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Governor

SYNERGISTIC WATER HEATING & DISTRIBUTION TECHNOLOGIES (SWHDT) PROGRAM FINAL REPORT

PIER FINAL PROJECT REPORT

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- TIAX, LLC (formerly Arthur D. Little Company)
- DOE Oak Ridge National Laboratory
- IPEX, LLC
- Maytag Corporation
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PREFACE

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

The PIER Program, managed by the California Energy Commission (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.

This document represents the final report for the Synergistic Water Heating & Distribution Technologies (SWHDT) Program, Contract No. 400-00-038, conducted by the Davis Energy Group (DEG).

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

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ABSTRACT

The Synergistic Water Heating and Distribution Technologies (SWHDT) Program was developed to design and demonstrate technologies that improve the performance of residential water heating systems in California. In the Program, Davis Energy Group and a group of subcontractors completed the following four R&D projects:

- Combined Refrigerator Water Heater (CREWH): This project developed new designs that use refrigerator heat for domestic water heating to save energy and water.
- Condensate Recovery System (CRS): This project evaluated the safety benefits of a device that facilitates heat pump water heaters by injecting recovered condensate into the hot water system.
- Hot Water Distribution Study (HWDS): This project applied a simulation model to analyze and optimize the design of hot water distribution systems.
- Rapid Radiant Deployment System (RRDS): This project developed and analyzed new designs that can reduce the cost of installing radiant floor systems in California homes.

The CREWH and RRDS projects involved basic R&D efforts in designing, prototyping, and demonstrating new technologies. The CRS project completed safety testing of the condensate recovery system device that had been developed in a prior PIER project. The SWHDT Program completed successful demonstrations in all three of these projects, although additional efforts are needed to optimize performance and progress toward commercialization. Partnerships with committed manufacturing, distribution, and marketing entities are essential for these emerging technologies to enter the market. The HWDS project successfully developed an analytical model and evaluated alternate hot water distribution systems. For this tool to be most valuable, better input data are needed to validate model assumptions. PIER funding supporting the 2008 Title 24 Building Standards should provide much of the needed data.

KEYWORDS: Synergistic Water Heating and Distribution Technologies (SWHDT), Combined Refrigerator Water Heater (CREWH), Hot Water Distribution, Condensate Recovery System (CRS), Hot Water Distribution Study (HWDS), Rapid Radiant Deployment System (RRDS)

EXECUTIVE SUMMARY

BACKGROUND

Residential water heating technology advances are needed to:

1. Improve distribution efficiency and hot water delivery times
2. Provide low cost, efficient alternatives to electric resistance water heating
3. Develop opportunities for integrating home appliances and systems
4. Cost-effectively measure energy savings of new technologies.

The target markets for these products are single and multi-family homebuilders, homeowners, and apartment occupants. The goal of the Synergistic Water Heating and Distribution Technologies (SWHDT) Program was to develop technologies that generate and capture the energy savings associated with high efficiency water heating, by:

- Developing an efficient combined refrigerator and electric water heater.
- Proving the safety of enabling technology to lower the first cost of heat pump water heaters that generate hot water efficiently.
- Studying hot water distribution options to identify those that deliver hot water most efficiently and minimize wasted water.
- Developing low cost, easy to install radiant floor tubing systems that improve distribution efficiencies and can be served by efficient water heaters.

In the SWHDT Program, Davis Energy Group and its team of subcontractors (TIAX, ORNL, Maytag, and IPEX) completed work aimed at each of these four goals. A brief description of each element and the work completed follows:

Combined Refrigerator Water Heater (CREWH)

The CREWH concept combines a residential refrigerator with components that capture refrigerator heat output and apply it to domestic hot water for use either in the kitchen or as a source of preheated water for the central water heater. Potential benefits include:

- Energy savings due to reduced hot water load and reduced distribution losses
- Reduced cooling loads due to capturing refrigerator heat output
- Faster hot water to the kitchen fixtures
- Reduced water waste while waiting for kitchen hot water
- Improved refrigerator efficiency

The objective was to build and test a combined refrigerator and water heater which would provide these benefits. A feasibility study conducted indicated the best approach was to integrate the storage tank with the refrigerator, rather than pump hot water to a

separate tank. A prototype was designed, constructed, and tested. Results indicated overall savings of 8% to 9% relative to a standard water heater and refrigerator.

Guidance from Maytag led to a second prototype with an unpressurized storage tank containing both refrigerant and domestic water heat exchangers. This design met two key objectives: low fabrication cost and production quality packaging. However, field monitoring indicated hot water temperatures were not always adequate for kitchen uses. Testing was completed by adding a resistance electric element to heat the top portion of the CREWH tank. Although this approach demonstrated potential for improved performance, significant redesign would be needed to fully implement the strategy.

The CREWH project demonstrated that a functional combined refrigerator/water heater could be built that is virtually identical in both external and internal appearance to a conventional refrigerator. While the project did not achieve the goal of delivering the majority of hot water to the kitchen from refrigerator heat output, the project outcomes strongly suggest that this goal could be achieved with further development work.

The CREWH concept faces market barriers as both builders and homebuyers are reluctant to adopt new technologies. Despite these barriers there is a substantial need for new energy efficient products to meet national energy targets. CREWH is projected to reduce California annual cooling energy consumption by up to 33 GWh/year and water heating energy by up to 258 GWh/year. Sequential market and technical research efforts are necessary to advance CREWH technology into the marketplace. The first effort must build on this project to establish a stronger relationship with a refrigerator manufacturer. The second effort must implement more advanced designs that increase CREWH heat extraction, retention, and delivery.

Condensate Recovery System (CRS)

Under a prior PIER contract, TIAX (formerly ADL) completed the development of an advanced residential heat pump water heater. As part of that project, a condensate recovery system (CRS) was developed to facilitate the installation of heat pump water heaters by eliminating the need for a gravity feed condensate line. The CRS heats condensate to the boiling point and then injects it into the hot water tank. The performance and operation of the CRS system was technically proven in the prior work, but regulatory issues were unresolved. The goal of this project was to test CRS safety by assessing how airborne contaminants affect domestic hot water and condensate quality.

A heat pump water heater with a CRS was operated in environments containing paint and gasoline vapors. The condensate produced was found to be safe except concentrations of MTBE higher than drinking water standards were produced in the gasoline vapor test. Mold dissolved in water was deactivated at the temperatures produced by the CRS. These results clearly demonstrate that the CRS can safely inject condensate into the domestic water system, clearing the way for lower cost heat pump water heater installations in California and elsewhere.

By facilitating heat pump water heater installations in California, CRS is projected to reduce cooling energy consumption by up to 35 GWh/year and water heating energy use by 169 GWh/year. Completing the following activities will help move the CRS from prototype to product:

1. Work with regulatory groups to make certain the design complies with applicable national mechanical and building codes.
2. Perform an additional design iteration to
   a. Evaluate carbon filter designs,
   b. Integrate the CRS into the HPWH, and
   c. Incorporate "design-for-manufacture" features that enable commercial production.
3. Demonstrate the product in a field-test program to determine energy impacts and verify safe operation.

Hot Water Distribution System (HWDS)

The performance of residential hot water distribution systems is currently not well understood. The goals of this project were to develop an analytical tool to simulate the energy performance, water waste, hot water wait time, and overall economics of domestic hot water distribution systems in typical new and existing California residences, and to evaluate the potential statewide impact of more efficient hot water distribution systems.

Researchers at Oak Ridge National Laboratory developed a detailed LabVIEW model to estimate heat transfer from insulated and non-insulated hot water pipes. Using this model, they compared alternative piping materials and levels of insulation, recirculation systems, appliance locations, and topologies. Energy use was evaluated under different use scenarios and in different house sizes, types, and ages.

The study determined that demand and continuous recirculation systems waste the least water, while demand recirculation and a central water heater location waste the least energy. Changing the use pattern to cold start (most wasteful) significantly improved the performance of the parallel pipe/manifold system relative to the other systems, placing it just behind the demand recirculation systems. Continuous recirculation systems waste the most energy of all the systems.

This work accomplished the project goal of determining preferred hot water system designs that minimize distribution losses. Implementing the knowledge gained in this project remains for future post-PIER activities. Implementation of improved hot water distribution systems are projected to yield annual California savings of up to 2.7 billion gallons of water, 150,000 therms of gas, and 75 GWh of electricity. Recommended future work includes gathering more field data to better understand actual construction and operation, validating simulation models with field data, integrating findings into 2008 Title 24 revisions, and developing design guides for architects, builders, and plumbers.

Rapid Radiant Deployment System (RRDS)

Radiant floor systems offer comfort and energy efficiency benefits over conventional forced air heating and cooling systems, but are currently installed only in custom homes due to high cost relative to conventional system alternatives. The goal of the Rapid Radiant Deployment System (RRDS) project was to develop and demonstrate a lower cost, standardized method for designing, fabricating, and installing radiant floor systems that might succeed in the production home market.

The project team successfully developed a method of prefabricating modules of hydronic tubing on concrete reinforcing steel mesh, reducing installation labor by 75%. Innovative techniques were developed for attaching the tubing to the mesh and for positioning the mesh in the concrete slab to eliminate the need for room-by-room tubing layout. A new design for an in-slab tubing manifold protects tubing components during construction. To demonstrate the efficiency potential of radiant hydronic systems 'full year' designs were developed which utilize domestic water heating combined with space heating and an advanced, multi-stage evaporative cooler for direct and radiant slab cooling.

This project accomplished its goal of developing and demonstrating a lower-cost radiant floor system that integrates with other energy efficient, ductless HVAC components. The results have already attracted the attention of one innovative builder who is implementing RRDS on a prototype "Zero Energy" project. Projected California annual cooling and water heating savings are 65 GWh and 56 GWh, respectively. The following activities are recommended to help bring RRDS technology into the marketplace:

1. Work with component suppliers to develop a pre-packaged hardware center that includes a tankless water heater, a floor circulation pump, a heat exchanger, automatic valving, and controls to select between heating and cooling mode. This packaging is needed to achieve "mature market" cost targets.
2. Find three to five "close-to-home" projects where the RRDS and ductless two-stage evaporative cooler combination can be implemented in the near future. Install and monitor the systems and gather occupant input.
3. Work with a selected production builder to implement the RRDS and ductless two-stage evaporative cooler combination on 30-40 one-story homes in an appropriate climate. Monitor selected units and comparable control homes.
4. Present the RRDS system to the radiant floor industry, which can benefit from the reduced costs and increased construction speed of these new floor components.

PROGRAM SYNERGIES

The four individual projects constituting the SWHDT program offer the following exciting synergies if they can achieve a significant market presence:

Synergy #1: Eliminate the Kitchen Hot Water Line and its Distribution Losses

An efficient hot water distribution system design has the potential for a positive synergy with CREWH, especially when the kitchen is far from the water heater and other hot water use points. A hot water distribution system that excludes the kitchen would often show significant savings in distribution losses and wasted water.

Synergy #2: CREWH/Heat Pump Water Heater

The CREWH could be integrated with a centrally located HPWH that needs no drain line due to use of the condensate recovery system. Since use of interior space for mechanical equipment is an issue for builders, integration of the hot water storage function, possibly using a phase-change storage material, with the refrigerator offers a clear advantage to builders. Also, the kitchen location often offers a reasonably central and therefore efficient origin for hot water distribution system. This synergy results in both water and energy savings, as well as reduced hot water wait times and space-cooling benefits.

Synergy #3: All-Electric "Zero-Energy" Configuration

An all-electric Zero Energy New Home concept could integrate photovoltaics with an all-electric space and water heating system. Intelligent design minimizing internal gains and solar gains could be combined with an integrated CREWH/heat pump water heater per Synergy #2. Space heating could be delivered with an air-to-water heat pump coupled with the RRDS.

1.0 INTRODUCTION

The overall goal of the SWHDT Program was to identify and develop technologies that enable the efficient generation and distribution of hot water, and that provide enhanced comfort and measurable energy savings to California residents. The long term SWHDT performance target was to complete activities that will lead to a projected 633 GWh/year of electricity savings for California ratepayers by the tenth year after program completion.

1.1 Background and Overview

Residential water heating technology advances are needed to improve distribution efficiency and hot water delivery times; to provide low cost, efficient alternatives to electric resistance water heating; to develop opportunities for integrating home appliances and systems; and to cost-effectively measure energy savings of new technologies. The essence of the Synergistic Water Heating and Distribution Technologies Program is to develop technologies that generate, measure, and capture the energy savings associated with high efficiency water heating, by:

- Developing a combined refrigerator electric water heater that generates hot water efficiently.
- Proving the safety of enabling technology to lower the first cost of heat pump water heaters that generate hot water efficiently.
- Studying hot water distribution options to identify those that deliver hot water most efficiently and minimize wasted water.
- Developing low cost, easy to install radiant floor tubing systems that improve distribution efficiencies and will be served by efficient water heaters.

The target market for the products from this effort are single and multi-family homebuilders, homeowners, and apartment occupants.

Beyond energy savings, SWHDT Program elements address a wide range of CEC PIER issues, goals and objectives. Additional SHWDT impacts include:

- Reduced cooling energy use in new and existing buildings.
- Increased consumer load management choices and load shift options.
- Increased functionality and use of energy efficient products.
- Increased building value through innovative energy strategies.

The SWHDT Program included three elements:

- Program Administration (Details can be found in Appendix A)
- Efficient Hot Water Generation
- Efficient Hot Water Distribution

The Efficient Hot Water Generation element included two appliance development projects, the ***C***ombined ***Re***frigerator ***W***ater ***H***eater project (CREWH) and a Condensate Recovery System (CRS) project for heat pump water heaters. The Efficient Hot Water Distribution element included a Hot Water Distribution Study (HWDS) and a Rapid Radiant Deployment System (RRDS) development project.

SWHDT was initiated in June 2001 and concluded in April 2005. $1,188,605 was committed to fund program activities over the three year schedule, including $767,038 of Energy Commission/PIER funds, plus $421,567 (35.5%) contractors' cost share. Approximate budgets by element are:

- Element 1: Administration - $179,000
- Element 2: Efficient Hot Water Generation - $673,000
- Element 3: Efficient Hot Water Distribution - $337,000

Davis Energy Group was the prime contractor of the SWHDT Program. Key subcontractors included:

- Oak Ridge National Laboratory, Oak Ridge, Tennessee
- TIAX, LLC (previously A.D. Little Company), Cambridge, Massachusetts
- Maytag Corporation, Newton, Iowa
- IPEX, Inc., Ontario, Canada

The overall Program organizational structure and relationships between key personnel and organizations are shown in Figure 1.

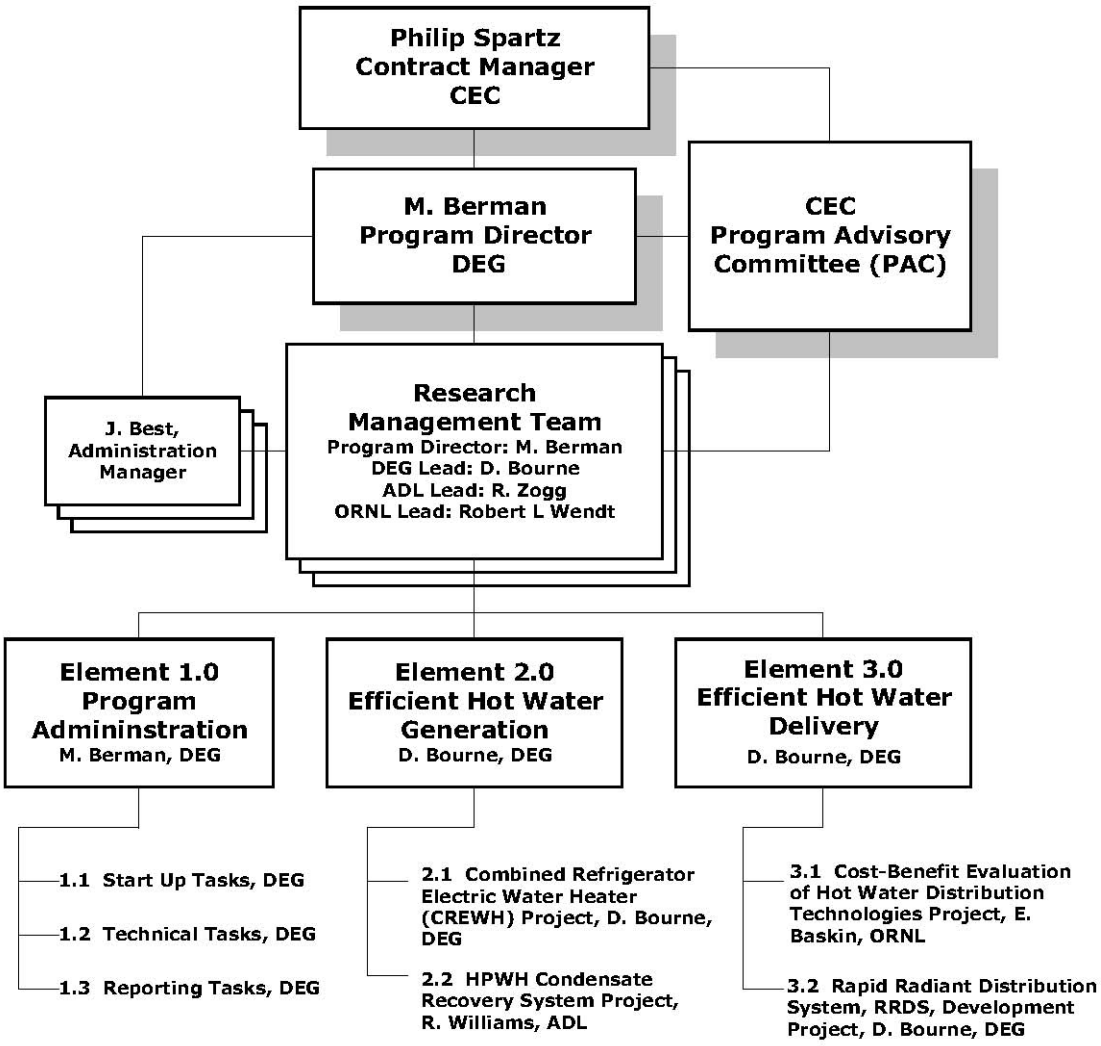

Figure 1 SWHDT Program Organizational Chart

1.2 Report Organization

This report is intended to present a synopsis of each of the four SWHDT program elements. The four elements are:

- ***C***ombined ***Re***frigerator ***W***ater ***H***eater project (CREWH)
- Condensate Recovery System (CRS)
- Hot Water Distribution Study (HWDS)
- Rapid Radiant Deployment System (RRDS)

Each of the individual program elements are discussed in the following format:

Section X.1	Introduction (description of project and background information)
Section X.2	Approach (objectives and brief methodology)
Section X.3	Outcomes (summary of project activities and results)
Section X.4	Conclusions and Recommendations (findings, next steps, benefits to California)

Detailed discussions of individual program elements can be found in the four project final reports (see attachments) and project deliverables listed in the references section of this report. A condensed summary of each of the four projects follows this section.

The Appendix and Attachments are as follows.

Appendix I.	Administrative Summary
Attachment A- 1	Combined Refrigerator Electric Water Heater: Project Final Report
Attachment A- 2	Safety Analysis and Testing of a Heat Pump Water Heater Condensate Recovery System: Project Final Report
Attachment A- 3	Evaluation of Residential Hot Water Distribution Systems by Numeric Simulation: Project Final Report
Attachment A- 4	Rapid Radiant Deployment System Development: Project Final Report

2.0 COMBINED REFRIGERATOR WATER HEATER PROJECT (CREWH)

2.1 Introduction

Current residential refrigerators and water heaters are separate appliances. Refrigerators are removable, plug-in units that typically are owned by the occupants in single-family homes and by the landlord in multi-family residences. New refrigerators must comply with Federal Appliance Standards and typically consume 400 to 800 kWh annually. Units sold before the Federal Appliance Standards may consume 2000 to 3000 kWh/year. The energy consumed by the refrigerator is ultimately rejected to the kitchen environment as waste heat[1]. In heating-dominated climates, the refrigerator waste heat is a benefit as it helps to reduce space-heating loads, with minimal impact on summer cooling loads. In cooling-dominated climates (such as much of California's inland growth areas) the added heat contributes to summer cooling loads, more than offsetting any heating benefit depending upon the balance point for heating and cooling loads. Reclaimed heat from the refrigerator condenser could be used to reduce household water heating loads. From refrigerator heat discharge, pre-1993 refrigerators (usage exceeding 1000 kWh/year) could heat up to 30 to 35 gallons of water per day, vs. about 15 gallons per day for new refrigerators[2].

To evaluate the feasibility of integrating the two appliances, Davis Energy Group has developed the concept of a ***C***ombined ***RE***frigerator ***W***ater ***H***eater (CREWH). The CREWH combines a water-cooled refrigerant condenser with hot water storage either for domestic hot water preheating or direct hot water delivery to kitchen use points. Capturing the condenser waste heat to reduce domestic hot water loads can result in the following benefits:

- Domestic water heating energy use is reduced due to "free" condenser waste heat
- Reduced internal gains contribute to favorable space conditioning impacts
- The integrated appliance may operate more efficiently than a conventional refrigerator

2.2 Approach

Specific CREWH project objectives were to:

1. Complete a feasibility study that evaluates the "fit" between refrigerator heat output and water heating needs, develops and analyzes potential CREWH design concepts and markets, and identifies a preferred CREWH strategy

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1 The energy balance is such that the net effect of a refrigerator is to act like a resistance heater to its immediate environment.

2 Assuming 100% of the rejected heat is recovered and utilized for domestic water heating.

2. Design, build, and lab test a first prototype unit (proof of concept)
3. Redesign unit to develop a production ready design concept
4. Install and monitor a second prototype unit
5. Report project findings and potential CREWH impact

Our manufacturing partner Maytag played a key role in this project both in terms of technical support and providing refrigerators for prototype and field test activities.

2.3 Outcomes

The feasibility phase of the CREWH project evaluated three potential CREWH system configurations. Configuration "2b", a design with the hot water storage tank integral to the CREWH (eliminates the need for a circulating pump) was projected to provide the most favorable economics, largely because of lower costs relative to the other options. In this configuration the refrigerant condenser is integrated with CREWH storage in one of two methods: either immersed in the CREWH storage tank or configured as a wraparound heat exchanger design.

Based on the feasibility results, a proof-of-concept Prototype I CREWH was designed and fabricated. Maytag provided a 27 ft^3 side-by-side refrigerator for use as the first CREWH prototype. This MSD2754 unit was one of Maytag's highest energy consumers in this size range rated at 740 kWh per year[3]. (High refrigerator energy use translates to greater heat recovery potential for the CREWH.) The MSD2754 was first monitored unmodified to document base case energy use. The unit was then modified (see schematic in Figure 2) to incorporate a refrigerant-to-water heat exchanger. The Prototype I CREWH was tested and found to deliver combined (refrigerator and water heater) performance 8-10% better than separate conventional appliances.

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3 relative to the current standard of 747 kWh per year

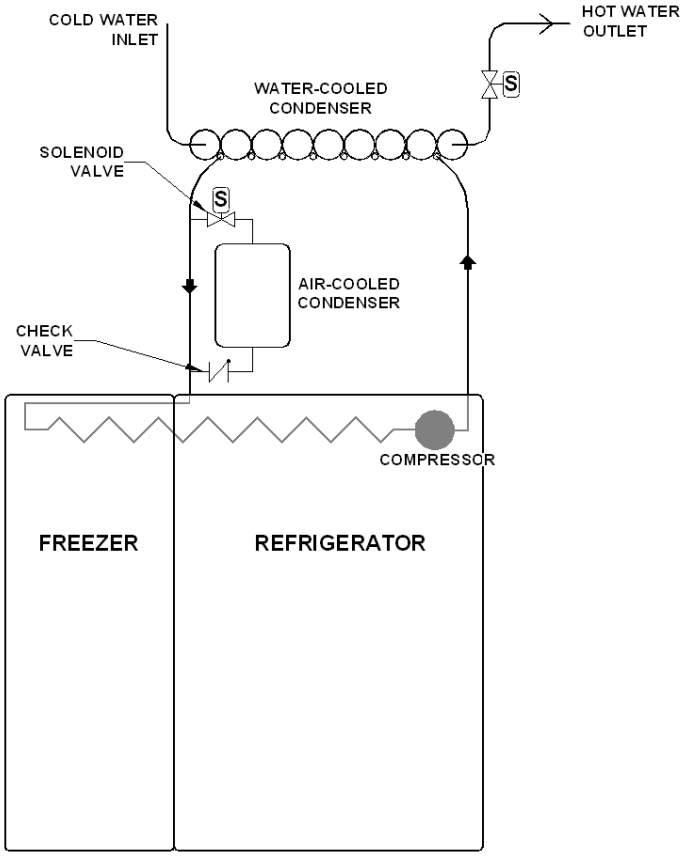

Figure 2 Schematic of Prototype I Design

The Prototype I design, although demonstrating a performance advantage, was not configured in a manner that could be inexpensively manufactured or easily integrated within existing refrigerator designs. The key objective for the second prototype redesign was to cost-effectively integrate the CREWH storage tank within an existing refrigerator cabinet.

