addition, we anticipated replacing no more than one field-test unit due to failure during the one-year field test, with only very minor maintenance/repairs on all other units (exclusive of instrumentation-related maintenance/repairs).

1.3 Report Organization

This report is organized as follows:

- Section 1.0 Introduction
- Section 2.0 Project Approach;
- Section 3.0 Project Outcomes:
  - Design Refinement;
  - Prototype Fabrication and Laboratory Testing;
  - Laboratory-Based Durability Testing;
  - Field Testing;
  - Lessons Learned;
  - Information Dissemination Plan;
  - Production Readiness Plan;
- Section 4.0 Conclusions and Recommendations;
- Glossary and References;
- There are three appendices.
  - Appendix I: Post-Field-Test Evaluations
  - Appendix II: Information Dissemination Plan
  - Appendix III: Production Readiness Plan
- There are three attachments.
  - Attachment 1: Prototype Design, Fabrication, and Testing
    - Component Selection and Design Refinement Report
    - Third-Generation Prototype Fabrication and Laboratory Test Report
  - Attachment 2: California Field-Test Data and Analysis
    - Field-Test Data Analysis
    - Field-Test Unit Summaries
    - Interview and Survey Templates
  - Attachment 3: Durability Testing Results
    - ORNL Report – "Durability Testing of a Drop-In Heat Pump Water Heater"

2.0 Project Approach

This section briefly outlines the approach taken to execute each technical task under this project. The technical task numbering in our contract starts with Task 2.1. Not included below are Tasks 1.1 to 1.4 (Project Start-Up Tasks) and Tasks 3.1 to 3.3 (Reporting Tasks).

2.1 Refine Design

The objective of Task 2.1 was to reduce the cost of, and set cost-reduction goals for, the third-generation HPWH prototype. Task 2.1 consisted of two subtasks, as outlined below.

2.1.1 Refine Component Design and Selection Subtask

The objective of Subtask 2.1.1 was to refine the design of and select components for the market-optimized HPWH. We (TIAX and EMI) approached design refinement and selection of key components as discussed below.

Compressor: Work with compressor manufacturers to select a compressor meets performance and operating-condition requirements at the lowest cost practical.

Condenser Thermal Bond to Tank Wall: Develop a bonding process that provides an adequate thermal bond, yet is inexpensive in production. Consider the following techniques:

- Pre-tinning the condenser tube;
- Increasing the length of the condenser tube (so that the thermal bond to the tank need not be as good), combined with a low-cost bonding technique (such as thermal epoxy or thermal mastic);
- Use a D-shaped condenser tube (to increase contact area with tank), combined with thermal epoxy or thermal mastic;
- Combination of Methods 2 and 3 above; and
- Other techniques that may be identified.

Expansion Device: Evaluate alternative expansion devices (including capillary tubes, automatic expansion valves, and thermostatic expansion valves), and select the most appropriate one.

Condensate Management: Evaluate alternative systems for handling condensate based on reliability, cost, and performance.

Fan Noise/Evaporator Air Flow: Evaluate the tradeoff between evaporator performance, fan power draw, and fan noise, and select the best combination.

2.1.2 Fabricate Third-Generation Prototype and Conduct Laboratory Test Subtask

The objective of Subtask 2.1.2 was to fabricate and laboratory test a refined prototype HPWH (third generation). EMI fabricated a prototype in accordance with the design developed in Subtask 2.1.1, and conducted the following laboratory tests to verify the performance of the prototype:

- Heat-up test. This test involves heating a cold tank of water from about 57°F to about 140°F (with the resistance elements locked out) to develop a performance map for the heat pump;
- Energy Factor test;

- Tests simulating a utility-closet installation; and
- Test simulating a garage installation.

2.2 Fabricate and Deliver Field Test Units

The objective of Task 2.2 was to fabricate and deliver field-test units, including two spare units, per the design established under Task 2.1. EMI fabricated units using pre-production tooling, then conducted heat-up tests on all units, and Energy Factor tests on two units. EMI then installed data-monitoring systems on each unit, and delivered the units to California.

2.3 Laboratory Testing

The objective of Task 2.3 was to determine the durability of the HPWH through laboratory testing. Task 2.3 consisted of the subtasks outlined below.

2.3.1 Prepare Laboratory Test Plan Subtask

The objective of Subtask 2.3.1 was to develop a laboratory test plan. We prepared a laboratory test plan to guide the laboratory testing effort.

2.3.2 Conduct Laboratory Testing Subtask

The objective of Subtask 2.3.2 was to conduct laboratory-based durability testing on sample units. The U.S. Department of Energy, Oak Ridge National Laboratory (ORNL) conducted a durability test on ten prototype units fabricated by EMI, and produced a report entitled *Durability Testing of a Drop-In Heat Pump Water Heater* (see Attachment 3).

2.4 Field Testing

The objective of Task 2.4 was to determine the reliability and performance of the HPWH in actual field conditions. Task 2.4 consisted of the two subtasks outlined below.

2.4.1 Prepare Field Test Plan Subtask

The objective of Subtask 2.4.1 was to develop a field test plan to guide execution of the field tests. We developed a field test plan that addressed the following: Description of the HPWH; Testing Rationale; Technical Objectives and Approach; Organizational Responsibilities; Field Site Selection Criteria; HPWH Data Monitoring System; Data Monitoring Instrumentation Package; Participant Interviews; Schedule; Quality Assurance Measures; Field Site Selection; HPWH Installation/Removal; Data Monitoring; Contingency Measures; and Reporting.

2.4.2 Conduct Field Testing Subtask

The objective of Subtask 2.4.2 was to conduct a yearlong field test on 20 units[3] in California. We generally followed the approach outlined in the field test plan, except where circumstances dictated a revised approach. Conducting the field test was the largest activity under this project, and is documented in detail herein.

[3] The contract called for a field test of 25 units. The Commission Contract Manager and TIAX subsequently agreed that a 20-unit field test would be sufficient to fulfill the requirements of the contract.

2.5 Evaluate Lessons Learned and Information Dissemination Plan

The objective of Task 2.5 was to evaluate the lessons learned from the laboratory and field tests and to develop an Information Dissemination Plan. We reviewed the project, focusing on the laboratory-testing and field-testing activities, to generate lessons learned. The lessons learned are incorporated herein where they apply.

2.6 Production Readiness Plan

The objective of Task 2.6 was to prepare a written Production Readiness Plan. The Production Readiness Plan includes:

- Identification of critical production processes, equipment, facilities, manpower, and support systems that will be needed to produce a commercially viable product;
- Capacity constraints imposed by the design (both for a manufacturer and suppliers);
- Identification of hazardous or nonrecyclable materials;
- Projected production costs;
- Expected investment threshold required to launch the commercial product; and
- An implementation plan to ramp up to full production.

3.0 Project Outcomes

This section includes a discussion of project outcomes, organized by project task. Further details are provided in attachments, as referenced below.

3.1 Refine Design

The specific objective of the design refinement activity was to perform component selection and component design refinements for the following components/subsystems for the third-generation prototype:

- Compressor;
- Condenser thermal bond to tank wall;
- Expansion device;
- Condensate management system; and
- Evaporator fan.

Although not contractually required, we added the objective of selecting the type of control system to be used for the HPWH (i.e., micro-controller based or conventional).

Table 1 lists the components selected through the component design and selection effort. The component design and selection process is documented fully in Section 3 below. Brief summaries of the process follow. See Attachment 1, *Component Selection and Design Refinement Report*, for a detailed discussion of the design refinement process.

Table 1. Components Selected for Third-Generation Prototype

Component	Description	Manuf., Model
Compressor	Capable of 3600 Btuh at 120°F condensing and 40°F evaporating.	Embraco, FF10HBK
Condenser	¼" OD by 100 ft. D-shaped copper tube, thermally bonded to tank with thermal mastic	N/A
Expansion Device	Thermostatic Expansion Valve	Parker, Model S ½ JW
Fan	Two fans having a total air flow rate of 200 CFM	EMB, Model 4715 MS0-23T-B50
Condensate Management System (CMS)	An electric-resistance heater contained in a drain pan located under the evaporator, with two float switches[a]	N/A
Controls	A micro-controller system	N/A

a) The CMS is offered as an option for EMI's commercialized product, and uses three level sensors rather than two float switches.

3.1.1 Compressor Selection

The second-generation prototype (the starting point for this project) used a Danfoss Model FF7.5GK compressor. This compressor provided appropriate capacity. However, it operated on 120 VAC power (not 240 VAC, which is generally used for electric water heaters), and cost

about $70 in volume. The third generation compressor selection was driven by several primary requirements:

- To achieve adequate heat-pump heating capacity to avoid significant use of back-up resistance heating;
- To limit capacity to avoid over cooling enclosures (such as utility closets);
- To limit capacity to limit material costs; and
- To utilize (to the extent practical) relationships EMI has with its current compressor suppliers to ensure the lowest costs can be achieved.

EMI has relationships with two well-established manufacturers of small, hermetic refrigeration compressors – Danfoss and Embraco. We selected Embraco because they have off-the-shelf compressors in the capacity and price range of interest. The Embraco FF10HBK model best matches the optimum capacity.

3.1.2 Condenser Design

The second-generation HPWH used a copper-tube condenser solder bonded to the water tank. While this design provides excellent heat transfer to the tank, it would potentially be costly in production. Therefore, we evaluated other bonding options.

The major uncertainty in evaluating bonding options was the magnitude of the contact thermal resistances between the tube and tank wall. We experimentally determined contact resistance for a variety of bonding techniques. Thermal mastic (a putty-like material) provided excellent heat-transfer characteristics, requiring only about 20 percent greater condenser length relative to a solder bond to achieve similar heat-transfer performance. Given the far lower cost and greater simplicity of applying thermal mastic relative to solder, we selected thermal mastic to bond the condenser to the tank wall.

Our semi-empirical analysis shows that a condenser length of 100 feet provides adequate heat transfer using thermal mastic while effecting acceptable refrigerant pressure drops through the condenser.

3.1.3 Expansion Device Selection

The second-generation HPWH used a capillary tube expansion device. While the capillary tube performed adequately, other expansion devices may offer performance, reliability, and/or cost advantages.

Our design evaluation, confirmed by laboratory testing, shows that a thermostatic expansion valve (TXV) offers performance advantages relative to a capillary tube, but adds cost. Our evaluation suggests that the capillary tube and TXV are similarly attractive when cost and performance characteristics are considered, so that the decision should be driven by other factors (such as HPWH manufacturer preference, design flexibility, etc.) not specifically included in our evaluation. We selected the TXV, but the capillary tube would also be a perfectly acceptable choice, and may ultimately be incorporated into the commercialized design.

3.1.4 Condensate Management System (CMS) (Factory Option)

One of the barriers to the widespread use of HPWHs has been installation difficulties associated with draining the condensate formed on the evaporator. While some installations provide ready access to a drain, many don't, thereby forcing the installer to site engineer a condensate-drainage solution. The market-optimized HPWH provides an option Condensate Management System (CMS) to circumvent this installation difficulty. The second-generation HPWH used an electric-resistance condensate re-evaporation system. Another obvious choice, however, is to utilize heat produced by the heat pump to re-evaporate condensate. While this uses heat that would otherwise be available for water heating, it may provide efficiency or design simplicity advantages over electric-resistance re-evaporation.

Our functional design evaluation demonstrated that electric-resistance re-evaporation is the preferred method of condensate re-evaporation. The key advantage of this method is that condensate evaporates when the heat pump is not operating. This is an important advantage for two reasons:

- If the condensate reservoir fills to its capacity (because the CMS is unable to evaporate condensate as fast as it is being generated), the heat pump must be shut off and the water heater operates on electric-resistance backup. However, unless an electric-resistance CMS is used, the only mechanism for evaporating the stored condensate is by natural evaporation – potentially a time intensive process; and
- Allowing condensate to be evaporated while the heat pump is off offers greater flexibility in the required evaporation rate – a lower evaporation rate could be used if condensate can be evaporated off cycle.

Following selection of electric-resistance re-evaporation, we evaluated the preferred configuration. The two key configuration options were:

- Evaporate condensate directly from the condensate pan; or
- Evaporate condensate from a second receptacle, into which the condensate drains from the condensate pan.

While Option 2 appears to involve additional components, it permits the use of pressure-switch level sensing, since the second receptacle can be tall enough (if positioned alongside the tank) to utilize pressure differentials created by the water depth in the receptacle. Our configuration evaluation showed that both options are equally attractive. We selected Option 1, however, based on EMI's preference (focusing on manufacturing simplicity and serviceability). This configuration does, however, require the use of two float switches.

All CMS design options present some reliability issues.

With the concurrence of the Commission Contract Manager, we did not incorporate the CMS in the units fabricated for the third-generation prototype (see Section 3.2) or the field test (see Section 3.4). The CMS design is discussed further in Section 3.2 below.

3.1.5 Evaporator Fan Selection

The second-generation HPWH used a single, 250 cfm (nominal) evaporator fan. This is a relatively high flow rate for the evaporator capacity, but was selected to minimize the condensate formation rate. We performed a design evaluation to determine airflow rate that

minimizes power consumption, which corresponded to 200 cfm. We then checked the expected noise level to verify that it fell within the noise-level range produced by other household appliances we judged to have acceptable noise levels. We also estimated the maximum condensate formation rate (for humid air conditions) to compare to the capability of the CMS.

In the second step of the evaporator selection process, we evaluated three evaporator-fan configurations:

- Single fixed-speed fan;
- Two fixed-speed fans; and
- Single variable-speed fan.

We determined that two fixed-speed fans was the most attractive option because:

- It provides greater operating flexibility relative to a single fan (can operate just one fan to limit evaporating temperature in high ambient temperatures); and
- It is substantially lower in cost relative to a variable-speed fan.

3.1.6 Control System

The second-generation HPWH used a conventional, electromechanical control system. While not in the original project scope, we evaluated whether to use conventional controls or a more sophisticated electronic control system using a micro-controller. The results of our analysis indicated that the micro-controller control system was the better choice because it allows the HPWH to operate safely in a wide range of installations (without requiring the installer to carefully evaluate the appropriateness of each installation for the HPWH). If a conventional control system were designed to achieve a similar level of protection against adverse operating conditions, it would actually cost more than the micro-control system (based on high-volume production).

The micro-controller design is discussed further in Section 3.2 below.

3.2 Prototype Fabrication and Laboratory Testing

A summary of the third-generation prototype fabrication and laboratory testing is provided below. More detailed descriptions of the prototype fabrication and testing are provided in Attachment 1.

3.2.1 Summary of Prototype Fabrication

We fabricated a third-generation prototype HPWH according to the design summarized in Section 3.1 above. Figure 2. Third-Generation HPWH Prototype shows the third-generation HPWH prototype. Table 2 lists the key preliminary specifications for the new design.

Third-Generation HPWH Prototype

Figure 2. Third-Generation HPWH Prototype

In addition to fabricating the HPWH, we undertook several other tasks:

- Completed the development of the micro-control system;
- Continued to design the condensate management system; and
- Performed initial tests and identified further design enhancements.

Table 2. Preliminary Specifications for the Market-Optimized HPWH (Production Version)

Performance	Energy Factor of 2.4 (for 50-gallon tank)
Maintenance Requirements	Air filter cleaning once a year
Tank Sizes	50 and 80 gallon (nominal)
Life Expectancy	Equivalent to conventional water heater (about 11 years)
Physical Size	No increase in diameter relative to conventional water heater, 10- to 12-inch increase in height
Installation	No change relative to conventional electric water heater. Requires only single trade (plumber only) - Electrical: 240 VAC, 30 Amp service; 4530 Watt maximum draw; - Plumbing: Inlet and outlet at top of tank
Condensate Drain	Standard, with option for CMS
Ventilation	No special provisions required
Thermostat Setting	100°F to 160°F range
Installation Locations	Any installation sheltered from the weather (garage, basement, utility closet, attic, laundry room, etc.)
Maximum Noise Output	60 dBA
Service/Repair	Serviced by plumbers. Replace HPWH in case of major refrigeration system failures

As described in Section 3.1, we selected a micro-controller control system (versus conventional controls) for the HPWH. The main advantages of the micro-controller are:

- It provides the level of control needed to prevent operation of the heat pump when conditions are not suitable for its operation (reverting temporarily to resistance-heating mode); and
- It reduces equipment cost relative to conventional controls.

Although the design of a micro-controller system was not part of our original work scope, we requested a reallocation of project funds (approved by the Energy Commission on December 23, 1999), in part, to provide the resources needed for this design/development effort. Practical constraints on fabrication costs and schedules prohibit the development of a production-ready micro-controller for use in prototype HPWHs for laboratory (durability) and field test purposes. Therefore, we designed a prototype micro-controller, and provided guidelines for a production-ready design (to be developed after laboratory and field testing, prior to full-scale production).

The key functions of the micro-controller include:

- Turning on the heat pump when the tank temperature drops below the thermostat set point (reduces deadband);
- Shutting off the heat pump when the thermostat is satisfied;
- Switching the HPWH to electric-resistance mode when conditions are not conducive to heat-pump operation:
  - Excessively cold or warm ambient temperatures;
  - Impending hot-water run out requires higher heating capacity;
  - Thermostat set point exceeds the safe operating temperature of the heat pump[4];
  - Condensate management system (CMS) cannot evaporate condensate as quickly as it is forming; and
  - Heat-pump failure.
- Preventing the heat pump (or optional CMS) from operating when an electric element is in use, thereby avoiding possible circuit overload;
- Preventing the upper and lower electric elements from operating simultaneously, avoiding (almost certain) circuit overload;
- Indicating operation of the upper element, the lower element, and the heat pump; and
- Delaying compressor start if the compressor has shut off in the last three minutes, and the high-side and low-side pressures may not be equalized.

We also completed the detailed design of the CMS consistent with the design concept documented in Section 3.1.

EMI intends to offer the CMS as a factory-installed or field-installed option. Providing the CMS as an option lowers the HPWH cost for installations having ready access to a drain line (where the CMS is not needed). This new requirement, however, necessitated a modest design change

[4] The heat pump can safely heat water to 140°F, well above the normal set-point temperature used by most households.

relative to the concept originally selected. A float switch, located in the evaporator drain pan, activates/deactivates the CMS as well as indicating an overflow condition.

The U.S. Department of Energy, Oak Ridge National Laboratory (ORNL) conducted an initial Energy Factor test on the prototype HPWH. Following this test, we identified a number of design enhancements that improved the performance and manufacturing, with little impact on cost. We made the following modifications:

- Enlarged the suction-line to reduce the suction-line pressure drop;
- Increased the face area of the evaporator, which raises the evaporator temperature and increases efficiency;
- Insulated the compressor shell to increase the heating capacity; and
- Incorporated a bleed port into the TXV to provide for off-cycle pressure equalization.

3.2.2 Summary of Laboratory Test Results

After incorporating the component modifications described above into the third-generation HPWH prototype, ORNL performed another Energy Factor (EF) test. With these component modifications, the prototype achieved an EF of 2.48, far exceeding our project goal of 2.0[5]! Table 3 compares the EF, heating capacity, and Coefficient of Performance (COP) of the third-generation prototype to the second-generation prototype design. Not only have we exceeded the performance of the previous prototype, but, more importantly, we have created a design more suitable for production and commercialization[6].

Table 3. Performance Summary for Third-Generation HPWH Prototype

Performance Parameter	Third-Generation Prototype[a]	Second-Generation Prototype[b]	Percent Improvement
Energy Factor	2.48	1.92	29%
Nominal Heating Capacity[c]	3500	2700	30%
Nominal Coefficient of Performance[c]	2.2	2.1	5%

a) From [ADL 1998].
b) From Attachment 1, Tables 2-2 and 2-3.
c) Nominal capacities and COPs calculated at a 120°F average tank temperature and 70°F air.

We also tested the third-generation HPWH in laboratory-simulated utility-closet and garage installations (the most common installation locations in California homes). The results of these tests suggest that the third-generation HPWH should operate satisfactorily in these installations. However, the utility-closet tests suggest that the HPWH heating capacity approaches its upper limit to overcome excessively low air temperatures inside small utility closets. A performance map for the HPWH based on these tests is presented in Table 4.

[5] While EF is an important indication of HPWH importance, and is very useful for comparisons, actual field performance can be lower due to operation of back-up resistance elements and the CMS.

[6] The key features of the third-generation design that make it more suitable for production are a) use of a less expensive compressor having the proper (240 VAC) voltage, b) a much more production friendly condenser-to-tank bonding technique, and c)use of a micro-controller control system.

Table 4. HPWH Performance Map

		50°F/80% RH	70°F/50%RH	90°F/50%RH
150°F	Capacity	3500 Btuh	3750 Btuh	7800 Btuh
	Power	350 Watts	425 Watts	560 Watts
	COP	2.9	2.5	4.1
120°F	Capacity	3050 Btuh	3500 Btuh	7000 Btuh
	Power	410 Watts	475 Watts	600 Watts
	COP	2.2	2.2	3.4
135°F	Capacity	2600 Btuh	3250 Btuh	5600 Btuh
	Power	460 Watts	500 Watts	680 Watts
	COP	1.7	1.9	2.4

Given the importance of proper micro-controller operation and the level of sophistication in the software needed, we performed a series of control-system tests to verify that the micro-controller performed properly under all possible operating conditions.

3.3 Laboratory-Based Durability Testing

The objective of Task 2.3, Laboratory Testing, was to laboratory test refined HPWH prototypes to determine their durability. ORNL conducted the laboratory-based durability tests and documented the results. The ORNL tests are summarized briefly below. See the ORNL report in Attachment 3 for details.

ORNL tested 10 prototype HPWHs fabricated by EMI in an environmentally controlled test facility for 9.5 months. The HPWHs were run through a durability test program of approximately 7300 compressor duty cycles (equivalent to ten years of cycling under normal use in residential applications). ORNL's test procedure placed the 10 units under increasingly demanding operating conditions as the test proceeded as follows:

- Approximately 2000 cycles at 75 to 80°F and 50 percent relative humidity (RH);
- Approximately 2000 cycles at 75 to 80°F and 80 percent RH;
- Approximately 2000 cycles at 100°F and 50 percent RH; then
- Approximately 1300 cycles at 100°F and 50 percent RH and 15 to 20 percent reduction in line voltage.