For the second prototype design we evaluated two potential options for integrating storage with an existing refrigerator. The first option was a pressurized tank design (potable water in the tank) with either an immersed double wall refrigerant heat exchanger or a wrap around heat exchanger. The second option was a non-pressurized tank (non-potable water in the tank) containing both a refrigerant-to-water heat exchanger and a load-side heat exchanger for heating potable water. In the latter configuration, the tank water serves as a captive heat transfer medium. The refrigerant-to-water heat exchanger rejects heat to the storage water and the immersed load side heat exchanger extracts heat from the tank. The second approach was selected primarily due to cost advantages and flexibility in configuring the storage tank.

Maytag provided a model ARB2557CW refrigerator (with bottom mount freezer) for the second prototype development effort. This 25 ft^3 unit is considerably more efficient than

the 27 ft^3 Prototype I unit (511 vs. 770 kWh/year), resulting in lower heat rejection capability. Rotational molding was chosen for the tank because it produces large hollow plastic parts with comparatively inexpensive tooling. Not only can the polyethylene tank be manufactured inexpensively[4] (~$3-4 per pound), but the mold can also be designed to fit any size space, as well as irregularly sized spaces. This is especially useful in applications such as the CREWH where the tank can be custom sized to fit in the mechanical space under the insulated refrigerator/freezer compartments.

This space-optimizing approach provides additional storage volume relative to a cylindrical pressurized tank. Figure 3 shows the final rotomolded tank with potable water connections shown. (Refrigerant condenser connections are the smaller lines positioned at the bottom of the tank.) The design allowed for the nine gallon tank to be heated by the refrigerant condenser and transfer heat to the approximately 60 feet of 3/8" copper load-side heat exchanger located primarily in the tower region of the tank. The CREWH hot water outlet is connected to a valve that preferentially supplies hot water from the CREWH to the kitchen sink, as long as temperatures exceed 100°F[5].

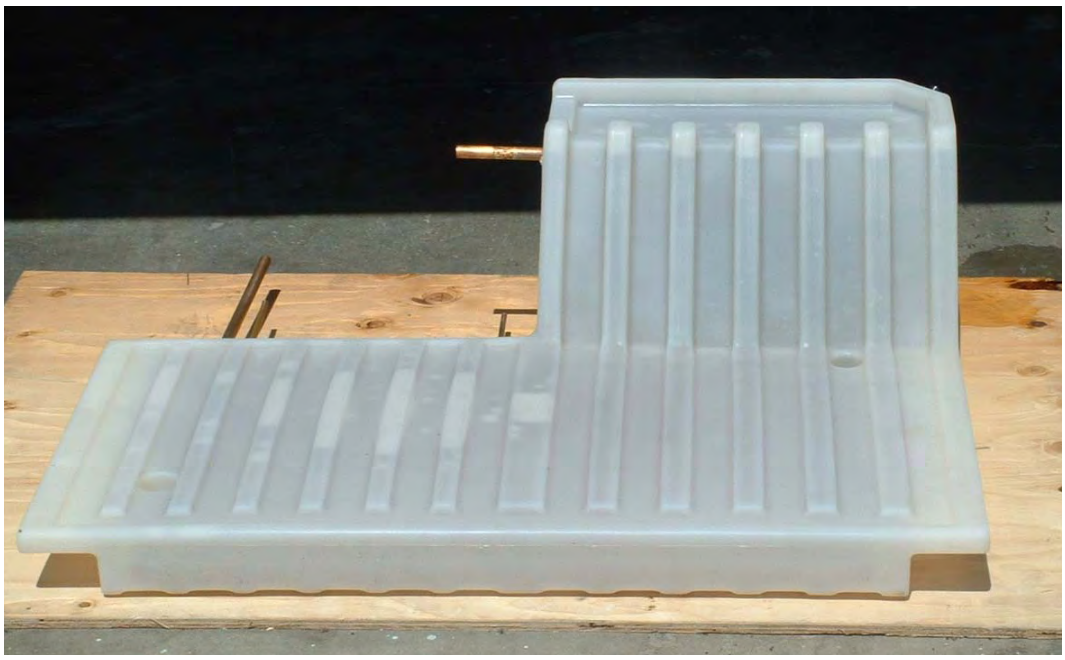

Figure 3 CREWH Tank with Potable Water Connections

Figure 4 shows the completed CREWH tank installed in the Maytag refrigerator prior to lab testing. After completion of initial start-up testing, the unit was installed at an

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4 The per unit cost is low after the initial mold development cost.

5 If the temperature falls below 100°F, water is drawn from the existing line to the hot water heater.

occupied house in November 2004. The unit was monitored in detail for 83 days. CREWH electrical energy use was found to be only 3% higher than the unmodified air-cooled refrigerator.

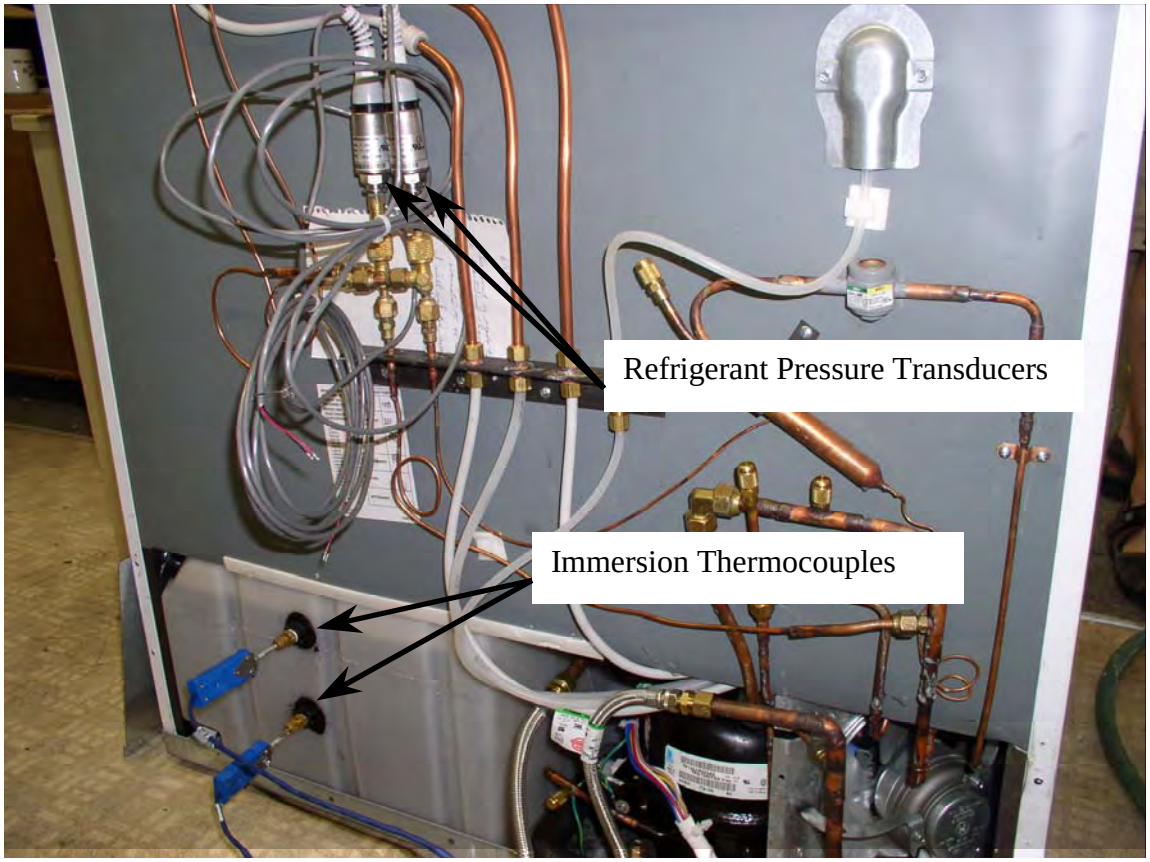

Figure 4 Prototype II Lab and Field Test Unit

Although the CREWH tank midpoint temperature averaged 106°F during kitchen hot water draws, only 20% of the total hot water consumed in the kitchen came from the CREWH due to inadequate hot water quality[6]. Three factors directly contributed to this result.

1. Monitoring occurred in mid-winter when cold water inlet temperatures (entering the CREWH load side heat exchanger) are at their lowest and the refrigerator compressor operating fraction (heat generation) is at a minimum.
2. The lack of space between the rotomolded tank and the refrigerator cabinet precluded insulation of much of the CREWH tank, resulting in higher storage losses and therefore lower tank temperatures.
3. We were unable to reclaim as much compressor waste heat as was assumed in the feasibility study.

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6 The remaining 80% came from the central gas water heater.

This result directed us to explore supplemental electric resistance water heating as an option to fully satisfy kitchen hot water loads[7], since only by efficiently providing reliable hot water to the kitchen will the CREWH be a marketable product. A second prototype II unit was tested to evaluate the performance of a 1500 Watt immersion heater heating the top portion of the CREWH tank. Unfortunately the load side heat exchanger is configured to spiral through the height of the tank and therefore the electrically heated tank top conducted heat to the bottom. Without stratification in the tank, we cannot provide both lower temperatures for the refrigerant condenser and higher temperatures for heating the CREWH outlet water.

Upon completion of the CREWH development project, significant work had been completed but additional R&D efforts are still needed. DEG has developed a well-packaged CREWH design that incorporates a low-cost storage tank and heat exchanger designer[8]. Further improvements are needed to maximize compressor heat reclaim, reduce tank storage losses, and optimize control and operation of an electric heating element. Further research could evaluate the potential of a full heat pump water heating CREWH design. Although rejected by Maytag due to its complexity, this design approach offers the potential of greater benefits with specific applicability to cooling-dominated multi-family applications.

2.4 Conclusions and Recommendations

The CREWH project has made considerable progress toward development of a viable, marketable combined refrigerator water heater. Working with Maytag, DEG has shown that a conventional refrigerator can be modified, without changing the food storage compartments, to store refrigerator heat output and deliver it to kitchen loads. The final design that incorporates an electric heater in the CREWH storage tank can eliminate the need for a hot water line to the kitchen, and the heat losses (and cost) associated with that line.

Development work in this project did not achieve the primary CREWH performance goal of delivering the majority of hot water to the kitchen from the CREWH. CREWH heat delivery to its internal storage tank was lower than desired due to both higher tank heat loss and less reclaimed heat from the compressor. More work is needed to achieve the full potential of the "kitchen-only" CREWH version, but there are no insurmountable technical obstacles to success. Currently the homeowner economics are tenuous at best, but potential technical improvements offer improved savings potential. The biggest potential marketing advantage for CREWH is likely the faster hot water to the kitchen.

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7 This approach allows for eliminating hot water piping to the kitchen which can have significant first cost advantages to the builder as well as eliminating hot water energy and water waste in houses where the kitchen is remote from the water heater.

8 The estimated incremental retail cost for the Prototype design is $205.

The CREWH faces market barriers as both builders and homebuyers are reluctant to adopt new technologies. But despite these barriers there is a substantial need for new energy efficiency products; for example, DOE's Building America program seeks 50% energy savings for new homes by 2010. In short, we believe that viable markets can develop for two CREWH versions:

1. The kitchen-only unit developed in this project, a design that can reduce peak loads, provide faster hot water delivery to the kitchen, save water, and reduce energy costs. This version should incorporate an on-board tank heater as lab-demonstrated at the end of this project and could be marketed at an incremental installed cost of about $200. The electric heater allows for the potential elimination of the kitchen hot water line.
2. A multi-family/small home unit that functions as both a refrigerator and a heat pump water heater, eliminating the traditional natural gas water heater. (This design approach was not the focus of this project, and should be pursued as a separate venture.)

To have any chance for success with CREWH, an R&D team with a committed manufacturer must be assembled. In June 2004, Maytag substantially reduced their engineering work force and many of the key Maytag personnel involved with the CREWH project were released. As a result, Maytag's interest level is much lower than it was early in the project. Since CREWH cannot be implemented without a seasoned refrigerator manufacturer, it will be necessary to rekindle the Maytag relationship or find an alternate manufacturer before further R&D efforts are pursued with the technology.

2.4.1. Benefits to California

It is premature to project CREWH impacts and benefits based on the development work completed to date. Based on Prototype II performance, refrigerator energy use and space conditioning cost impacts are roughly a wash relative to standard equipment. Projected water heating savings amount to approximately 8 therms per year for a natural gas storage water heater and 110 kWh per year for an electric storage water heater. Cooling energy savings of up to 200 kWh per year are estimated in the hottest California climates. In milder regions, added heating costs may offset any homeowner cooling savings due to the high current cost of natural gas relative to electricity. Hot water savings will increase with a redesigned CREWH that centralizes the compressor in the storage tank (to maximize reclaimed heat from the compressor), improved tank insulation, and integration of an intelligent electric booster element. If a motivated manufacturing partner can be found, these design improvements can be implemented and evaluated.

3.0 CONDENSATE RECOVERY SYSTEM (CRS) PROJECT

3.1 Introduction

SWHDT team member TIAX was involved in the development of a market-optimized heat-pump water heater with support from the California Energy Commission PIER Program, Oak Ridge National Laboratory, and Enviromaster International (EMI) of Rome, New York (completed in April 2004 under contract number 500-98-028). The unique characteristics of the HPWH allow it to be installed in any location a conventional electric water heater is installed with no provisions for ventilation, however, a drain line for condensate drainage is required.

While developing the HPWH, the staff of TIAX also conceived and developed a prototype of a patented condensate recovery system[9] (CRS) for use with a heat-pump water heater. As condensate forms on the evaporator of the HPWH it is collected in a condensate pan located below the evaporator. The condensate is gravity fed to the condensate recovery system, heated to a point of boiling and then is injected it into the hot water tank of the HPWH (see Figure 5). The CRS allows for elimination of a gravity fed condensate line or condensate that can be problematic or costly in many applications. The performance and operation of the CRS system was technically proven in the prior work, however, the regulatory issues are still unresolved. The goal of this project was to test the safety of the CRS.

9 U.S. Patents 6,199,395 and 6,257,002

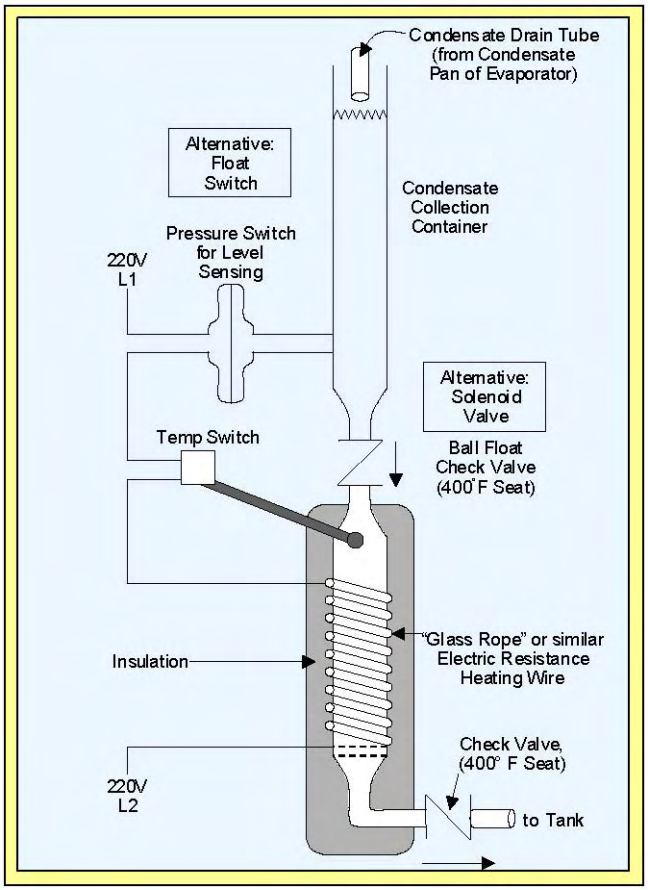

Figure 5 CRS Conceptual Drawing

3.2 Approach

The overall objective of the CRS project was to obtain laboratory evidence supporting the safety of injecting sterilized condensate from a residential HPWH into the hot water storage tank. We were specifically interested in the potability of the water that is injected into the HPWH storage tank. The project tasks required to accomplish this were to perform a preliminary hazard analysis (to identify key water-quality concerns, such as biological, volatile organic compounds, particulate, surface contaminants, and others), to fabricate and test a prototype CRS, and to recommend next steps based on results of the testing.

Four tests were completed: a baseline test, a paint test, a gasoline test, and a mold test. The baseline test allowed us to determine the potability of the condensate without any intentionally introduced contaminants. For the paint test, we filled the room containing the HPWH with spray paint and measured the contaminants making their way from the air into the condensate exiting the CRS. Similarly for the gasoline test we exposed the HPWH to gasoline vapors and measured the contaminants. When testing the mold and mold toxins we proposed performing the test in a two step process. In the first step we performed a bench test in which mold is heated in water to 150°F for 100 seconds. If the mold was not deactiviated in the first test, we proposed to perform a second test in

which mold spores were placed in the evaporator pan of the HPWH and allowed to flow into the CRS.

3.3 Outcomes

The contaminant levels in the baseline test, paint test, and gasoline test were all below the prescribed EPA limits. However, the level of MTBE found in the condensate exiting the CRS exceeds the level allowed by the State of California Department of Health Services (DHS). While this is of some concern, there are two mitigating factors:

1. The level of MTBE, once diluted in the storage tank of the HPWH, was far below the regulated level.
2. The State of California was expected to completely phase out MTBE from its gasoline supply by the end of 2003 and, therefore, MTBE will no longer be a contamination source.

During a typical CRS cycle, the condensate is heated to a minimum temperature of 150°F and remains at or above 150°F for at least 100 seconds before being injected into the HPWH storage tank. Results of the testing indicates that the mold and mold toxins are deactivated when exposed to a temperature of 150°F for 100 seconds. Therefore, we conclude that the CRS will deactivate any mold or mold toxins that are present in the condensate prior to being injected into the HPWH storage tank.

3.4 Conclusions and Recommendations

Following the safety testing of the CRS we recognize there are a number of activities that ought to be completed before the commercialization of the CRS is likely to move forward. While the CRS is technically proven and the safety of the device has been demonstrated (relative to drinking water), market barriers remain. Completing the following activities will help to move the CRS from prototype to product:

1. Work with regulatory groups to make certain the design complies with applicable national mechanical and building codes.
2. Contact companies (individuals) that are engaged in and approved to test water treatment devices for the state of California and have them review and test the CRS integrated with the HPWH.
3. Perform an additional design iteration to integrate the CRS into the HPWH and incorporate design-for-manufacture features that enable commercial production.
4. Develop a focus group of consumers to determine the reaction of consumers to the product and idea of injecting condensate from the air into their water.
5. Demonstrate the product in a field-test to determine energy impacts and provide more information regarding the safety of the device.
6. Review potential carbon filter designs and determine if there is a cost-effective filter that could be incorporated into the CRS.

7. Develop an education program to increase the understanding of the system.

3.4.1. Benefits to California

The CRS has the potential to favorably impact HPWH retrofits in California. Although the HPWH market is currently small, the CRS is a fairly low-cost component that could facilitate the replacement of existing indoor electric water heaters that do not have a gravity flow condensate option. In cooling dominated climates, indoor HPWH's can provide a favorable space conditioning benefit, offsetting air conditioner energy use.

4.0 HOT WATER DISTRIBUTION STUDY

4.1 Introduction

The goal of the ORNL Hot Water Distribution Study was to develop an analytical tool to simulate the energy performance, water waste, homeowner convenience (in terms of hot water wait time), and overall economics of various domestic hot water distribution systems in new and existing California residences, and to evaluate the potential statewide impact of the use of more efficient hot water distribution systems. A numerical model, developed using LabVIEW, was used to estimate heat transfer from insulated and non-insulated hot water pipes. Heat loss from hot water system distribution piping affects overall hot water energy use, water consumption (and waste), and homeowner hot water waiting time at the end use points.

4.2 Approach

The primary objective of the HWDS project was to develop a detailed analytical tool for modeling of hot water distribution systems. Once completed the model was used to project performance impacts of various system configurations, material options, and control systems.

With the detailed LabView model, the following alternative cases to conventional trunk and branch distribution systems were evaluated:

- Alternative piping materials (PEX, CPVC)
- The impact of relocating the water heater to a more central location
- The impact of added pipe insulation on distribution system performance
- Continuous and demand-actuated recirculation systems
- Parallel-piping systems with a manifold located near the water heater and ½" piping from the manifold to each individual fixture.

Two hot water draw patterns were investigated. The first "worst case" scenario assumed that each individual draw was a "cold start", i.e. the water had reached the ambient temperature surrounding the pipe before each use. The second was a "clustered use" pattern with individual draws clustered in the early morning and late afternoon/evening, thereby retaining some hot water in the piping between draws.

Both new construction and existing housing cases were evaluated. Five new construction cases ranging in size from a four bedroom, 2½ bath, 3080 ft^2 single family detached home down to a one bedroom, one bath, 580 ft^2 apartment. The existing residences evaluated included a three bedroom, two bath, 1100 ft^2 single family home and a four bedroom, 2½ bath, 1960 ft^2 single family home.

4.3 Outcomes

Modeling results demonstrate a fairly consistent pattern of energy performance and water waste among the house types studied, however, the results varied significantly with the assumed water use pattern (cold start or clustered).

Demand and continuous recirculation systems waste the least water, while demand recirculation and a central water heater location waste the least energy. Changing the use pattern to cold start (most wasteful) significantly improved the performance of the parallel pipe/manifold system relative to the other systems, placing it just behind the demand recirculation systems. Continuous recirculation systems waste the most energy of all the systems.

All systems had "reasonable" average hot water wait times (<30 seconds), but demand and continuous recirculation systems and the parallel pipe systems had shorter maximum waiting times. If a cold start use pattern is assumed, the typical waiting time for the various conventional systems increase significantly while the other systems remain about the same.

Continuous recirculation systems add substantial construction cost as well as operating cost and energy waste when compared to any other system. Although they minimize wait times for hot water and water waste, continuous recirculation systems should not be installed due to their high cost and energy waste.

Adding a demand recirculation pump and controls increases conventional system costs by about $600 but reduces operating cost, waste and wait times. Wait times can be similar to continuous recirculation systems, with the added benefit that water and energy wastes are significantly reduced compared to conventional systems. Demand recirculation systems can be installed in both new construction and retrofit housing.

Parallel pipe distribution systems may also offer an attractive alternative for some house designs and distribution system layouts. These systems are less costly to install than conventional systems and can reduce wait times to acceptable levels, however, the energy and water savings of parallel pipe systems are sensitive to hot water use patterns. When assuming clustered hot water draws, parallel pipe systems use similar amounts of water and energy as conventional systems and offer no advantage with regard to waste. However under the cold start pattern, parallel pipe systems perform better than conventional systems. Parallel systems would demonstrate improved performance with 3/8" piping (instead of ½"), although current code issues complicate this approach.

4.4 Conclusions and Recommendations

The HWDS project successfully developed a sophisticated analytical tool for evaluating energy, water waste, and wait time performance of alternative hot water distribution system design. Project outcomes suggest the following conclusions and recommendations:

1. Gather field data to better understand what is being installed and how these systems perform. Issues of interest include: typical piping layout, pipe

sizing, pipe location, hot water usage data (how much, how frequently, where used), how common are recirculation systems, what type of controls, what are regional differences in cold water inlet and supply water temperatures.

2. Utilize field data to validate available computer models. Integrate the results into the next round of Standards revisions.
3. Consider banning continuous recirculation systems.
4. Consider ways to encourage centrally locating hot water heaters.
5. Consider ways to encourage installation of parallel pipe systems.
6. For Home Designer, Builders, and Plumbers: Consolidate bathrooms and other hot water consuming activities in the same areas to take advantage of clustered uses of hot water.
7. Consider centralizing the location of water heaters to minimize piping trunk lengths.
8. Locate plumbing in the attic for single story homes without basements and interstitial space between floors for multistory homes.
9. Do not oversize hot water piping. Use code permitted minimums. Bigger isn't better.
10. If a recirculation system is needed, the demand recirculation (1-pipe) system is the best option.
11. Consider CPVC or PEX plastic piping in lieu of copper when appropriate quality and durability can be demonstrated.

4.4.1. Benefits to California

The impact of applying more efficient alternative hot water distribution systems on California's overall residential energy and water consumption was estimated for the period beginning 3 to 5 years after initiation of a recommended Implementation Plan. From this viewpoint, a penetration rate of 100% was assumed for new construction in the state (estimated 150,000 units/year). For the estimated 3 million hot water systems in existing California housing with excessive waiting periods, a 10% per year penetration rate for retrofit demand recirculation systems was assumed until the market was saturated. The penetration rate for all replacement systems in existing housing (11 million units) was assumed to be an on-going 0.1% per year.

The projected annual savings in water and energy for both new and existing California homes are shown in **Table 1** based on the penetration rate assumptions. Projected savings in each case are given as a range reflecting the difference between the cold start and clustered water use assumptions, but actual savings are likely to be between these extremes. Improved hot water distribution could provide energy savings comparable to the household energy consumption of between 7,000 and 22,000 typical California households. Potential annual water savings from using alternative hot water distribution systems is projected to equal the total annual water consumption of between 8,000 and 27,000 California homes.

Table 1 Projected Savings for Efficient Distribution Systems

Water (10^6 gallons)	Natural Gas (10^9 Btu)	Electricity (MWh)
850 to 2,670	470 to 1,450	24,200 to 74,800

5.0 RAPID RADIANT DEPLOYMENT SYSTEM PROJECT

5.1 Introduction

The focus of Rapid Radiant Deployment System (RRDS) was to design and demonstrate a lower cost hydronic radiant floor (HRF) systems approach to facilitate increased penetration of radiant floor systems into the production home market. HRF systems offer comfort and energy efficiency benefits, but are currently installed only in custom homes due to high cost relative to conventional system alternatives. Benefits include the ability to utilize one efficient heat source for space and water heating (vs. conventional furnace and storage water heater), energy advantage of distributing heat via pumps rather than less efficient blowers, and the comfort advantage (mean radiant temperature) of heating surfaces which avoid creating a thermally stratified indoor environment.

5.2 Approach

The primary objectives of the RRDS project were to:

1. Assess hydronic radiant floor market barriers
2. Develop an optimized RRDS design and fabrication approach
3. Complete a prototype RRDS project
4. Project RRDS savings potential and overall economics
5. Identify an optimal RRDS implementation strategy.

A study of current radiant floor market barriers reinforced the project objectives in seeking time and labor-saving advances in installing the tubing, to facilitate introduction in the production home market. The study also helped to identify strategies that can:

- Better protect the tubing during construction
- Allow installation by contractors already on site
- Facilitate combination with energy-efficient ductless cooling technologies

Manufacturing partner IPEX, a leading manufacturer of components and thermoplastic pipe products headquartered in Toronto, Canada, joined DEG as a subcontractor in this effort. IPEX played a key role by providing prototype materials, consulting on design, and estimating retooling costs for a preferred tubing system.

5.3 Outcomes

After reviewing market barriers and establishing design requirements, DEG and IPEX generated and compared four alternate configurations for a prefabricated tubing/ substrate product. A preferred concept was ultimately selected that pre-assembles a unique serpentine tubing arrangement to flat sheets of reinforcing steel mesh. The "figure 8" serpentine tubing fabrication greatly facilitates tubing installation by

eliminating tubing resistance during placement and securement. Since the mesh chosen is identical in pattern to the normal slab reinforcement, the product does not require added time for HRF tubing placement at the job site. DEG evaluated methods for rapidly securing the tubing to the mesh, and selected a preferred approach that reduces required labor by 75% compared to current methods. Figure 6 shows the tubing/mesh system installed at the test house. In addition to the tubing/mesh system, the team also developed a low-cost in-floor radiant tubing manifold system that fully protects components during construction (Figure 7).

Figure 6 RRDS Tubing/Mesh Array Installed at Test House

To maximize utilization of the radiant floor tubing, DEG developed a design approach that combines space and water heating with efficient cooling. The "full-year" RRDS design includes the modular floor tubing/reinforcing mesh panels plus tubing manifolds, a "combined hydronic" instantaneous gas water heater, and a two-stage evaporative cooler that directly cools conditioned space and also indirectly cools the space via nighttime slab cooling using circulated evaporative cooler sump water. The two-stage cooler operates very efficiently, especially at night when outdoor wet bulb temperatures are lowest, resulting in greater cooling capacity.

Figure 7 Low Cost Manifold Box (prior to slab pour)

DEG worked with IPEX of Toronto and homebuilder Pyramid Construction to install a prototype RRDS on a large custom home in Davis, CA. After the manifolds were placed, fourteen mesh/tubing panels were assembled off-site and rapidly placed in the waiting foundation. Pyramid's concrete and plumbing subcontractors completed the work, with DEG guidance. The prototype project confirmed the technical viability of the RRDS concept, as well as the speed and quality benefits of the system.

IPEX estimated that a $1,276,000 investment would be needed to start manufacturing the preferred figure-8 tubing. This high cost forced the conclusion that conventional rolled tubing should be used initially, to allow near-term RRDS marketing until the market is proven.

5.4 Conclusions and Recommendations

The following specific activities are recommended for continuing the effort to bring RRDS technology into the residential marketplace.

1. **Verify Tubing Depth:** Working with concrete and framing subcontractors, form and pour a 7′ by 20′ slab with an RRDS array installed on stand-offs. Secure "dummy" floor plates across the 7′ dimension at 1′ intervals using explosive-charged fasteners. Monitor the tubing for leaks, and subsequently saw the slab at regular intervals to measure tubing depth. Create a video suitable for presentation to builders and to the Radiant Panel Association[10] that verifies tubing safety from fasteners.
2. **Present to the HRF Industry:** Present the RRDS system to the HRF industry, which can benefit from the reduced costs and increased construction speed of these new floor components. The RRDS videos and contractor interviews will be valuable in this effort.
3. **Develop Hardware Center:** Work with component suppliers to develop a pre-packaged hardware center that includes a tankless water heater, a floor circulation pump, a heat exchanger, automatic valving, and controls to select between heating and cooling mode. This package would minimize on-site plumbing time and facilitate meeting "mature market"cost targets used in the economic analyses.
4. **Implement Prototype Projects:** Find three to five "close-to-home" projects where RRDS and ductless two-stage evaporative cooler combination can be implemented in the near future. Install and monitor the systems and gather occupant input.

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10 RPA; see http://www.radiantpanelassociation.org/

5. **Develop a Production Builder Demonstration Project:** Work with a selected production builder to implement the RRDS and ductless two-stage evaporative cooler combination on 30-40 one-story homes in an appropriate climate. Monitor selected units and comparable control homes; provide technical support as needed. Monitor for a minimum of one year. This project would be large enough to resolve outstanding implementation issues, including:
   - Pricing schedules, promotions, and sales plans
   - Need for additional safety, quality, and codes certifications
   - Optimal RRDS packaging/assembly format
   - Building trades process flow and options

Support from other governmental agencies and electric utilities might be available to further advance the RRDS system and, where cooling systems are commonly installed, the RRDS/two-stage evaporative cooler combination. Completion of these recommended activities should provide further evaluation and ample exposure for judging the potential of the RRDS/IDEC combination to substantially reduce energy consumption and peak demand in new California homes.

5.4.1. Benefits to California

To evaluate the performance of the full-year RRDS design, DEG simulated base case and "full-year" RRDS systems in five California climates for both one and two-story house designs. We then estimated costs under both "current" and "mature market" scenarios. Mature market economics assume a technology has achieved significant production volume and market share. Results indicate significant energy savings potential for the RRDS design approach where the floor slab is used for both heating and cooling delivery. Table 2 below shows "bottom line" annual savings considering mortgage and energy costs for the five climate zones.

Table 2 RRDS Full-Year System Homeowner Economics

	Current		Mature Market	
Location	One-story	Two-story	One-story	Two-story
Santa Rosa	$130	$21	$266	$270
El Toro	$69	($47)	$205	$202
Riverside	$205	$88	$341	$337
Sacramento	$184	$76	$320	$325
Fresno	$351	$240	$487	$489

6.0 OVERALL RECOMMENDATIONS

6.1 Program Synergies

The four individual projects constituting the SWHDT program offer the potential for some exciting synergies if they can achieve a significant market presence. Three synergies are described below.

Synergy #1: Eliminate the Kitchen Hot Water Line and its Distribution Losses

An efficient hot water distribution system design has the potential for a positive synergy with CREWH, especially when the kitchen is far from the water heater and other hot water use points. A hot water distribution system that excludes the kitchen would often show significant savings in distribution losses and wasted water.

Synergy #2: CREWH/Heat Pump Water Heater

The CREWH could be integrated with a centrally located HPWH that needs no drain line due to use of the condensate recovery system. Since use of interior space for mechanical equipment is an issue for builders, integration of the hot water storage function, possibly using a phase-change storage material, with the refrigerator offers a clear advantage to builders. Also, the kitchen location often offers a reasonably central and therefore efficient origin for hot water distribution system. This synergy results in both water and energy savings, as well as reduced hot water wait times and space-cooling benefits.

Synergy #3: All-Electric "Zero-Energy" Configuration

An all-electric Zero Energy New Home concept could integrate photovoltaics with an all-electric space and water heating system. Intelligent design minimizing internal gains and solar gains could be combined with an integrated CREWH/heat pump water heater per Synergy #2. Space heating could be delivered with an air-to-water heat pump coupled with the RRDS.

6.2 Expected Program Impacts

Initial SWHDT Program work developed preliminary quantitative and qualitative performance targets for each of the four program elements. These targets were based on cost and performance estimates for each element at assumed market penetration levels.

Table 3 summarizes the initial savings estimates for assumed penetration ten years after completion of the SWHDT Program. With R&D work completed, it is difficult to evaluate the validity of our initial assumptions because market implementation still has not begun. Success in achieving the initial targets depends as much on establishing an appropriate manufacturing and marketing infrastructure as it does on R&D results. Response to the next challenge- bridging the "emerging technology chasm" will determine whether the R&D promise can be realized and benefits will be returned for California's investment.

Table 3 Preliminary SWHDT Program Savings Targets by Element

Element	Cooling Savings (GWh/Year)		Electric DHW Savings (GWh/Year)	
	New Homes	Existing	New Homes	Existing
CREWH	4.0	29.0	31.0	227.0
CRS	2.6	32.0	12.5	156.0
HWDS			7.6	10.5
RRDS	65.0		56.0	
Total	71.6	61.0	107.1	393.5

6.3 CREWH

CREWH development activities under the SWHDT program resulted in a well-packaged, low cost system, but preliminary performance fell short of project goals. In part the disappointing results can be attributed to design constraints that forced development activities away from the full "indoor heat pump water heater" CREWH design concept11. The simpler "kitchen only" CREWH water heating design developed in this project did not achieve the high savings levels originally projected. Based on monitored CREWH Prototype II performance, we estimate approximately 110 kWh/year of hot water savings for homes with an electric water heater and typical cooling energy savings of up to 200 kWh/year in the hottest regions of California. Design improvements discussed in the CREWH project final report should significantly improve the hot water savings potential of CREWH beyond this level. Further R&D with a committed manufacturer partner is needed to accurately determine the full savings potential of a market-ready CREWH design. Therefore, projecting ten-year CREWH savings is premature at this time given the lack of a market ready product.

6.4 CRS

The CRS was demonstrated in a prior PIER project. The SWHDT project demonstrated that the system did not pose any safety issues in dealing with potential contaminants. (The only source of concern was MTBE, which has since been phased out by the State of

11 The full water heating CREWH design now appearsto have been too ambitious for the available budget, time, and manufacturer commitment.

California.) In almost all applications, the CRS represents a lower cost alternative to conventional gravity fed condensate lines, therefore improving the economics of heat pump water heater installations. A fundamental problem is that residential HPWH's are not a mature technology. Currently national sales are on the order of one to two thousand units per year. California sales are minimal because of high electric rates relative to the cost of natural gas. Until the market grows, HPWH sales in California will remain low and equipment prices will remain high. As sales increase, HPWH cost effectiveness will improve and CRS will play a role in increased sales and the advent of indoor HPWH locations. Indoor locations are beneficial from two viewpoints: centralizing the water heater location, and providing additional space cooling in hot inland climates.

6.5 HWDS

The LabView model developed by ORNL has the potential to be an effective tool for designing optimal hot water distribution systems. Two key elements are needed before the full potential of the LabView model can be realized. First, precise laboratory and field test data are needed to characterize the heat loss performance of different piping materials in the full range of operating environments. These data are essential for model validation. Second, current plumbing practice must be documented in the field to determine what is most typically installed in new homes. PIER funding is being made available to complete both of these activities in support of the 2008 Title 24 Building Standards. The additional data will greatly improve the accuracy of the LabView tool and facilitate accurate savings projections.

6.6 RRDS

The Rapid Radiant Deployment System (RRDS) facilitates the installation of radiant floor systems in production homes by reducing installation costs and improving space conditioning energy efficiency. The RRDS project demonstrated that the field installation of prefabricated tubing/mesh arrays can be accomplished with no additional labor relative to the installation of standard slab reinforcing mesh. Cost projections suggest that in the current market the RRDS system with combined hydronic heating and two-stage evaporative cooling can be installed at $1200 cost premium in one-story homes and roughly $3300 in two-story homes. In a mature market scenario, installed costs are projected to be lower than for a standard HVAC installation. As with the CREWH, further technology demonstration is needed to improve the reliability of economic projections.

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GLOSSARY

BLOWER	An air moving device
CAPACITY	The amount of heat energy a device can add or remove in a certain amount of time. Evaporative cooler capacity only measures sensible cooling capacity.
COMBINED HYDRONIC	The application of a single heat source (e.g. boiler or high capacity water heater) to provide heat for both space heating and domestic hot water.
COMBINED REFRIGERATOR WATER HEATER (CREWH)	Concept combines a residential refrigerator with components allowing condenser waste heat to be used to preheat domestic hot water for use either in the kitchen or as a source of preheated water for the central water heater
CONDENSATE RECOVERY SYSTEM (CRS)	A system for capturing and disposing of heat pump water heater condensate that eliminates the need for a gravity feed condensate line
CPVC – Chlorinated Polyvinyl Chloride	Plastic compound used for production of high temperature (200°F) plumbing pipe and fittings
DRY BULB TEMPERATURE	A measure of the sensible temperature of air
EER – (Energy Efficiency Ratio)	The ratio of cooling capacity of an air conditioning unit in Btus per hour to the total electrical input in Watts under specified test conditions.
EFFECTIVENESS	a measure of the efficiency of how well an evaporative cooler can approach the outdoor wet bulb temperature
ENVELOPE	The construction components separating conditioned space from unconditioned space, including windows, walls, ceiling, and floors.
FORCED AIR	A space conditioning delivery system utilizing a blower and a duct system. In California, conventional forced air systems have a gas-fired furnace and a vapor compression cooling system.
HEAT EXCHANGER	A device that transfers heat from one medium to another
HPWH	Heat Pump Water Heater
HWDS	Hot Water Distribution System Project successfully developed a sophisticated analytical tool for evaluating energy, water waste, and wait time performance of alternative hot water distribution system design.

HYDRONIC RADIANT FLOOR	A heating system utilizing hot water circulated through floor tubing as a means of space heating.
INDIRECT EVAPORATIVE COOLER	A device that cools one airstream without moisture addition via heat exchange with a second airstream that is evaporatively cooled.
INDIRECT STAGE –	The indirect evaporative cooling section of a two-stage evaporative cooler
MANIFOLDS	A distribution device that feeds individual hydronic heating circuits from a single hot water supply line.
MICROPAS	An hourly building energy simulation model certified by the California Energy Commission to meet the Title 24 Energy Standards.
MTBE	Methyl Tertiary-Butyl Ether, a potentially harmful chemical compound that is manufactured by the chemical reaction of methanol and isobutylene. MTBE is produced in very large quantities (over 200,000 barrels per day in the U.S. in 1999) and is almost exclusively used as a fuel additive in motor gasoline.
NAECA	The National Appliance Energy Conservation Act. Passed in 1987, NAECA sets minimum efficiency levels for various appliances.
PEX	Cross-linked polyethylene. Commonly used for tubing in radiant floor applications and for potable water in domestic hot water systems.
PIER	Public Interest Energy Research program, sponsored by the California Energy Commission
RAPID RADIANT DEPLOYMENT SYSTEM (RRDS)	Project designed and demonstrated a lower cost hydronic radiant floor systems approach to facilitate increased penetration of radiant floor systems in production homes.
ROTATIONAL MOLDING	Production process that produces large hollow plastic parts with comparatively inexpensive tooling.
SEER (Seasonal Energy Efficiency Ratio)	The total cooling output of an air conditioning unit in Btus during its normal usage period for cooling divided by the total electrical energy input in watt-hours during the same period, as determined using specified federal test procedures
SWHDT PROGRAM	Synergistic Water Heating & Distribution Technologies, Califon\rnia Energy Commission PIER Contract No. 400-00-038, conducted by the Davis Energy Group (DEG)

TANKLESS HEATER	An instantaneous heater used to heat water for either domestic water heating, space heating, or both.
TWO-STAGE EVAPORATIVE COOLER	A device that combines an indirect evaporative cooling stage and a direct evaporative cooling stage in series.
VAPOR COMPRESSION COOLING SYSTEM	The conventional refrigerant and compressor-based mechanical system used for space cooling.

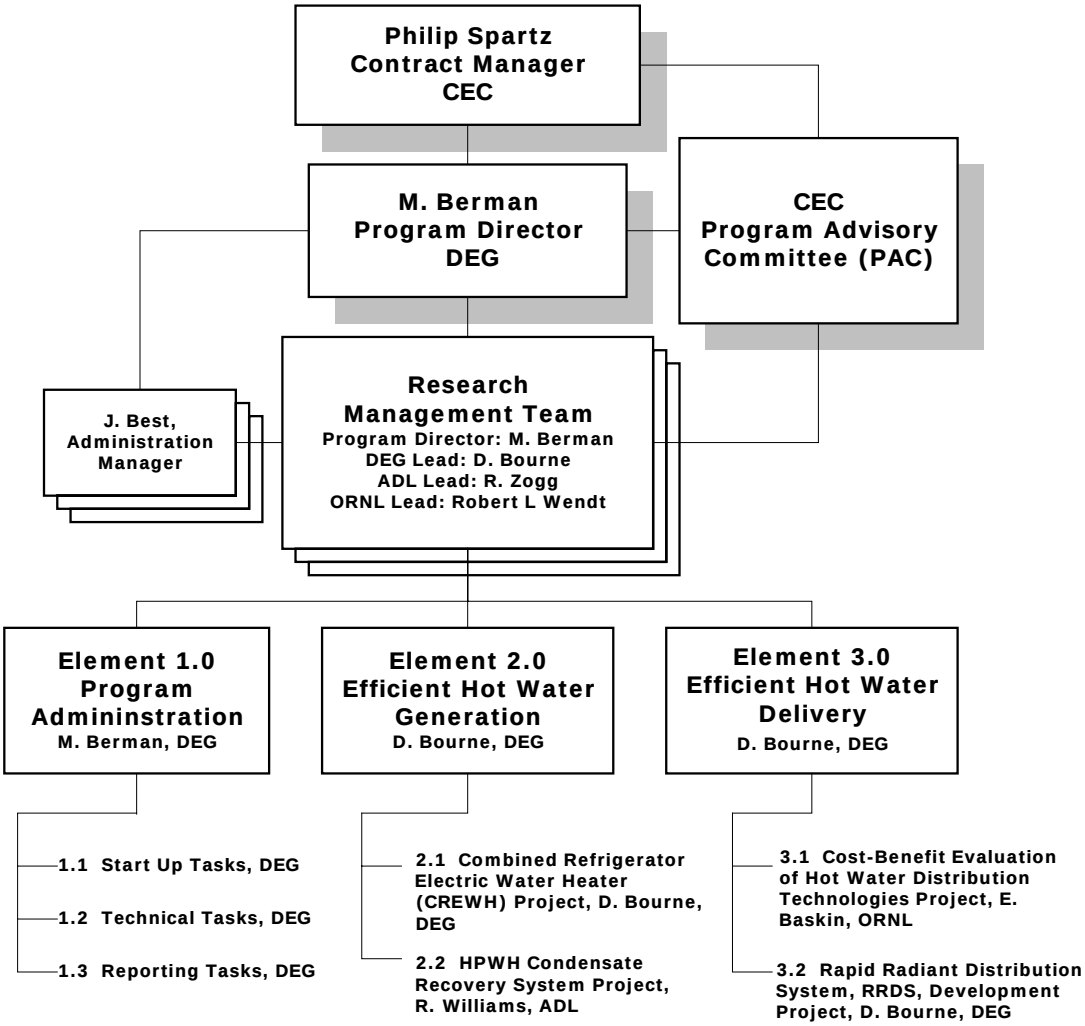
APPENDIX A: ADMINISTRATIVE SUMMARY

SWHDT PROGRAM ADMINISTRATION

SWHDT was initiated in June 2001 and will conclude in April 2005. $1,188,605 was committed to fund Program activities over the three year Program schedule. Funding consisted of $767,038 Energy Commission/PIER funds, plus $421,567 (35.5%) contractors' cost share. Approximate element budgets are $179,000, Administration (1.0); $673,000, Efficient Generation (2.0); and $337,000, Efficient Delivery (3.0).

SWHDT Program work was directed by prime contractor, Davis Energy Group, in concert with Energy Commission management and advisory committee (PAC) personnel. Key subcontractors include Oak Ridge National Laboratory, Oak Ridge, TN, A.D. Little Company (TIAX, LLC), Cambridge, MA., Maytag Corporation, Newton, IA, and IPEX, Inc., Ontario, Canada. The overall Program organizational structure and relationships between key personnel and organizations are shown in Figure A-1.

Figure A-1: SWHDT Program Organization Chart



Project Advisory Committees were established for each of the individual projects and played an important role in directing project activities. Consisting of volunteers with particular expertise in each project area, the participants are listed in Table A-1 below by project.

Table A-1: Project Advisory Committees and Members

CREWH PROJECT	
Steve Cooke	National Energy Technology Laboratory
Loralynn Perry	Nexant, Inc.
Ted Pope	Energy Solutions
Mark Rutheiser	Pyramid Construction
CONDENSATE RECOVERY SYSTEM	
Marshall Hunt	City of Davis
Ted Pope	Energy Solutions
Mark Rutheiser	Pyramid Construction
HOT WATER DISTRIBUTION STUDY	
Larry Acker	ACT, Inc. Metlund System
Tom Baker	Dynamic Plumbing Systems
David Johnston	What's Working
John Koeller	Koeller and Company
Jim Lutz	Lawrence Berkekely National Laboratory
Doug Mahone	Heschong Mahone Group
RAPID RADIANT SYSTEM	
Larry Drake	Radiant Panel Association
David Johnston	What's Working
Mike Luttrell	WarmFloors
Doug Mahone	Heschong Mahone Group
Randel Riedel	California Energy Commission
Bruce Vincent	Sacramento Municipal Utilities District

Table A-2 summarizes the SWHDT programs relationship to the PIER Buildings Program issues.