There were no compressor, evaporator fan, or power relay failures of the heat-pump portion of the HPWHs during the test. One thermostatic expansion valve had to be replaced due to a blocked bleed port. The control system on the prototypes tested, however, proved to be less reliable. Of 40 total sensors, 16 failed during the test. These failures were due to spliced joints in the sensor lead wires. One unit experienced two control-board failures. In addition, there was evidence that electromagnetic interference was impacting control-system performance. While not a test failure, ORNL noted that poor drainage in their test facility caused overflow of the condensate pans in some units. The condensate overflow generally leaked into the electrical connection (junction box) at the top of the water-heater tank, then down through the tank

insulation to the upper element access area. Post-test evaluation of nine of the ten compressors examined by the compressor manufacturer uncovered wear on the crank pin and crank-pin bushing. In three cases, the crank-pin polishing was considered "moderate" (hardened surface layer not worn through). In one case, the bushing wear was considered "severe" (hardened surface layer of bushing was worn through), and in two cases the wear was considered "moderate" (hardened surface layer not worn through). ORNL's report provides more details of the compressor teardown analysis. In some cases, the wear was severe enough to degrade the hardened surface layer of the bushing.

The results of "Energy Factor"[7] tests (efficiency tests) completed at the end of the durability test ranged from 1.8 to 2.1, as shown in Table 5. While these results suggest the prototypes were at least twice as energy efficient as a typical electric-resistance water heater, they fell short of the 2.48 Energy Factor[8] achieved on the first EMI prototype tested under this project. The "Energy Factors" did, however, generally meet the technical performance objective of this project—a 2.0 Energy Factor or better.

Table 5. Energy Factor Test Results (Measured Near the End of the Durability Test)

Unit	"Energy Factor"[a]
1	1.95
2	1.80
3	1.99
4	2.08
5	2.14
6	2.05
7	2.08
8	1.87
9	1.48[b]
10	1.91
Average	**1.99[c]**

a) Test conditions varied somewhat from those specified in the DOE Energy Factor test procedure. From ORNL Report; Table 4.3 (See Attachment 3).
b) Unit 9 experienced a refrigerant charge leakage during the durability test, so we did not consider this a valid test result.
c) The average excludes Unit 9.

[7] ORNL conducted these tests at ambient conditions that were close to, but not within the specified tolerances of, the conditions specified in the DOE Energy Factor test procedure.
[8] Conducted as specified in the DOE Energy Factor test procedure, by Oak Ridge National Laboratory. See Attachment 1, *Third-Generation Prototype Fabrication and Laboratory Test Report*, for more details.

3.4 Field Testing

Section 3.4 includes a detailed discussion of the field test and the field-test results.

3.4.1 Site Selection

We developed a detailed plan for the selection of the 20 sites that included the following general criteria:

- The site must currently use a 50-gallon (nominal) electric-resistance water heater to match the tank size of the prototype HPWH[9];
- Each water heater must serve only one single-family household. The largest potential market for the HPWH in California exists with single-family, detached dwellings. Data show that, in general, nearly 60 percent of the homes in California are single-family, detached, households [California 2000]. In addition, the electricity consumed for water heating in single-family, detached, homes is 15 percent to 35 percent more than in other types of homes [PG&E 1995], thus enhancing the energy savings and economics (as compared to other household types);
- The water heater must be located so that a dedicated phone line (for data transmission) was available or could be readily installed; and
- A minimum height of 7 ft. is required for placement of the HPWH. The size difference between a conventional electric water heater and the HPWH is not very different, however, additional access space is required around the HPWH to remove the top shroud for installation or repair.

We also identified a list of secondary factors to ensure diversification in the test sites:

- Population centers;
- Climate zone;
- Water quality;
- Installation types; and
- Household size.

After combining the data from population, climate, and water hardness maps into a single map, we began the process of securing test sites. Two utilities, Southern California Edison (SCE) and Sacramento Municipal Utility District (SMUD), helped secure field test sites within their respective service areas. We spent significant effort locating appropriate willing participants. Word of mouth, including networking through the California Energy Commission, colleagues at TIAX's California office, electric utility contacts, and direct email distribution yielded many responses. Although we developed a detailed website to help communicate necessary information to potential participants, a thorough telephone screening of the respondents ruled out many that did not meet our desired criteria.

Of the 20 sites, 18 were single-family residences, and two were commercial. One commercial site services the restrooms in an office building, and the second (in series with an electric-

[9] EMI anticipates offering at least two HPWH tank sizes (50 and 80 gallon nom.) in the future.

resistance water heater) provides hot water to restrooms and showers of a marina. (We included two non-residential sites at the request of SCE. The Energy Commission Contract Managers approved this decision).

A map showing each installation location and California climate zone is shown in Figure 3. Five locations were in the Los Angeles area, five were in the Sacramento area, and ten were in the San Francisco Bay/Silicon Valley area.

The 20 installation sites represent a wide range of installation locations within the home. The most typical was a garage/laundry room installation, followed by a closet, and finally basement installation. There was also good variation found among the other critical factors, such as number of occupants, water hardness, and climate. Site characteristics are summarized in Table 6 and Figure 3.

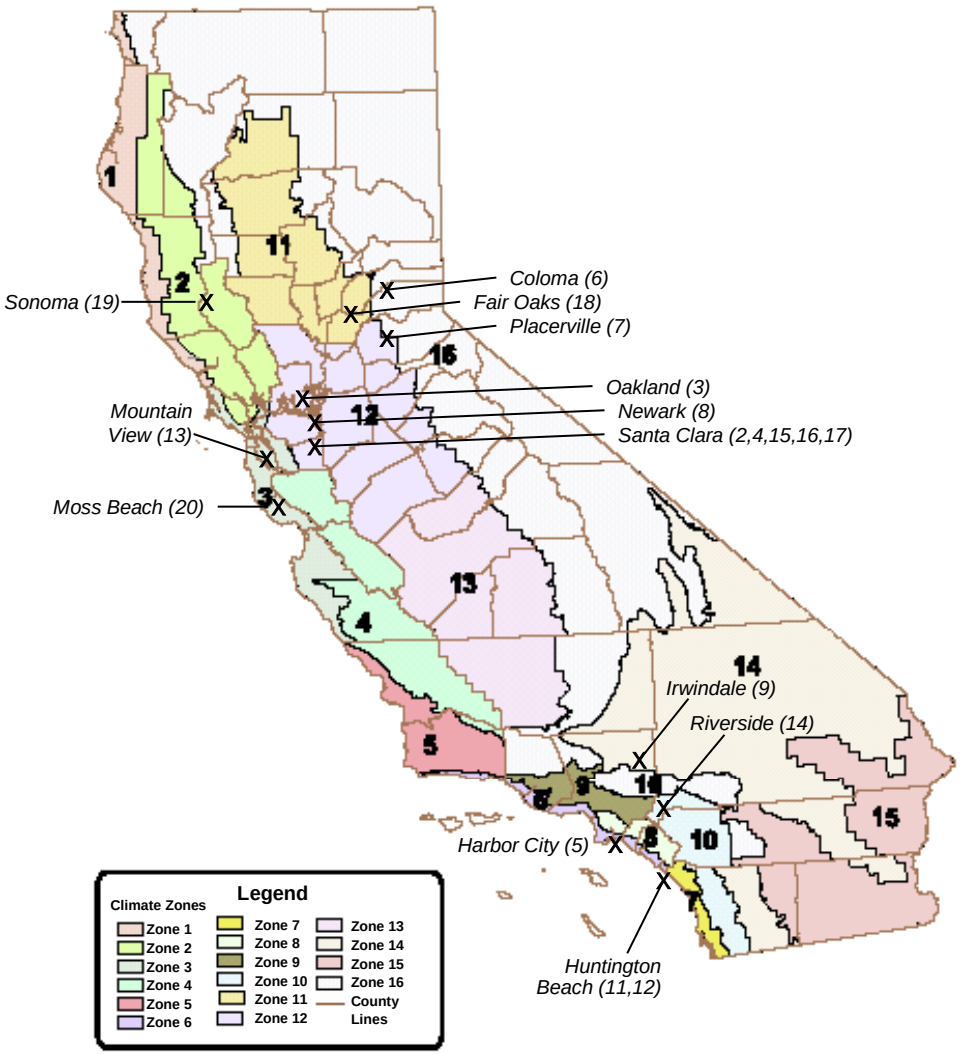
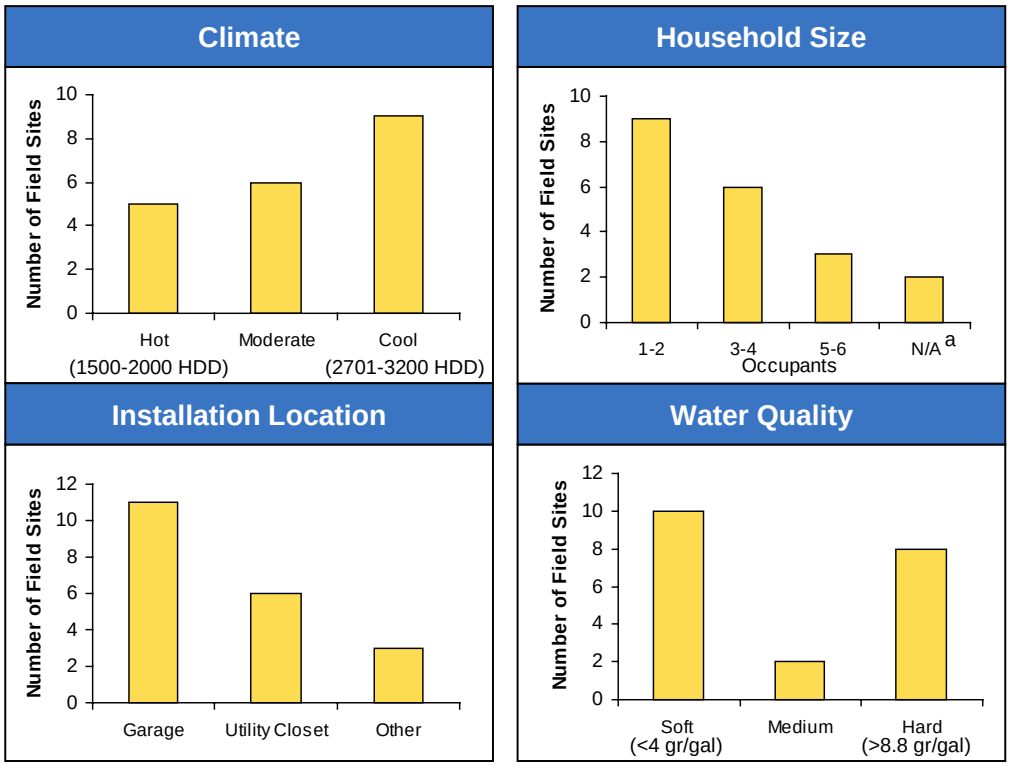


Figure 3. Map of Installation Locations (Unit Numbers in Parentheses)

Table 6. Summary of Field-Test-Site Characteristics

Unit #	City	CA Climate Zone	No. of Adults	No. of Children	Installation Location	Conditioned Space[a]	Water Hardness[b]
1	Sacramento	12	2	3	Laundry Room	Semi	Soft
2	Santa Clara	4	2	0	Outside Closet	No	Soft
3	Oakland	3	2	0	Closet	Semi	Soft
4	Santa Clara	4	1	0	Garage	No	Soft
5	Harbor City	8	2	0	Garage	No	Hard
6	Coloma	12	2	2	Laundry Room	Yes	Hard
7	Placerville	12	2	2	Garage	No	Soft
8	Newark	3	3	1	Garage	No	Hard
9	Irwindale	9	N/A[c]	N/A[c]	Closet in office building	Yes	Hard
10	Sacramento	12	3	2	Garage	No	Soft
11	Huntington Beach	6	4	0	Garage	No	Soft
12	Huntington Beach	6	N/A[c]	N/A[c]	Closet for public shower at a marina	No	Soft
13	Mountain View	4	2	2	Garage	No	Moderate
14	Riverside	10	2	1	Closet	Yes	Hard
15	Santa Clara	4	2	0	Closet	No	Soft
16	Santa Clara	4	2	0	Garage	No	Hard
17	Santa Clara	4	1	0	Garage	No	Hard
18	Fair Oaks	12	3	3	Garage	No	Moderate
19	Sonoma	12	2	0	Basement	No	Soft
20	Moss Beach	3	2	0	Garage	No	Hard

a) Indicates whether HPWH is installed in a space that is heated and/or cooled. "Semi" means that the space has some indirect heating and/or cooling, but that the temperature is not controlled.
b) From United States Geological Survey, courtesy of the Sacramento Water Quality Laboratory. Levels of hardness are: Soft (less than 4.4 grains/gallon); Moderate (4.4-8.8 grains/gallon); and Hard (greater than 8.8 grains/gallon).
c) Non-residential installation



a) Not applicable - non-residential installation

Figure 4. Summary of Field-Test-Site Characteristics

Instrumentation, Data Monitoring, and Data Analysis

Each HPWH prototype was equipped with a self-contained, data-monitoring instrumentation package. EMI instrumented the HPWHs during field-unit fabrication to maintain consistency and to simplify installation in the field. A list of the measurement instrumentation is shown in Table 7, and an instrumentation schematic is shown in Figure 5. The data-monitoring instrumentation contained seven thermistors that measured four refrigerant system temperatures, one ambient air temperature, and two tank temperatures.

Table 7. Instrumentation and Data-Acquisition Equipment for HPWH Field Test

No.	Variable	Description	Model Number
--	--	Data Logger	Onset TFX-11
--	--	Modem (56K)	CNET 18-1A-R51F-1B
--	--	Current Sensor	Newark CSDA1BA
--	--	240/120 VAC Transformer	McMaster-Carr 7010K65
1	Compressor Discharge Temp	Surface-Mounted Thermistor	Cornerstone TS1113
2	Saturated Evaporator Temp	Surface-Mounted Thermistor	Cornerstone TS1113
3	Suction Temp	Surface-Mounted Thermistor	Cornerstone TS1113
4	Compressor Shell Temp	Surface-Mounted Thermistor	Cornerstone TS1113
5	Ambient Temp	Probe-Thermistor	Cornerstone TS1113
6	Upper Tank Temp/Delivery Water Temp	Tank-Wall-Mounted Thermistor (8” from Top of Tank)	Cornerstone TS1113
7	Lower Tank Temp	Tank-Wall-Mounted Thermistor (36” from Top of Tank)	Cornerstone TS1113
8	Inlet Water Temp	In-Flow Thermistor	Cornerstone TS1113
9	Water Flow	Flow Meter in Outlet Water Line	Omega FTB-4607
10	Power	Wattmeter Connected to Inlet HPWH Power Line	Ohio Semitronics PC5-002CX5
11	Time	Output from Datalogger	N/A

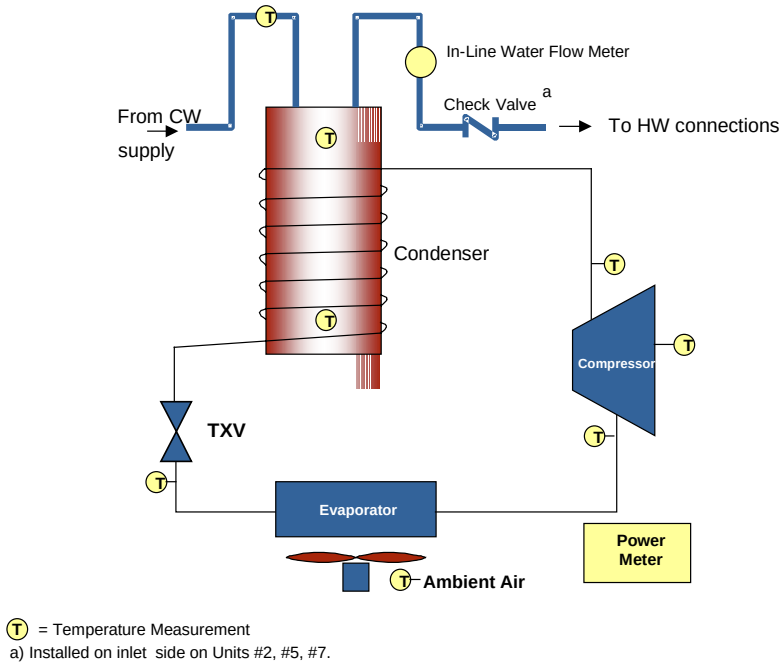


Figure 5. Instrumentation Schematic for HPWH Field Test

Specific placement of each sensor was as follows:

- The discharge temperature was measured using a thermistor attached to the discharge line of the compressor;
- The saturated evaporator temperature was measured by a thermistor attached to the evaporator inlet line, directly after the thermostatic expansion valve (TXV);
- The suction temperature was measured with a thermistor attached to the suction line of the compressor. It was located at least 3 in. away from the compressor to limit any false readings due to conduction from the hot compressor shell;
- The compressor shell temperature was measured using a thermistor attached to the top of the compressor;
- The ambient air temperature was measured with a thermistor placed behind the vent of the HPWH shroud to sense the ambient air temperature as it was drawn in by the evaporator fan;
- The upper and lower tank temperatures were measured by thermistors attached to the exterior of the tank wall beneath the insulation;
- The inlet water temperature was measured using an in-flow thermistor inserted into the waterline under the shroud near the inlet to the tank;

- The water flow was measured by a flowmeter integrated into the water piping below the profile of the HPWH shroud. It requires a 12 VDC input produces 75.7 pulses per gallon. A plug-in transformer in the data monitoring package provided input voltage;
- A watt meter measured the power consumed by the HPWH. It was self-powered and provided a 0-10 VDC output;
- Current sensors located at the power supply of each heater measured the on/off status of the upper and lower electric-resistance heating elements; and
- The hot-water delivery temperature was not measured directly. The analysis program assumed that the hot-water delivery temperature was the same as the upper tank water temperature.

A datalogger and modem assembly was attached to each HPWH for data acquisition and upload to a dedicated data-collection computer at TIAX in Cambridge, MA. Each sensor was connected to an instrumentation connector located at the top of the unit. When the plumber finished the installation of the unit, the TIAX field engineer placed a datalogger/modem assembly on top of the unit. The TIAX field engineer then attached the instrumentation connector, power cord, and dedicated telephone line to the datalogger/modem assembly. The datalogger/modem was typically taped securely to the top of the shroud in a waterproof container. Communication to the TIAX computer was verified before leaving the site.

There were numerous failures of the data-acquisition systems on many of the units. The modem/dataloggers were very sensitive to fluctuations in line voltage and the quality of the communication signal. 19 of the 20 installations required "resetting" at least once, and in some cases "resets" were so frequent that they became a nuisance for the homeowner. Homeowners had to switch the power off, then back on, to reset the modem/dataloggers. These failures did not affect the performance of the HPWH, but did cause loss of data for periods when the data-acquisition system was not operational.

Once operating, the datalogger automatically scanned and recorded the output signals from each sensor at a sample rate of once per minute. The memory of the datalogger provided enough space to hold a single day's worth of data before it would overwrite previously recorded data. For this reason, data was uploaded daily to the TIAX computer for storage and analysis.

We developed a custom communication program and used the TIAX computer to individually dial each unit, verify communication, and upload the daily data. Some debugging of the communication program was required at the beginning of the field test. During this period, EMI manually uploaded data from the units to a computer at their facility, processed the data, and forwarded it to TIAX. All of the uploaded data was summarized into one daily file containing data from each operating unit in the field. The uploaded data was in raw form, meaning the temperatures were stored as the millivolt readings from the thermistors and the flow-meter readings were in pulses. Before storing the daily data, the temperature readings were converted from millivolts to degrees Fahrenheit and pulse counts were converted flow rates. TIAX checked these data files to verify if any communication errors had occurred or if a unit was not operating properly. We backed up the daily files to a company server approximately twice each week.

We used two programs to analyze the field test data: a Weekly Analysis Program, and an Annual Analysis Program. These programs were written in Visual Basic code and run through Microsoft Excel. The two programs are briefly summarized below. Detailed descriptions of each program are included in Attachment 2.

Weekly Analysis Program: The Weekly Analysis Program organized the data that was downloaded each night and calculated weekly performance results. We typically ran the program weekly, on Monday. An overview of the program is shown in Figure 6.

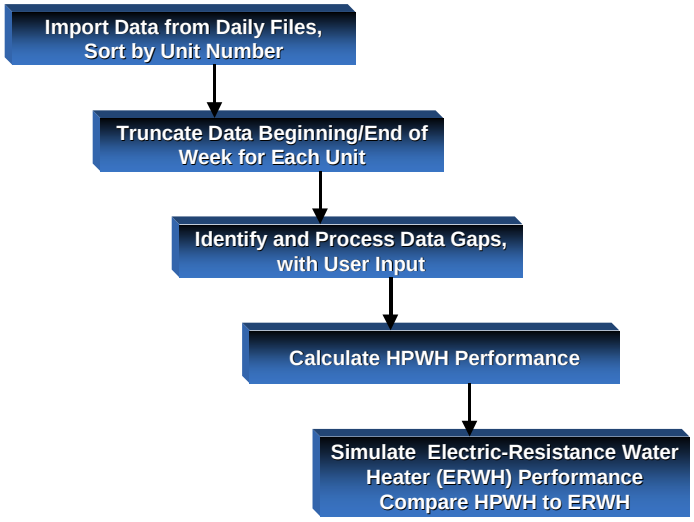


Figure 6. Overview of the Weekly Data Analysis Program

The input data and the calculated results are summarized in Table 8. The results of the Weekly Analysis Program were saved as weekly results files, and were used to monitor and report unit operation in the field. We also backed up these files weekly as they were created.

Table 8. Key Weekly Data Analysis Inputs and Outputs

Inputs: From Daily CSV Files/Data Logger
Date & Time
Compressor Discharge (Temperature)
Evaporator Inlet (Temperature)
Compressor Suction (Temperature)
Compressor Shell (Temperature)
Ambient Air (Temperature)
HPWH Upper Tank Water (Temperature)
HPWH Lower Tank Water (Temperature)
Inlet Water (Temperature)
Upper Element Status (On/Off)
Lower Element Status (On/Off)
Water Flow (Pulses)
HPWH Power Draw (kW)

Outputs: To Weekly Analysis
Average Water Consumption (GPD)
Energy Delivered to Home (kBtu)
Energy Loss from Tank to Ambient (kBtu)
Energy Change of Tank (kBtu)
Load Served by Heat-Pump (%)
ODE (unitless)
Heat-Pump Capacity (Btuh)
Heat-Pump Coefficient of Performance (unitless)
Maximum Compressor Discharge (Temperature)
Hot Water Deficit (%)

To evaluate the energy savings of the HPWH, developed a Visual Basic computer program to simulate the theoretical behavior of a typical electric-resistance water heater (ERWH). The simulation program used the same water draw data and initial water tank temperatures as the HPWH for each analysis period. After simulating the behavior of the ERWH for the same time period as the corresponding HPWH data set (usually a week), the computer program provided a summary of the simulated ERWH performance over that week's time. The weekly energy consumption and hot-water deficits of the ERWH were then compared to empirical values for the corresponding HPWH.