Table A-2: PIER Buildings Program Issues, Goals, and Objectives Addressed by SWHDT Elements

CEC Issue	Technical Goal	Objective	Element
Rapid energy consumption growth inland	Characterize issue and identify highest value future opportunities	Future program plans	
	Load reduction strategies	Reduce cooling energy use in new and existing buildings	2.1, 2.2 , 3.2
	Load management	Increase consumer load management choices	2.1, 2.2, 3.2
		Increase consumer options to shift load	2.1, 2.2, 3.2
		Energy-efficient design and construction strategies for distributed heating, cooling and generation.	
Non-energy benefits	Characterize issue and identify highest value future opportunities	Future program plans	3.1
	Quantitative metrics for non-energy benefits	Enable account for non-energy benefits	2.1
	Technologies that are energy-efficient and provide non-energy benefits	Increase functionality and use of energy-efficient products by integrating with non-energy considerations (reduced maintenance, increased comfort)	2.1, 3.1, 3.2
	Develop design methods	Increase functionality and use of energy-efficient products by integrating with non-energy considerations	
Public health and safety	Characterize issue and identify highest value future opportunities	Future program plans	
		Building features and construction practices for IAQ and moisture	
	Metrics, sensors, and controls for health, safety and energy	Enable mitigation of health and safety problems	
		Options for sensing and controlling moisture and IAQ	
	Improve energy efficiency and enhance health and safety	Ventilation and construction techniques that mitigate moisture and IA problems.	2.2
	Characterize issue and identify highest value future opportunities	Future program plans	3.1

CEC Issue	Technical Goal	Objective	Element
Building and housing affordability & value and state's economy	Software tools	Design and compliance tools for energy standards	
		Simulation software for CA to improve HVAC performance and design	
		Simplified design tools for CA climates	
	Increase building value	New innovations	2.2, 3.1, 3.2
		Highest value strategies and technologies for retrofit	2.2
		Strategies responsive to current construction practices (including metal framing)	
		Create downsized equipment for multi-family applications.	2.2
	Strategies and tools to verify performance and investment value	Tools for M&V (commissioning & diagnostic tools)	
		Tools to verify installation of insulation, envelope sealing, and duct sealing	
	System approaches that maximize value	Integrated, multi functionality equipment and appliances	2.1, 3.2
		Increase building functionality and decrease operating costs by design and construction for CA climates	3.1, 3.2
		Integration of energy-efficient strategies and products with other building elements	3.2

2.0. Program Approach

Task plans including task definitions, deliverables and schedules for each of the three program elements are tabulated below.

2.1 - Administration (tasks are divided into "Program Administration", "Start-Up", and "Meetings & Reporting" sub-sections).

Table A-3: Deliverables and Schedules (Administration Element)

Task Number			Planned Start - Complete Dates
1.0	**Program Administration**		
1.1	Attend Kick-Off Meeting	Kick-Off Meeting Documentation	6/26/01
1.1-1.2	**Start-Up Tasks**		
1.2.1	Public Presentation	PowerPoint Presentation	6/1 - 8/30/01
1.2.2	Program Software Standardization	Compliance	6/1 - 8/30/01
1.2.3	Finalize PAC	Members List, Documentation	6/1 - 8/30/01
1.2.4	Document Match Funding	Cash/In-kind Lists, Commitment Letters	6/1 - 8/30/01
1.2.5/6	Identify & Obtain Required Permits	Permit Plan	6/1 - 8/30/01
1.2.7/8	Establish & Maintain Website	Public Access & Password Sites	6/1 - 8/30/01
1.3-1.7	**Meetings & Reporting**		
1.3/4	CPR, PAC, PMT Meetings, Tech Briefings	Meeting Documentation	8/10/2001 - 4/30/04
1.5/6	Progress & Final Reports	Periodic Reports	8/10/2001 - 4/30/04
1.6.1	Final Report Outline	Final Report Outline for comment	12/1/03 - 12/31/03
1.6.2	Draft Final Report	Draft Final Report for comment	12/31/03 - 2/12/04
1.6.3	Final Report	Final Report	2/12/04 - 4/2/04
1.7	Final Meeting	Final Meeting	5/3/04

Table A-4: Deliverables & Schedules (Efficient Generation Technologies -CREWH & CRS)

Table 2. 3A – Efficient Delivery Technologies (Evaluation and RRDS Projects)

Task Number	Task Name	Deliverable(s)	Planned Start - Complete Dates
2.0	**Efficient Generation**		
2.1	**CREWH Development**		
2.1.1	Management/Administration		
2.1.2	Feasibility Study	Feasibility Report	7/3/01 - 4/26/02*
2.1.3	Fabricate & Test Prototype 1	Prototype 1 Report	4/3/02 - 11/1/02
2.1.4	Fabricate & Test Prototype 2	Prototype 2 Report	12/3/02 - 6/2/03
2.1.5	Analysis & Report	Final CREWH Report	7/2/03 - 10/1/03
2.1.6	Reports	Progress	
2.2	**Condensate Recovery System**		
2.2.1	Management/Administration		
2.2.2	Preliminary Hazard Analysis	Analysis Report	10/22/01 - 11/16/01
2.2.3.	Design Test Apparatus	Test Plan	11/19/01 - 12/28/01
2.2.4	Fabricate Prototype CRS, Test Apparatus	Fabrication Report	12/31/01 - 2/8/02
2.2.5	Tests and Analysis	Test and Analysis Report	2/11/02 - 6/28/02
2.2.6	Document and Recommend	Results Presentation & Report	7/1/02 - 8/9/02
2.2.7	Periodic Reports	Progress	

Table A-5: Deliverables & Schedules (Efficient Distribution Technologies (HWDS & RRDS)

Task Number	Task Name	Deliverable(s)	Planned Start - Complete Dates
3.0	**Efficient Generation**		
3.1	**Technology Evaluations**		
3.1.1	Management/Administration		
3.1.2	Evaluate New Systems	Interim Report (4/8/02)	10/1/01 - 7/29/02
3.1.3	Evaluate Existing Systems	Interim Report (4/8/02)	3/1/02 - 7/29/02
3.1.4	Impact Evaluation and Report	Final Simulation and Evaluation Report	5/1/02 - 10/7/02
3.1.5	Reports	Progress	
3.2	**RRDS Development**		
3.2.1	Management/Administration		
3.2.2	Develop Requirements and Concepts	Report	11/1/01 - 4/26/02
3.2.3	Product Design & Tooling	Report	3/5/02 - 6/3/02
3.2.4	Fabricate and Install Prototypes	Report	6/4/02 - 9/2/02
3.2.5	Production Readiness Plan	Report	7/8/02 - 11/4/02
3.2.6	Analysis and Final Report	Final Task Report	7/8/02 - 3/5/03
3.2.7	Reports	Progress	

3.0 Program Outcomes

Table A-6 tabulates completed tasks in the right-hand column titled “Actual Start – Complete Dates” and allows completion date comparisons to the original schedule. Schedule slippage

ultimately required the program completion date to be extended to June 30, 2005. Major factors contributing to slippage include CREWH and RRDS fabrication and testing delays due to relocating DEG's shop to a new location in Davis, delays in the RRDS prototype construction schedule, and delays in resolving CREWH refrigeration issues, as well as additional CREWH testing to evaluate supplemental resistance heating impacts.

As reflected in Program progress and deliverable technical reports, all scheduled and critical administrative and technical goals and objectives were achieved through the end of the program. DEG maintains the SWHDT Program public access and program management websites, accessible via a link on the DEG home page at www.davisenergy.comT. The site was regularly updated with periodic and technical reports including monthly progress report copies, technical reports, other meeting reports and briefings including Critical Progress Review (CPR), Program Advisory Committee (PAC), Program Management Team (PMT), and other proceedings.

Table A-6: Program Completion Status

Task Number	Task Name	Deliverable(s)	Planned Start – Complete Dates	Actual Start – Complete Dates
1.0	**Program Administration**			
1.1	Attend Kick-Off Meeting	Kick-Off Meeting Documentation	6/26/01	6/26/01
1.1-1.2	**Start-Up Tasks Subtotal**			
1.2.1	Public Presentation	PowerPoint Presentation	6/1 – 8/30/01	6/1 – 8/30/01
1.2.2	Program Software Standardization	Compliance	6/1 – 8/30/01	6/1 – 8/30/01
1.2.3	Finalize PAC	Members List, Documentation	6/1 – 8/30/01	6/1 – 8/30/01
1.2.4	Document Match Funding	Cash/In-kind Lists, Commitment Letters	6/1 – 8/30/01	6/1 – 8/30/01
1.2.5/6	Identify & Obtain Required Permits	Permit Plan	6/1 – 8/30/01	6/1 – 8/30/01
1.2.7/8	Establish & Maintain Website	Public Access & Password Sites	6/1 – 8/30/01	6/1 – 8/30/01
1.3-1.7	**Meetings & Reporting Subtotal**			
1.3/4	CPR, PAC, PMT Meetings, Tech Briefings	Meeting Documentation	8/10/01 – 4/30/04	8/10/01 – 4/30/05
1.5/6	Progress & Final Reports	Periodic Reports	8/10/2001 – 4/30/04	8/10/01 – 4/30/05
1.6.1	Final Report Outline	Final Report Outline for comment	12/1/03 – 12/31/03	- 3/1/05
1.6.2	Draft Final Report	Draft Final Report for comment	12/31/03 – 2/12/04	- 3/31/05
1.6.3	Final Report	Final Report	2/12/04 – 4/2/04	- 6/30/05
1.7	Final Meeting	Final Meeting	5/3/04	- 6/30/05

2.0-3.0	**Technical Tasks**			
2.1	**CREWH Development**			
2.1.1	Management/Administration			
2.1.2	Feasibility Study	Feasibility Report	7/3/01 – 4/26/02	7/3/01 – 5/31/02
2.1.3	Fabricate & Test Prototype 1	Prototype 1 Report	4/3/02 – 11/1/02	6/1/02 – 7/8/03
2.1.4	Fabricate & Test Prototype 2	Prototype 2 Report	8/7/02 – 611/04	7/8/03 – 1/31/05
2.1.5	Analysis & Report	Final CREWH Report	4/26/04 – 7/30/04	1/31/05 – 4/8/05
2.1.6	Reports	Monthly Progress		
2.2	**Condensate Recovery System Development**			
2.2.1	Management/Administration			
2.2.2	Preliminary Hazard Analysis	Analysis Report	10/22/01 – 11/16/01	10/22/01 – 11/21/01
2.2.3.	Design Test Apparatus	Test Plan	11/19/01 – 12/28/01	11/19/01 – 2/12/02
2.2.4	Fabricate Prototype CRS, Test	Fabrication Report	12/31/01 – 2/8/02	1/28/02 – 3/11/02
2.2.5	Tests and Analysis	Test and Analysis Report	2/11/02 – 6/28/02	3/11/02 – 5/9/02
2.2.6	Document and Recommend	Results Presentation & Report	7/1/02 – 8/9/02	5/9/02 – 12/19/02
2.2.7	Reports	Monthly Progress		
3.1	**Technology Evaluations**			
3.1.1	Management/Administration			
3.1.2	Evaluate New Systems	Interim Report (5/3/02)	10/1/01 – 7/29/02	(Interim – 5/3/02)
3.1.3	Evaluate Existing Systems	Interim Report (5/3/02)	3/1/02 – 7/29/02	(Interim – 5/3/02)
3.1.4	Impact Evaluation and Report	Final Evaluation Report	5/1/02 – 10/7/02	5/1/02 – 3/28/03
3.1.5	Reports	Monthly Progress		
3.2	**RRDS Development**			
3.2.1	Management/Administration			
3.2.2	Develop Requirements & Concepts	Report	11/1/01 - 4/26/02	11/1/01 - 5/23/02
3.2.3	Product Design & Tooling	Report	3/5/02 - 6/3/02	6/1/02 – 10/25/02
3.2.4	Fabricate and Install Prototypes	Report	6/4/02 - 9/2/02	11/1/02 - 7/3/03
3.2.5	Production Readiness Plan	Report	7/8/02 - 11/4/02	7/8/02 – 7/7/03
3.2.6	Analysis and Final Report	Final Task Report	7/8/02 - 3/5/05	7/8/02 – 4/8/05
3.2.7	Reports	Monthly Progress		

LIST OF ATTACHMENTS

Attachment Title	Description	Publication Number
Combined Refrigerator Electric Water Heater: Project Final Report	Describes CREWH project in detail.	A-1
Safety Analysis and Testing of a Heat Pump Water Heater Condensate Recovery System: Project Final Report	Describes CRS project in detail.	A-2
Evaluation of Residential Hot Water Distribution Systems by Numeric Simulation: Project Final Report	Describes Hot Water Distribution Systems project in detail.	A-3
Rapid Radiant Deployment System Development: Project Final Report	Describes the Rapid Radiant Deployment Systems project in detail.	A-4

CALIFORNIA
ENERGY
COMMISSION

Combined Refrigerator Electric Water Heater

Project Final Report

TECHNICAL REPORT

JULY 2005
CEC-500-2005-111-A1

Arnold Schwarzenegger, *Governor*

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Preface

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

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million 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
- Energy Systems Integration

What follows is an attachment to the final report for the Synergistic Water Heating and Distribution Technologies program, Contract Number 400-00-038, conducted by Davis Energy Group. This project contributes to the PIER Building End-Use Energy Efficiency program. This attachment, "Combined Refrigerator Electric Water Heater: Project Final Report" (Attachment 1), provides supplemental information to the program final report.

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.

DAVIS ENERGY GROUP
INCORPORATED

Combined Refrigerator Electric Water Heater Project Final Report

Issued:	**April 29, 2005**
Presented To:	**Chris Scruton** **California Energy Commission**
Contract:	**Energy Commission Contract No. 400-00-038**
Prepared By:	**Davis Energy Group, Inc.** **123 C Street** **Davis, CA 95616**

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APPENDICES

Appendix A: Refrigerator Efficiency Calculations
Appendix B: Prototype I Monitoring Plan
Appendix C: Focus Group Report

Executive Summary

Background

Residential refrigerators and domestic water heaters have traditionally been separate appliances but there is potential synergy in applying refrigerator heat output to domestic water heating loads. Davis Energy Group (DEG) has pursued the opportunities for a ***C***ombined ***R***efrigerator ***E***lectric ***W***ater ***H***eater (CREWH) since 1989. The CREWH concept integrates a water-cooled refrigerant condenser with hot water storage and applies the captured heat either to general hot water preheating or to kitchen hot water use points. Applying refrigerator heat output to reduce domestic water heating loads promises the following benefits:

- Reduced water heating energy use
- Reduced space cooling loads from refrigerator heat output
- Potential overall efficiency gain for refrigerator and water heating functions
- Reduced waiting time for kitchen hot water
- In new construction, possible elimination of hot water line to the kitchen

When Davis Energy Group (DEG) first began working on the CREWH concept, refrigerators were much less efficient than those built under current NAECA requirements. As efficiency has improved, less waste heat is available to offset water heating loads. Refrigerator efficiency improvements influenced the CREWH market direction pursued in this project.

Objectives

The overall project objective was to develop a cost-effective combined refrigerator electric water heater that can significantly reduce overall energy consumption in California homes by fully or partially heating domestic water with refrigerator discharge heat, simultaneously delivering "free" cooling to the kitchen. Specific objectives that define project tasks are to:

1. Complete a feasibility study that evaluates the "fit" between refrigerator heat output and water heating needs, develops and analyzes potential CREWH concepts and markets, and identifies a preferred CREWH strategy
2. Design, build, and lab test a first prototype unit
3. Develop, field install, and monitor a second prototype unit
4. Report project findings and potential CREWH impact

Approach

To start the project, DEG worked with subcontractors Oak Ridge National Laboratory and Maytag to develop design requirements for the proposed development tasks. DEG and ORNL completed a detailed feasibility assessment of the performance and operating cost impacts of alternate CREWH designs. Feasibility study results quantified projected water heating energy savings, energy impact due to changes in refrigeration system performance, and space conditioning impacts. Interest focused on the kitchen water heating application, rather than full house hot water pre-heating. Simulation results indicated that in hot California regions, the CREWH benefit to the homeowner for this application could exceed

$50 per year. At the conservatively estimated $440 incremental cost, paybacks might be acceptable, and Maytag felt that reduced hot water wait time could significantly improve market acceptance.

After the feasibility study, DEG designed and fabricated a proof-of-concept CREWH unit. This first prototype incorporated an external heat exchanger/hot water reservoir of large copper pipes. The prototype stored 6 gallons of hot water and showed 8-10% efficiency advantage relative to individual appliances. After prototype testing, DEG met with Maytag engineers at their Amana, Iowa production facility to discuss design directions for a second prototype. Maytag expressed three design objectives:

1. Incorporate CREWH components into existing the refrigerator enclosure
2. Maintain reliable operation through all test and field conditions
3. Minimize incremental cost

DEG then developed a low-cost storage and heat exchanger tank design that fits within the lower mechanical space in Maytag's existing refrigerator line. Building on prior rotational molding experience, DEG engineered a 9 gallon plastic tank with internal heat exchangers. The storage water serves as a thermal buffer, gaining heat during refrigerator operation and discharging heat as cold water flows through the heat exchanger toward the dishwasher or kitchen sink. The integrated design lowers incremental product cost.

Using another refrigerator supplied by Maytag, DEG fabricated and lab tested a second prototype. We monitored kitchen hot water use in an occupied house to document base case usage patterns before installing the second CREWH prototype. After monitoring CREWH field operation for nearly three months, we determined that performance might be improved by adding an internal tank electric heater and removing an automatic valve system used to select delivery between CREWH and direct hot water for the kitchen loads. This modification should improve performance and reduce costs. We fitted a third prototype with an internal heater and lab-tested this option. But late project results indicate that this design must be refined with careful integration of the tank, compressor, and heater before it can reliably and cost-effectively deliver all kitchen hot water from the refrigerator. In mid- 2004, Maytag substantially reduced their engineering work force and key Maytag personnel involved with the CREWH project departed. As a result, Maytag's interest level appears lower than it was early in the project.

DEG hired Energy Market Innovations, Inc. of Seattle to hold two focus group sessions to solicit preliminary market feedback on the CREWH technology. The first included builders and contractors, and the second session was for homebuyers. The builder group wanted known cost and reliability, quick installation and limited liability. Key homebuyer concerns were appearance, operation, and reliability. Neither group seemed likely to "pull" CREWH into the marketplace, but the builder group was willing to pre-plumb for CREWH. They noted that other systems for speeding kitchen hot water delivery are expensive. Homeowners wondered whether they could take a CREWH from one home to another.

Outcomes

1. Feasibility Study: The major outcome was the selection of a preferred CREWH design strategy that applies refrigerator heat output to kitchen loads, thereby reducing waiting time for hot water at the kitchen sink.
2. First Prototype: The major outcome was the successful lab testing of a first prototype that was more efficient than a base case refrigerator and standard water heater.
3. Second Prototype: The major outcome was demonstration of a second CREWH system fully integrated within the conventional refrigerator, installed and working at a field test site.
4. The major outcome is this report which concludes that the CREWH concept still has great promise but needs greater manufacturer involvement to achieve commercial success.

Conclusions

This project has demonstrated that a functional combined refrigerator/water heater can be built that is virtually identical in both external and internal appearance to a conventional refrigerator. Initial test results indicate that the design can operate successfully through expected operating conditions, and can potentially eliminate the cost and energy losses associated with the kitchen hot water line. The energy value of this device varies with climate and load patterns, but in typical California valley applications this "kitchen only" CREWH can potentially reduce net monthly costs when included in a typical mortgage.

The CREWH faces market barriers as both builders and homebuyers are reluctant to adopt new technologies. But despite these barriers there is a substantial need for new energy efficient products. For example, DOE's Building America program seeks 50% energy savings for new homes by 2010. CREWH offers an opportunity for a manufacturer to gain a competitive advantage that responds to societal needs and saves homeowners money. An alternative CREWH design aimed at the multi-family market may offer even more advantages than the "kitchen load" CREWH. But this design was not the focus of this project, and should be pursued as a separate venture.

In this project we did not achieve the major CREWH performance goal of delivering the majority of hot water to the kitchen from refrigerator heat output. CREWH heat delivery to its internal storage tank was lower than desired for two reasons that can be resolved with further work. But a working CREWH R&D team must be re-assembled if the work begun in this project is to continue.

Recommendations

Sequential market and technical research elements appear necessary to advance CREWH technology into the marketplace. We focus the following recommendations on the near-term opportunity for a "kitchen-only" CREWH.

1. Market Element: Complete a detailed market and economics study to assess how many homes have kitchens relatively far from the water heater, and compare costs and energy impacts of CREWH and other available measures that reduce kitchen hot

water wait times. If the study finds a large CREWH market, re-establish manufacturer involvement in the project.

2. Research Element: After completing the recommended market element, work with the participating manufacturer to design and build a CREWH "production prototype." Develop a "ground up" undercarriage for standard refrigerators that fully integrates the tank, compressor, heat exchanger, and tank emergency cooling system for optimal performance. Sequentially complete lab and field tests, and evaluate economics and market impacts.

Abstract

The ***C***ombined ***R***efrigerator ***E***lectric ***W***ater ***H***eater (CREWH) concept applies refrigerator heat output to domestic hot water loads. Potential benefits include reduced water heating energy use and space cooling loads, efficiency gains, faster hot water to the kitchen, and elimination of the kitchen hot water line. In this PIER-supported project, DEG and partners Maytag and Oak Ridge National Laboratory completed the following tasks:

- Evaluation of alternative CREWH configurations and the performance impact of climate and load variations
- Development and testing of a "proof-of-concept" prototype
- Design, fabrication, lab testing, and field testing of an "integrated prototype"
- Focus groups to assess market issues
- Preparation of a final report

Initial prototype results demonstrated an 8-9% advantage relative to the performance of a separate water heater and refrigerator. The integrated prototype design repackaged hardware to reduce system cost and to achieve a more production-ready configuration. Prototype II field testing demonstrated reliable operation but did not achieve the key performance goal of providing the majority of kitchen hot water from the CREWH. CREWH heat delivery was lower than expected for two reasons that can be resolved with further effort, provided a working CREWH R&D team can be re-assembled. Maytag, which has lost their key employees who participated in the CREWH project, or another major manufacturer must be an active participant in future work for the CREWH technology to achieve market success.

1. TECHNOLOGY BACKGROUND

Current residential refrigerators and water heaters are separate appliances. Refrigerators are removable, plug-in units that typically are owned by the occupants in single-family homes and by the landlord in multi-family residences. In many single-family homes with large refrigerators, the units are less portable than formerly because they are plumbed for icemakers and "through-the-door" water dispensers. New refrigerators must comply with Federal Appliance Standards and typically consume 400 to 800 kWh annually. Units sold before the Federal Appliance Standards were implemented in 1993 may consume 1500 to 3000 kWh/year. In heating-dominated climates, refrigerator waste heat reduces space-heating loads, but with the equivalent of resistance electric heat which is typically much more expensive than heat supplied by gas furnaces or electric heat pumps. In cooling season, refrigerators add heat in the kitchen and thus increase cooling costs.

Water heaters are permanently installed in locations that vary with type. Gas and propane water heaters represent nearly 90% of the California stock and are usually located in garages or outdoor closets for combustion air access. Electric resistance and heat pump water heaters may be located indoors, but heat pump units are usually located in garages because they extract heat from their surroundings, and must discharge condensed water from their evaporator coils. Typical water heater life is 8 to 15 years. Most residential water heaters heat an average of 25 to 70 gallons per day. Water heating loads vary widely by day and household, from near zero on vacation days to more than 100 gallons on "big wash days." Typical annual efficiencies for new storage-type water heaters are 57 to 63% for gas-fired units and 87 to 92% for electric resistance units. At current energy costs gas water heaters have much lower operating costs in comparison with electric resistance units.

Reclaiming refrigerator heat could reduce household water heating energy use. Pre-1993 refrigerators discharged enough heat to satisfy 30 to 35 gallons of hot water use per day, vs. about 15 gallons per day for new refrigerators. Applying refrigerator heat output to domestic hot water loads has the following potential benefits:

- Reduced water heating energy use
- Reduced space cooling loads from refrigerator heat output
- Potential overall efficiency gain for refrigerator and water heating functions
- Reduced waiting time for kitchen hot water
- In new construction, possible elimination of hot water line to the kitchen

DEG began developing a combined refrigerator electric water heater (CREWH) in 1989, and secured R&D funding from Southern California Edison Company for further development of the concept in 1991. In the Edison funded project we developed analytical studies showing that for a typical gas-heated California home, a CREWH unit could reduce annual gas use by almost 50% while increasing annual electric use by over 500 kWh, generating a $66 net annual cost savings. The analyses also concluded that the unit would generate 48% source energy savings compared to a "refrigerator plus gas

water heater" base case. DEG modified a new refrigerator to heat domestic water stored in a detached storage tank, and completed lab tests verifying CREWH promise.

In 1992, DEG designed a more advanced CREWH for the PG&E's Advanced Customer Technology Test (ACT^2). We modified a standard refrigerator, adding a top-mount storage tank, and installed the unit in the Davis ACT2 house. Since the project included a high efficiency condensing water heater, the CREWH, used in a preheating mode, was not found to be cost-effective. Nonetheless, the project demonstrated an integral design that could, with addition of an auxiliary heating cycle, eliminate the conventional water heater and achieve the previously defined CREWH potential.

Since the ACT^2 project, the Oak Ridge National Laboratory (ORNL) has also initiated a refrigerator water heater project. ORNL has modified a conventional refrigerator, demonstrated its performance in a heat pump water-heating mode, and developed controls that select alternate operating modes. This CREWH project funded under the Synergistic Water Heating and Distribution Technologies project has extended prior research by pooling the resources of the two organizations with the most prior CREWH experience, and by bringing a manufacturer into the effort.

2. PROJECT ORGANIZATION

This research effort was led by Davis Energy Group, Inc (DEG), with support from ORNL and Maytag, a major refrigerator manufacturer. ORNL provided continuing advice, and simulation expertise in the feasibility studies. Technical staff from Maytag's Advanced Engineering Group, led by group manager Ron Anderson helped guide product design and provided both technical support and hardware for prototyping.

A Project Advisory Committee (PAC) provided project guidance and reviews of project progress. We held PAC phone calls at regular intervals during the project. Members of the PAC included:

- Steve Cooke, project manager with National Energy Technology Laboratory
- Loralyn Perry, energy efficiency program manager with Nexant
- Ted Pope, energy efficiency program manager with Energy Solutions
- Mark Rutheiser, building construction professional with Pyramid Construction

This report documents the entire CREWH development effort funded under the SWHDT program, summarizing prior project deliverables and focusing on the design, testing, and "next steps" for the second CREWH prototype.

Prior project reports are listed below:

CREWH Feasibility Report, July 24, 2002
CREWH Prototype I Performance Assessment Project Report, July 8, 2003

3. PROJECT OBJECTIVES

The overall project objective was to develop a cost-effective combined refrigerator electric water heater (CREWH) that can significantly reduce overall energy consumption in California homes by fully or partially heating domestic water with refrigerator discharge heat, simultaneously delivering "free" cooling to the kitchen. Specific objectives that define project tasks are to:

1. Complete a feasibility study that evaluates the "fit" between refrigerator heat output and water heating needs, develops and analyzes potential CREWH concepts and markets, and identifies a preferred CREWH strategy
2. Design, build, and lab test a first prototype unit
3. Develop, field install, and monitor a second prototype unit
4. Report project findings and potential CREWH impact

4. SELECTION OF PREFERRED CREWH CONFIGURATION

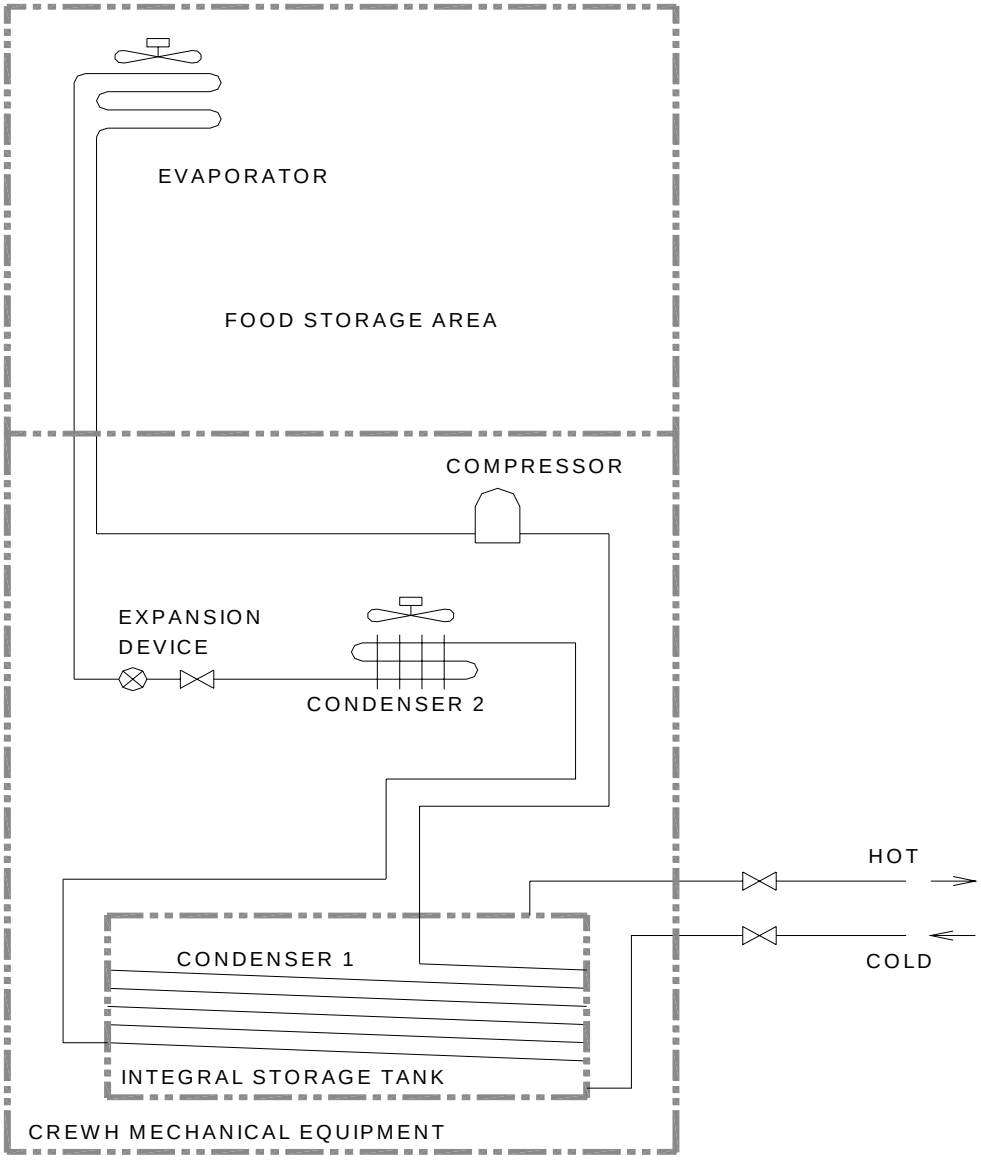
Our July 2002 feasibility study ("Combined Refrigerator Water Heater Feasibility Report") used simulations to evaluate alternate CREWH design configurations. We used a TRNSYS simulation to analyze various CREWH options under a range of hot water load scenarios, climates, and CREWH storage volumes. We interpolated compressor performance tables to model a refrigerant-to-water heat exchanger under varying environment conditions. Oak Ridge National Laboratory (ORNL) ran the simulations to assess which of three CREWH configurations generated the most favorable economics. The three configurations are briefly described below:

> Configuration 1a: A combined refrigerator and heat pump water heater designed to supply all household hot water needs
>
> Configuration 2a: CREWH with an external hot water storage tank and circulating pump, designed to heat water only when the compressor operates to cool refrigerator compartments
>
> Configuration 2b: The same as configuration 2a, except that the hot water storage tank is integral to the CREWH and no pump is needed to move water from the CREWH to the storage tank.

Feasibility study analyses indicated the "2b" CREWH configuration with an integral 15-gallon storage tank resulted in the most favorable economics. Projected savings ranged from $25 to $70 per year based on several factors including climate, hot water load, and distance from kitchen to water heater. Not modeled in the economics was the value of faster hot water delivery to the kitchen fixtures, reducing customer inconvenience due to long hot water wait times.

Figure 1 shows the "2b" configuration with a wrap-around tank heat exchanger in series with the air-cooled condenser[1]. Storage volume is a critical factor affecting performance, as larger volumes maximize the storage of refrigerator heat output without overheating the water volume and compromising refrigerator performance. But larger storage volume increases tank costs, complicates integration with the refrigerator, and reduces the average stored hot water temperature. Thus, optimizing storage volume is a key CREWH design objective.

Figure 1: Preferred CREWH Configuration



[1] A double-walled immersed heat exchanger is also a viable 2b configuration.

After the feasibility study, DEG consulted with ORNL and Maytag to determine key constraints affecting the design of the first prototype. Maytag indicated two paramount concerns: First, the CREWH must maintain refrigeration performance comparable to a standard refrigerator, and secondly, integration of CREWH components should not affect the external dimensions of the refrigerator (especially depth and width). In other words, integrating the storage tank and heat exchanger could change internal "cold space" volumes, but not exterior dimensions. Given these parameters, DEG and ORNL re-evaluated tank sizing to assess the impact of smaller storage tank volumes. Storage volumes ranging from 3 to 10 gallons were analyzed. Results indicated diminishing CREWH returns as the storage volume shrinks due to greater reliance on the air-cooled condenser for discharging excess heat. We identified a six-gallon optimal storage volume based on simulation results and the space constraints for the refrigerator selected by Maytag.

5. PROTOTYPE I CONFIGURATION, DESIGN, AND TESTING

We began the CREWH Prototype I design process with a review of heat exchanger design options. The following three options were considered:

1. A pressurized tank with wrap-around heat exchanger
2. A counterflow heat exchanger design with refrigerant tubing thermally bonded directly to the pressurized load-side copper pipe heat exchanger, and
3. A rotationally molded, non-pressurized tank with immersed copper piping for potable water

Since Prototype I development work was largely proof-of-concept, we chose configuration #2 for its simplicity in fabrication. We designed the Prototype I heat exchanger to fit on the back of the selected refrigerator, and fabricated it from nine- four foot tall, 2" copper pipes with a total storage volume of 6 gallons. The water flow path through the heat exchanger was a series configuration with cold water entering at one end and hot water exiting the other end. We brazed thirty-two feet of 3/16" refrigeration tubing in the valleys formed by adjacent 2" pipes, thereby providing good thermal contact between the refrigerant tubing and the storage pipes. We insulated the heat exchanger with an R-4 water heater blanket[2].

Figure 2 shows the completed prototype heat exchanger and Figure 3 is a schematic showing how the heat exchanger integrates with the refrigerator and the air-cooled condenser. The CREWH heat exchanger was placed upstream of the conventional air-cooled condenser where it could serve as the primary point of heat rejection[3]. We placed a solenoid valve at the air-cooled condenser inlet to allow it to be bypassed when desired. The valve was controlled by one of the two dataloggers used for monitoring. Hot water

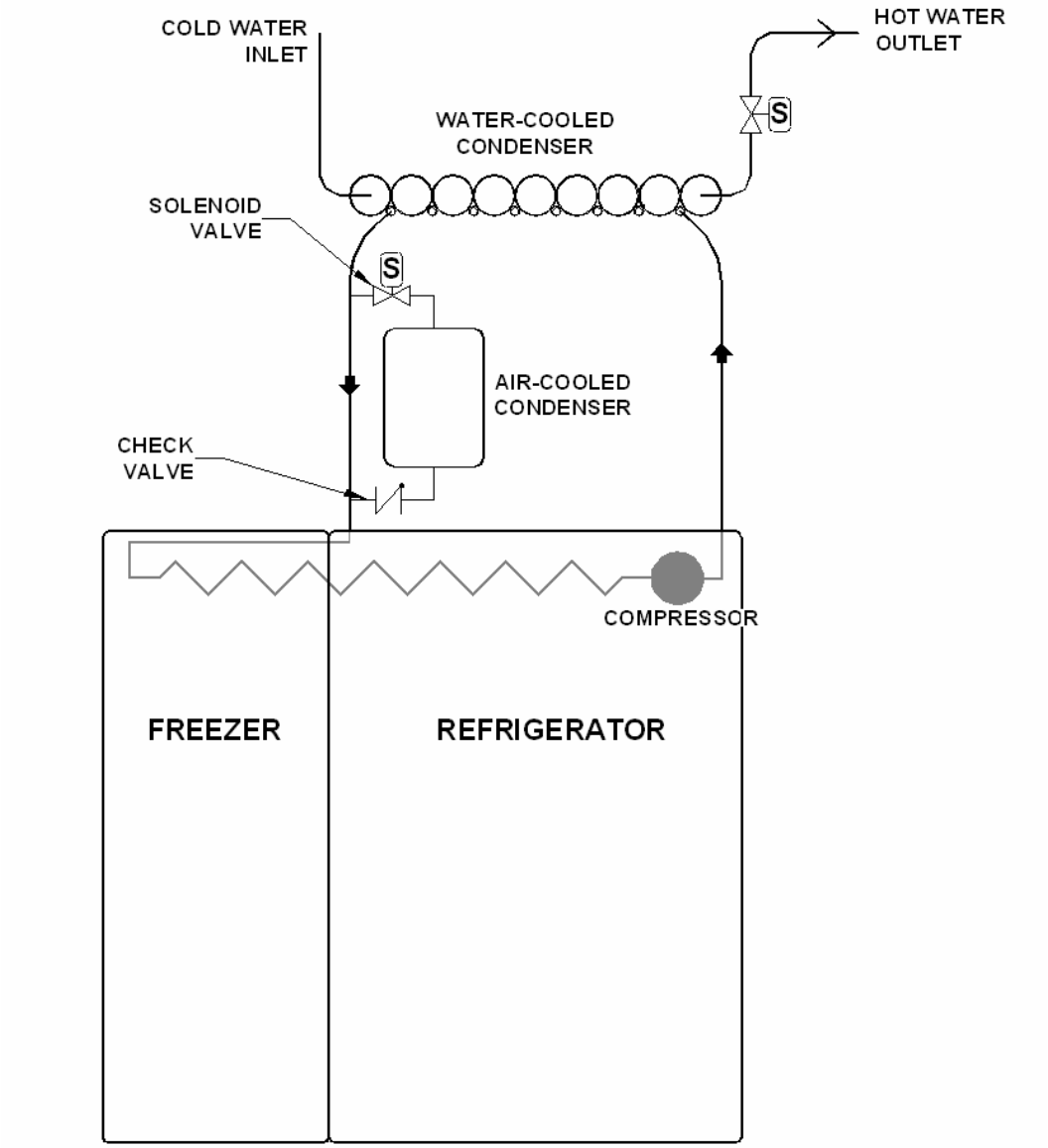
[2] Figure 3 shows the stand that supports the CREWH heat exchanger. The heat exchanger supports compromised the insulation of the assembly, increasing storage losses.
[3] The air-cooled condenser was included for prototype field testing to prevent over-heating of the water-cooled condenser during extended vacation periods when there would be no hot water draws.

draw use patterns representative of typical kitchen use were scheduled using the data logger.

Maytag provided a 27 ft^3 MSD2754 side-by-side refrigerator for our first CREWH prototype. This unit was one of Maytag's highest energy consumers in this size range (rated at 740 kWh per year relative to the current standard of 747 kWh per year), and thus was a prime CREWH candidate due to its substantial heat output.

Figure 2: Prototype I CREWH Heat Exchanger

Figure 3: Plan View of Prototype I CREWH Configuration



5.1. Prototype I Monitoring and Evaluation Approach

The primary goals of the Prototype I monitoring were to:

- obtain comparative performance data on the standard refrigerator before and after CREWH modification
- demonstrate concept feasibility
- generate performance results useful for design of a "production prototype" unit.

Since the CREWH is a combined appliance, a combined system efficiency calculation is needed to account for both refrigeration and water heating performance. This calculation neglects space conditioning impacts, which can only be evaluated with full-year "whole house" simulations. The three equations below present the overall efficiency calculation for a base case refrigerator and natural gas water heater. For the CREWH, the calculation is more complicated since a portion of the water heating load is met by the CREWH, which alters the seasonal efficiency of the water heater in meeting the remaining load. Appendix A documents these calculations in detail, including calculations for systems with electric resistance water heating.

Equation 1: Refrigerator Efficiency

$$Eff_R = \frac{Q_{daily,cooling}}{Watts_{Refr,daily}} \quad \text{(units of Btu/Watt)}$$

Equation 2: DHW Efficiency

$$Eff_{DHW} = \frac{Q_{daily}, DHW_{output}}{Q_{daily}, DHW_{input}} \quad \text{(units of Btu/Btu)}$$

Equation 3: Combined Efficiency

$$Eff_T = \frac{(Q_{daily,\ cooling} + Q_{daily,}\ DHW_{output})}{(Watts_{Refr,daily} + (Q_{daily,}\ DHW_{input} / 3.413))} \quad \text{(units of Btu/Watt)}$$

where, Eff_R = refrigerator efficiency
Eff_{DHW} = water heating efficiency
Eff_T = total efficiency

We first monitored the unmodified refrigerator at our test lab to document base case energy use. We fabricated a 4' x 4' x 8' tall insulated enclosure that allowed control of ambient conditions surrounding the refrigerator. Small heaters and fans were controlled in stages by one of the dataloggers to maintain ± 2ºF temperature uniformity within the chamber. We ran tests under a range of ambient temperatures to assess performance, based on a monitoring plan included in Appendix B. Key monitoring points included:

- Refrigerator and freezer temperatures
- Refrigeration circuit temperatures including compressor discharge, suction line, and multiple evaporator and condenser locations
- Chamber and ambient temperatures
- CREWH heat exchanger water inlet, outlet, and midpoint temperatures
- Water flow rates
- Compressor and total refrigerator power

We collected data on 1-minute intervals during refrigeration system operation. During the scheduled hot water draws, we collected data on 10-second intervals to facilitate water-side energy flow calculations per Equation 4.

Equation 4: $\text{Btu} = 8.33\ \text{Btu/gal-}^{o}\text{F} * \text{GAL} * (T_{hot} - T_{cold})$

Where,

Btu = energy flow during 10 second interval
GAL = flow (in gallons) during 10 second interval
T_{hot} = water temperature exiting CREWH heat exchanger
T_{cold} = water temperature entering CREWH heat exchanger

5.2 Prototype I Test Results

We completed testing of the unmodified refrigerator after receiving the unit from Maytag. We ran tests at several average chamber temperatures, but only report here the 75ºF ambient case. Typical refrigerator and freezers temperatures were dialed in and verified at 37ºF and 0ºF, respectively. Results showed an average usage of 2.15 kWh/day and a compressor duty cycle of about 46%. Defrost cycles were found to occur at 17-18 hour intervals.

Other key data:

- Average refrigerator demand during full-load operation of 173 Watts.
- Average compressor discharge line temperature of 119ºF.
- Average condenser mid-point temperature of 90ºF.
- Average evaporator mid-point temperature of –18ºF.

After completing the CREWH modifications (see Figure 4), we operated the system for several days to assess the refrigerant charge. Early CREWH performance was somewhat erratic, primarily due to the inability of the capillary tube metering device to handle the fluctuations in refrigerant flow that occurred through the range of storage water temperatures that were accompanied by up to 50ºF ranges in condensing temperature.

In final tests (summarized in Table 1) we used our best estimate of 11.7 gallons per day for typical daily kitchen water heating loads. We ran tests both with and without

compressor insulation added to direct more heat to the CREWH heat exchanger. Key results were:

- Average daily refrigerator energy use was lower (5% and 13%) for both CREWH cases than for the baseline monitoring. Compressor duty cycles and average compressor demand were also slightly lower for the CREWH.
- Insulating the compressor raised the compressor "top of shell" temperature, the average CREWH storage and discharge water temperatures, daily energy use, and average compressor runtime (although still lower than the base case result).
- Maximum compressor "top of shell" temperatures approached 200ºF. Embraco, the compressor manufacturer, advised that maximum discharge temperatures should not exceed 240ºF.
- Insulation on the compressor resulted in higher CREWH water temperatures, although daily energy delivered did not increase since cold water inlet temperatures were higher during the "insulated" compressor test.
- Freezer temperatures were slightly higher than baseline monitoring, despite the fact that the internal control settings were not modified.

Table 1: Summary of Prototype I Base Case and CREWH Operating Data

	Base Case	w/o shell Insulation	With Shell Insulation
Avg Chamber temperature (ºF)	75.2	75.2	76.9
Refrigerator energy use (kWh/day)	2.15	1.88	2.04
Avg Compressor demand (Watts)	173	161	164
Avg Refrigerator temperature (ºF)	39.2	39.2	39.8
Avg Freezer temperature (ºF)	-0.2	4.2	5.3
Avg Evaporator temperature (ºF)	-18.0	-12.7	-12.0
Avg Compressor shell temp (ºF)	Not measured	123.0 (max 150)	157.2 (max 195)
Compressor duty cycle (%)	46%	39%	42%
Avg CREWH storage temp (ºF)	--	104.4	112.8
Avg CREWH discharge temp (ºF)	--	107.3	118.0
Avg CREWH heat delivered (Btu/day)*	--	3,213	3,172

* cold water inlet temperature = 73.0ºF (w/o insulation) and 79.1ºF (with insulation)

Table 2 summarizes results from the overall efficiency calculation procedure outlined in Appendix A. These results are based on the "without insulation" results shown in Table 1 and do not account for the space conditioning benefits that CREWH provides in most California climates. Table 2 results include preliminary calculations including the water heater average efficiency or "Energy Factor." For a "typical" 64 gallon per day load, the CREWH is projected to meet approximately 8% of the load. With a reduced load on the

central water heater, the efficiency of the water heater is slightly lower[4]. Overall "combined" Energy Factors are reported in the column to the right in Table 2.

Table 2: Prototype I Overall Efficiency Calculation Results

	Refrigerator Case Load (Btu/day)	Refrigerator Energy Use (kWh/day)	CREWH DHW Contribution (Btu/day)	Overall Energy Factor
Gas DHW				
Base	6,650	2.15	0	0.607
CREWH	6,650	1.88	3,213	0.657
Electric				
Base	6,650	2.15	0	0.909
CREWH	6,650	1.88	3,213	0.992

"*" sum of refrigerator case load and daily water heater recovery load

5.3 Prototype I Conclusions

Prototype I test results were encouraging from a "proof of concept" perspective. The prototype provided reliable refrigeration operation while consuming less energy than the unmodified refrigerator. Maytag was sufficiently interested in these initial results to remain an active part of the design team for the second prototype.

Heat delivered from the CREWH heat exchanger (equal to 5+ gallons per day at a 75ºF temperature rise) was less than originally anticipated, primarily due to higher storage losses from the heat exchanger. Although the daily heat extraction should increase with better tank and compressor insulation, a more efficient refrigerator would have less available heat output. Prototype I results suggested the need for a CREWH supply water valve package to optimize hot water delivery and allow direct hot water supply to kitchen use points under some conditions. Optimal CREWH operation balances condenser performance (cooler is better) with hot water needs (hotter is better). We designed a valve system to regulate the flows of water from the CREWH and the hot supply line based on relative water temperatures.

As reported in Table 2, the overall CREWH "energy factor" was 8 to 9% higher than for a baseline refrigerator and central water heater. Our goal for the second prototype was to improve on this efficiency advantage and to package the CREWH components efficiently from a space perspective, while minimizing anticipated production costs.

[4] This is due to the water heater operating in standby mode for slightly more time than the base case. The impact on Energy Factor was calculated using the algorithms currently in place in the California Residential Title 24 Water Heating Methodology.