Annual Analysis Program: The Annual Analysis Program compiled the weekly results and generated annualized, or installation-to-date, averages for performance characteristics for each field test site. The relevant inputs and outputs of the program are shown in Table 9.

Table 9. Key Annual Data Analysis Inputs and Outputs

Inputs: From Weekly Summary
Average Water Consumption (GPD)
Energy Delivered to Home (kBtu)
Energy Loss from Tank to Ambient (kBtu)
Energy Change of Tank (kBtu)
Load Served by Heat-Pump (%)
ODE (unitless)
Heat-Pump Capacity (kBtu)
Heat-Pump Coefficient of Performance (unitless)
Maximum Compressor Discharge Temperature (°F)
Hot Water Deficit (%)

Outputs: To Annual Summary
Data Start and End Dates
Total time for which we have data (days)
Average Water Draw (GPD)
Annualized Total Energy Delivered (kBtu)
Annualized Total Element Energy Consumed (kWh)
Annualized Total HPWH Energy Consumed (kWh)
Average Heat-Pump COP (unitless)
Average Heat-Pump Capacity (kBtu)
Average HPWH ODE (unitless)
Average ERWH ODE (simulated)
Average Annual Energy Savings (%)
Hot-Water Deficit (%)

3.4.2 Installation of Field-Test Units

We used two plumbing contractors for all the HPWH installations: Pacific Plumbing[10] for the Northern California locations, and PHD Plumbing for the Southern California locations. Installation time and complexity varied widely at the various installation sites. Detailed unit-specific installation descriptions are included in Attachment 2.

The installation of the HPWH is similar to the installation of a conventional electric-resistance water heater. Both types of water heaters require the connection of cold and hot water piping, electrical power connection, and piping of the temperature and pressure relief valve (T&P). The HPWH requires the piping of one additional line, a condensate drain line, to remove any condensation that may accumulate in the drain pan[11]. The added time and complexity of installing the drain line was primarily dependent on how close the HWPH was to an existing drain. This varied widely among the installation sites. The additional time was significant – in

[10] Pacific Plumbing is the Disabled Veteran Business Enterprise (DVBE) for this project.

[11] Our original plan was to use HPWHs having a condensate re-evaporation device, which would have eliminated the need for a condensate drain. Upon agreement with the Commission Contract Manager, TIAX proceeded with the field test using HPWHs that require a condensate drain.

some cases adding 2 to 4 hours to the installation time. In other installations, for example near a laundry area, where there was easy access to an existing drain or sink, installation of the condensate line added minutes. In garages and other remote closets, a long drain line was installed, or a condensate drain pump was installed to pump the condensate outdoors.

The HPWHs were taller and heavier than the units that they replaced, with the exception of one commercial location (Unit 12) where a HPWH replaced an 80-gallon water heater. Conventional 50-gallon electric-resistance water heaters weigh between 110 lbs. and 150 lbs., depending on manufacturer. The weight of the HPWH is 180 lbs. It was difficult for one person to safely move the HPWH into position, and impossible for the installations that required that the unit be positioned on a platform above the floor[12]. Both plumbers felt that two people were required to safely position the unit.

The height of the HPWH is comparable to the height of a tall electric-resistance water heater, approximately 60 inches, and roughly 12 inches taller than a medium-height conventional unit. Height was not a major issue in installation. However, in one case a shelf that was above the old, medium-height water heater was cut to accommodate the additional height of the HPWH.

Generally, the footprint of the HPWH was the same size as the water heater it replaced. However, additional space is required around the HPWH to remove the top shroud for installation or service. At one site, the closet in which the water heater was installed was about 25.5″ by 25.5″, and the HPWH had a diameter of 22.25″. At this site, installation was difficult and the plumber believed that, if servicing the unit were required, it would require removing the unit from the closet.

In some cases it was necessary for the plumber to bring an installation up to the current building code. This additional labor included: installing earthquake strapping, plumbing the T&P valve outside of the building, and in one garage installation, adding a platform.

The installation time, along with comments from difficult installation sites, are shown in Table 10. While installation time is dependent on site specifics and varies in complexity, both plumbers involved felt that the time needed to install a conventional electric-resistance water heater would generally be in the range of 3 to 3.5 hours. They both felt that the additional installation steps required for the HPWH would add 1.0 to 1.5 hours to a typical installation. The installation times shown reflect the total time spent on the installation, any building code upgrades to the site, and the time required to verify proper operation of the heat pump. Verifying proper operation of the refrigeration system required waiting for the upper tank element to heat the water to satisfy the upper thermostat. After the upper thermostat is satisfied, the heat pump starts. We expect that installation times would decrease as the plumbers gain further installation experience. Figure 7 and Figure 8 show a typical closet garage installations, respectively. Figure 9 shows an installation having a simple T&P and condensate drain configuration.

[12] Many California building codes require that gas water heaters be installed on a platform to reduce the possibility of igniting flammable vapors (if present in the vicinity of the water heater). Some code officials interpreted this requirement to apply to the electric HPWH as well.

Table 10. Field-Test-Unit Installation Times (Excluding Instrumentation)

Unit Number	Installation Time (Hours)	Notes
1	4.5	Straightforward Installation
2	4.5	Straightforward Installation
3	8	No drain nearby. Condensate drain exits up to ceiling across room, through cement wall, across the garage and through the exterior wall using the condensate pump.
4	6	Straightforward Installation
5	6	Straightforward Installation
6	7	HPWH installed in laundry room which is inside the house, down some stairs, and through a bedroom. Shut off valve did not work. Existing T&P exit was plugged.
7	6	Straightforward Installation
8	4.5	Straightforward Installation
9	6	Straightforward Installation
10	7	Existing platform is very tall. Unstable power from house (eventually an electrician replaced the circuit breaker).
11	8	Installed drain pipe for condensate through wall into drain under the bathroom sink above p-trap for condensate drain and T&P exit.
12	6	HPWH put in series with electric element water heater with HPWH seeing the cold water first.
13	7	First Unit that was installed in the field.
14	6	Small elevated closet in the laundry room. Very small closet is 25.5" by 25.5" and is 25" above the ground due to a cabinet below. No drain so T&P is plumbed through cabinet and floor into crawlspace below house and across to exterior wall.
15	8	Water heater in a small closet (28" wide, 30" deep and a 25" wide door) in garage. Inspector required a platform built to elevate the water heater in the closet.
16	4.5	Shelf was too low for HPWH and required the shelf to be cut to accommodate the HPWH.
17	4	Straightforward Installation
18	5	Straightforward Installation
19	7	HPWH installed in basement/crawl space which is on the side of a mountain. Very little lighting. Long pipe run for T&P and condensate line to exit through wall.
20	6	Straightforward Installation

The plumbers had the following suggestions to improve the installation ease and time:

- **Explore ways to reduce HPWH size and weight**. Conventional water heaters can be installed by one person, while the HPWH currently requires two people to install. This is a significant added cost barrier to widespread use of the HPWH.
- **Design the shroud so that removal (and reinstallation) is not required for installation**. This would require that the hot and cold water pipe/connections extend above the shroud, the condensate tubing extend out the side of the shroud, and an external junction box be provided for easy electrical hook up. The current electrical connection requires removal of the shroud, followed by power line connection, mounting the existing electrical conduit in a hole in the shroud and replacement of the shroud. For some sites where the electrical

conduit from the house was large, the plumber had to cut a bigger hole in the shroud by hand to accommodate the larger size;

- **Simplify the removal and fastening of the shroud**. The shroud of the HPWH is held together with screws on the side (and top). Removing and installing the shroud sometimes required a special tool, for example, when there was only a clearance of a few of inches from the wall (a typical short Phillips screwdriver would not have worked);
- **Supply a short length of tubing for nearby drains and a condensate vent kit with each unit**. Plumbers do not usually have plastic tubing (for the condensate drain) with them. Their usual mode of operation is to arrive on site and see what they can do with what they have. If they need parts, they would then go to a local hardware store/supplier to get anything that they may need. For some sites the plugging of the condensate line was fixed by adding a condensate vent line;
- **Standardize condensate tubing size so that common size fittings can be used**. Currently the primary condensate line is ¼" I.D. and the secondary condensate line is 3/8" I.D;
- **Extend the T & P valve further from the tank jacket**. The temperature and pressure relief valve does not extend far enough from the side of the water heater, which makes it difficult to install the discharge line; and
- **Redesign the HPWH to avoid abrasions and damaged thermostat knobs.** The plumbers noted some HPWH packaging and shipping issues. They observed vertical abrasions on the side of several HPWHs upon opening the box. The abrasions did not effect the performance of the HPWHs, but it did effect the look and impression of the unit coming out of the box. They speculated that the abrasions were caused by rubbing against the four vertical cardboard triangular tubes that hold the HPWH in place inside the box during shipment. They also noted that some thermostat knobs had a small crack, and one unit had a broken thermostat knob upon unpacking. They speculated that this damage was also caused by the knobs rubbing against the sides of the box during shipment.

Figure 7.Typical Closet Installation

Figure 8. Typical Garage/Laundry Installation

Figure 9. Simple T&P and Condensate Drain Plumbing

3.4.3 Energy Savings

Summary of Energy Savings: Table 11 summarizes the results of the 20-unit field test, indicating that the average energy savings (relative to an electric-resistance water heater, over the duration of the field test) ranged from 28 to 52 percent for the residential installations (excluding Unit 2, as discussed below under *Recirculation Loops*). The commercial office building installation (Unit 9) averaged only 1 percent energy savings, and the public shower installation (Unit 12) averaged 30 percent energy savings. These results are discussed further below. Attachment 2, *Field Test Unit Summaries*, includes detailed performance information for each individual unit.

The table lists two primary performance metrics for each unit:

- Average Overall Delivery Efficiency (ODE), without space-conditioning impacts; and
- Average energy savings relative to a simulated electric-resistance water heater (ERWH).
- These performance metrics are briefly described below. Attachment 2, *Field Test Data Analysis*, includes a more detailed description of each metric, and how it is calculated. In each case, "average" means average over the duration of the field test for the unit in question.

Table 11. Summary of Field-Test-Unit Energy Savings

Unit	City	Conditioned Space[a]	Average Consumption (GPD)	Avg. ODE (w/o Space Cond. Impact)[b]	Simulated ERWH ODE	Avg. Energy Savings (%)
1	Sacramento	Semi	64.0	1.78	0.831	52
2	Santa Clara	No	39.0[c]	1.15[c]	0.729[c]	36[c]
3	Oakland	Semi	20.0	1.06	0.628	40
4	Santa Clara	No	29.3	1.12	0.602	44
5	Harbor City	No	1362.0[c]	1.36	0.922	29
6	Coloma	Yes	63.8	1.28	0.838	33
7	Placerville	No	56.2	1.23	0.825	32
8	Newark	No	56.2	1.21	0.824	29
9	Irwindale	Yes	9.6	0.43	0.408	1
10	Sacramento	No	166.0	1.88	0.931	47
11	Huntington Beach	No	70.5	1.49	0.822	43
12	Huntington Beach	No	130.1	1.27	0.882	30
13	Mountain View	No	74.4	1.70	0.876	46
14	Riverside	Yes	26.9	1.37	0.733	46
15	Santa Clara	No	35.9	1.22	0.726	40
16	Santa Clara	No	43.2	1.49	0.788	47
17	Santa Clara	No	19.1	0.89	0.631	28
18	Santa Clara	No	51.3	1.19	0.823	30
19	Sonoma	No	42.3	1.15	0.765	33
20	Moss Beach	No	39.0	1.10	0.738	31
Simple Averages			**54.5**	**1.27**	**0.766**	**36**

a) Indicates whether HPWH is installed in a space that is heated and/or cooled. "Semi" means that the space has some indirect heating and/or cooling, but that the temperature is not controlled.
b) Does not account for the energy-consumption impacts of drawing heat from the conditioned space.
c) For test period when recirculation loop was disabled. See discussion below entitled Recirculation Loops.

Overall Delivery efficiency (ODE) is the water-heating load supplied by a water heater (not including losses in piping runs) divided by the energy input to the water heater. ODE can be used to characterize the field performance of a water heater. Dr. Carl Hiller, formerly of the Electric Power Research Institute, originally coined the term ODE. Energy Factor, a common metric for water-heater efficiency, cannot be used to characterize field performance since Energy Factor is, by definition, the result of a laboratory test, following a prescribed test procedure, used to provide a consistent rating condition for residential water heaters. Researchers who use "Energy Factor" to report field performance are using the term imprecisely. However, these researchers generally intend "Energy Factor" to be interpreted in the same way as ODE. As the table shows, the average ODE is not the same as the Energy Factor, but varies from unit to unit, depending on the actual operating conditions experienced by that unit.

We report ODE without including the energy impacts on the conditioned space (if HPWH is installed in a conditioned space). Since the evaporator of the HPWH extracts heat from its

surroundings, it cools (and frequently dehumidifies) the surrounding air. If the HPWH is installed within the conditioned space of the home, the HPWH will tend to cool (and dehumidify) the home, which, in turn, changes the loads placed on the space-heating and space-cooling systems. Since 15 of the 20 units were installed in unconditioned spaces (usually garages), only five units will impact space-conditioning loads. We did not attempt to measure space-conditioning impacts directly during the field test. Five units were installed in conditioned or semi-conditioned spaces. Unfortunately, detailed temperature data were not available for the California Climate Zones involved (Zones 3, 9, 10, and 12). Therefore, it was not possible to accurately estimate the cooling and heating-season durations, which were needed to estimate space-conditioning impacts. However, based on previous TIAX analyses for the U.S., we found that space-conditioning impacts reduce energy savings by well under 10 percent for homes heated and cooled by a heat pump. A thorough discussion of a calculation methodology is presented in Attachment 2.

Recirculation Loops: Two installations (Units 2 and 5) used hot-water recirculation loops[13], which impacted our ability to assess performance of these two units. (A third installation site– Unit 7– also used a recirculation loop, but the participant was able to switch off the loop, so it was of no consequence during the field test.) Unit 2 used a natural-circulation, recirculation loop. The flow meter (part of the unit instrumentation) was apparently interfering with the operation of the recirculation loop (due to increased flow restriction). Seven months into the field test, we moved the flow meter to the cold-water side of the HPWH because the participants wanted the recirculation loop to function properly. While in the original position, the unit presumably operated as if there were no recirculation loop. This provides a unique opportunity to assess the impact of the recirculation loop by comparing performance before and after the flow meter was moved. Table 12 compares water-heating loads and HPWH performance with and without the recirculation loop. Since this was a field test, we did not have a comparison under controlled conditions. A distinct change in average water consumption, inlet water temperature, and supply temperature was noted between the two periods. A comparison of the two HPWH ODEs (one including the recirculation loop losses, the other not) yields some insight to the magnitude of losses associated with the recirculation loop. The comparison suggests that the free-convection recirculation loop affects roughly a 50 percent increase in overall water-heating loads for the household. This increase in water-heating load is *not* related in any way to the use of the HPWH. While this comparison is for one system only and includes uncontrolled variables, it does suggest that recirculation loops can significantly increase energy consumption.

[13] Recirculation loops can be designed and operated in many ways, but the intent is to make sure that the water in the distribution system piping is warm when the end user wants to use hot water. Recirculation loops avoid the inconvenience of waiting for the water to warm up when a tap is opened, and they lower water consumption by reducing the amount of water dumped to the drain during this waiting period. However, depending on their design, recirculation loops can significantly increase the water-heating load.

Table 12. Unit 2—Comparison of Performance with and without Natural-Circulation, Recirculation Loop

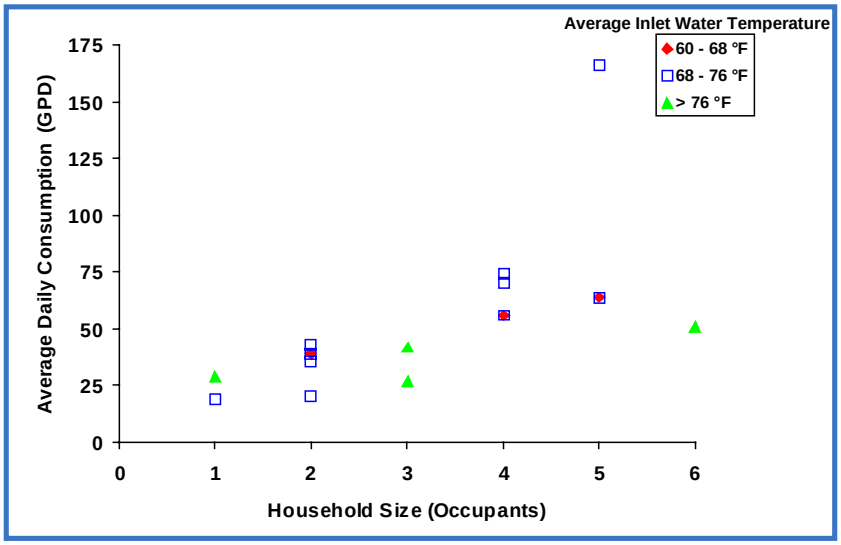
	W/O Recirculation Loop (March–Oct.)	With Recirculation Loop (Oct.–March)	Difference
Average Hot-Water Consumption (GPD)	39.0	33.4	(16%)
Average Inlet Water Temperature (°F)	52.3	65.7	—
Average Supply Water Temperature (°F)	129.0	137.3	—
Average Temperature Difference (°F)	76.7	71.6	(7%)
Average Water-Heating Load (kBtu)	24.9	19.9	(25)%
Average ODE (see Footnotes)	1.15[a]	0.59[b]	(48%)[c]
Average ODE for Resistance Water Heater (Simulated)	0.699[a]	0.729 [a]	4%
Average Energy Savings	36%	N/A[d]	N/A

a) Does **not include** losses associated with the hot-water distribution system.
b) **Includes** losses associated with hot-water distribution system, so this is not an ODE for the HPWH alone.
c) Since the two ODEs are defined differently, this comparison is suggestive of the energy penalty associated with recirculation systems, but is not an ODE comparison
d) Energy savings comparison not possible because electric-resistance ODE does not include recirculation loop losses.

Unit 5 utilized a forced-circulation, recirculation loop. For Unit 5, we left the flow meter in the hot-water delivery line, which means that the hot-water "consumption" measured includes the recirculation loop flow as well as actual water draws. We measured an average flow of 1362 gallons per day (GPD)! Clearly, this recirculation-loop pump is oversized, and is wasting energy for pumping alone. Unfortunately, we have no measurement of actual hot-water consumption for Unit 5.

See the individual unit histories in Attachment 2 for further discussions of the recirculation loops.

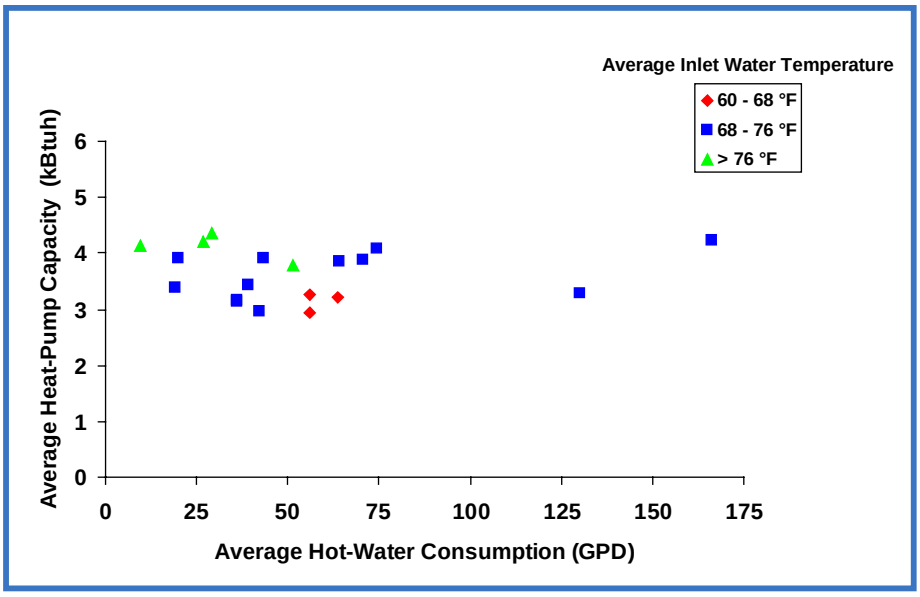
Hot-Water Consumption: As shown in Figure 10, the average hot-water consumption for each site ranged from 19.1 to 166.0 GPD for the residential installations. The commercial office building installation (Unit 9) averaged 9.6 GPD, and the public shower installation (Unit 12) averaged 130 GPD. The figure suggests a correlation between household size and hot-water consumption, at least for between one and four occupants. The leveling and drop off of consumption between four and six occupants is probably simply a statistical anomaly due to the small number of households in this size range. There is, however, no clear consumption trend with cold-water inlet temperature. Cold-water inlet temperature should impact hot-water consumption because cold water is mixed with hot water for showering. The colder the inlet water, the higher the percentage of hot water required to achieve a given shower temperature. However, given our relatively small sample size and the limited range of cold-water inlet temperatures experienced across all installation sites, the lack of a clear trend is not surprising.



Note: Unit 2 based on first seven months only because of recirculation loop. Unit 5 not included because of recirculation loop. Does not include non-residential installations

Figure 10. Average Hot-Water Consumption by Household Size

Heat-Pump Capacities: Figure 11 shows the average heat-pump capacity as a function of hot-water consumption, with values ranging from 2.94 to 4.78 kBtuh. The average of all units is 3.69 kBtuh. Heat-pump capacity is the heating capacity of the refrigeration system of the HPWH, not the HPWH heating capacity. The two are different because the HPWH has back-up resistance heating elements. The figure suggests that average heat-pump capacity remains relatively constant as water consumption increases. This is expected, since the heat-pump capacity is governed primarily by the HPWH design, air temperature, and water temperature—not by water consumption. There does appear to be a slight correlation between capacity and inlet water temperature, with higher capacities at higher inlet water temperatures. This correlation is expected, as higher inlet water temperatures mean a lower average temperature lifts for the heat pump. The average heat-pump capacities are consistent with the heat-pump capacity measured in the laboratory for the first prototype built under this project, which showed a 3500 Btuh capacity at 120ºF (See Attachment 1, *Third-Generation Prototype Fabrication and Laboratory Test Report*, Table 4-2).