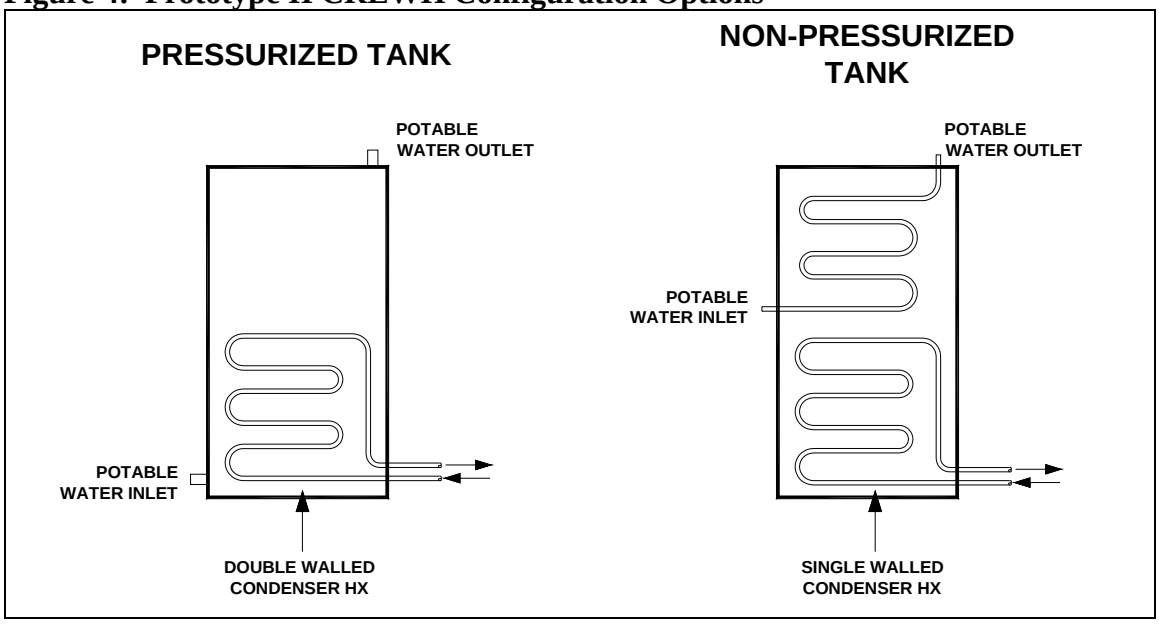
6. PROTOTYPE II CONFIGURATION, DESIGN, AND TESTING

6.1 Design Review

Favorable results to the Phase I design and testing process convinced the design team that a market viable second prototype could be developed. The key effort in developing a Prototype II design was to effectively package the CREWH heat exchanger/storage tank with the refrigerator. The Prototype I design, although demonstrating a performance advantage, was not an approach that could be inexpensively manufactured or easily integrated with existing refrigerator designs.

We evaluated the available options for integrating storage with an existing refrigerator. The first option was a pressurized tank (potable water) with either an immersed double wall refrigerant heat exchanger or a wrap around heat exchanger. The second option was a non-pressurized tank (non-potable water) containing both a refrigerant-to-water heat exchanger and a load-side heat exchanger for heating potable water. In this configuration, the tank water serves as a captive heat transfer medium. The refrigerant-to-water heat exchanger delivers heat to the storage water and the immersed load side heat exchanger extracts heat from the tank. Figure 4 shows the two tank configurations.

Figure 4: Prototype II CREWH Configuration Options



We chose the non-pressurized approach because it allowed a low cost, complex storage shape that could be incorporated into available space in the refrigerator's mechanical compartment. Rotational molding can produce large hollow plastic parts at approximately $2.50 per pound of plastic and with comparatively inexpensive tooling. This space-optimizing approach offered additional storage volume relative to a cylindrical pressurized tank. In rotational molding, powdered plastic resin is poured into a clamshell-type two part mold. The mold is then moved into an oven operating at about

600° F and rotated on two axes so that the plastic resin cascades across all of the interior surfaces of the mold. During the oven cycle, the plastic sticks to the mold walls and builds in thickness until all of the resin is consumed. The mold then leaves the oven and continues to rotate as the part cools. A vent tube through the mold wall ensures that pressures do not build up as the mold is heated, as well as avoiding a vacuum as the part cools. For this reason, there is very little pressure on the mold. Unlike thermoforming and blow-molding which transform an sheet or plug of plastic into a final shape, there are no residual stresses in roto-molded parts.

Roto-molded parts have generally uniform wall thicknesses, with external corners tending to be thicker and internal corners tending to be thinner. Material selection is relatively limited, and most roto-molded parts are of polyethylene. Because the typical roto-molding cycle is about 30-45 minutes long, each mold can produce only about 10,000 parts per year. For high volume products, multiple molds are used to increase yield and, depending on the size of the oven, many molds can be run at the same time. However, many roto-molded products migrate to blow-molding as annual volumes reach 10,000 to 100,000. The high internal pressures of blow-molding require expensive molds but can produce parts with cycle times on the order of seconds rather than minutes. Blow-molding the CREWH tank would be difficult because of the internal copper heat exchanger.

With this preferred tank design concept identified, Davis Energy Group met with Maytag engineers at their Amana, Iowa facility in July 2003. Maytag representatives included the Manager of Advanced Engineering (AE), two engineers from the AE department, and the Manager of Side-by-Side Structures. Discussions subjects included:

- Prototype I results
- The roto-molded tank fabrication process
- Alternative heat exchanger design options
- CREWH water valving design
- The Maytag product development perspective on technical and marketing issues
- Prototype II fabrication and component procurement issues
- Refrigerator selection for Prototype II

The meeting was productive and provided a solid basis for Prototype II design. The consensus goal of Prototype II design was to develop and implement a production-ready concept that integrated components offering reliable operation, good performance, and low incremental cost. Maytag agreed to provide two bottom-freezer refrigerators for Prototype II development. In addition, Maytag would provide design review and technical assistance to DEG.

After the meeting, we selected a model ARB2557CW refrigerator for second prototype development. Based on its annual kWh rating, this 25 ft^3 unit is 34% more efficient than the 27 ft^3 Prototype I unit, resulting in lower heat rejection capability. The selected model has the following performance characteristics at the standard refrigerator rating condition:

- 270 Btu/hour case load (cooling effect)
- 1.40 kWh/day ± 0.4 (511 kWh/year)
- Compressor duty cycle 45% ± 10%

6.2 Design Process

The major goals of the design process were to:

- Design a storage tank with integral condenser and load side heat exchanger that would fit within the mechanical compartment of the selected refrigerator.
- Develop and evaluate a valve system and logic to maximize kitchen hot water supplied from the CREWH, and minimize the wait time for hot water from the primary water heater.

Storage tank design. DEG's decision to pursue the rotationally molded tank design followed from several considerations. First, DEG has designed several rotationally molded products, and we have pioneered methods for "roto-molding" water-tight parts with internal heat exchangers. Second, rotational molding also facilitates the production of very complex parts with thin walls that can be strengthened with molded-in corrugations. Third, we felt that the finished appearance and ease with which the roto-molded part could be produced would be an asset to our manufacturing partner.

We took several considerations into account as we developed the tank design:

- Tank volume
- Depth and width of strengthening corrugations
- Airflow path for heat rejection from the tank surface
- Location of integral condensate reservoir
- Condenser and valving location relative to the tank
- Location of heat exchanger supports and tank penetrations

Due to heat exchanger penalties we increased our desired storage volume to 9 gallons, and secured Maytag's approval to achieve this target by raising the height of the refrigerator one inch. After completing the tank design we procured a custom mold from the Lakeland Mold Company in Brainerd, Minnesota. The mold was designed to accommodate the copper heat exchanger, which is placed in the mold at the start of the cycle along with the plastic resin. The resulting part has watertight seals at the copper/plastic interface. This process was first developed by Davis Energy Group and Scribner Plastics of Rancho Cordova, California for use in DEG's SunCache solar water heater. Scribner molded the CREWH prototype tanks.

The CREWH tank was roto-molded from a grade of polyethylene (PE) made by A. Schulman known as SuperLinear. This material has the greatest strength, stiffness and high-temperature performance of any roto-molding grade of polyethylene. Other PE grades, such as linear low density polyethylene or high density polyethylene could be interchanged with SuperLinear to reduce cost, pending the outcome of high temperature

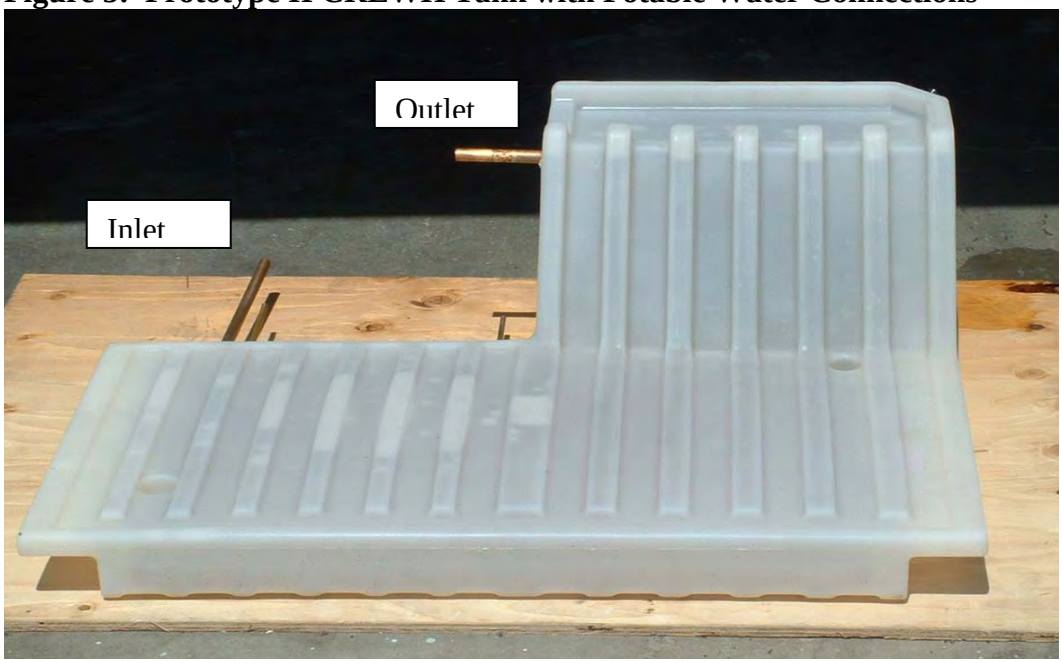
testing. Figure 5 shows the completed tank with potable water inlet and outlet connections. The toe of the tank extends to the front of the refrigerator and the taller portion is at the back. The void at the left rear is where the compressor, condenser fan, and other components are located.

Once the CREWH tank design was finalized, we began designing the load side heat exchanger based on the available space constraints. We established the following design parameters for the load side heat exchanger:

- Counterflow design for optimal heat transfer
- Small diameter tubing to maximize the surface area to flow volume ratio
- Configured to fit within the tank rotational mold

We accomplished the first goal by routing the incoming cold water through the lowest part of the tank first, then through progressively higher parts of the tank, and finally exiting from the highest point of the tank. This path exploits naturally occurring thermal stratification in the tank.

Figure 5: Prototype II CREWH Tank with Potable Water Connections



The lower section of the heat exchanger comprises two ½" tube headers connected by 14 parallel ¼" tube risers that direct the flow horizontally through the toe of the tank. After leaving the header-riser section of the heat exchanger, water flows through the main "tower" section of the tank in four helical ¼" copper coils. The four 4" diameter helices are nested. The design maintains at least ½" between the mold wall and any part of the heat exchanger. The mold is designed to clamp the headers of the lower heat exchanger section as well as the inlet and outlet of the heat exchanger. Plastic builds around the mold support points, assuring effective support after de-molding the part.

The refrigerant condenser consists of a simple serpentine design made of 18.5 feet of 5/16" refrigeration tubing secured to the load side heat exchanger for support. The condenser is located in the cooler toe region of the tank.

Valving layout and logic. Figure 6 shows the valve system developed to optimize flows to the kitchen use points. Water leaving the CREWH tank is piped to the valve assembly located under the kitchen sink. As shown in Figure 6[5], both CREWH hot water and water from the domestic hot water line supply the valve. The valve is set to preferentially supply hot water from the CREWH line and send it to the kitchen fixtures. The valve is controlled by a datalogger that reads temperature inputs and controls the valve position. If the water temperature falls below an adjustable comfort threshold of about 100°F, the valve switches from the CREWH supply to the direct hot water line. At all times a minimum of 10-15% of the hot water flow passes through a bypass valve to slowly purge the hot water line. This strategy reduces hot water waiting times after the CREWH tank is depleted.

Figure 6: Photo of CREWH Valve Installed at Field Test Site

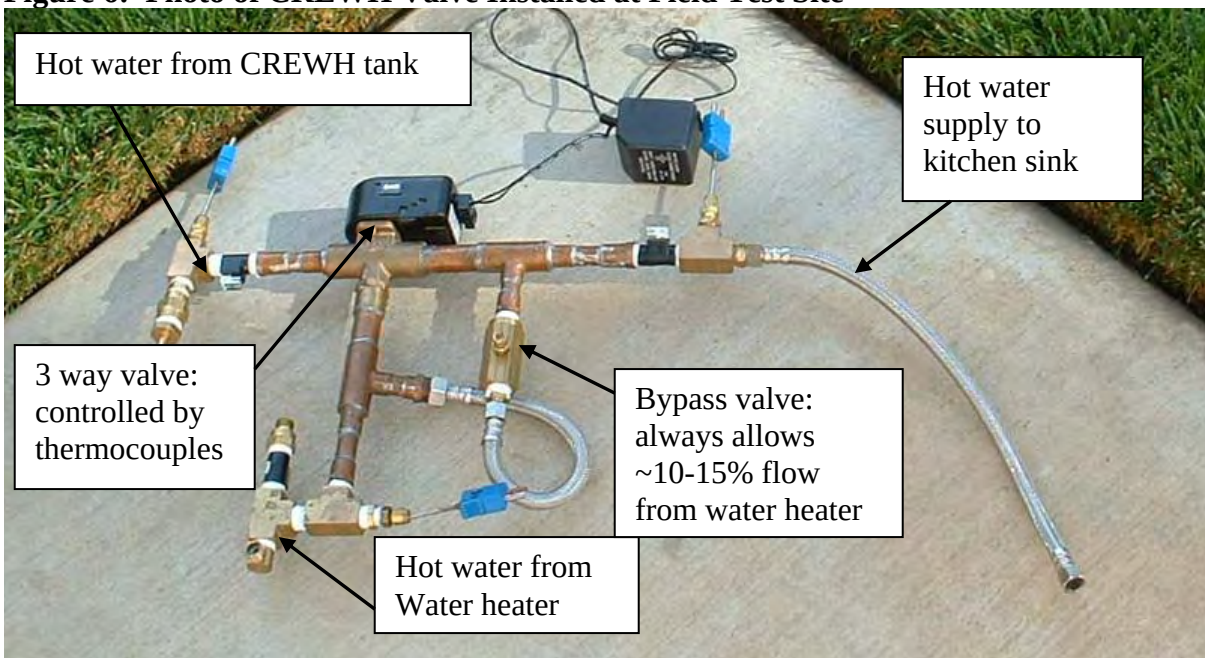


Figure 7 shows the CREWH tank, compressor, condenser fan, and refrigerator drinking and ice maker water supply assembly prior to installation in the refrigerator. Figure 8 shows the completed unit ready for laboratory and field testing.

[5] The prototype valve assembly is considerably larger than needed for a production component.

Figure 7: Prototype II CREWH Mechanical Assembly

6.3 Prototype II Testing

6.3.1 Lab Testing

The Prototype II unit was completed in early July 2004 and subjected to preliminary lab testing to demonstrate basic system operation and verify that refrigerant pressures, energy use, and compressor duty cycles were comparable to the air-cooled unit. During this initial shakedown testing we adjusted the refrigerant charge until data indicated that operating characteristics were consistent with expectations.

6.3.2 Field Testing

Prior to installing the CREWH at the field test site, we monitored baseline hot water usage from February through September 2004 at the Davis field test site. We used a Data Electronics DT-50 datalogger and the sensors shown in Table 3, logging most data at 15-minute intervals. During hot water flows to the kitchen, we logged data at 2-second intervals, providing high resolution data on water temperature profiles, draw duration, flow rates, energy flows, and hot water waiting times. Additional description of the field monitoring procedures can be found in Appendix B.

Figure 8: Prototype II Lab and Field Test Unit

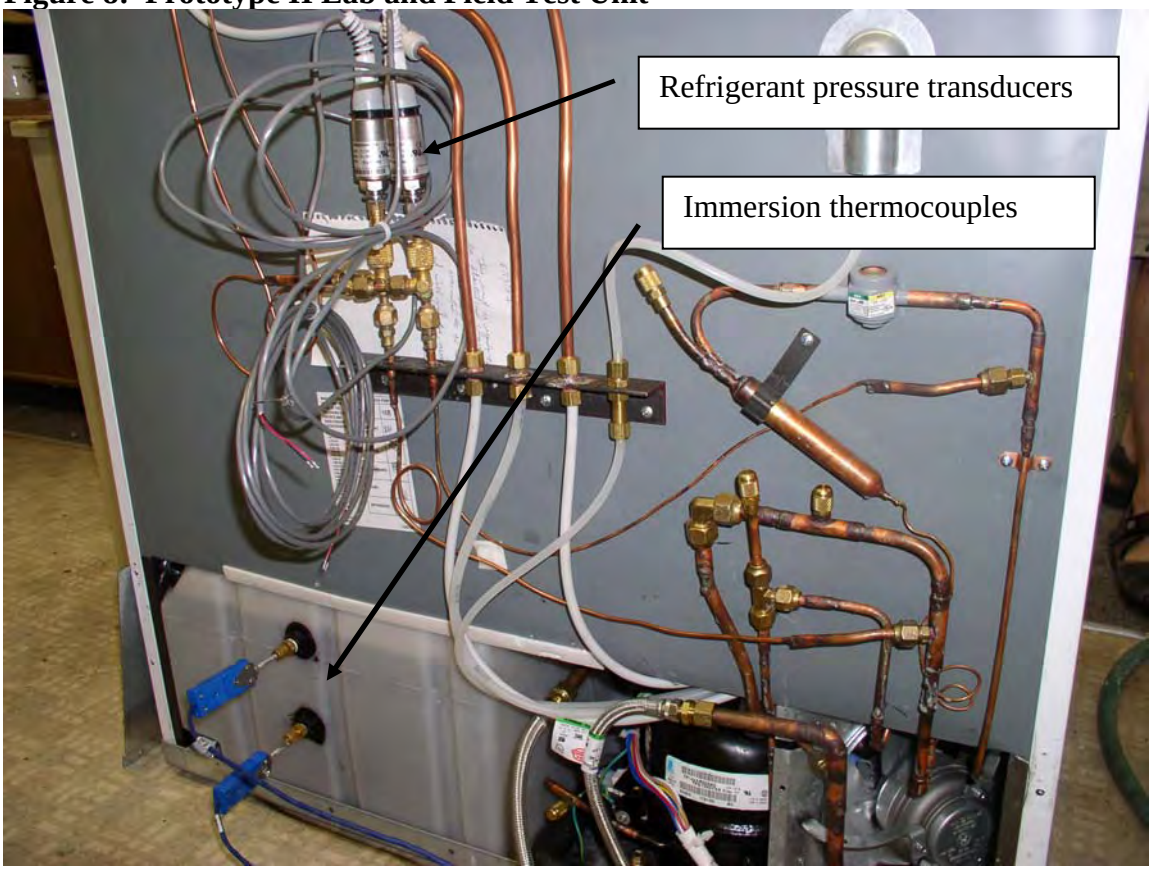


Table 3: Field Test Site Monitoring Points (Pre and Post CREWH)

Monitoring Point	Sensor Description
<u>Baseline Monitoring</u>	
Indoor Temperature	AD592
Outdoor Temperature	ACI-TT100 (RTD)
Water Heater Cold Water Inlet	Type T Immersion Thermocouples
Water Heater Hot Water Outlet	"
Kitchen Sink Hot Water Supply	"
Dishwasher Hot Water Supply	"
Kitchen Sink Hot Water Flow	Omega FTB2004 turbine flow meter
Dishwasher Hot Water Flow	Omega FTB2004 turbine flow meter
Refrigerator Energy Consumption	RIS true RMS power monitor
<u>CREWH Monitoring (additional sensors)</u>	
CREWH Tank Hot Water Outlet	Type T Immersion Thermocouples
CREWH Tank Cold Water Inlet	"
Mixing Valve: CREWH Hot Water Inlet	"
Mixing Valve: Hot Water Line Inlet	"
Mixing Valve: Hot Water Outlet	"

Summary data on baseline performance from February 1, 2004 through September 20, 2004 are shown in Table 4. Kitchen hot water use averaged 8.5 gallons per day with an average volume per draw of 0.44 gallons[6]. Using 100°F as an approximate hot water comfort threshold, we found that only 31% of the hot water draws (and 44% of the hot water flow) exceeded this level. Under the assumption that "hot" water is wasted until the comfort threshold is met, 4.7 gallons per day of water (0.56 x 8.5) could be saved if the water heater were located at the kitchen use points. If the CREWH were implemented for 2 million California households, the annual water savings would approach 3.5 billion gallons per year, or more than 10,000 acre-feet of water.

We found average hot water wait time, for cold pipe start up conditions, to be 46 seconds. At any average flow rate of 1.33 gpm, a 0.76 minute delay indicates approximately 1 gallon of water must be purged from the hot water line before the comfort threshold is achieved. For the full monitoring period, a total of 683.7 kBtu's flowed from the water heater towards the kitchen fixtures. 318.3 kBtu arrived, resulting in an overall distribution system efficiency of 47%. Extrapolated to an annual basis, gas water heater savings for a standard 76% recovery efficiency unit would be 7.6 therms/year; for an electric resistance heater, annual savings would be approximately 110 kWh year[7].

Table 4: Baseline Monitoring Summary

Parameter	Value
Duration of Baseline Monitoring	Feb 1, 2004 – Sept 20, 2004 (232 days)
Hot Water Consumed (Kitchen only)	1961 gallons (8.5 gal/day)
Average Hot Water Draw Volume	0.44 gallons (19.1 draws/day)
Average Hot Water Draw Duration	0.33 minutes (20 seconds)
Average Hot Water Flow Rate	1.33 gallons per minute
Hot Water Draws Achieving 100°F Supply	31%
% of Hot Water Used > 100°F	44% (864 of 1961 gallons)
Average Hot Water Wait Time*	0.76 minutes (45.6 seconds)
Average Distribution Efficiency**	47% (683.7 kBtu from the water heater; 318.3 kBtu arrived at kitchen fixtures)

* time needed to reach 100°F at kitchen after two hour lull since prior hot water draw

** Btu's calculated by integrating flow and hot-to-cold water temperature difference (2 second data)

In late October 2004, we moved the CREWH unit to the field test site and replaced the standard refrigerator used in the baseline monitoring. We also added the sensors listed in the bottom of Table 3 to the monitoring system, and modified the plumbing as required for the CREWH unit. After a debugging process, we set the valves to supply CREWH

[6] For purposes of this monitoring study, a draw was defined as a string of continuous 2-second intervals with hot water flow. Under this methodology, two events separated by a 2 second "no flow" interval would constitute two individual draws.

[7] At average rates of $1.10 per therm and $.142 per kWh, gas and electric savings are approximately $8 and $16 per year, respectively. These savings are smaller than anticipated due to continuing hot water line losses as a result of the "mixing valve" strategy.

hot water to the kitchen fixtures as long as the CREWH tank outlet temperature exceeded 100°F. If the temperature fell below 100°F, the valve would switch to supply water from the water heater line until the tank outlet temperature rose back to 103°F.

Formal CREWH monitoring began November 16, 2004. Early operation showed excessive compressor operation and resulting high energy consumption. We made a minor adjustment to refrigerant charge and the system responded favorably. Data collected from December 2nd to February 22, 2005 are summarized in Table 5.

Table 5: CREWH Prototype II Field Monitoring Summary

Parameter	Value
Duration of Baseline Monitoring	Dec 2, 2004 – Feb 22, 2005 (83 days)
Hot Water Consumed (Kitchen only)	871 gallons (10.5 gal/day)
Average Daily Refrigerator Energy Use	1.44 kWh/day (vs. 1.4 base case)
Average Compressor Part Load Ratio	0.455 (vs. 0.45 base case)
Average Tank Temp During CREWH Draw	106.2°F
Avg CREWH Outlet Temp During Draw	102.9°F
% of Hot Water Used > 100°F (90°F)	41% (62%)
Fraction of Hot Water Provided by CREWH	20%
Average Hot Water Wait Time	18 seconds (CREWH draws only)

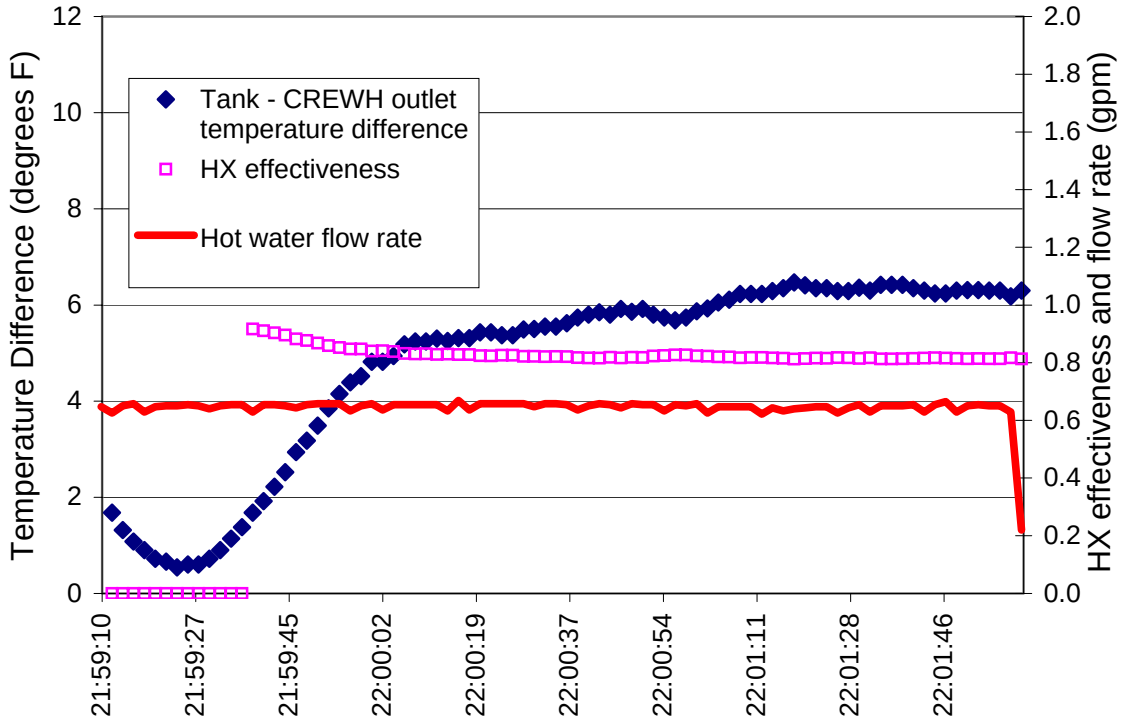
We found refrigerator energy use and compressor part load ratio to be almost identical to the nominal data for the air-cooled version of the refrigerator. During hot water draws from the CREWH tank, the average water temperature leaving the CREWH was 3.3°F cooler than the tank midpoint temperature. Figure 9 plots the performance of the CREWH load-side heat exchanger during one of the extended hot water draws. After the 0.33 gallons of water that had stagnated in the heat exchanger flows out, the CREWH supply water temperature stabilizes at 5 to 6 °F below the tank water temperature. This "delta T" results from the heat exchanger inefficiency; with a very large (but very expensive) heat exchanger water would always exit at the surrounding water temperature. The CREWH did cut hot water wait time by just over 50%, a valuable benefit[8].

Unfortunately only 20% of the water consumed from the kitchen came from the CREWH. The following factors contributed to this disappointing result:

1. The valve system does not allow the CREWH to continue delivering heat when tank outlet temperature is lower than the desired temperature setting. The final solution with internal tank heater (see Section 6.3.3) allows inlet water to continue to cool the condenser even when the heater is operating to raise temperature at the top of the tank. Also, the valve package allows a parallel hot water path that bypasses the CREWH through all flows, thus preventing the CREWH from maximizing its output.

[8] In a more typical kitchen the hot water wait time would be significantly shorter than the average 22 seconds. In this house the kitchen sink was approximately 20 feet from the refrigerator.

Figure 9: CREWH Heat Exchanger Performance



2. Monitoring was completed during mid-winter when both the house temperature and cold water inlet temperature are lowest. In summer, the compressor will run longer due to higher indoor temperatures, and tank temperatures will be higher[9]. The warmer inlet water will also need less heat, increasing CREWH's fractional share.
3. Adding minimal insulation on all CREWH tank surfaces would reduce storage losses and increase the average tank temperature. The tight tolerances with the CREWH tank and refrigerator cabinet precluded optimal tank insulation.
4. To balance collecting/storing condenser heat, delivering useful heat to the kitchen fixtures, and allowing the refrigerator to operate efficiently, we left the storage tank uninsulated. Field results indicate that minimal insulation would improve the average tank temperature without threatening overheating of the refrigerant system.
5. Much of the compressor surface heat output is being lost to surrounding air rather than stored in the CREWH tank for application to hot water loads. This problem could be resolved with a more integrated compressor design, but such an approach was beyond the scope of this project.

[9] A three day experiment with indoor temperatures maintained at 78°F demonstrated average CREWH tank temperatures roughly 10 degrees warmer than typically monitored.

6.3.3 The Modified CREWH Prototype

To improve CREWH heat delivery, we implemented an alternate configuration with an electric resistance element in the tower portion of the tank. This design can potentially eliminate the expensive valve package and the hot water line to the kitchen. With sufficient heating capacity, electrically heating the upper 3+ gallons of the stratified tank to a minimum temperature can ensure relatively constant supply water temperatures. When refrigerator heat output is sufficient, the heater does not operate. But the 120 Volt power system effectively limits the heater size to about 1500 Watts, and the heater must interlock with the compressor so that during hot water draws, which are typically short duration, the compressor does not operate.

Late in the project, we procured and installed a 1500 Watt heater at the appropriate level in the tank of a second "Prototype II" unit. To evaluate performance impacts, we first lab tested the unit without operating the heater. We installed three immersion thermocouples in the tank to monitor tank temperature and stratification. After completion of the baseline testing at a 75° environmental temperature, we activated the heater to maintain tank temperatures of 118 and 140°F. We recorded CREWH energy use and resistance element energy use for each test, and ran hot water supply tests at a one gpm flow rate to assess how the heated tank water affected delivery performance.

Results were inconclusive; the tank did not maintain stratification between draws, causing more heater operation than expected. Our hypothesis for the lack of tank stratification is that the helical load side heat exchanger conducted heat from the top of the tank to the cooler bottom of the tank. We concluded from the results that a more comprehensive design process is necessary to fully integrate tank, compressor, and heat exchanger components in a configuration that optimizes performance. Also, the configuration should be designed to incorporate an air cooling path for overheat protection, as may be needed during vacations when no hot water draws occur.

6.4 Compressor Cooling

In its typical use the refrigerator compressor case is cooled by air moving through the lower mechanical space. For CREWH, compressor heat would ideally be transferred directly to the storage water. For the 1993 CREWH fabricated for the ACT^2 project, DEG did place the compressor in the center of the water container, with the water contained by a flexible membrane liner held in contact with the compressor through water pressure. As a result, substantially all refrigerator heat output was transferred to the water. At that time, DEG engineers were not aware that refrigerator compressors were designed to transfer most of their heat through the case: we surrounded the compressor with water because it was the easiest design to implement in the space available.

Results from this PIER project make clear that capturing the compressor heat in CREWH water has multiple benefits. The cooler compressor means higher efficiencies, and transferring more heat to the water recaptures more refrigerator heat for application to water heating loads. Unfortunately, it was not possible in this project to design the roto-

molded CREWH storage tank to surround the compressor without a significant change in the refrigerator undercarriage- a task that the budget for this project would not support. But there are no technical reasons why it cannot be done, and it would not substantially increase the cost of the water storage tank. Ultimately, such a design would have two other advantages. First, it could reduce compressor mounting costs by firmly holding it in an annular space in the tank. Second, the refrigerator should operate at low sound levels because the water container would cushion the compressor and suppress noise.

7. MARKET ASSESSMENT

With its integration of refrigerator and water heating features, the CREWH presents a marketing challenge. Through the project we frequently solicited input from all project participants to consider marketing issues. We also held two focus groups to solicit input from key stakeholders.

7.1 Stakeholder and PAC Input

We received regular input from Energy Commission staff, project advisory committee (PAC) members, and our key project team partners (Maytag and ORNL) on issues affecting the design or marketability of CREWH. The following list summarizes key issues discussed during the project.

- ISSUE #1: Instead of tying the CREWH supply hot water into the existing household DHW system, should the CREWH be a stand-alone water heating appliance with under-sink or onboard point-of-use (POU) electric water heater? The POU heater would eliminate the hot water line to the kitchen and kitchen hot water waiting time, with varying impact on operating costs.
  RESOLUTION: Our original goal was to avoid adding a POU heater in the kitchen. Field test experience has indicated that a POU heater in the CREWH storage tank is the best approach, and will reduce installed cost while improving hot water delivery patterns.

- ISSUE #2: Should the air-cooled condenser be left in parallel or in series with the CREWH water-cooled condenser?
  RESOLUTION: Test data indicate that the air-cooled condenser is no longer required. We designed the unit to allow the condenser fan to move air across the tank surface if necessary to prevent overheating of the tank, but the cooling fan has not been used on the prototype CREWH units. It remains available if necessary.

- ISSUE #3: How will CREWH comply with Federal test procedures that determine efficiency ratings?
  RESOLUTION: Under current Federal National Appliance Energy Conservation Act (NAECA) standards, both refrigerators and water heaters are certified products. Since the CREWH is a combined appliance, it would either require a waiver from testing or development of a combined efficiency metric. A CREWH

test procedure could combine refrigerator testing at a fixed temperature with the four hot water draws used in the Energy Factor test. Developing a test procedure is a key step in future CREWH development efforts.

- ISSUE #4: Should the CREWH have a hot water dispenser?
  RESOLUTION: This issue was discussed both with the focus groups and with Maytag. Although there is favorable consumer reaction to the benefits of a hot water dispenser at the refrigerator, achieving "coffee ready" temperatures requires an additional heater and incurs potential liabilities.

- ISSUE #5: How much water can the CREWH save by eliminating the kitchen hot water line?
  RESOLUTION: Base case field monitoring measured 4.7 gallons of hot water line flow wasted daily, or about 1700 gallons per year per household. This quantity will vary with use patterns and length and size of piping from the water heater to the kitchen, but represents a significant source of water savings if CREWH is commercially successful.

7.2 Focus Group Input

DEG hired Energy Market Innovations, Inc. of Seattle to hold two focus group sessions to solicit preliminary market feedback on the CREWH technology. The focus groups included the following stakeholders:

- **Builders and Contractors** –key participants who would select, speciy, and/or install CREWH units
- **New home buyers** – homeowners who have recently selected appliances and furniture for a new home

The focus groups were both held on December 7, 2004. Table 6 summarizes key CREWH features and benefits from the perspectives of both builders and homebuyers. (The complete focus group report is provided in Appendix C.) Certain product features and benefits stand out as important to build on in future CREWH marketing and development efforts. Generally both groups identified similar perspectives. The builders focused on "no surprises" – they wanted products with known cost and reliability, quick installation and limited liability. The homebuyers focused on the longer term, with interest in amenities related to attractiveness, operation, and reliability.

Focus group participants identified the following potential market barriers:

- **Builders and contractors are unlikely to push the market for CREWH.** Appliance marketing, sales and installation are not a core part of their business. However, manufacturer advertising or utility energy program rebates could help launch the CREWH product.
- **CREWH will raise liability concerns about water damage.** Technical fixes suggested include making water connections visible, so leaks would be detectable; and having CREWH be a refrigerator-only hot water device, with no

connections to the water heater or the sink area. However, this issue has not prevented success of refrigerators with concealed water lines for ice makers and "through-the-door" water and ice features.

Table 6: CREWH Focus Group Features and Benefits

Desired Features	
Builders and Contractors	**Homebuyers**
Leak-proof, or leak- evident	Leak-proof
"Installer Friendly" - Designed for installation in 15 minutes or less	"Installer Friendly" - Low added construction cost; ability to uninstall or disable
Fast hot water from refrigerator only	Fast hot water from refrigerator and kitchen tap
Available as a "built-in" appliance	Available as a "built in" and in other styles
Safeguards against scalding	Safeguards against scalding
Homebuilder rebate	

Desired Benefits	
Builders and Contractors	**Homebuyers**
Reliability - Limited or no liability for product installation	Reliability - Safe, with no breakdowns
Low installation cost	Low cost-to-value
Increased revenue (for "built-ins")	Increased value of convenience

- **Builders and plumbers would be willing to pre-plumb for a CREWH.** The group suggested that energy programs could compensate for CREWH pre-plumbing. (The post-focus group conclusion that CREWH should have an on-board heater means that the units will reduce net plumbing costs.)
- **New homebuyers may prefer other amenities over CREWH.** The product would have to compete with items providing benefits in terms of comfort, convenience, visual appeal or dollar savings.
- **The builders group noted competition in the "fast hot water" market.** Recirculating hot water systems are currently being installed in some Sacramento area homes. These devices, often costing more than $1000, provide fast hot water at the tap. With lower installed cost and cooling energy savings, CREWH may compete well in this market.
- **Both groups felt that CREWH should feature a hot water dispenser**. Further, builders felt that a self-contained CREWH could reduce the potential for water damage, and possible contractor liability. Both groups thought a hot water dispenser should include safeguards to prevent scalding.
- **Both groups felt that, to maximize product acceptance, CREWH should be available in various refrigerator styles, and should be featured in various**

kitchen suites. Refrigerator appearance, size and function are likely to be the factors driving product purchase.

- **Homebuyers are concerned about limited portability of a CREWH.** They would like the ability to reinstall a CREWH in another home, to resell a CREWH, and to disable a CREWH if desired. We do not see this issue being a show-stopper, as ranges and dishwashers stay in place at time of sale.

7.3 CREWH Cost Evaluation

DEG and ADL (now TIAX) included cost estimates for the various CREWH configurations in Appendix E of the July 2002 CREWH feasibility report. For the integral tank configuration "2b", the total incremental retail cost was estimated at $295[10]. Installation costs[11] estimated at $146 resulted in a total "2b" installed cost of $441. However, eliminating the kitchen hot water line and valve package would likely counter the $146 incremental installation cost.

During the Prototype II design process, we were better able to detail cost estimates. Table 7 summarizes estimated costs at an assumed 5000 unit per year production level.

Table 7: Estimated CREWH Incremental Costs

Item	Cost Estimate	Description
Load side heat exchanger	$ 20	$.35/ft for Type M 3/8" Cooper
Condenser	$ 4	3/16" soft copper
Roto-molded CREWH tank	$ 18	
Tank insulation	$ 7	
Miscellaneous parts	$ 4	
Heater and controls	$ 20	
Eliminate air-cooled condenser	($ 10)	
Incremental labor	$ 30	One hour at $30 per hour
Manufacturing Cost Total	**$ 93**	
Estimated Incremental Retail Cost	**$205**	Based on 2.2 multiplier

7.4 CREWH Performance Projections

The impact of CREWH on household energy use results from the following three factors:

- Hot water savings due to elimination of kitchen loads and hot water line
- Change in refrigerator energy use relative to a standard air-cooled unit
- Changes in internal gains, affecting space conditioning loads

[10] At an annual production volume of 5000 units per year, ADL estimated an incremental material cost of $63.50, and an added labor cost of $70.50. With ADL's manufacturer-to-retail multiplier of 2.2, the total incremental manufacturing cost ($134) resulted in a $295 retail cost.

[11] Materials totaled $39 (isolation valve, copper piping, pipe insulation, fittings) and labor with overhead was estimated at $107.

CREWH non-energy impacts include a reduction in hot water wait time and reduced water consumption.

Because the project did not demonstrate a final working design that effectively captures a large percentage of refrigerator heat output to hot water, we did not complete a set of comprehensive analyses projecting probable CREWH cost savings. We did complete detailed projections of space conditioning impacts, based on MICROPAS runs for a 2,400 ft^2 prototype house that complies with current Title 24 Building Standards. We modeled heating and cooling loads for California climate zones 3 (mild), 11 and 12 (hot and milder valley) and 15 (very hot summers, mild winters). We found that CREWH space conditioning impacts are less favorable now than in prior projections, with savings due to reduced internal gains projected only in climate zone 15. Changes in glazings, relative gas and electric rates, and increased cooling system efficiencies (13 SEER) have all contributed to the reduced benefit derived from converting the refrigerator from a heater to a cooler in the kitchen space. These analyses do not consider the benefit of peak load reduction that derives from eliminating refrigerator heat output in the kitchen.

The major potential economic benefits of the "kitchen only" CREWH developed in this project are the removal of kitchen loads from the central water heating system, and the elimination of the distribution line losses to the kitchen. These savings will vary by house and household, but for natural gas water heaters will likely average 40 to 50 therms annually for typical customers[12]. Any increase in electricity use by the refrigerator, due either to reduced refrigerator efficiency or to the CREWH tank heater will counter these gas savings.

7.4.1 Economic Bottom Line

If refrigerator efficiency improves, as it did in our first prototype, and if gas rises to $1.50 per therm, net annual savings for the optimal kitchen CREWH would likely exceed $50 per year in California's population centers. If neither of these outcomes materializes, annual savings could be as low as $30 per year. Thus, we expect paybacks in the 4 to 7 year range for a marketable kitchen CREWH. Since the field prototype in this project only satisfied 20% of kitchen water heating loads, it cannot approach these payback levels. Capturing more compressor heat and substituting an internal heater for the mixing valve set are essential to achieving viable paybacks. From a development standpoint, better transfer of compressor heat to the storage water is the more expensive of these tasks, as it requires re-designing the refrigerator's undercarriage and the storage tank.

7.5 Implementation Plan and Statewide Impacts

The CREWH concept is not yet ready to implement as a marketable product, but could be with additional development work. The automatic valve delivery concept on which we

[12] Example based on prior DEG water heating studies for the CEC: 250 therms (th) annual use comprising 115 th end use, 25 th distribution loss, 35 th recovery loss, 75 th storage loss, 20% of end use to kitchen= 23 th to kitchen. Based on Table 4, 11 th used in kitchen, 12 th lost in kitchen lines. Removing kitchen load and line causes new breakdown: 206 th annual use comprising 92 th end use, 13 th distribution loss, 26 th recovery loss, 75 th storage loss; savings 44 therms annually.

focused for much of the project did not prove workable. At the end of the project we implemented an alternate strategy using an electric heater immersed in the CREWH storage tank. This improvement offers low initial cost and facilitates elimination of the mixing valve package and the hot water line to the kitchen. But under project time and budget constraints, this approach could only be tested in the laboratory, and initial results indicate that the heater must be fully integrated with the tank, compressor, and overheat system for optimal performance. Further development is warranted and necessary before estimating statewide impacts and developing an implementation plan.

7.6 Alternate CREWH Configuration

The initial feasibility evaluations discussed in Section 4 did not consider a fully-integrated refrigerator/water heater with onboard water storage. Configuration 1a, discussed in the feasibility report, assumed external storage and associated hardware. Progress at DEG on other projects since that report was completed suggests that a fully-integrated design is possible and would have major advantages over the 1a configuration that was rejected early in this project. This configuration appears particularly promising for multi-family and small home applications where it would save space, reduce peak cooling loads, and eliminate natural gas use for water heating. This concept represents a more radical departure from current practice than the "kitchen CREWH" developed in this project, and therefore should be pursued after an initial CREWH product, deriving from work in this project, achieves market success.

8. CONCLUSIONS

Viability: The CREWH project has made considerable progress toward development of a viable, marketable combined refrigerator water heater. Working with Maytag, DEG has shown that a conventional refrigerator can be modified, without changing the food storage compartments, to store refrigerator heat output and deliver it to kitchen loads. The final design that incorporates an electric heater in the CREWH storage tank can eliminate the need for a hot water line to the kitchen, and the heat losses associated with that line. While builders expressed reluctance to eliminate the kitchen hot water line, the CREWH may be treated as a built-in appliance like dishwashers, ranges, and compactors, so that ultimately an obsolete CREWH would be repaired or replaced by a new CREWH. In the interim, utility incentives that reflect CREWH's value as a peak load reducer could cover the cost of an installed but unused hot water line.

The CREWH faces market barriers as both builders and homebuyers are reluctant to adopt new technologies. But despite these barriers there is a substantial need for new energy efficiency products; for example, the DOE's Building America program seeks 50% energy savings for new homes by 2010. CREWH offers an opportunity for a manufacturer to gain a competitive advantage that responds to societal needs and saves homeowners money. In short, we believe that viable markets can develop for two CREWH versions:

1) The kitchen-only unit developed in this project, a design that can reduce peak loads, provide faster hot water delivery to the kitchen, save water, and reduce energy costs. This version should incorporate an on-board tank heater as lab-

demonstrated at the end of this project and could be marketed at an incremental installed cost of about $200. The heater allows the kitchen hot water line to be eliminated.

2) A multi-family/small home unit that functions as both a refrigerator and a heat pump water heater, eliminating the traditional natural gas water heater. But this design was not the focus of this project, and should be pursued as a separate venture.

Performance: Development work in this project did not achieve the major CREWH performance goal of delivering the majority of hot water to the kitchen from refrigerator heat output. CREWH heat delivery to its internal storage tank was lower than desired for two reasons: First, the delivery valve set prevented full use of CREWH heat storage (see Section 6.3), and second, the refrigerator compressor is discharging much of its heat through its enclosing metal case (see Section 6.4) instead of into the storage water. More work is needed to achieve the full potential of the "kitchen-only" CREWH version, but there are no technical obstacles to success. The project has lab-demonstrated a version that provides more complete use of CREWH storage, but additional work is necessary to develop a design that promotes tank stratification and more fully captures (and stores) heat output from the compressor shell.

The Future: A working CREWH R&D team must be re-assembled if the work begun in this project is to continue. In June 2004, Maytag substantially reduced their engineering work force and many of the key Maytag personnel involved with the CREWH project were released. As a result, Maytag's interest level is much lower than it was early in the project. Since CREWH cannot be implemented without a seasoned refrigerator manufacturer, it will be necessary to rekindle the Maytag relationship or find an alternate manufacturer before further R&D efforts are pursued with the technology.

Additional effort is needed for the promise of an integrated refrigerator-water heater is to be realized. This project has made a valuable start, but currently lacks the most necessary ingredient- a committed manufacturer. In this project we enticed Maytag, a major manufacturer with mild interest, into supporting our effort to show that we could capture refrigerator heat for water heating without major design modifications of their refrigerator. But the result may not perform well enough for market success. It is likely that a "from the ground up" redesign of the refrigerator undercarriage is needed. This redesign should include either integration of the compressor with the storage tank or a refrigerant-cooled compressor to facilitate more delivery of refrigerator heat into stored domestic hot water.

9. RECOMMENDATIONS

Sequential market and technical research elements appear necessary to advance CREWH technology into the marketplace. These efforts could build on the accomplishments of this project and, pending favorable results of the market research element, lead to one or more CREWH products that have substantial impact on California's residential energy

use. We focus our recommendations on the near-term opportunity for a "kitchen-only" CREWH.

9.1. Market Research Element

Since continued CREWH development will require additional investment, a detailed market and economics study is recommended before proceeding. For the kitchen-only CREWH, more data are needed on the number of homes with kitchens relatively far from the water heater, and of those, what fraction would buy a CREWH based on its more rapid hot water delivery and combined energy and water savings. The research is more straightforward for new homes, where eliminating the kitchen hot water line improves economics. For existing homes, there is the added cost and physical challenge of adding a hot water line from the refrigerator to the sink/dishwasher set. (On the other hand, existing home occupants may already be primed for purchase by their personal experience with long hot water wait times.)