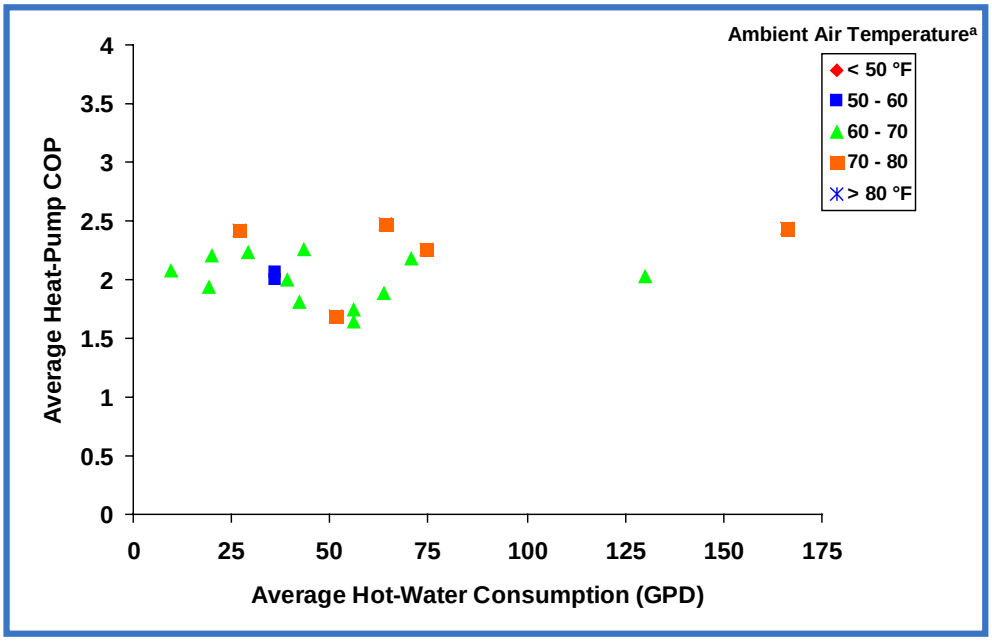


Note: Unit 2 based on first seven months only because of recirculation loop. Unit 5 not included because of recirculation loop.

Figure 11. Average Heat-Pump Capacities

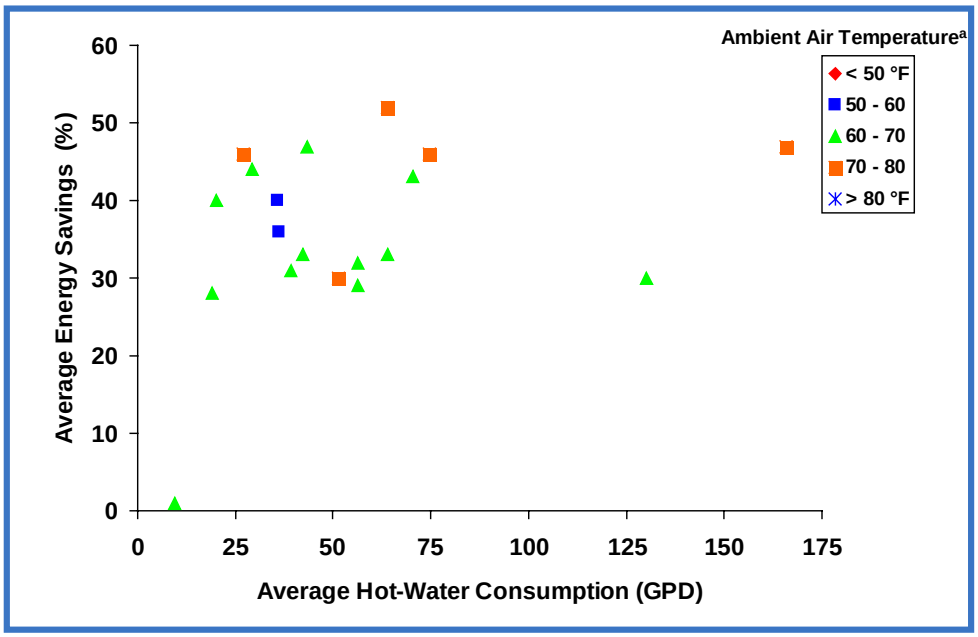
Heat-Pump COPs: Figure 12 shows average heat-pump Coefficient of Performance (COP) as a function of hot-water consumption. COP values apply only to the heat pump, not the HPWH. COP remains relatively constant (averaging 2.15 for all units) as water consumption increases. This is expected, since the heat-pump capacity is governed primarily by the HPWH design, air temperature, and water temperature—not by water consumption. There is no clear trend with average ambient air temperature, although one would expect higher COPs at higher ambient temperatures (due to the lower lift). The average heat-pump COPs are consistent with the heat-pump COP measured in the laboratory for the first prototype built under this project, which showed a 2.2 COP at 120ºF (See Attachment 1, Third-Generation Prototype Fabrication and Laboratory Test Report, Table 4-2).

Average Energy Savings: Figure 13 and Figure 14 show average energy savings of the field test units (relative to electric-resistance water heaters) as a function of ambient temperature, and as a function of installation location, respectively. As reported above, the average energy savings of the field test units at residential sites ranged from 28 to 52 percent (excluding Unit 5, for which energy savings could not be calculated because of a recirculation loop). There is little correlation to either ambient air temperature (for the ranges experienced in the field test) or installation location (garage, utility closet, or laundry room). Even tight (closed closets) enclosure (Units 2, 9, 12, and 14) energy savings did not seem to impact energy savings. (See Attachment 2 for descriptions of installation locations.)



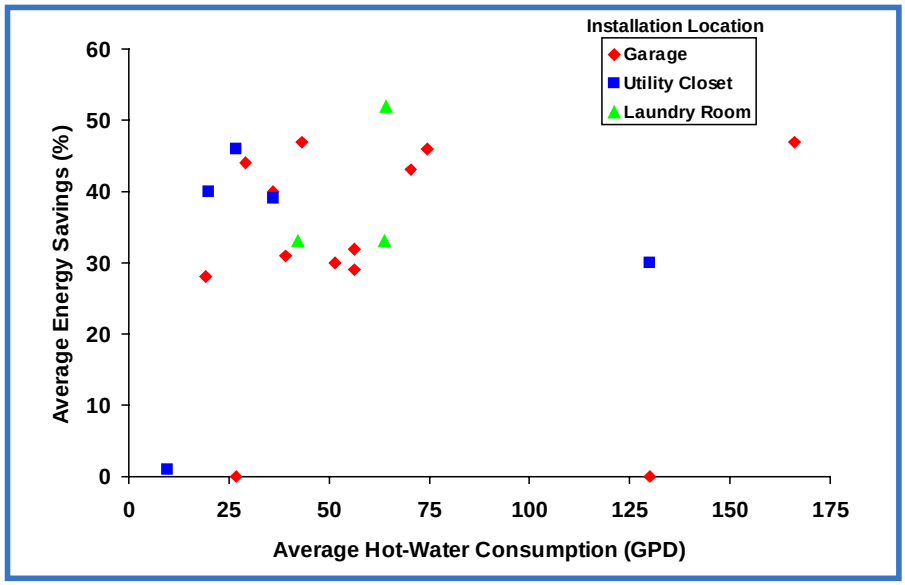
Note: Unit 2 based on first seven months only because of recirculation loop. Unit 5 not included because of recirculation loop.
a) As measured at HPWH while heat pump is operating

Figure 12. Average Heat-Pump COPs



Note: Unit 2 based on first seven months only because of recirculation loop. Unit 5 not included because of recirculation loop.
a) As measured at HPWH while heat pump is operating

Figure 13. Average Energy Savings by Ambient Temperature



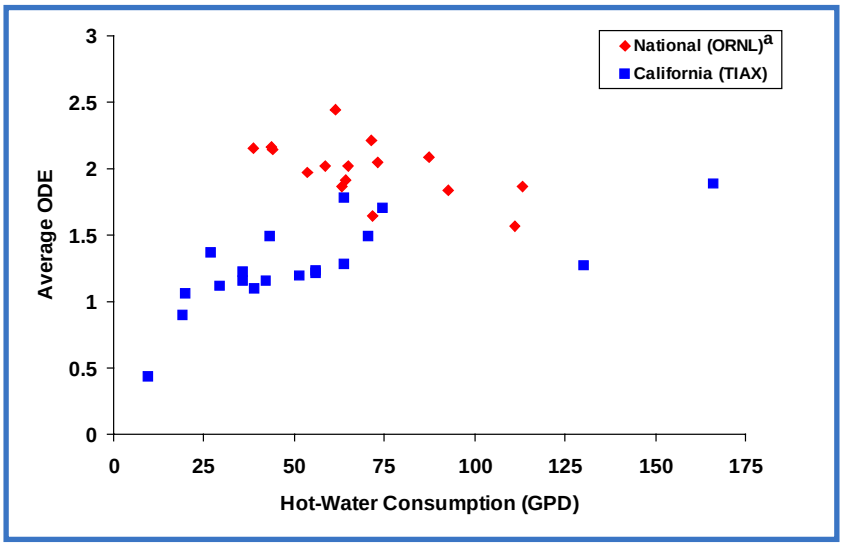
Note: Does not include units that have active re-circulation loops

Figure 14. Average Energy Savings by Installation Location

Figure 15 compares the results of this field test to those determined from Oak Ridge National Laboratory's (ORNL's) national field test [ORNL 2002; Table 7.1]. ORNL field tested prototype HPWHs, fabricated by EMI, that were similar (but not identical) in design to the units field tested in California. ORNL field tested 20 units for one year in nine states (excluding California). The energy savings for the units in the national field test ranged from 40 to 60 percent, with an overall average energy savings of 55 percent. However, the differences in reported energy savings between the California and national field tests may be due to differences in how energy savings were determined, rather than due to differences in the HPWHs or differences in operating conditions. ORNL determined the performance of an electric-resistance water heater by actual measurement. They alternated operation of the HPWH between "normal" HPWH mode and electric-resistance mode (in which they locked out the heat pump so that the water heater operated on resistance heating only). TIAX, on the other hand, ran the HPWHs only in "normal" mode, and determined the performance of electric-resistance water heaters by simulation (using water-temperature and water-draw profiles identical to those measured in the field). (See Attachment 2, *Field Test Data Analysis,* for a detailed discussion of the simulation methodology used.) There are advantages and disadvantages to each method. The advantage of ORNL's method is that it uses only measured field data, and does not rely on simulations. One advantage of TIAX's method is that it accounts for the lower stand-by losses achieved by an electric-resistance water-heater tank. An electric-resistance water-heater tank achieves lower stand-by losses relative to the HPWH because it has:

- Better insulation;
- No refrigerant lines to conduct heat away from the tank; and

- No chance of the "heat-pipe effect". (When the heat pump of the HPWH is idle, the refrigerant can evaporate in what is normally the condenser, and then migrate to other parts of the refrigerant loop to condense, hence cooling the tank.)



Note: Unit 2 based on first seven months only because of recirculation loop. Unit 5 not included because of recirculation loop.
a) From [ORNL 2002; Table 7.1]

Figure 15. Comparisons of California (TIAX) and National (ORNL) Field Tests

The second advantage of TIAX's method is that it uses operating conditions and water-draw profiles for the simulation that are identical to the actual conditions experienced in the field. It is not possible to duplicate operating conditions and draw profiles when the HPWH is switched from "normal" operating mode to electric-resistance mode (as ORNL did).

Diversified Demand Impacts: "Diversified demand impact" is the change in electric demand (i.e., power, *not* energy) seen by an electric utility associated with the installation of a large number of a particular new appliance or equipment type in the utility's service area. It is not simply the demand impact of one appliance multiplied by the number of installations. Rather, it must account for the expected distribution of demand impacts for each individual appliance. Measuring or estimating diversified demand impacts for the HPWH is beyond the scope of this project. However, we discuss below some of the issues associated with diversified demand impact, as well as referencing a preliminary assessment of diversified demand impact by other researchers.

One of the benefits of HPWHs is a decrease in electric demand. The demand-reduction benefit is greater than one would expect based on energy savings alone. This occurs because the heating capacity of the heat pump is lower than the heating capacity of a typical heating element in a conventional electric water heater. Lower heating capacity means that water heating is distributed over a longer period of time, at a lower average power draw. The market-optimized HPWH (for example, the EMI WATTER$AVER) should effect an even greater reduction in electric demand than a typical HPWH, because its heating capacity is lower than a typical HPWH.

ORNL estimated the diversified demand impact of the market-optimized HPWH in their report *Field Test of a "Drop-In" Residential Heat Pump Water Heater* [ORNL 2002]. ORNL defines "diversified demand" as the average demand of a large number of appliances all operating as designed and installed in a single climate (and utility region). ORNL measured the demand for six market-optimized HPWHs ("drop-in" HPWHs in ORNL's parlance) for six-week periods, both in summer and winter, and compared measured demand for the same water heaters operating in electric-resistance mode (simulating conventional electric water heaters). In winter, they found that the average demand during the morning peak was reduced from about 2.6 kW to about 1 kW (1.6 kW savings), and the evening peak was reduced from about 1.6 kW to about 0.7 kW (0.9 kW savings). In the summer, the morning peak was reduced from about 2.1 kW to about 0.6 kW (1.5 kW savings), and the evening peak was reduced from about 1.0 kW to 0.3 kW (0.7 kW savings) [ORNL 2002; Figures 7.7 and 7.8]. Note that ORNL defined "morning peak" and "evening peak" based on peak draw of the water heater, which may or may not correspond to the electric utility peak demand periods.

While the sample size used by ORNL may be too small to be statistically valid, their results do suggest that the demand reduction (60 to 70 percent) can be greater than the demand reduction associated with energy savings alone (40 to 60 percent [ORNL 2002; Table 7.1]).

However, an electric utility wishing to minimize the demand impact of residential electric water heaters has other alternatives, including:

- Using timers or other load-control devices on conventional electric water heaters. Customers are usually offered some type of financial incentive to agree to this control of their water heater; or
- Algorithms for control systems have been developed that can modulate the power draw of the lower element of a resistance water heater to reduce demand impacts, without significantly increasing the probability of a hot-water deficit [AIL 2003].

Furthermore, a utility would need to compare the likely timing of the demand impacts of electric water heating with their overall peak demand periods to see if they are coincident. If they are not coincident, then reducing the diversified demand impacts of water heaters is unlikely to benefit the utility.

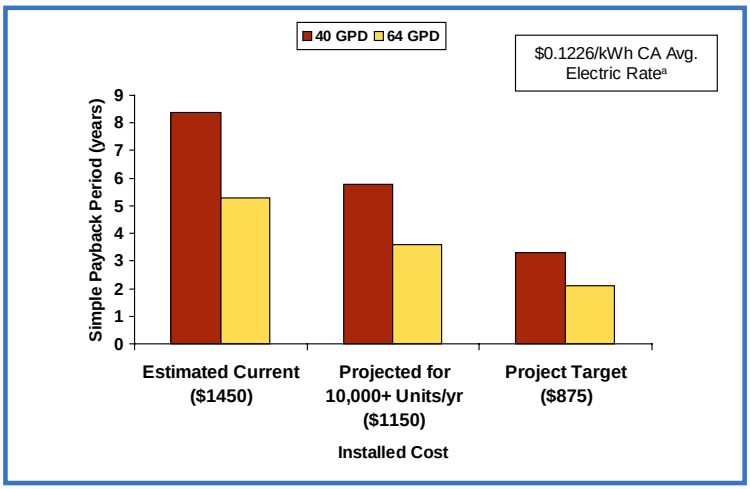
3.4.4 Economics

Figure 16 shows estimates of simple payback periods for the WATTER$AVER (EMI's trade name for the market-optimized HPWH) for California. The payback periods range from roughly 5 to 8 years at current installed costs, and roughly 4 to 6 years for future projected costs, based on hot-water consumptions ranging from 64 to 40 GPD. Had the project achieved its economic performance objective (an installed cost of $875), payback periods would have ranged from roughly 2 to 3 years in California. Still, the current and projected payback periods should provide returns that are attractive to a significant portion of Californians who currently use resistance water heaters. We discuss several design changes that could reduce the cost of the WATTER$AVER in Section 3.6.2, including cost reduction of the evaporator fans, expansion device, the control system, and the shroud. Section 3.6.2 also discusses co-locating HPWH fabrication with the tank fabrication as a cost-savings measure (although this strategy may not be practical until production volumes increase well beyond current levels). However, achieving a particular payback period is typically not a criterion for homeowners. In the replacement

market, energy-saving appliances are often purchased based on non-energy-savings benefits, or based simply on the fact that they save energy (without considering payback or any other economic parameter). The primary non-energy-saving benefit of the HPWH is that it dehumidifies the surrounding air[14]. Unfortunately, this benefit will be of limited value to many Californians because:

- Water heaters are installed outside the conditioned space (such as in garages) in many California homes; and
- The California climate is generally dry, so dehumidification is not generally beneficial.

In the new-construction market, the WATTER$AVER should help builders achieve the energy efficiency requirements of the California Energy Commission's Title 24 building standards, which should help make the Californian market attractive. Also, as discussed in Section 3.4.4, HPWHs (especially the market-optimized HPWH) can reduce electric demand. California utilities may see benefit in promoting HPWHs for this reason.



a) CA average revenue per kWh from retail sales, for Jan. - June 2003. [EIA 2003: Table 5.6B]
b) Assuming 1.15 ODE for 40 GPD, 1.28 ODE for 64 GPD and 65 °F average water temperature rise (based on actual averages for field test). Compared to 0.87 EF conventional electric-resistance water heater (0.79 ODE at 40 GPD and 0.85 ODE at 64 GPD having an installed cost of $500.

Figure 16. Simple Payback Periods

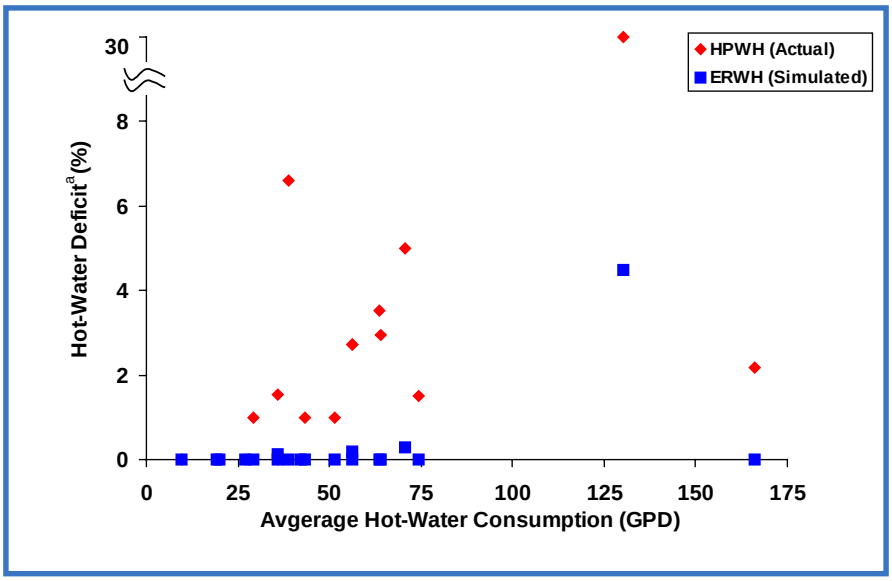
3.4.5 Hot-Water Deficits

Figure 17 shows average hot-water deficits for the field test units, and compares these to the simulated hot-water deficits for a conventional, electric-resistance water heater operating under the same conditions. We define hot-water deficit as the percentage of water (on a volume basis) delivered below 105°F, regardless of thermostat set point. 105°F is a typical shower-water temperature and, therefore, generally reflects the minimum hot-water temperature that occupants will find acceptable. (Refer to Attachment 2, *Field Test Data Analysis*, for the details of

[14] While we describe this as a "non-energy-saving" benefit, if the household currently uses a dehumidifier, then this becomes an energy-saving benefit.

how we calculate hot-water deficits.) However, there is no standardized definition of a hot-water deficit. Some researchers determine the *number* of hot-water run outs ([ORNL 2002] for example), rather than the volume of water delivered below the acceptable temperature limit.

The figure shows that measured deficits for the HPWH range from 0 to 6.6 percent (excluding the unit installed in a public shower—Unit 12). Simulations of electric-resistance water heaters for the same range of operating conditions suggest that the hot-water deficits would have ranged from 0 to 0.3 percent. For the public shower installation, we measured 30.0 percent hot-water deficits, compared to 4.5 percent for a simulated electric-resistance water heater.



a) Percent of volume of hot water delivered below 105 °F Unit 2 based on first seven months only because of recirculation loop. Unit 5 not included because of recirculation loop.

Figure 17. Hot-Water Deficits

Clearly, the field test HPWHs show higher levels of hot-water deficits compared to simulated electric-resistance water heaters. This is not surprising because the heat pump of the HPWH has a significantly lower heating capacity relative to a resistance element. However, quantification of hot-water deficits is at best an imperfect indication of an end-user's acceptance of water delivery temperature because:

- End users may modify their behavior to accommodate the hot-water delivery capability of their water heater, typically by avoiding multiple sequential showers or by shortening showering time. End users may be frustrated by the need to modify their water-use habits, but their modified behavior will not be reflected in measured deficits;
- End users have widely varying tolerances for hot-water deficits. While we can report deficits, it may be difficult to access whether the level of deficits would be acceptable to most end users; and
- End users may not be aware of certain deficit situations. For example, hot-water used by a washing machine.

In the end, perhaps the best indicators of satisfaction with delivery water temperature are the results of the participant surveys (see Section 3.4.8 below). Even here, one cannot assume that the participants in this field test are representative of all Californians. First, the sample size is too small. Second (and probably more important), end users willing to participate a field test are probably more willing than the average person to tolerate some inconvenience to save energy.

3.4.6 Field Failures and Reliability

We experienced several failures during the field test. Failures that resulted in a loss of hot-water service are summarized in Table 13.

Table 13. Summary of Reported Failures Resulting in Loss of Hot Water

Unit	# of No-Hot-Water Complaints	Reason for Failure	Resolution
2	1	Control Board	Removed Ground Wire
	2	Control Board	Replaced Control Board
5	1	Control Board	Replaced HPWH & Installed new EMI design Control Board
7	1	Control Board	Reset Circuit Breaker
	2	Control Board	Reset Circuit Breaker
	3	Control Board	Reset Circuit Breaker
	4	Control Board	Reset Circuit Breaker
	5	Control Board	Replaced Control Board with new EMI design
8	1	Control Board	Replaced Control Board
	2	Control Board	Reset Circuit Breaker
	3	Refrigerant Leak	Replaced HPWH
9	1	Control Board	Reset Circuit Breaker
	2	Control Board	Reset Circuit Breaker
	3	Control Board	Reset Circuit Breaker
10	1	Thermostat	Replaced Thermostat
	2	Control Board	Reset Circuit Breaker
13	1	Control Board	Replaced Control Board
	2	Thermistor	Replaced Evaporator Thermistor
	3	Control Board	Reset Circuit Breaker
15	1	Control Board	Reset Circuit Breaker
	2	Control Board	Removed Ground Wire
	3	Control Board	Replaced Control Board
20	1	Control Board	Reset Circuit Breaker
All Others	No Complaint		

Controls system failures were the dominant failure type. Seven units required periodic "resetting" of the unit by switching the circuit breaker off and then on again. This seemed to reset the control algorithm to allow the controls to operate properly after a disturbance. It was

later determined that the problem may have been aggravated by a grounding wire attached to the control board. The ground wire was removed from these units, which reduced the number of resets required, but did not eliminate them. For subsequent installations, the ground wire was removed at the time of installation. Six units received a replacement control board from EMI to resolve frequent failures. Three of these six units, Unit 5, 7, and 10 (at time of installation), received a new-model control board developed by EMI in March 2003. No resetting of the new-model control boards was required, confirming the improvements to the design.

An EMI technician replaced two HPWH units in the field. The first unit (Unit 5) was replaced because it was not meeting the participant's hot-water-delivery expectations. Troubleshooting in the field could not determine the cause of the problem, so we returned the unit to EMI. EMI could not determine the cause of the poor performance, although we suspect a shorted thermistor wire caused the failure of the control board. The second unit (Unit 8) experienced a high evaporator temperature, which we determined was due to a loss of refrigerant caused by a broken copper tube that connects the TXV to the sensing bulb

We diagnosed and repaired the remaining two component failures in the field. One unit (Unit 13) had an evaporator frosting problem that was caused by a failed thermistor. Replacing the thermistor resolved the problem. Another unit (Unit 10) did not produce hot water above 90 °F. Troubleshooting the unit revealed a failed thermostat. We replaced the thermostat, and the unit returned to normal operation.

The compressor discharge temperature was monitored because of its impact on compressor life. Compressor discharge temperatures above 240°F may lead to lubricant breakdown and eventual compressor failure[15]. The HPWH refrigeration system was designed to limit the compressor discharge temperature to less than 220°F to provide a safe operating margin. The compressor discharge temperature was monitored, with the frequency of high (greater than 220°F) discharge temperatures shown in Figure 18. Typical maximum compressor discharge temperatures experienced were 220 °F to 226 °F, with the exception of Unit 18, which peaked at nearly 270°F.

[15] The compressor lubricant, polyol ester oil, can breakdown at roughly 300 °F, decreasing its lubricating ability. Internal compressor temperatures can be 40°F to 50°F higher than the measured discharge temperatures due to heat loss. To ensure satisfactory compressor life, compressor manufacturers typically recommend a maximum compressor discharge temperature of 240°F.

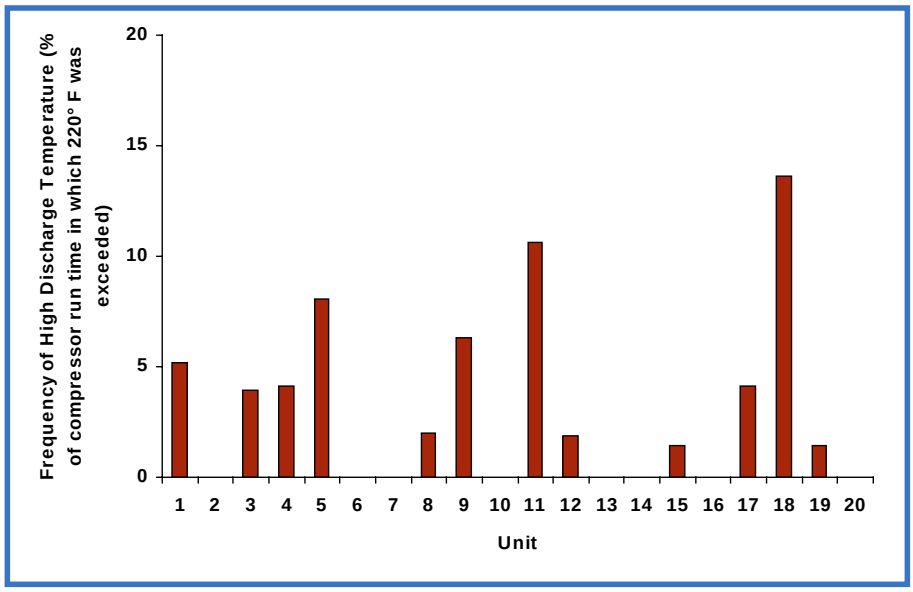


Figure 18. Frequency of High Compressor Discharge Temperatures

3.4.7 Participant Satisfaction

We conducted one participant background interview and three satisfaction surveys over the course of the one-year field test. We conducted the interview at the time of the installation to obtain background information on the participants, expectations, and site specifics, such as type of heating system, location, etc. All of the participants indicated that energy efficiency was important to them. In fact, the primary reason that most people said they participated in the field test was to save electricity/money.

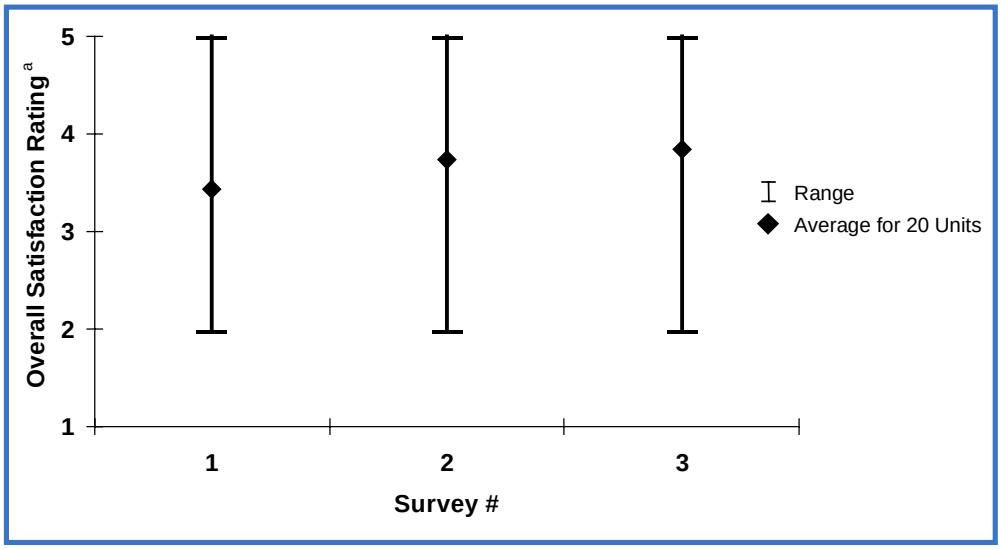
The purpose of the three surveys was to assess the level of satisfaction of the participants with their new water heaters. These surveys were conducted at regular intervals throughout the field test: two months after the HPWH installation, four months after installation, and at the conclusion of the field test. Survey results for each installation site can be found in Attachment 2, *Field Test Unit Summaries*. Attachment 2 also includes the interview and survey templates.

The surveys asked participants to quantify their reaction to various characteristics of the HPWH. The rating scale ranged from 1 to 5 as follows:

- 1 = much worse than previous water heater;
- 2 = somewhat worse than previous water heater;
- 3 = about the same as previous water heater;
- 4 = somewhat better than previous water heater; and
- 5 = much better than previous water heater.

The overall satisfaction rating for each of the three surveys is shown in Figure 19. They consistently ranged from 2 to 5 for the three surveys. The average satisfaction rating improved over time and was most likely due to the participants increasing familiarity with the HPWH

and adjustment to its operation. At the beginning of the field test, there were a number of control-board failures (discussed previously in Section 3.7), which may also have lowered initial satisfaction ratings.



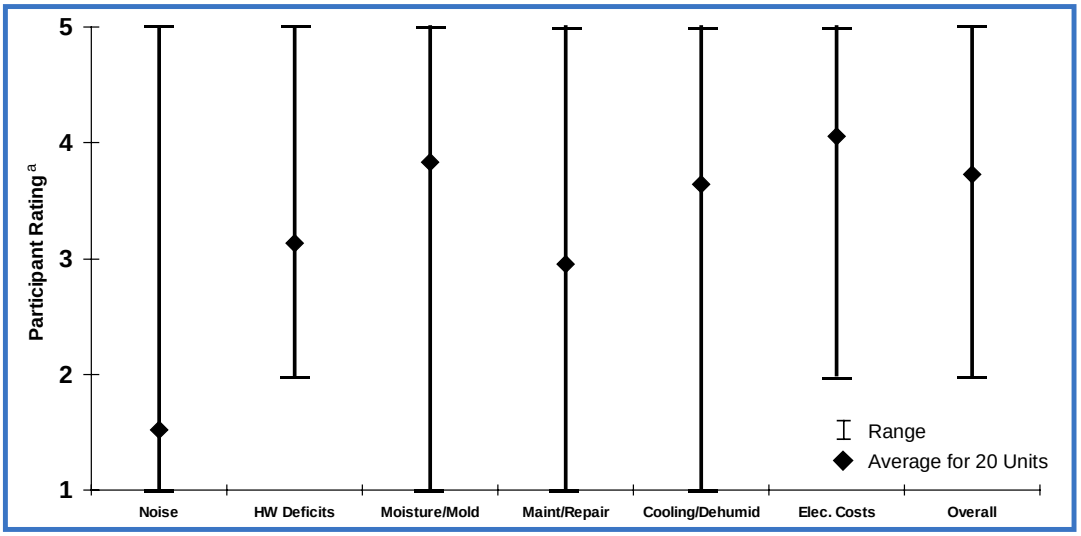
a) Ratings defined as:
1 = Much worse than previous water heater
2 = somewhat worse than previous water heater
3 - About the same as previous water heater
4 = Somewhat better then previous water heater
5 = Much better than previous water heater

Figure 19. Participant Overall Satisfaction Rating

We understood that there were certain criteria, such as noise, that would likely receive a lower rating than a conventional electric-resistance water heater. The initial "target" ratings are shown in Table 14. The "target" ratings were simply TIAX's projections of where average ratings would fall. The combined results of the three surveys are summarized in Figure 20.

Table 14. Target Customer Satisfaction Criteria for the HPWH

Criterion	Target Rating	Survey Ratings			
		1	2	3	Average
Sound Level (including cycling noise)	2	1.5	1.5	1.6	1.53
Hot-water Runouts	3	3.1	3.3	3.0	3.13
Moisture / Mold / Mildew / Odors	3	3.3	3.3	3.6	3.40
Repairs/Maintenance	2	2.9	2.9	3.0	2.93
Cooling / Dehumidification	4	3.6	3.6	3.8	3.67
Energy and cost savings	5	3.7	4.3	4.1	4.03
Overall Satisfaction	3	3.5	3.8	3.9	3.73



a) Ratings defined as:
1 = Much worse than previous water heater
2 = somewhat worse than previous water heater
3 - About the same as previous water heater
4 = Somewhat better then previous water heater
5 = Much better than previous water heater

Figure 20. Summary of Participant Survey Results (Average for Three Surveys)

Noise: The lowest average rating, 1.5, was in response to the noise from the compressor/fans of the HPWH. Participants were particularly sensitive to noise in sites where the installation was near frequently occupied areas (such as an office or guest bedroom). We anticipated that the noise category would yield unfavorable ratings compared to a silent electric-resistance water heater. The rating of 4 from one participant may have arose from confusion in filling out the survey. The participant may have misinterpreted a rating of "4 = Somewhat better than previous water heater" to mean that the noise level of the HPWH is somewhat greater than the previous water heater.

Hot-Water Deficits: Participants generally seemed satisfied with the hot-water delivery of their HPWHs, resulting in an average rating of 3.3 for the category. In the case of Unit 10, which used an average of 166 GPD, some comments indicated that there was less hot water available than with their previous water heater. The impression of the TIAX field engineer is that some participants subtly change their usage habits to accommodate the slower recovery time of the HPWH. Again, field-test volunteers may be more accepting then the general public of inconveniences associated with energy savings.

Moisture/Mold/Mildew: Ratings ranged from 1 to 5, with an average rating of 3.4. Participants concentrated their comments on the condensate line. The participants could observe the condensate (moisture) coming out of the HPWH and, in some cases, mold/mildew formed around the condensate drain connector. In one instance, the primary condensate line was plugged and the secondary condensate line was dripping along a wall that started forming mold/mildew.

Maintenance/Repair: We expected a rating of 3 or less because a conventional electric-resistance water heater rarely requires maintenance/repair/attention. Some HPWHs in the field test

required attention/repair, as described in Section 3.4.7. Generally, participants gave ratings of 5 if they had no maintenance or operational problems, which skewed the average rating upward, to 3.0.

Cooling/Dehumidification: . The HPWH evaporator removes moisture from its environment, so we expected a favorable rating. However, reaction to this category varied widely, from 1 to 5. There were five HPWH installations in conditioned spaces. Participant reaction in these cases depended on the season. In the hot season, the added cooling provided by the HPWH was perceived as a benefit, while in the cold season, the addition of cool air to the room resulted in complaints. In other parts of the country (for example, in New England, where basements are common), the dehumidification effect might be more highly valued. The remaining fifteen sites were not effected by the cool evaporator air, as is reflected in the 3.7 rating for the category.

Electricity Savings: Participants were generally happy with the electricity/cost savings when they were able to notice a change in their utility bills. The overall average for the category was 4.0. The rating of 2 came from a participant who noticed their energy bill was higher than the previous year. However, the host also said that this may be due to the use of new space heaters.

Each survey also asked the participants to provide additional comments, observations, or suggestions. Several participants recommended HPWH design changes:

- **Add an access panel to see if there is power to HPWH.** This point is probably not important to a "typical consumer", but it would have been helpful for this field test for troubleshooting when units would sometimes not produce hot water. When the HPWH is not in heating mode, there is no visible indication that there is power to the unit. There is a light-emitting diode (LED) on the control board that lights up when there is power to the unit, but it can not be seen when the shroud is installed;
- **The air inlet filter should be in a position that is more easily accessible for maintenance.** The current position of the inlet filter is in the back (opposite side from the thermostat). In small confined spaces (such as a closet), access to the filter is very difficult (if not impossible). For example, Unit 14 was installed in a closet where the door and doorframe on the closet needed to be removed, the HPWH installed, and the door replaced. (See Figure 21);

Figure 21. Unit 14 Installation

- Add an external switch to change from HPWH mode to electric-resistant mode when needed. The Unit 8 participant used the garage (where the HPWH was installed) as a guestroom and had to turn off the power to the HPWH at night when he had overnight guests. The Unit 3 participant had a guest room next to the closet having the HPWH and the participant personally installed a switch/lever to switch the HPWH from heat-pump mode to electric-resistant mode without having to remove the shroud; and
- Use a larger condensate line. Plugging in the ¼" ID condensate lines was observed in some of the units. We resolved the problems by installing larger condensate lines and/or putting in a condensate vent line.

As noted previously, the survey results may reflect a bias relative to the general population because participants were willing to participate in this field test. Also, the participants realized that this was a field test, so they were a little more (in some cases a lot more) tolerant of problems that arose and may have been more lenient in answering the survey questions as a result.

*Overall, most of the participants were generally happy with their HPWHs. All participants were given the opportunity to have a new electric-resistance water heater installed at no cost at the end of the field test. 14 of the 20 participants were interested in keeping their HPWH. Some sites did not have the opportunity to choose to keep the HPWH because the units needed to be shipped back to EMI for post-field-test evaluation. Table 15 shows the disposition of the 20 field-test units.

Table 15. Unit Disposition at End of Field Test

Unit	Participant Request at end of Field Test	TIAX Action
1	Keep	Transferred Ownership
2	Remove	Replaced HPWH
3	Keep	Transferred Ownership
4	Keep	Replaced HPWH (Sent back to EMI for testing)
5	Remove	Replaced HPWH
6	Remove	Replaced HPWH
7	Keep	Transferred Ownership
8	Remove	Replaced HPWH (Sent HPWH to EMI for testing)
9	Keep	Replaced HPWH (Sent back to EMI for testing)
10	Keep	Transferred Ownership
11	Remove	Replaced HPWH
12	Remove	Replaced HPWH
13	Keep	Transferred Ownership
14	Keep	Transferred Ownership
15	Keep	Transferred Ownership
16	Keep	Replaced HPWH (Sent back to EMI for testing)
17	Keep	Transferred Ownership
18	Keep	Transferred Ownership
19	Keep	Transferred Ownership
20	Keep	Transferred Ownership

The following participants elected not to keep the HPWH upon completion of the field test:

- The host for Unit 2 was satisfied with the unit and was interested in keeping it. However, the limited warranty and lack of service network dissuaded him from keeping the unit. Parts are covered as part of the 1-year warranty, but labor is not covered;
- The host Unit 5 had difficulty with the performance of his recirculation loop. We suspect that the difficulty was caused by an incorrectly installed check valve, however, the cause was never determined. The ultimate decision to remove the unit was based on the failure of the upper electric-resistance heating element that occurred shortly after the field test ended;
- The host for Unit 6 noticed some rust around the base of the tank that caused him some concern. He was also disappointed in the limited warranty offered at the end of the field test. When the unit was removed we determined that the rust was cosmetic, and was caused by a leaking check valve dripping into the bottom of the unit;
- The host for Unit 8 uses the garage (where the HPWH is installed) as a guestroom and a play area for his child. The HPWH's noise and cold air were not desirable in this occupied space;

- The host for Unit 11 has an office located next to the room where the HPWH was installed. The noise from the HPWH was undesirable; and
- The host for Unit 12 had the HPWH installed in a public bathroom (supplying showers for men and women) at a marina. The HPWH could not keep up with the high hot-water demand, resulting in many complaints of not enough hot water.

3.4.8 Pre- and Post-Field-Test Unit Evaluations

EMI performed cold-water heat-up tests on 16 units, and DOE Energy Factor tests on two units, before they were shipped to the field. The purpose of these tests was to establish a pre-field-test performance baseline so that a few units could be checked after the field test to determine if any performance degradation had occurred. Following the field tests, EMI conducted cold-water heat-up tests on two units, and DOE Energy Factor test on another two units. The results of the pre- and post-field-test evaluation tests are shown in Figure 22 and Table 16. A plausible explanation for the improvement in Energy Factor shown in the figure is that the compressors have worn in during the field test, which reduced friction in bearings and between the pistons and cylinder walls.

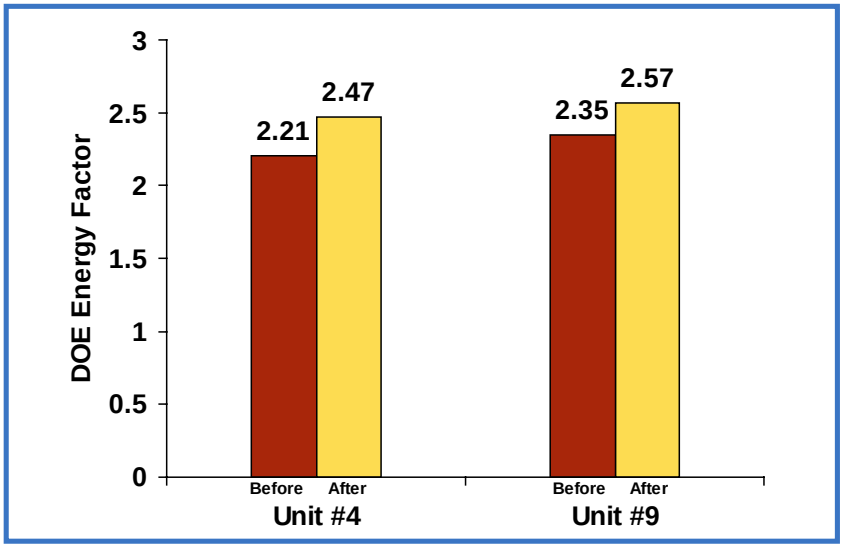


Figure 22. DOE Energy Factor Test Results—Before and After Field Test

Table 16. Cold-Water Heat-Up Test Results—Before and After Field Test

	COP[a]			COP[a]	
Unit	**Before**	**After**	**Unit**	**Before**	**After**
1	2.39		**11**	No Data[b]	
2	2.49		**12**	No Data[b]	
3	2.13		**13**	2.44	
4	No Data[b]		**14**	2.85	
5	2.12		**15**	2.57	
6	2.42		**16**	2.72	2.52
7	2.16		**17**	2.31	
8	2.65	2.62	**18**	2.15	
9	No Data[b]		**19**	2.54	
10	2.72		**20**	2.50	

a) COPs are not corrected for stand-by losses that occurred during the test. The electric-resistance elements were disabled during the tests.
b) Unspecified problem encountered during test.

EMI also performed a destructive evaluation of the same four units that were performance tested after the field test (Units 4, 8, 9, and 16). Three of the four units (Units 8, 9, and 16) had been installed in locations having high mineral content in the local water supply. One of the key objectives of destructive evaluations was to assess whether mineral content in the water supply was creating scale in the tanks that could impact long-term performance. The results of the destructive evaluations are photographically documented in Appendix I. The air filters typically had a visible coating of dust, although the filter on Unit 8 exhibited a high concentration of lint, apparently from a clothes dryer. Units 8 and 16 exhibited a light coating of scale on the tank inner walls, anode rods, and resistance heating elements. Units 4 and 9 exhibited heavy scale on the anode rods, but light scale elsewhere. Unit 9 also exhibited spotty surface rust on the inner tank wall. The heavy scale on the two anode rods is not necessarily a call for concern. It is not uncommon for anode rods to become heavily scaled. Furthermore, there is little reason to think that heat-pump operation would impact scale formation on the anode. The evaluations show no evidence of accelerated scale formation on the inner tank walls due to operation of the heat pump.

3.5 Information Dissemination Plan

As part of the scope of this project, we developed an Information Dissemination Plan (see Appendix II). The Plan outlines a comprehensive approach to communicating the results of this project, and information on HPWHs in general, to key stakeholder groups. The key objectives of the Plan are:

- To publicize the results of the PIER project, focusing on the lessons learned and next steps in further developing HPWHs that are ready for mass commercialization;
- To communicate the potential economic and energy savings benefits of energy-efficient electric water-heating technologies, such as the WATTER$AVER, to the general public;
- To educate those affected by and those responsible for enforcing Title 24—California utilities, organizations, public agencies and homeowners—about electric HPWHs;

- To attract the attention of manufacturers, industry experts, and other stakeholders who may be interested in the continued development of the HPWH; and
- To increase exposure of the WATTER$AVER by raising the visibility and profile of experts who have worked on this project through media coverage and speaking opportunities.

The Plan is written for any organization that is seeking to promote markets (especially California markets) for residential electric HPWHs.

3.6 Production Readiness Plan

3.6.1 Overview of Production Readiness Plan

The scope of this project included developing a Production Readiness Plan (see Appendix III). The purpose of the Production Readiness Plan is to provide the information necessary for a manufacturer to assess whether the market-optimized HPWH is a good match to the manufacturer's existing production capabilities, including the additional investment in production equipment and labor skill base that would be needed to commercialize the HPWH. As such, the Production Readiness Plan includes:

- Identification of critical production processes, equipment, facilities, manpower, and support systems that will be needed to produce a commercially viable product;
- Capacity constraints imposed by the design under consideration for internal manufacturing capabilities, as well as suppliers. The project manufacturing effort may include "proof of production processes";
- Identification of hazardous or non-recyclable materials;
- A projected "should cost" for the product in production at some expected rate;
- The expected investment threshold required to launch the commercial product; and
- An implementation plan to ramp up to full production.

In this particular case, EMI has already developed a production capability for the market-optimized HPWH, and is currently developing a market base. EMI calls their product the WATTER$AVER.

The Production Readiness Plan shows that the project economic objective ($875 installed cost) could be achieved by a large manufacturer (greater than $1 billion in annual sales) with annual production volumes of 10,000 units or greater. A small manufacturer is unlikely to achieve this cost, even at high production volumes. However, as summarized in Section 3.6.2, further design enhancements could reduce HPWH cost significantly, even without the purchasing power of a large manufacturer.

3.6.2 Recommendations for Equipment Cost Reduction

There are areas worthy of further investigation for cost reduction, including the following.

Evaporator Fans: The WATTER$AVER currently uses two muffin fans[16] to circulate air through the evaporator. It may be possible to utilize a single, lower-cost fan.

Expansion Device: We selected a thermostatic expansion device (TXV) largely to ensure that the HPWH would operate safely and properly under a wide range of ambient conditions. However, the TXV and capillary tube scored similarly in our component selection and design refinement process. If a capillary tube could be sized to work properly under the wide range of operating conditions that the HPWH sees, it would reduce manufacturing costs. Alternatively, installers could be trained to install units only in areas having temperature ranges suitable for use with a capillary tube.

Control System: The HPWH uses a sophisticated control system to assure safe and reliable operation over a wide range of conditions. We took a conservative approach in that we did not wish to rely on the discretion of the installer to limit installations to those that are "HPWH friendly". Control simplifications (and associated cost reductions) may be possible. However, this would require significant laboratory and field-testing to verify that adverse operating conditions can be sustained without damage to the HPWH. Alternatively, it may be possible to educate installers to avoid installations that would place a HPWH at risk if it had a simpler control system.

Shroud: The shroud assembly, which houses and protects the heat-pump components and controls mounted on top of the water tank, is a relatively expensive sheet-metal design. With some design and prototyping effort, it may be possible to develop a lower-cost plastic molded shroud.

Co-Locating HPWH Fabrication with Tank Fabrication: A significant contribution to tank cost is associated with the need to package and ship the tanks from the tank manufacturer to the HPWH manufacturer. If the HPWH production facility could be co-located with the tank manufacturing facility, packaging and shipping costs could be eliminated. Of course, this would require reaching a business agreement with the tank manufacturer, building a new HPWH production facility, and hiring staff for the new facility. While this is probably not practical at current production levels, it should be considered as production levels increase.

[16] A muffin fan is a small electric fan. It is typically black plastic, having the motor integral with the hub of the fan, a square shroud, and mounting holes. Muffin fans are often used for electronics cooling.

4.0 Conclusions and Recommendations

Conclusions and recommendations from the project are summarized below.

4.1 Conclusions

Energy Savings
Overall energy savings for the field test generally ranged from 30 to 50 percent, relative to simulated electric-resistance water-heater performance. This is somewhat lower than the 40 to 60 percent observed in ORNL's national field test [ORNL 2002], but differences may be due to differences in how electric-resistance water-heater performance was determined.

While we had only four installations in tight enclosures, there is no evidence that tight enclosures had any significant impact on performance.

Although we have insufficient data to draw firm conclusions, the results from at least one site suggest that re-circulation loops can significantly increase energy consumption. There could be a false economy associated with installing re-circulation loops to conserve water.

Installed Cost
We did not achieve our economic performance objective of $875 installed cost. The estimated installed cost is $1450, which should drop to $1100 to $1200 for production volumes of 10,000 units/year or more. The key contributing factor is that actual component costs are higher than originally estimated. One of the largest contributors to equipment cost is the control system. There is an appliance-industry-wide trend towards more sophisticated control systems. As advanced control systems are more widely deployed, their costs should drop. Alternatively, a major appliance manufacturer entering the HPWH market would probably have a cost structure consistent with our $875 installed-cost objective (based on annual production volumes of 10,000 units or more), even with today's control-system costs.

Even at current estimated costs, EMI's WATTER$AVER should provide attractive economic returns (payback periods under five years) for California households that use electric water heating and have four persons or more (64 GPD or more hot-water consumption).

Reliability
The failure rate observed during the field test is higher than would be acceptable in the water-heater market. Control-system failures were the most common failure source. EMI has enhanced the design of the WATTER$AVER to address key reliability issues and their production product should be more reliable than the pre-production units tested under this project. Outside of this project, ORNL completed a second round of laboratory-based durability tests on five production WATTER$AVER units. While those test results have not yet been published, ORNL indicates that the units experienced no failures related to the durability test [ORNL 2004].

End-User Acceptance
Overall, field test participants were satisfied with their HPWHs, as evidenced by their ratings on surveys and by the fact that 14 of the 20 participants wanted to keep their HPWHs after the field test ended (although only 12 were allowed to because of the need for post-field-test evaluations). There was no evaluation criterion upon which participants agreed—there was always a significant range in satisfaction levels for any given criterion. Several participants

expressed concerns about noise levels. At least two issues were at work here: 1) participants were not accustomed to any noise from their water heaters, and 2) some water heaters were installed near bedrooms (including guest rooms), and the noise interfered with sleeping. Surprisingly, the average score for "hot-water deficits" suggests that participants generally thought their HPWHs performed at least as well as their old electric-resistance water heaters in delivering hot water, even though our measurements show that actual hot-water deficits were higher than would be expected for electric-resistance water heaters. Participants also indicated that they valued the electricity cost savings associated with their HPWHs, although some participants mentioned that they had trouble actually discerning a difference by examining their electric bills.

4.2 Recommendations

Design Improvement Opportunities

The field test provided insights into further design improvements for the HPWH to lower cost and/or improve performance, user acceptance, or ease of installation. Component cost reduction should be explored, in particular for the evaporator fans, expansion device, control system, and shroud. Co-locating the fabrication of the HPWH with the fabrication of the tank assembly offers further potential cost savings. In addition, several design enhancements for ease of installation should be explored (see Table 17).

Table 17. Recommended Design Enhancements for Ease of Installation

Reduce HPWH weight or otherwise permit installation by a single installer.
Redesign the HPWH so that the shroud need not be removed during installation (i.e., allow electrical and plumbing connections to be made without removing the shroud).
Use a common condensate drain line size for both the primary and back-up condensate drains.
Develop guidelines for installers so that they can readily determine whether to recommend EMI's optional condensate re-evaporation system.
Develop a procedure by which the installer does not have to wait for the heat pump to operate when first starting up the HPWH.

Finally, to facilitate maintenance and failure detection, two additional design enhancements should be explored (see Table 18).

Table 18. Recommended Design Enhancements to Facilitate Maintenance and Failure Detection

Locate the removable air filter on the front (thermostat side) of the unit for ease of removal and cleaning.
Make status-indicating lights visible to the exterior of the unit without removal of the top shroud.

Reliability

While EMI has taken steps to address reliability issues identified through this project, the reliability of the EMI's production product has not been demonstrated through a documented field test. Further field testing of the production WATTER$AVER is needed to verify that adequate reliability has been achieved.

Further R&D Opportunities
In two other projects conducted by TIAX in parallel with this project, we explored the feasibility of a Condensate Recovery System (CRS) for the HPWH. The CRS "disposes" of condensate by first heat sterilizing it, and then injecting it into the water tank. Thus, using the CRS with a HPWH removes the need to run condensate drain lines (and possibly condensate pumps) without eliminating the dehumidification benefit or significantly eroding energy savings (both of which are drawbacks of re-evaporation of condensate). The first project, performed for the U.S. Department of Energy, demonstrated the feasibility of the CRS through a prototype design, development, and laboratory testing effort [DOE Condensate 2001]. The second project, also performed under the Energy Commission's PIER program, preliminarily demonstrated the safety of the CRS through a preliminary hazard analysis and laboratory testing [CRS 2002]. Should the HPWH begin to achieve market success, further development efforts (and regulatory acceptance efforts) may be warranted.

Additional energy savings (and other performance advantages) may be achievable by using carbon dioxide as a refrigerant in HPWHs. At least four Japanese manufacturers currently offer carbon dioxide HPWHs. On October 15, 2003, the U.S. Department of Energy announced its intent to award a contract (through the National Energy Technology Laboratory) to United Technologies, East Hartford, CT to develop a carbon dioxide HPWH for commercial-building applications in the U.S. market. We are unaware of any current efforts to develop a residential carbon dioxide HPWH for the U.S. market. While we generally believe that there are more compelling issues to address (such as cost reduction and reliability improvement), current carbon dioxide development efforts should be tracked. If successfully demonstrated in commercial-building applications, development of a carbon dioxide HPWH for the residential market may be justified.

Promotional Activities
Near-term promotional efforts should focus on major appliance manufacturers who have the resources to break open the HPWH market, such as a) brand recognition, b) extensive design and manufacturing expertise, c) component purchasing clout, and d) well developed distribution, sales, and service infrastructures. In addition, continued work with utilities and energy efficiency organizations will help refine product requirements and define the true nature of the HPWH market potential, which major manufacturers will need to understand before investing in such a technology. As products having proven reliability emerge, broader-scale promotional efforts will be warranted.

Further "Data-Mining" Opportunities
The extensive field-test data collected could provide additional useful information. For example, researchers who model household energy consumption would benefit from having access to more realistic hot-water-draw profiles. Statistical analysis of our field-test data could provide such profiles. In addition, there is a need for a better understanding of the diversified demand impacts of HPWHs and other technologies, as well as mechanisms for controlling demand impacts associated with water heating. Statistical analysis of our field-test data might provide a better understanding of potential demand impacts. The same applies for the data obtained from other field tests, such as ORNL's national HPWH field test [ORNL 2002].

Other Recommendations

Quantifying the differences in hot-water deficits between HPWHs and resistance water heaters will continue to be important to stakeholder groups. There is a need to develop a standardized definition for a hot-water deficit so that, in the future, researchers report hot-water deficits on a consistent and comparable basis.

An easy-to-use analytical tool would be beneficial for predicting HPWH energy savings for specific installation sites. Pertinent site data, such as climate region, estimated water usage, installation location of HPWH, and electric rate would be key inputs. The tool should account for space-conditioning impacts as well.

5.0 Glossary

ADL	Arthur D. Little, Incorporated—as of May 2002, the Technology and Innovation Business of ADL is TIAX LLC.
AXV	Automatic Expansion Valve
Btu	British Thermal Unit
Btuh	British Thermal Unit per hour
CFM	Cubic Feet per Minute
CMS	Condensate Management System—a system designed to dispose of the condensate generated by a HPWH without use of a condensate drain.
COP	Coefficient of Performance (unitless)—energy delivered to the water tank by the heat pump divided by the total energy input to the heat pump (compressor, fans, and controls). COP does not account for stand-by losses from the tank or electric-resistance heating. Therefore, COP does not reflect the overall performance of a heat-pump water heater.
CRS	Condensate Recovery System—an experimental condensate management system that disposes of condensate generated by a HPWH by first heat sterilizing the condensate, and then injecting the condensate into the storage tank.
CW	Cold Water
Deficit	Quantity (or fraction) of hot water delivered below 105°F.
DOE	The U.S. Department of Energy
EF	Energy Factor (unitless)—a standardized efficiency rating for a tank-type residential water heater that is determined by a specific U.S. Department of Energy laboratory test procedure. EF cannot be used to report field performance of a water heater.
Energy Commission	California Energy Commission
EMI	EnviroMaster International, LLC (Rome, NY)—a subsidiary of ECR International.
ERWH	Electric Resistance Water Heater (i.e., a conventional electric water heater)
GPD	Gallons per Day
HFC	Hydro Fluoro Carbon
HPWH	Heat Pump Water Heater
HW	Hot Water
ID	Inside Diameter
kBtu	1000 British Thermal Units
kBtuh	1000 British Thermal Units per Hour

LED	Light Emitting Diode
ODE	Overall Delivery Efficiency (unitless)—the water-heating load delivered by a water heater divided by the energy input to the water heater. ODE can be used to characterize the field performance of a water heater. Dr. Carl Hiller, formerly of the Electric Power Research Institute, originally coined the term ODE.
ORNL	Oak Ridge National Laboratory (a U.S. Department of Energy national laboratory)
PIER	Public Interest Energy Research
RD&D	Research, Development, and Demonstration
RH	Relative Humidity
SCE	Southern California Edison
SMUD	Sacramento Municipal Utility District
TMY2	Typical Meteorological Year 2
TXV	Thermostatic Expansion Valve
T&P	Temperature and Pressure relief valve
UA	Overall heat transfer coefficient (Btu/hr- °F)
VDC	Volts, Direct Current
WH	Water Heater

6.0 References

[PG&E 1995] Pacific Gas & Electric; *Residential Energy Survey Report*; Appendix 1: Estimation of Appliance Usage; 1995.

[ADL 1998] Zogg, Robert A., et. al.; *Market-Optimized Heat-Pump Water Heater – Phase I*; Final Report; prepared for Oak Ridge National Laboratory under Lockheed Martin Subcontract No. 62X-SX974V; prepared by Arthur D. Little, Inc.(ADL Reference 35390-00); November 20, 1998.

[California 2000] State of California, Department of Finance; *City/County Population and Housing Estimates, 1991-2000, with 1990 Census Counts*; Sacramento, California; May 2000.

[DOE Condensate 2001] *Heat Pump Water Heater Condensate Disposal System*; Final Report; prepared by Arthur D. Little, Inc.; prepared for the U.S. DOE National Energy Technology Laboratory under Contract No. DE-FC26-99FT40652; May 24, 2001.

[CRS 2002] *Safety Analysis and Testing of a HPWH Condensate Recovery System*; Final Report; prepared by TIAX LLC (under subcontract to Davis Energy Group, Davis, CA); prepared for the California Energy Commission under Public Interest Energy Research Contract 400-00-038, titled Synergistic Water Heating and Distribution Technologies Program; December 19, 2002.

[ORNL 2002] Murphy, Richard W., and John J. Tomlinson; *Field Tests of a "Drop-In" Residential Heat Pump Water Heater*; prepared by Oak Ridge National Laboratory; prepared for the U.S. Department of Energy under Contract DE-AC05-00OR22725; ORNL/TM-2002/207; September 2002.

[AIL 2003] *Water Heater Control*; Intellectual Property of AIL Research, Inc., Princeton, NJ; from website www.ailr.com/water_heater_control.htm; accessed November 25, 2003.

[EIA 2003] *Electric Power Monthly*; U.S. Dept. of Energy, Energy Information Administration; Sept. 2003.

[ORNL 2004] Telephone conversation between Van Baxter of Oak Ridge National Laboratory and Robert Zogg of TIAX LLC; April 8, 2004.

List of Attachments

This section lists the attachments to the final report of the PIER project *Design Refinement and Demonstration of a Market-Optimized Residential Heat-Pump Water Heater*, Contract Number 500-98-028, conducted by TIAX LLC. These attachments are part of report P500-04-018. To obtain copies of these attachments, or for more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Energy Commission's Publications Unit at 916-654-5200.

Report Title	**Publication Number**
Prototype Design, Fabrication, and Testing • *Component Selection and Design Refinement Report* • *Third-Generation Prototype Fabrication and Laboratory Test Report*	P500-04-018A1
California Field-Test Data and Analysis • *Field-Test Data Analysis* • *Field-Test Unit Summaries* • *Interview and Survey Templates*	P500-04-018A2
Durability Testing Results	P500-04-018A3

Appendix I: Post-Field-Test Evaluations

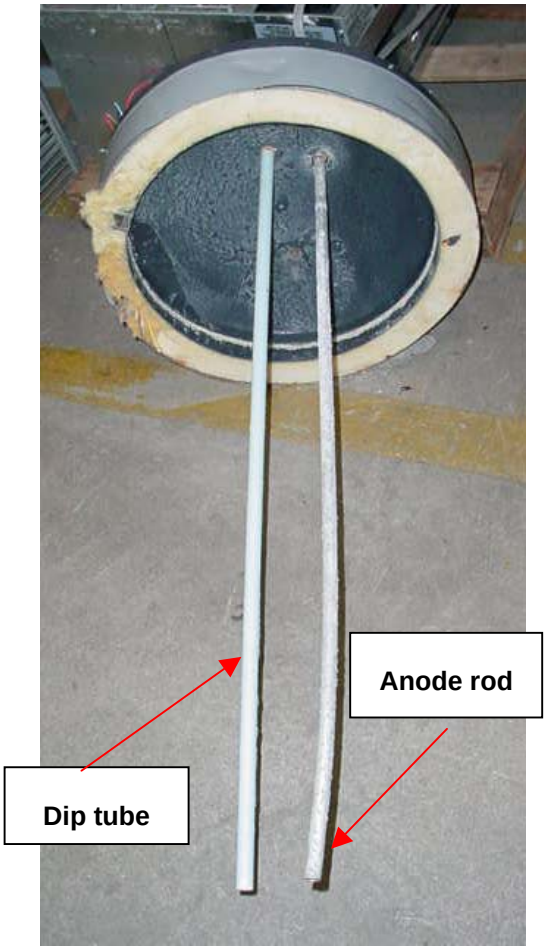
Appendix I: Post-Field-Test Evaluations

EMI performed a destructive evaluation of the same four units that were performance tested after the field test (Units 4, 8, 9, and 16). Three of the four units (Units 8, 9, and 16) had been installed in locations having high mineral content in the local water supply. One of the key objectives of destructive evaluations was to assess whether mineral content in the water supply was creating scale in the tanks that could impact long-term performance. The results of the destructive evaluations are photographically documented in Figures I-1 to I-17. The air filters typically had a visible coating of dust, although the filter on Unit 8 exhibited a high concentration of lint, apparently from a clothes dryer. Units 8 and 16 exhibited a light coating of scale on the tank inner walls, anode rods, and resistance heating elements. Units 4 and 9 exhibited heavy scale on the anode rods, but light scale elsewhere. Unit 9 also exhibited spotty surface rust on the inner tank wall. The heavy scale on the two anode rods is not necessarily a call for concern. It is not uncommon for anode rods to become heavily scaled. Furthermore, there is little reason to think that heat-pump operation would impact scale formation on the anode. The evaluations show no evidence of accelerated scale formation on the inner tank walls due to operation of the heat pump.

I-1: Field Test Unit 8

A high concentration of clothes dryer lint was present on the inlet air filter of this unit.

I-2: Unit 8 Air Filter



A light coating of scale was present on the inside walls of the tank, anode rod, and electric heating elements.

I-3: Unit 8 Anode rod and Dip Tube

Views inside the tank with the top removed.

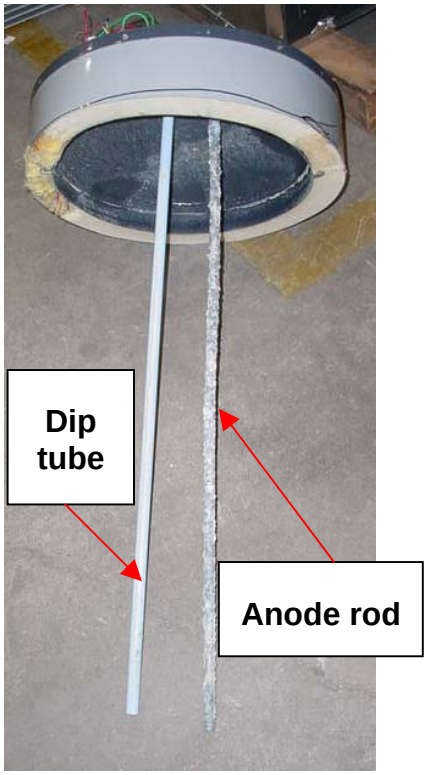
I-4: Unit 8 Tank and Elements

Field-Test Unit 16
EMI Unit 1-01-H-0797-35

I-5: Unit 16

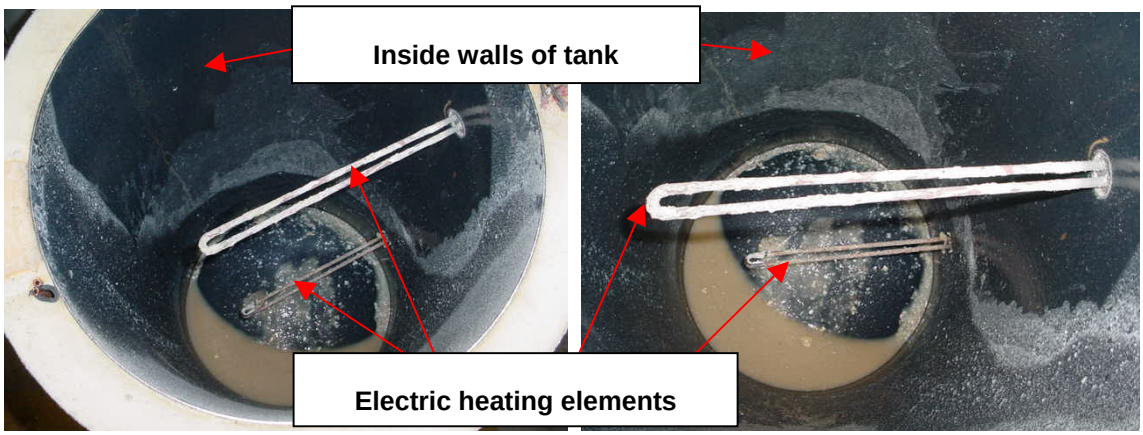
The light coating of dust present on the inlet air filter of this unit was typical of what was found on the remaining 2 units examined.

I-6: Unit 16 Air Filter



A light coating of scale was present on the inside walls of the tank, anode rod, and electric heating elements.

I-7: Unit 16 Anode Rod and Dip Tube



Views inside the tank with the top removed.

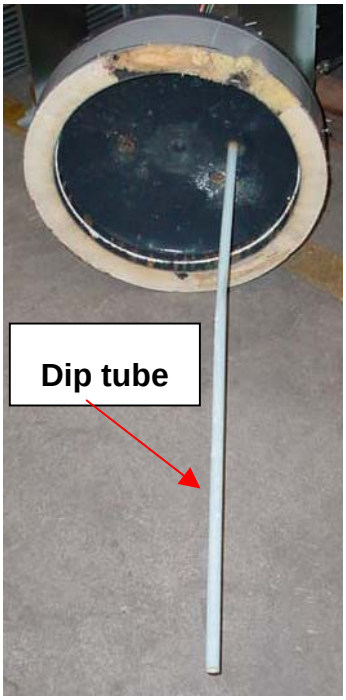
I-8: Unit 16 Tank and Elements

Field-Test Unit 9
EMI Unit 1-01-H-0795-35

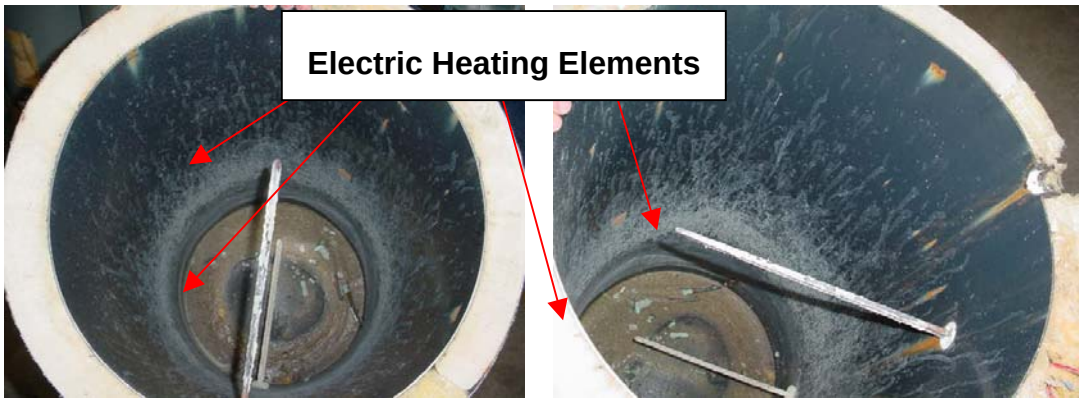
I-9: Unit 9

The above views show the heavy coating of scale that was present on the anode.

I-10: Unit 9 Anode Rod



I-11: Unit 9 Dip Tube



View inside the tank with the top removed. This was the only tank with spotty surface rust present on the inner tank walls.

I-12: Unit 9 Tank and Elements

The above photo shows the remains of a failed electric heating element found on the bottom of this tank. Heating elements burned through in this manner are indicative of a “dry fire”. It is presumed that this failure occurred prior to the field test, because no element occurred during the field test.

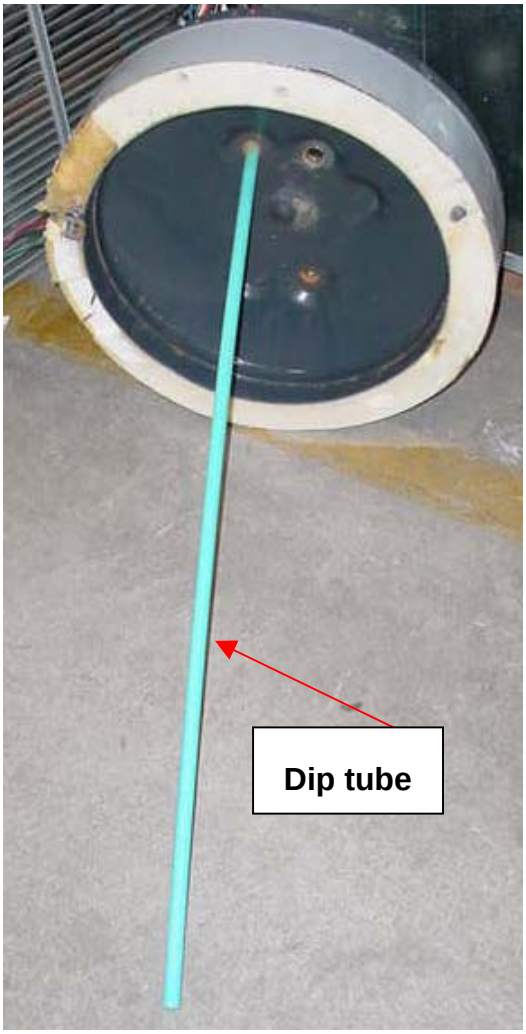
I-13: Unit 9 Element Remains

Field-Test Unit 4
EMI Unit 1-02-C-0972-11

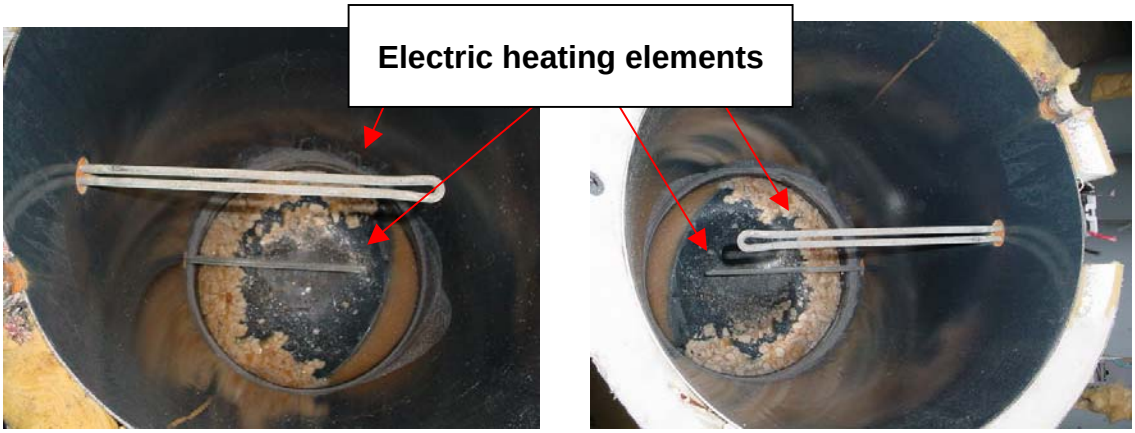
I-14: Unit 4

The above views show the heavy coating of scale that was present on the anode.

I-15: Unit 4 Anode Rod



I-16: Unit 4 Dip Tube



Views inside the tank with the top removed.

I-17: Unit 4 Tank and Element

Appendix II: Information Dissemination Plan

Appendix II: Information Dissemination Plan

This Plan is written for any organization that is seeking to promote markets (especially California markets) for residential electric HPWHs. We refer to the organization simply as the "Promoting Organization". Should the Energy Commission choose to promote HPWH technology in the future, this Plan could provide a starting point. Any Energy Commission communications with external media would be coordinated through the Energy Commission's Media and Public Communications Office.

Situation and Challenges

Rolling blackouts, power shortages and sharp increases in fuel prices have demonstrated that America's energy troubles are far from over. Regardless of price increases, energy consumption among Americans continues to rise every year, while natural energy resources become more and more scarce.

Most Americans do recognize the energy shortage as a situation that can, with their cooperation, be alleviated. According to research conducted by the New Alliance to Save Energy, 92 percent of homeowners feel that business, government and consumers are all responsible for reducing energy consumption. And to that end, innovation and development of energy efficient appliances are integral to conserving our valuable and limited energy resources.

Due in part to the California Energy Commission's (Energy Commission's) Title 24 building standard, great strides have been made in the development and promotion of energy efficient appliances used in homes throughout the state, including energy saving air conditioners and cooling systems, washing machines and dryers. Through this policy California has successfully reduced its electricity load and residents have saved millions of dollars in energy related expenses.

About one in ten (11 percent) of Californians heat their water electrically. However, many of those using electric water heating do not realize that their water heater may account for nearly 25 percent of their total energy usage, and that there is an energy saving alternative. Heat-pump water heaters (HPWHs) have been in the market for decades. During the mid-1980's, the market peaked at about 8,000 units per year, and manufacturers included two of the largest water-heater manufacturers in the U.S. However, early HPWH products failed to meet market needs. Key problems included:

- High first cost;
- Poor reliability, leading to high warranty costs for the manufacturers and user dissatisfaction;
- Weak service infrastructure;
- Difficult to install and large footprint; and
- Lack of consumer awareness.

The Energy Commission's Public Interest Energy Research (PIER) project to refine the design of, then demonstrate, a market-optimized, residential HPWH was recently completed by TIAX LLC and its manufacturing partner Enviromaster International (EMI). The purpose of the PIER project was to bring to market a HPWH design concept that addressed the key technical barriers (i.e., high cost and installation difficulties). The PIER project leveraged earlier development and testing efforts funded by the U.S. Department of Energy's Oak Ridge National Laboratory (ORNL) and TIAX. Project results confirm that

the market-optimized HPWH design, tested using EMI's WATTER$AVER model, could have a significant impact on the amount of energy used by the average American household. In addition to reducing energy usage, EMI's WATTER$AVER provides consumers considerable return on their investment, with operating cost savings averaging 30-60 percent per year.

To take the next step and bring the WATTER$AVER and other HPWH designs closer to mass commercialization, it is important to call attention to the PIER project, its results, and recommendations for moving forward. By highlighting the groundwork that has been laid in the development process and the importance of these products to energy and cost savings, it will be possible to attract the attention of key stakeholders whose expertise and capabilities could assist in further development and market penetration. Those key stakeholders include: plumbers, manufacturers, utilities, contractors, developers, mechanical designers, and "green" architects.

Objectives

The main objectives of this Information Dissemination Plan are:

- To publicize the results of the PIER project, focusing on the lessons learned and next steps in further developing HPWHs that are ready for mass commercialization.
- To communicate the potential economic and energy savings benefits of energy-efficient electric water-heating technologies, such as the WATTER$AVER, to the general public.
- To educate those affected by and those responsible for enforcing Title 24—California utilities, organizations, public agencies and homeowners—about electric HPWHs.
- To attract the attention of manufacturers, industry experts, and other stakeholders who may be interested in the continued development of the HPWH.
- To increase exposure of the WATTER$AVER by raising the visibility and profile of experts who have worked on this project through media coverage and speaking opportunities.

Strategy

The strategy for disseminating the information about this the project would run on two parallel tracks: outreach to the media and outreach to government officials, utilities and trade organizations.

Given the continued focus surrounding energy issues within the media and on the public policy front, the Promoting Organization has an opportunity to draw a considerable amount of attention to the project. By conducting outreach on several levels, the Promoting Organization would ensure that it reaches each of its target audiences -- from the contractors and utilities that can promote the WATTER$AVER and similar products to California energy officials who can incorporate HPWHs in the list of approved energy appliances -- thereby successfully meeting each of the plan's objectives.

The first track involves calling attention to the project and its results through the mainstream and trade media. The press component would include a number of earned media related activities including the placement of bylined pieces and coverage in larger trend and industry stories. In order to introduce the PIER project and call attention to the need for continued refinement of HPWHs, we recommend beginning outreach by distributing a press release. The release would summarize the project's results for a large audience including the media, public officials, and decision-makers in relevant industries – plumbing, manufacturers, etc.

In tandem with the release, the Promoting Organization could initiate larger trend stories in which the importance of HPWHs can be referenced. We feel that by tying the results of the PIER project to larger industry stories, such as concerns surrounding the rising cost of fuel sources and the lack of infrastructure to support the continual increase of energy consumption, the Promoting Organization would be able to significantly increase press coverage.

While this media outreach would focus primarily on California news outlets, the Promoting Organization could target relevant trade publications and media outlets in other select energy and environmentally focused markets throughout the country such as Massachusetts and Washington. In this way, the greater message that HPWHs are essential to energy efficiency would be disseminated to key audiences across the United States, including national contractors, manufacturers and non-California members of congressional energy committees. This outreach would benefit the California market and accelerate commercialization of these products.

The second track of the information dissemination strategy would focus on outreach to relevant trade organizations, utilities and government officials, and participation in industry events, meeting and conferences. Among targets would be organizations in the plumbing and manufacturing fields, as well as energy associations, which have been affected by Title 24. Through their efforts to comply with current state mandates, these organizations could prove helpful in promoting the HPWH, which in turn may attract interest among potential partners and drive faster mass commercialization through consumer demand.

Working with California-based utilities may also prove helpful, many which have gone to great lengths to promote the use of energy efficient appliances through incentive programs. Although utilities may need further demonstration in terms of the reliability and practicality of large-scale commercialization of the HPWH before endorsing it, we feel it would be beneficial to effectively present the findings of the project, as well as next steps in the development process, to begin to garner their support and commitment.

The Promoting Organization could also provide information to and arrange briefings with public officials including members of the House Energy & Commerce Committee, as well as other key legislative and administrative leaders within California. Given the state's commitment to energy preservation, we feel this group would be receptive to learning about the development of HPWHs that have the capability to reduce water-heating energy consumption by 30-60 percent in households that use electric water heaters. Local public officials have tremendous influence within the communities they serve—business and residential—and could be helpful in paving the way for HPWHs to become among the recommended energy-saving devices used in the construction of new homes and during replacement of conventional electric water heaters in existing homes. To address the replacement market, one must confront another key barrier—most water-heater replacements are emergency replacements. Consumers must have significant exposure to the HPWH option prior to needing a water heater, or the benefits must be so clear that it is a "no-brainer" to install a HPWH.

Key Messages

As part of the information dissemination plan, we recommend developing two or three core messages that support the PIER project and its objectives and highlight the benefits of the WATER$AVER and similar products. These messages would be delivered consistently and incorporated into all interactions with the press, trade organizations and public officials, and be reflected in all external communications. Some example messages might be:

Americans continue to use exorbitant amounts of energy, whether for electricity, transportation or hot water. Government, business, research institutions and academia must collaborate in order to bring to market more efficient devices that will decrease energy consumption.

HPWHs, including the WATTER$AVER, have the potential to save significant amounts of electricity in households using electric water heaters. In addition, they can help reduce electric demand, producing considerable savings for homeowners over time.

As with other new devices and appliances entering the market, the continued development and refinement of HPWHs, coupled with an increase in market demand, will drive down costs resulting in higher rates of consumer adoption in homes using electric water heating.

Target Audiences

Included in the Promoting Organization 's outreach would be the media, public officials, and industry, business and thought leaders. Each of these groups needs—and wants—to be informed of new innovations that have the potential to decrease energy consumption, and they can be a powerful and active force in promoting new devices such as the WATTER$AVER.

Media

Mainstream Media

Media outreach would focus predominately on California press outlets. However, we also suggest communicating with other outlets in key media markets where energy conservation and the environment are high on the agenda. Such outreach would help continue to raise awareness of the work of the Energy Commission in developing and bringing to market energy efficient, cost saving devices. Also, adoption of these technologies nationally would accelerate adoption in California.

Among the press targets we recommend are:

California Print Media

- San Francisco Chronicle
- Los Angeles Times
- San Diego Union Tribune
- Sacramento Bee
- San Jose Mercury News
- San Francisco Examiner
- San Mateo County Times
- Alameda Times-Star
- Orange County Register
- Los Angeles Daily News
- The Oakland Tribune
- Alameda Times-Star
- Fresno Bee
- Modesto Bee

California Business and Public Radio

- Pasadena - KPCC 89.3
- Santa Monica - KCRW 89.9
- San Francisco - KALW 91.7
- San Francisco - KQED 89.3
- San Diego - KPBS 89.5
- Sacramento - KXPR 90.9

Other Media Outlets

- NPR National
- Boston Globe
- New York Times
- Washington Post
- Baltimore Sun
- Chicago Sun Times
- Chicago Tribune
- Denver Post

Trade Publications

- Energy and Environment
- Energy Efficiency Journal
- Energy Engineering
- California Energy Markets (http://www.newsdata.com/cem/)
- Environmental Business Journal (http://www.ebiusa.com/)
- Energy Design Update (http://www.aspenpubs.com/energy/lpext.dll?f=templates&fn=main-h.htm)
- Environmental Design & Construction (http://www.edcmag.com/)
- Home Energy (http://homeenergy.org/hewebsite/)

Plumbing

- Plumbing Engineer (http://www.plumbingengineer.com/)
- The Wholesaler (http://www.thewholesaler.com/)
- HVACR & Plumbing Distribution (published by Penton Media)
- Plumbing and Heating Contractor News (http://www.tmbpublishing.com/cn_ad.html)
- Plumbing FrontPage
- Plumbing Industry News
- Plumbing Systems and Design (http://209.224.198.110/)

Building Trade Press

- Journal of Light Construction (http://www.jlconline.com/cgi-bin/jlconline.storefront)
- Contractor Magazine (published by Penton Media) (www.Contractormagazine.com)
- Contracting Business (published by Penton Media)

- Manufacturing
- Manufacturing News
- Manufacturing and Technology News
- Advanced Manufacturing Magazine

Trade, Industry, and Energy Organizations

Plumbing

- Plumbing Manufacturers Institute
- United Association of Journeymen and Apprentices
- American Society of Plumbing Engineers (ASPE) (http://www.aspe.org/)

Manufacturing

- Association for Manufacturing Excellence
- GAMA

Energy

- Alliance for Affordable Energy
- National Association of State Energy Officials (NASEO)
- Northeast Energy Efficiency Council (NEEC)
- Alliance to Save Energy (ASE)
- Midwest Energy Efficiency Alliance (MEEA) (http://www.mwalliance.org/)
- Northwest Energy Efficiency Alliance (NEEA) (http://www.nwalliance.org/)
- Southwest Energy Efficiency Alliance (SWEEP) (http://www.swenergy.org/)
- American Council for an Energy-Efficient Economy (ACEEE)
- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
- Air-Conditioning and Refrigeration Institute (ARI) (http://www.ari.org/)
- Affordable Comfort (http://www.affordablecomfort.org;)
- Consortium for Energy Efficiency (CEE) (http://www.ceeformt.org/)

Elected/Appointed Officials

We also recommend using the PIER project as a vehicle to connect with elected/appointed officials in California who value the continued development of devices that will help alleviate some of the strain on energy resources.

Key California legislative and administrative officials:

Assembly Committee on Environmental Safety and Toxic Materials

- Chair - John Laird (D)

- Vice Chair - Greg Aghazarian (R)

Assembly Committee on Utilities and Commerce

- Chair - Sarah Reyes (D)
- Vice Chair - Keith Richman (R)

Senate Committee on Energy, Utilities and Communications

- Chair - Sen. Debra Bowen (D)
- Vice Chair - Sen. Bill Morrow (R)

Senate Committee on Environmental Quality

- Chair – Sen. Byron Sher (D)

California Energy Commission

- Commissioner (appointed) - Arthur Rosenfeld

Members of the House Energy & Commerce Committee from California

- Rep. Chris Cox (R)
- Rep. George Radanovich (R)
- Rep. Mary Bono (R)
- Rep. Darrell Issa (R)
- Rep. Henry Waxman (D)
- Rep. Anna Eshoo (D)
- Rep. Lois Capps (D)
- Rep. Hilda Solis (D)

California Utility Companies

California utility companies have played a large role in disseminating information about energy efficient appliances to customers. It would be valuable for the Promoting Organization to share information with these companies—through press activities, informational packets, and briefings—about the WATER$AVER and similar products.

The utilities we would brief include:

Investor-Owned Utilities (IOUs)

- Southern California Edison Company (SCE)
- Pacific Gas and Electric Company (PG&E)
- San Diego Gas and Electric (SDGE)

Municipally Owned Utilities (Muni's)

- Sacramento Municipal Utility District (SMUD)
- Silicon Valley Power (SVP)
- Los Angeles Department of Water and Power (LADWP)
- Possibly other water utilities in southern California

Third-Party Spokespeople

To make this campaign most effective, it may be necessary to engage a core group of third-party spokespeople who can attest to the benefits of the HPWH and its potential market impact. The Promoting Organization would call on third parties to speak about the PIER project in a variety of situations including media outreach and conferences.

Third-party spokespeople may include members of the organizations listed in the target audience section as well as industry analysts and those in academia. Potential third-party validators include:

- California Institute for Energy Efficiency
- Consortium for Energy Efficiency
- The Energy Foundation
- Energy & Environmental Building Association
- Supporters of the Energy Commission

Tactics

Below are the primary tactics we would employ in order to highlight the results of the PIER project.

Media Activities

Media outreach is one of the most effective ways to build awareness of HPWH and in particular, the PIER project involving the WATER$AVER. Members of the media are widely perceived as providing objective, third-party commentary, so their endorsement can give an issue clout and exposure that a paid advertisement or government announcement cannot.

Press Release

We would suggest that the Promoting Organization distribute a press release announcing the key findings of the PIER project. Although the results of the PIER project are not overwhelming in terms of positive findings, we feel there is an opportunity to use the release to highlight the progress that has been made and the need for further collaboration in order to bring energy efficient water heaters to the mainstream market. Once distributed, the Promoting Organization should follow up with key reporters to determine if they would like to publish the story or conduct an interview on the larger issues.

Press Kit

The Promoting Organization should develop a press kit that could be distributed to target audiences and would contain background information on the PIER HPWH project such as:

- Press release on the results of the project
- Bios of experts who led the project
- A project summary
- A fact sheet on the WATTER$AVER electric HPWH
- Relevant studies on the benefits of using energy efficient appliances, including HPWHs.

Media Briefings

In the weeks following the press release, the Promoting Organization could arrange face-to-face meetings between reporters and HPWH experts (including Energy Commission staff), which would provide an opportunity to go more in-depth into the issue than would a phone interview. This tactic would give

reporters the opportunity to talk with those who played an integral role in the PIER project and other HPWH development/promotion efforts.

Below is a list of outlets and reporters in California who we feel would be receptive to such meetings:

- Frank Clifford, Environment and Conservation Editor, *Los Angeles Times*
- Lynette Evans, Home reporter and Jane Kay, Energy reporter, *San Francisco Chronicle*
- Craig Rose, Energy reporter, *San Diego Union Tribune*

Trend Stories

By seeking opportunities to incorporate the PIER project and its results into larger industry trend stories, there is the possibility to extend the shelf life of the PIER project and keep the Energy Commission and its initiatives in the news. Among the stories that could be written include:

- Planning for the future. There are many technologies currently under development that have the ability to lessen energy consumption by significant amounts. What are they? What are the roadblocks to their commercialization?

- Government support of efficiency development and promotion. Should the government play a more significant role in promoting the development and use of energy-efficient technologies in homes and commercial buildings?

- Lessons from around the world. Are Californians adopting energy and environmentally friendly technologies as quickly as their counterparts in Europe and Asia? If not, why not?

- Effective incentive programs. What incentives need to be incorporated to encourage more rapid deployment of energy-saving technologies? How do those incentives need to be structured and promoted to be effective?

Expert Commentary

Given the extent of the PIER project and the industry knowledge that each participating organization brings, the Promoting Organization should consider the value of promoting the profiles of HPWH experts, including those associated with the PIER project. In doing so, the Promoting Organization could expose a wider audience to the project and the benefits possible through widespread adoption of electric HPWHs. These experts include:

- Robert Zogg, TIAX LLC
- John Hoyt, EMI
- Karl Mayer, ECR International (parent company of EMI)
- John Tomlinson, Oak Ridge National Laboratory (ORNL)
- Van Baxter, ORNL
- Richard Murphy, ORNL
- Brad Hollomon, Pacific Northwest National Laboratory (PNNL)
- Marc Ledbetter, PNNL
- Titu Doctor, CENC Inc.

There are several ways to accomplish this:

- Introduce the experts in conjunction with the press release about the project.
- Develop an expert sheet that would be distributed to the media. The sheet would highlight the project, and describe each person's expertise and the role he/she played in the project, and outline potential stories involving the WATTER$AVER and other energy-efficient appliances on which the experts could comment.
- Monitor the news for relevant opportunities in which one or more of the project's experts could provide comment or background. The recent coverage involving the energy bill, which includes tax incentives for improving energy efficiency of homes and appliances, is one example of a story where project experts could discuss the WATTER$AVER and other energy-saving products.
- Arrange presentations by experts at relevant conferences and workshops, including HPWH workshops sponsored by ORNL and PNNL, the National Energy Services Conference (Association of Energy Services Professionals International), and the Emerging Technology Summit (E Source).

Editorial and Bylined Pieces

In addition to making experts available for interviews and news stories, we would suggest that the Promoting Organization seek opportunities to promote the PIER project through op-eds and bylined pieces in both trade and mainstream media.

Topics that could be pursued:

- Call to action. States such as California, New York, Connecticut, and Massachusetts have taken significant measures to promote energy savings through energy programs, studies and initiatives. Other states and industry leaders must join in this effort to effectively reduce energy consumption and waste[1].
- Innovation is an essential component to solving America's energy crisis. New devices such as the HPWH can and will play a major role in alleviating energy demands.

Organizations

There are significant opportunities to promote the WATTER$AVER and HPWHs through energy efficiency programs already established and run by the state of California, utility companies and conservation organizations. Throughout California, businesses from all facets of the energy industry have become involved in many of these programs.

We feel outreach to these organizations would be beneficial for two reasons. The first is that these organizations touch many of our target audiences directly and indirectly. By reaching out to the leaders of these programs to further educate them about heat pumps water heaters such as the WATTER$AVER and their benefits, the Promoting Organization also would be reaching out to their partners -- utility companies, public officials, etc. For example, the California Association of Building Energy Consultants (CABEC) is geared toward helping energy consultants, architects, and engineers in their efforts to comply

[1] It may be appropriate to make this call to action through an organization such as ASERTI. ORNL proposed a HPWH promotional program to ASERTI in January 2002 (http://ciee.ucop.edu/docs/heatertech.pdf).

with Title 24. However, given the nature of the organization, state electric and gas utility companies are affiliate members and therefore also receive its materials and attend its events.

In addition, working with these types of organizations would allow the Promoting Organization the opportunity to communicate with a large consumer audience. As we know, the Internet serves as an information clearinghouse, enabling consumers to quickly gain access to information on potential new purchases. There are numerous energy organizations aimed at consumers, whose websites contain information on the latest concepts and trends as well as the hottest new energy saving technologies to hit the market. These organizations include:

- U.S. DOE, Energy Efficiency and Renewable Energy (EERE)
- Energy Star Program
- Alliance to Save Energy
- EnergyGuide
- The Energy Commission's California Consumer Energy Center
- California Home Energy Efficiency Rating System, Inc. (CHEERS)
- The California Association of Building Energy Consultants (CABEC)

In addition to these organizations, we feel it would be beneficial for the Promoting Organization to work in cooperation with the Department of Energy and two of its labs, Oak Ridge National Laboratory and Pacific Northwest National Laboratory, which have been instrumental in promoting the development and use of HPWHs. Through ORNL's and PNNL's extensive ties into utilities, trade and energy organizations and their presence at relevant trade events and meetings, they could play a role in helping to raise awareness of the WATTER$AVER and related products among key audiences. During 2002, ORNL and PNNL organized two HPWH workshops—one in Atlanta, GA (April 2002) and the second in Portland, OR (December 2002)[2]. In addition, the DOE publishes a newsletter entitled *In Hot Water … A Newsletter about Heat Pump Water Heaters and efficient domestic water heating*, which is edited by Russ Johnson of Johnson Research, LLC, Glastonbury, CT[3].

Trade Shows, Conferences and Industry Meetings

Energy, energy conservation, and technology innovation conferences, trade shows and industry meetings would serve as ideal venues to publicize the PIER HPWH project and interest potential new partners. There are a number of opportunities for the Promoting Organization to promote the WATTER$AVER through speaking opportunities, booths and demonstrations at various conferences and trade shows in California and throughout the country.

Among the upcoming events that representatives of the Promoting Organization may want to consider attending in order to discuss the project:

- Northeast Sustainable Energy Association, Building Energy 2004 (Boston, MA; March 10 – 13, 2004)
- The 2004 Residential Energy Services Network (RESNET) Conference, Planning for Success, Delivering Quality (San Diego, CA; March 1 – 3, 2004)
- GreenBuild 2004

[2] The proceedings of the Portland, OR workshop are at http://www.pnl.gov/hpwh/
[3] Contact Johnson Research at johnson.research@att.net or 860-633-9020 to subscribe to the newsletter.

- Energy & Environmental Building Association, Building America: Houses that Work Seminar (Dallas, TX; September 29 – October 2, 2004)
- Affordable Comfort 2004 (Minneapolis, MN; April 26 – May 1, 2004)

The Promoting Organization may also consider participating in smaller meetings among target audiences such as the California Municipal Utilities Association monthly gatherings, or their Annual Conference & Policy Makers' Seminar in Monterey, CA, March 24 – 26, 2004. These types of meetings and conferences would be optimal for open discussions regarding reliability and installation concerns.

In addition to participating in planned meetings, the Promoting Organization may want to consider setting up teleconferences where members of utility associations could participate in hour-long discussions regarding the advances and commercialization of HPWHs.

Preliminary Timeline

Table II-1 shows an eight-month timeline that lays out the suggested activities.

Table II-1: Preliminary Timeline of Information Dissemination

Date	Initiative
Month 1	Draft press release announcing the results of the PIER project Begin to develop press kit materials
Month 2	Final review and approval of release Develop media list and get contact information of trade organizations and selected public officials Continue to draft press kit materials. Begin distributing drafts for review/approval.
Month 3	Distribute release to targeted reporters, organizations, and public officials Conduct follow-up and schedule interviews and briefings Target California media for face-to-face briefings with experts who led the PIER project Monitor news for relevant issues involving the development of energy efficient devices on which experts can comment
Month 4	Follow up with and confirm briefings with CA media, organizations and public officials Begin outreach to trades on bylined piece opportunities Seek out potential industry conference opportunities to present at or participate in the first half of 2004 Continue to monitor news for expert pitch opportunities
Month 5	Continue briefings Begin drafting bylined pieces for mainstream and trade media Continue to monitor news for expert pitch opportunities Continue to look for opportunities to participate in industry conferences and meetings
Month 6	Continue briefings Incorporating feedback from press and interviews, develop trend pitches involving energy efficiency/conservation and send to media Continue to monitor news for expert pitch opportunities Solidify any conference speaking opportunities Seek out meetings and/or plan teleconference with utility organizations
Month 7	Continue briefings Edit, finalize and submit bylined pieces Follow up with select targets and set up interviews on trend pitch stories
Month 8	Continue briefings Complete all media opportunities Compile media audit

Appendix III: Production Readiness Plan

Appendix III: Production Readiness Plan

Introduction

The scope of this project included developing a Production Readiness Plan. The purpose of the Production Readiness Plan is to provide the information necessary for a manufacturer to assess whether the market-optimized HPWH is a good match to the manufacturer's existing production capabilities, including the additional investment in production equipment and labor skill base that would be needed to commercialize the HPWH. As such, the Production Readiness Plan includes:

- Identification of critical production processes, equipment, facilities, manpower, and support systems that will be needed to produce a commercially viable product;
- Capacity constraints imposed by the design under consideration for internal manufacturing capabilities, as well as suppliers. The project manufacturing effort may include "proof of production processes";
- Identification of hazardous or non-recyclable materials;
- A projected "should cost" for the product in production at some expected rate;
- The expected investment threshold required to launch the commercial product; and
- An implementation plan to ramp up to full production.

In this particular case, EMI has already developed a production capability for the market-optimized HPWH, and is currently developing a market base. EMI calls their product the WATTER$AVER.

Processes and Resources

This section identifies critical production processes, equipment, facilities, manpower, and support systems needed to produce a commercially viable product. We define "critical" to mean different or new for a manufacturer that currently produces packaged refrigeration and/or air-conditioning products for residential and commercial markets.

Manipulating Arm

The first main process in manufacturing a WATTER$AVER is wrapping the condenser coil around the tank. The tanks must be loaded into a special winding machine to perform this operation. Initially, tanks were manually loaded and unloaded into the machine. This method required two people, and was cumbersome and unsafe to the operators.

EMI purchased a manipulating arm to aid the operator in loading and unloading tanks into the winding machine. The manipulator is capable of handling up to 125 pounds, and uses compressed air and suction cups to maneuver the tanks into position.

Use of the manipulator not only reduced the risk of operator injury, but also the labor needed for this operation.

Using the manipulating arm requires minimal training, and no specialized skills. Each control is labeled describing its function (up, down, rotate, hold, release).

PLC Controlled Tank-Winding Machine

Wrapping the condenser tubing around the tank is a critical operation in the production of the WATTER$AVER. Since the condenser transfers heat to the water tank during heat-pump operation, if manufactured incorrectly, the performance of the unit is greatly diminished. In the early stages of development, EMI:

- Hand-applied heat-transfer compound to the tank (to improve heat transfer to the tank);
- Manually drew the condenser coil through a set of dies to deform it into the cross sectional "D" shape (to increase the contact area); and
- Hand wrapped the condenser around the tank.

While these methods are suitable for building a small number of prototypes for laboratory testing, they are very labor intensive and, therefore, not practical for mass production.

EMI consulted a specialty equipment manufacturer, and jointly designed a machine that would meet mass production needs. The result is a machine that:

- Is capable of wrapping various sizes of tanks;
- May be programmed to start, stop, advance (without rotating) to clear any tappings or protrusions that may be present on the tank;
- Deform the condenser coil to a cross sectional "D" shape; and
- Simultaneously apply the heat-transfer compound.

The use of this machine greatly reduces the amount of time and labor required to wrap the condenser around the tank. In addition, since it operates automatically, quality and consistency are maintained.

The greatest challenge in the design of this machine was applying the heat-transfer compound evenly on the tank. The heat-transfer compound used in this application has a consistency similar to peanut butter. As a result, a specialized pump was necessary to deliver the compound to the applicator. EMI found a suitable pump That operates using compressed air. Development was necessary to regulate the air pressure in a manner that would allow the heat-transfer compound to be uniformly distributed onto the tank.

Prior to removing the tank from the winding machine, the condenser area is wrapped with a cellophane membrane. This is done for two reasons:

1. The cellophane protects the heat-transfer compound during handling; and
2. The cellophane eliminates the potential for the insulation chemical to migrate behind parts of the condenser coil, and interfere with the transfer of heat from the condenser to the tank.

The winding machine is a relatively sophisticated piece of equipment, and requires the operator to undergo extensive training to properly use. Since the machine is PLC controlled, the operator must be able to program it to perform the operations necessary (hold tank, activate dies, start, apply heat-transfer compound, rotate, advance traverse, stop application of heat-transfer compound, stop, deactivate dies, release tank) to wrap the copper tube (condenser) around the tank.

When EMI took delivery of the winding machine, the machine's designers, set it up, provided a detailed manual on the machine's operation, and conducted hands-on training to the operators. In addition, they are available to resolve any problems that are encountered.

In addition to knowledge of the winding machine, the operator must possess brazing skills to attach the copper tube (condenser) to the tank.

Insulation

The most difficult manufacturing process to perfect was insulating the tank. It is crucial that the correct amount of insulation is injected into the cavity between the tank and outer sheet metal jacket. Too little insulation results in a poorly insulated water heater. Too much results in a bulging outer jacket, or damage to the foam dams that prevent the expanding insulation from entering areas where the heating elements are located.

The insulation used in the production of the WATTER$AVER is a rigid polyurethane foam that is produced with a mix ratio of isocyanate and resin. Each chemical is stored in a separate container, then pumped through a heated hose to an applicator gun where it is mixed just prior to dispensing. When the isocyanate and resin are mixed, a chemical reaction occurs that results in the formation of polyurethane foam.

When production first began, the operator would determine the amount of dispensed foam by counting the number of cycles from the transfer pump. This method of dispensing foam proved to be inconsistent, and not acceptable for production. To improve this process, a programmable counter, and automatic valve were installed on the transfer pump. When the correct amount of foam is delivered, the valve automatically closes, and stops the flow. The operator then resets the counter, and is ready to perform the operation again.

Another discovery in the foaming process was that ambient conditions affected the rate at which the isocyanate and resin react with each other. Changing ambient conditions resulted in inconsistencies in the density of the foam. As a result, the insulating properties of the foam would vary. While the previously mentioned counter and automatic valve will ensure consistency in quantity when dispensing the foam, they will not compensate for changes in the temperature or humidity of the facility. To remedy this situation, EMI erected a chamber that encapsulates the entire insulating area in a climate-controlled environment, thus ensuring the temperature and humidity remain constant.

As previously stated, mastering the foaming process was the most difficult manufacturing operation to perfect. The operator of the foaming station must have the training necessary to program the counter (described above) to ensure the correct amount of foam insulation is dispensed during the operation (to ensure that the unit is insulated properly).

When EMI took delivery of the foaming machine, representatives from the machine's manufacturer, set it up, provided a detailed manual on the machine's operation, and conducted hands-on training for the operators. In addition, they are available as needed to resolve any problems that are encountered.

Processing / Testing

Immediately after compressor piping connections are brazed, the process lines are connected to the Process / Test machine. Pressure transducers within the machine monitor the pressure of the system. If at any time the pressure reaches a level outside the acceptable parameters, the machine will abort the test, and alert the operator that the unit failed the pressure test.

The machine automatically pressurizes the system with dry nitrogen. If the pressure remains within acceptable parameters, the machine automatically goes into a vacuum mode, and evacuates the system. Again, if the pressure is within acceptable parameters, a charge of HFC-134a refrigerant is automatically injected into the system, and the operator is alerted that processing is complete.

When testing and processing are complete, the process lines are crimped and brazed. After the process lines are brazed, an HFC-134a leak detector is used to verify the integrity of the braze joints. The original crimping tool left a sharp impression in the copper that created a leak potential if flexed or vibrated during handling or installation. A new crimping tool was designed that creates a flat, slightly cupped seal prior to brazing. Flexing or vibration does not affect this crimp.

Early prototypes featured Schrader valves for charging (similar to an automobile air conditioner), which were later eliminated due to leak potential, cost, and the fact that the unit is designed to be a sealed system similar to a household refrigerator.

The charging and testing process requires one operator. As with the tank winding machine, the charging / testing machine is PLC controlled. As a result, the individual responsible for charging and testing must be familiar with the operation of the charging / testing machine, and be able to program the settings (pressure, vacuum, refrigerant charge, and tolerances in pressure variation) as needed. In addition, he/she must have brazing skills, and knowledge of proper refrigerant handling procedures.

When EMI took delivery of the charging / testing machine, shown in Figure III-1, representatives from the machine's manufacturer, set it up, provided a detailed manual on the machine's operation, and conducted hands-on training for the operators. In addition, they are available to resolve any problems that are encountered during production.

Figure III-1: HPWH Undergoing Charging and Testing

Functional Testing

Prior to final inspection and packaging, every WATTER$AVER is Hy-pot tested[1] to verify electrical integrity. In addition, functional tests are performed by the control board vendor, and then on EMI's assembly line to verify operation of <u>every</u> control before shipment. For the functional test, the unit is wired to a test fixture, and heat is applied to temperature sensors in a manner that forces the control into

[1] High Potential and Ground Continuity Test. Tests for electrical failure in accordance with U.L. 1995 clause 52 and 69, or U.L. 484.

responding. Operation of each unit is monitored and recorded. If a unit does not pass this test, the source of the problem is identified and corrected.

The individual responsible for functional testing must be familiar with Hy-pot testing procedures, and have a thorough understanding of the WATTER$AVER's operation. With these skills, he/she is able to identify any anomalies that occur during testing. The individual who performs the functional tests is trained on WATTER$AVER operation by the engineer responsible for overseeing the WATTER$AVER product.

Hazardous or Non-Recyclable Materials

This section identifies any hazardous or non-recyclable materials used in the production of the WATTER$AVER.

Hazardous Materials

According to the Material Safety Data Sheets, certain chemicals (foam insulation, heat transfer compound, and refrigerant) used in WATTER$AVER production may cause irritation to unprotected skin and respiratory system after prolonged exposure. To protect the individuals who work with chemicals that have the potential to irritate unprotected skin, the necessary personal protection equipment (safety glasses / face shields, rubber gloves, coveralls) is issued to them to prevent any direct contact with the chemicals. Proper ventilation is installed in areas where the chemicals used have the potential to irritate the respiratory system.

Non-Recyclable Materials

EMI recycles all scrap copper and sheet metal generated in the production of the WATTER$AVER. The only exceptions are that poorly foamed WATTER$AVER tanks that are rejected cannot be recycled due to the difficulty of separating the foam from the sheet metal surfaces. Under normal conditions, EMI scraps less than one percent of the tanks that are foamed.

Manufactured-Cost Projections

This section provides a projected material and labor cost for the market-optimized HPWH, as well as projected installed costs. Material and labor costs for the WATTER$AVER are confidential, therefore, we provide material and labor-cost projections for a large manufacturer only. We do, however, provide projected installed costs for both the WATTER$AVER and a market-optimized HPWH manufactured by a large manufacturer. In this context, a "large manufacturer" is defined as a residential water-heater manufacturer, residential air-conditioner manufacturer, or other residential appliance manufacturer having total annual sales exceeding $1 billion and HPWH manufacturing volumes exceeding 10,000 units per year. Table III-1 lists projected manufacturer material and labor cost for the market-optimized HPWH.

Table III-1: Material and Labor Cost Projected for the Market-Optimized HPWH (for a Large Manufacturer)

Component	Large Manufacturer[a]
Tank Assembly[b]	$82
Compressor	$46
Evaporator Coil	$17
Evaporator Fans	$7
Expansion Device	$11
Sheet Metal for Evaporator	$8
Condensate Management System (CMS)	$10 (Optional)
Condenser Coil	$8
Sheet-Metal Shroud (Insulated)	$10
Controls	$19
Refrigerant R-134a	$4
Foam Insulation	$8
Thermostat and Knob	$2
Packaging	$8
Miscellaneous[c]	$15
Material Subtotal	**$245 w/o CMS** **$255 with CMS**
Assembly Labor[d]	$30
Total Cost of Material and Labor[e]	**$275 w/o CMS** **$285 with CMS**

a) A "large manufacturer" is defined as a residential water-heater manufacturer, residential air-conditioner manufacturer, or other residential appliance manufacturer having total annual sales exceeding $1 billion and HPWH manufacturing volumes exceeding 10,000 units per year
b) Includes tank, outer jacket, heating elements, T&P valve, high-temperature limit, drain, and foam dams.
c) Includes wiring, copper fittings, labels, and other fasteners.
d) Fully marked-up cost for assembly labor.
e) Factory overhead not included.

Table III-2 shows that the projected installed cost for the market-optimized HPWH achieves the project goal of $875 only with the purchasing power achievable by a large manufacturer. For a small manufacturer, installed cost projections significantly exceed the goal, even with a 10,000 unit annual production volume.

Table III-2: Projected Installed Costs for the Market-Optimized HPWH

Scenario	Without Optional Condensate Management System			With Optional Condensate Management System		
	Material and Labor	Factory Price	Installed Cost	Material and Labor	Factory Price	Installed Cost
Large Manufacturer 10,000+ Units	$275	$426[a]	$746[b]	$285	$442[a]	$773[b]
Small Manufacturer 2000 Units	Confidential	Confidential	$1450[c]	Confidential	Confidential	Not Available[d]
Small Manufacturer 10,000+ Units	Confidential	Confidential	$1100 to $1200[c]	Confidential	Confidential	Not Available[d]

a) Based on 55 percent gross factory markup.
b) Based on 75 percent distributor and installer markup (assuming traditional two-step distribution).
c) EMI estimates for the WATTER$AVER.
d) Not available from EMI.

Implementation Plan

This section documents how EMI ramped up to full production capability.

As an established manufacturer of HVAC equipment, EMI had already addressed issues concerning safety and the environment, inventory management, and quality assurance. With the exception of the tank assembly, all other components used to manufacture the WATTER$AVER are sourced by vendors that currently serve EMI for other products.

To prepare for full-scale production, it was first necessary to define the production equipment needed. Most was standard "off-the-shelf" equipment from standard suppliers. However, some of the equipment, such as the tank-winding machine, and processing / testing station, had to be custom built for this application.

When all equipment necessary for production was identified, the layout for the assembly area was completed.

Summary/Conclusions

ECR International is a well established manufacturer of HVAC/R equipment. The addition of the WATTER$AVER heat-pump water heater, produced at ECR International's EMI Cooling Products Division, expanded the corporation's product offerings to the marketplace.