In addition to identifying the potential market size, the research should compare costs and energy impacts of CREWH and other available measures that reduce kitchen hot water wait times. If this study suggests that CREWH will compete well with other alternatives, the next recommended step is to estimate potential CREWH market penetration for both new and retrofit markets. If the potential combined market appears to be reasonably large, the final market research step should be implemented. This step will use the assembled data in a concerted effort to re-establish manufacturer involvement in the project.

9.2 Technical Research Element

After successful completion of the market research steps recommended in Section 9.1, we recommend working closely with the participating manufacturer to design and build a CREWH "production prototype." This work should develop a "ground up" undercarriage for standard refrigerators that fully integrates the tank, compressor, heat exchanger, and tank cooling system (needed for overheat protection). This design should provide "direct contact" heat transfer between the compressor and the storage tank, with components sized for optimal performance. We have shown this possibility in prior work, where the compressor and storage tank were located atop the refrigerator. The design challenge that remains is to cost-effectively surround much of the compressor surface in a molded tank in the available undercarriage space. The tank outer surface should be selectively and convectively cooled by room air during vacation periods when hot water is not used.

There are many possible solutions to this design challenge, but they cannot be implemented without the enthusiastic participation of a refrigerator manufacturer. After developing the improved design, the team should sequentially complete lab and field tests, and evaluate economics and market impacts.

APPENDIX A:

Refrigerator Efficiency Calculations

The goal of the CREWH monitoring is to assess operating efficiencies in base case operating mode (where the refrigerator and water heater are separate appliances) and in CREWH mode. Base case water heating calculations are based on a representative 60 gal/day DHW load estimate and the concept of Load Dependent Energy Factor (LDEF), which adjusts the rated Energy Factor of a water heater by the load magnitude. The LDEF concept recognizes the impact of water heating load on storage water heater efficiency, wherein efficiency decreases with decreasing load because a greater fraction of the heat input becomes tank standby loss. Prior DEG work in the development of the California Title-24 Standards has been used to characterize LDEF for both electric and gas water heaters.

A combined "base case" efficiency can be calculated by combining useful "Q" (daily refrigerator space cooling and daily water heating heat delivered) and dividing by total energy consumption (see Equation 1). We will obtain refrigerator space cooling loads from Maytag for the specific refrigerator model and the range of operating conditions we will be testing. We will complete total efficiency calculations assuming both gas and electric water heating. Water heating recovery load and operating efficiency (LDEF) will be based on assumptions used in the California Standards. Equations 2 & 3 present the calculations for combining refrigerator and water heater performance in one parameter (Equation 2 for electric water heaters, 3 for gas).

Terms

EFF_R = base case refrigerator efficiency EER (unitless)
$EFF_{R,C}$ = CREWH operating efficiency EER; includes added energy used to heat water (unitless)
$EFF_{D,E}$ = DHW efficiency for electric water heater at 60 gal/day usage level (unitless)
$EFF_{D,G}$ = DHW efficiency for gas water heater at 60 gal/day usage level (unitless)
$REFR_W$ = Refrigerator average hourly power draw (Watts)
$REFR_{W,C}$ = CREWH average hourly power draw (Watts)
$LDEF_{D,E}$ = load dependent Energy Factor for electric water heater (adjusts reported EF for usage at a representative 60 gpd usage level)
$LDEF_{D,G}$ = load dependent Energy Factor for gas water heater (adjusts reported EF for usage at a representative 60 gpd usage level)
$EFF_{T,E}$ = combined overall efficiency of refrigerator and separate electric water heater (unitless)
$EFF_{T,G}$ = combined overall efficiency of refrigerator and separate gas water heater (unitless)
Qcase load = reported evaporator case load at specified conditions (from Maytag data)
$SDRL_{60}$ = standard daily recovery load at 60 gpd usage (Btu/day) from CEC DHW study
Q_{CREWH} = Monitored CREWH contribution to kitchen water heating loads (Btu/day)
$LDEF_{A,E}$ = electric LDEF (adjusted for CREWH contribution, usage <60 gpd)
$LDEF_{A,G}$ = gas LDEF (adjusted for CREWH contribution, usage <60 gpd)

Base Case Monitoring
($REFR_W$ is monitored, all other parameters from prior testing/analysis)

1. $$EFF_R = \frac{\text{Qcase load (Btu/hr)}}{\boldsymbol{REFR_W}}$$

2. $$EFF_{T,E} = \frac{(24 \times \text{Qcase load}) + SDRL_{60}}{(24 \times \boldsymbol{REFR_W}) + SDRL_{60} / (3.413 * LDEF_{D,E})} = \frac{\text{Btu/day}}{\text{Watt-hr/day}} = \frac{\text{Btu}}{\text{W-hr}}$$

3. $$EFF_{T,G} = \frac{(24 \times \text{Qcase load}) + SDRL_{60}}{(24 \times \boldsymbol{REFR_W}) + (SDRL_{60} / (3.413 * LDEF_{D,G})} = \frac{\text{Btu}}{\text{W-hr}}$$

We will complete CREWH combined efficiency calculations in a manner similar to base case "combined" efficiency calculations. For CREWH, monitoring will determine the amount of electrical energy needed to meet the refrigerator/freezer cooling load. This electrical energy consumed may be greater than the base case refrigerator consumption due to higher average CREWH condensing temperatures. Equations 5 & 6 (for electric and gas water heating, respectively) represent the CREWH combined efficiency recognizing the CREWH heat contribution to the load. For the CREWH test cases, LDEF's need to be recalculated since the load on the water heater is reduced due to the CREWH contribution to the total daily water heating load.

($REFR_W$ and Q_{CREWH} are monitored, all other parameters from prior testing/analysis)

First, calculate efficiency in CREWH operating mode (all energy consumed by the CREWH is included in the denominator. Case load is equivalent to Eqn 1.

4. $$EFF_{R,C} = \frac{\text{Qcase load (Btu/hr)}}{\boldsymbol{REFR_{W,C}}}$$

Q_{CREWH} = Monitored CREWH heat delivered (Btu/day) determined from measured flow rates and temperature differences across the CREWH storage tank. (Q = 8.33 x gals x delta T)

The CREWH heat contribution, Q_{CREWH}, reduces the SDRL and also slightly reduces the LDEF (since the water heating load is reduced in the CREWH case).

5. $$\text{CREWH } EFF_{T,E} = \frac{(24 \times \text{Qcase load}) + SDRL_{60}}{(24 \times REFR_{W,C}) + (SDRL_{60} - Q_{CREWH}) / (3.413 * LDEF_{A,E})}$$

6. $$\text{CREWH } EFF_{T,G} = \frac{(24 \times \text{Qcase load}) + SDRL_{60}}{(24 \times REFR_{W,C}) + (SDRL_{60} - Q_{CREWH}) / (3.413 * LDEF_{A,G})}$$

APPENDIX B:

Prototype I and II Monitoring Plans

CREWH PROTOTYPE I TESTING PLAN
Created: March 6, 2003

1. Baseline Refrigerator Testing

1.1. Objectives

The baseline testing will establish the current operating efficiency and operating characteristics of the Maytag refrigerator under various environmental conditions and to estimate the contribution of the refrigerator to the space conditioning loads on the house. This information will be compared to the CREWH data in the second phase of this testing to determine CREWH's impact on refrigeration and overall efficiency.

1.2. Environmental Chamber

The environmental enclosure will be constructed out of 1.5 inch, foil-coated foam board. The dimensions are 4' by 4' by 8' (L x W x H). Cooling will be accomplished by bringing in ambient warehouse air when the temperature is above the upper setpoint, and three 100W lightbulbs will be used to heat the air if the temperature falls below the lower temperature setpoint. A DT50 datalogger will be used to control the temperature of the environmental chamber, operating lights and fans as necessary to maintain chamber temperatures within test specification. One mixing fan will be mounted inside the chamber to reduce temperature stratification.

1.3. Test Methodology

For all testing scenarios, the refrigerator will be loaded with five 2-gallon water jugs and the freezer will be loaded with five 7-lb bags of ice. These items will act as thermal mass to simulate the normal grocery load that a refrigerator/freezer would encounter.

The attached cable list shows the temperature, energy and status points for this proposed test plan. The chamber temperature will also be used to control the heating and cooling functions of the chamber. The six refrigerant temperatures will be used for comparison in the future to the performance of the CREWH equipped refrigerator. The energy consumed by the unit and by the compressor will be used to help determine the efficiency of the refrigerator, and the condenser fan will be monitored for operation.

Table 1 below shows the various environmental conditions under which tests will be performed to establish baseline performance characteristics for the refrigerator. Each test should take no longer than three days.

Table 1: Base Case Refrigerator Test Scenarios

Test	Chamber Temperature Range	Refr Setting	Freezer Setting
1	79°F to 84°F	37°F	0°F
2	72°F to 77°F	37°F	0°F
3	63°F to 68°F	37°F	0°F

The monitoring schedule will be based on 6-second readings with a 1 minute logging interval. The logged temperatures will be the averages of the 6-second temperature readings, and the 6-second status and power readings will be used to establish duty cycles for each logging interval.

1.4. Test Site Location

The location for the baseline testing will be at the rear of the DEG space at the West Sacramento TDC warehouse, on the left-hand side (where HYPAK testing took place). This location does not have moisture problems and has 110V power available for the refrigerator, the computer and the monitoring equipment. A different location may be selected for the CREWH testing where there is access to water and drainage.

2. CREWH Testing

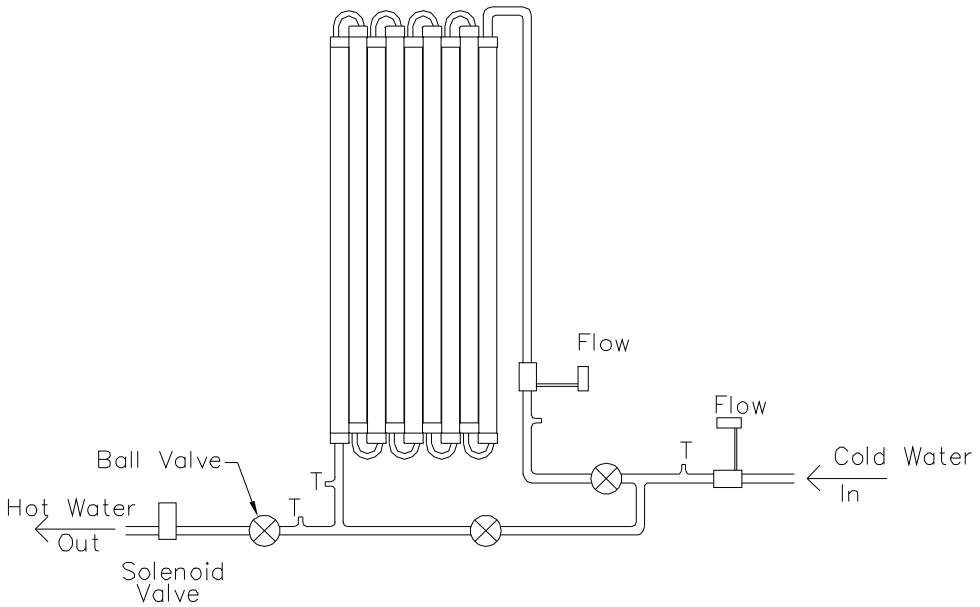
2.1. Objectives

The primary goal of the CREWH testing is to determine if the prototype CREWH can operate more efficiently than a conventional refrigerator with either electric or gas water heating. The CREWH will reduce the DHW load by providing a fraction of the daily load (kitchen fixtures and dishwasher), but it may consume more electrical energy to maintain refrigerator and freezer temperatures. Testing will be completed to assess the overall energy balance and efficiency of the CREWH.

2.2. CREWH Design

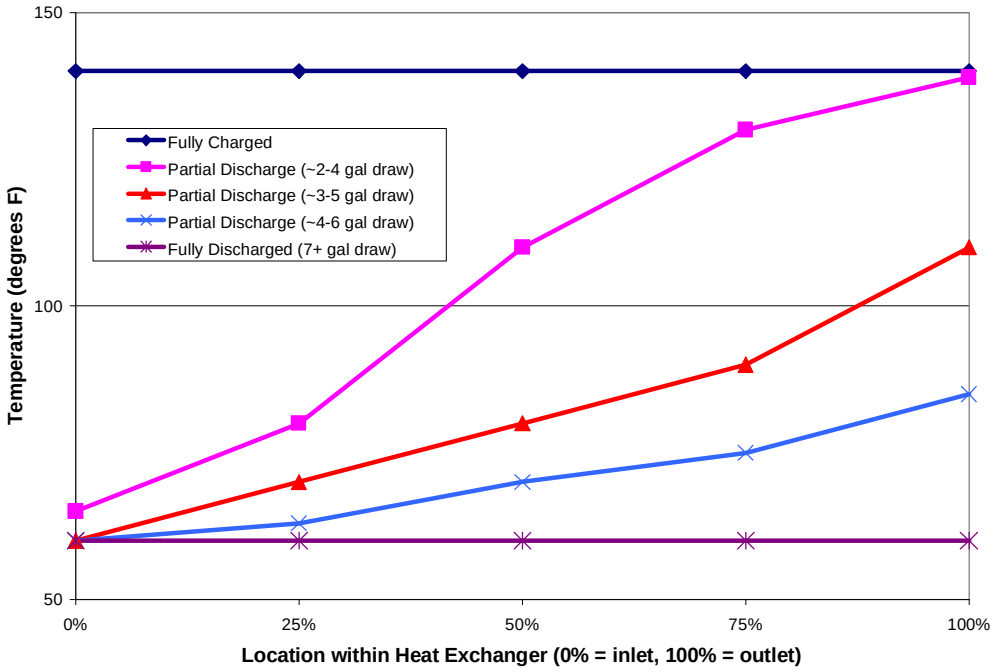
A CREWH prototype heat exchanger was designed and fabricated as part of this project. The heat exchanger stores potable water heated by the condenser and supplies hot water to kitchen fixtures during hot water demand. The goal of the heat exchanger design was to design a heat exchanger whose physical dimensions were compatible with the refrigerator cabinet. The materials used in building the heat exchanger were selected for ease of use, not necessarily for what may ultimately be used in a production prototype. The prototype heat exchanger was comprised of nine 4 foot sections of Type L copper pipe, connected in series as shown in Figure 1. Approximately 30 feet of 3/16” soft copper tubing was nested in a serpentine fashion between the larger two inch pipe to provide good thermal contact between the refrigerator condenser and the storage volume. The storage volume will be heated during refrigerator compressor operation and will be cooled as water is drawn from the CREWH heat exchanger. Prior modelling indicates typical CREWH water temperatures should average about 100ºF during the course of a day, with significant daily variation due to the timing and magnitude of kitchen hot water draws. Figure 2 plots representative temperatures through the heat exchanger as a function of the hot water draw magnitude.

Figure 1: Schematic of CREWH Heat Exchanger and Key Monitoring Points



Cold supply water will pass through a flow meter and temperature sensor before entering a Tee, directing water either to the CREWH heat exchanger or bypassing the CREWH. Each of these flow paths will have a gate valve to provide control on flow rate through the CREWH heat exchanger. We will investigate the impact of flow rate differences on hot water delivery temperature profiles during longer draws. The water flowing through the CREWH heat exchanger will move through the CREWH heat exchanger displacing previously heated water. Draws will be controlled by a second DT datalogger, which will also monitor key temperatures and flows. The DT will be directed to open the solenoid valve on a pre-programmed draw schedule.

Figure 2: Representative Temperature Profiles in the CREWH Heat Exchanger



2.3.CREWH Monitoring

Table 2 lists monitoring points and sensors required for the CREWH monitoring phase. A second DT50 datalogger is required to monitor these datapoints and to also provide control function. The DT50 will be programmed to activate a solenoid valve on a schedule to mimic typical kitchen domestic hot water draws.

A series of experiments will be completed to assess CREWH prototype performance under a range of operating conditions, domestic hot water loads, and valving configurations. It is anticipated that each test will run 2-3 days. Table 3 lists the tests to be performed. Two load magnitudes will be tested. Kitchen only loads will utilize a daily flow volume of 10 gallons and "kitchen + dishwasher" will use a volume of 18.5 gallons per day. Tests 1-4 represent annual average indoor temperature conditions and will therefore involve more detailed testing. Tests 5-8 will evaluate more typical mid-summer and mid-winter ambient conditions. Prior testing will dictate valve positions to be used in this testing. Additional tests may be added if the need arises. The expected duration for the testing phase is 3-5 weeks.

Table 2: Required Monitoring Points for CREWH Prototype

Monitoring Point	Sensor	Objective
Solenoid Valve & Relay		Control of hot water draws
Inlet Water Flow	Onicon F-1300	Total flow
CREWH HX Water Flow	Onicon F-1300	CREWH HX flow
Cold Water Inlet Temperature	Type T immersion thermocouple	Inlet water temp
CREWH HX Outlet	"	CREWH outlet temp
Supply Water Temperature	"	Mixed temperature
Intermediate CREWH Temp #1	Type T surface TC	1/3 of the way thru CREWH
Intermediate CREWH Temp #2	Type T surface TC	2/3 of the way thru CREWH

Table 3: CREWH Test Cases

Test	Chamber Temperature	DHW Load (gal/day)	CREWH Bypass Valve Position
1	72°F to 77°F	10.0	0% bypass
2	"	10.0	25% bypass
3	"	18.5	0% bypass
4	"	18.5	25% bypass
5	63°F to 68°F	10.0	T.B.D.
6		18.5	T.B.D.
7	79°F to 84°F	10.0	T.B.D.
8		18.5	T.B.D.

CREWH Prototype II Field Testing Plan
Created: March 11, 2004

1. Background

Testing of the second CREWH prototype involves both laboratory and field testing. Davis Energy Group will complete limited laboratory testing on the first unit fabricated prior to that unit being field-tested in an occupied home. Maytag will perform more detailed laboratory testing at their manufacturing/engineering facility in Amana, Iowa. Laboratory testing will focus on categorizing performance under controlled conditions as well as determining how the unit responds under extreme operating conditions.

This monitoring plan addresses the monitoring goals, methods, and analysis procedures to be used in field-testing.

2. Objectives

The CREWH Project work statement specifies both pre-monitoring (prior to CREWH installation) and post-monitoring. The pre-monitoring is useful to "..monitor refrigerator and water heating use before and after CREWH installation to verify these patterns and provide base case data." Pre-monitoring will continue for approximately three months with the key goals being the characterization of the following:

- How much energy and hot water is consumed at both the kitchen sink and the dishwasher?
- How much energy leaves the water heater for each of these draws relative to how much arrives at the end use point?
- How long does it take for hot water to arrive at the fixture?
- How much energy does the existing refrigerator consume?

Although the existing refrigerator energy use cannot be compared directly to the CREWH prototype to be installed at the residence, it does provide a basis for estimating internal gain impacts on the kitchen. Post-CREWH monitoring will also address energy use, water use, and hot water waiting time to allow comparisons to be made.

3. Description of Pre-monitoring Methodology

Pre-monitoring will define performance of the existing plumbing system in delivering hot water to the kitchen fixtures. We will monitor energy consumed by the refrigerator and energy supplied by the water heater and delivered to the kitchen end use points. A Science Electronics DT-50 datalogger will be programmed to log data on 15 minute intervals (temperatures, BTU's and hot water flows, and refrigerator energy).

If hot water flow is detected on either the kitchen sink or dishwasher flow meters, the DT-50 will immediately start recording temperatures (and calculating Btu's delivered) on a two second interval. This short interval data will provide improved data resolution and tracking of hot water temperature rise, flow rate, and delivered Btu's at each of the fixtures. The two-second data will also provide sufficient resolution in determining the length of time it takes hot water to reach the fixture after the draw has begun. The data will be analyzed to determine how long it takes to reach a useful temperature (90 or 100°F) at the fixture and how much water is wasted before hot water arrives.

Short-term measurements will be taken of refrigerator and freezer temperatures using HOBO temperature dataloggers. These will be placed in the food compartments of the refrigerator and freezer for one week. The average refrigerator and freezer temperatures determined from this test in the pre-monitoring stage will be used to set compartment temperatures in the CREWH prototype. Table 1 summarizes sensors to be installed for pre-monitoring.

Table 1: Pre-monitoring Data Points

Point No.	Abbrev.	Description	Sensor Location	Sensor Type	Sensor Mfg./Model
1	TAI	Indoor Air Temperature	Near thermostat	AD592	AD592
2	TAO	Outdoor Air Temperature	Outside	RTD, 4-20ma	ACI TT100(40-130)-O
3	TWKS	Hot water temperature (KS)	Kitchen sink	Type T therm.	Immersion
4	TWKD	Hot water temperature (DW)	Kitchen Dishwasher	Type T therm.	Immersion
5	FKS	Hot water flow at kitchen sink	Under sink, in hot water line	Flow Meter	Omega F2004
6	FKD	Hot water flow at dishwasher	Under sink, in hot water line	Flow Meter	Omega F2004
7	TWHC	Cold water to WH	Cold water supply to water heater	Type T therm.	Immersion
8	TWHH	Hot water from WH	Hot water line from water heater	Type T therm.	Immersion
9	EREF	Refrigerator Energy	At refrigerator	Watt-hour meter	Rochester

4. Description of CREWH Monitoring Methodology

The CREWH prototype will replace the existing refrigerator after several weeks of lab testing. The CREWH will have a customized valve assembly that will preferentially provide hot water to the kitchen fixtures from the CREWH tank, and secondarily, from the water heater. Figure 1 depicts the valve configuration. The bypass line always allows a small fraction of the hot water flow to come from the hot water line. (Part of the lab experimentation will involve determining the optimal bypass flow rate.) The bypass feature improves the hot water response of the system by drawing water from the hot water line at all times, shortening the hot water wait time after the CREWH has become depleted by large hot water draws.

Figure 1: Schematic of CREWH Mixing Valve

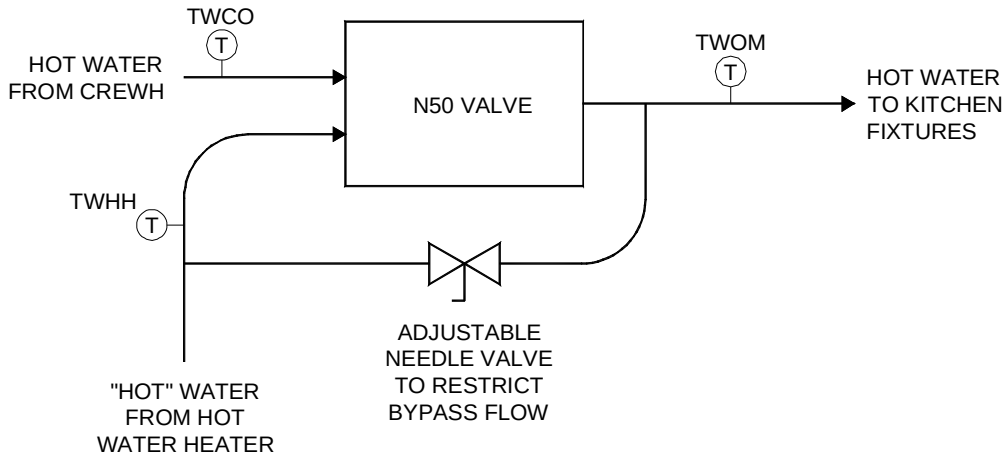


Table 2 summarizes the sensors needed for CREWH monitoring. Three temperatures associated with the valve assembly (TWCO, TWOM & TWMH) have been added, as well as a flow meter.

Table 2: CREWH Monitoring Data Points

Point No.	Abbrev.	Description	Location	Sensor Type	Sensor Mfg./Model
1	TAI	Indoor Air Temperature	Near thermostat	AD 592	AD592
2	TAO	Outdoor Air Temperature	Outside	RTD, 4-20ma	ACI TT100(40-130)-O
3	TWKS	Hot water temperature	Kitchen sink	Type T therm.	Immersion thermocouple
4	TWKD	Hot water temperature	Kitchen Dishwasher	Type T therm.	Immersion thermocouple
5	FKS	Hot water flow to kitchen sink	Under sink, in HW line	Flow Meter	Omega F2004
6	FCR	Hot water flow from CREWH	mixing box	Flow Meter	Omega F2004
7	FHW	Hot water flow from WH	mixing box	Flow Meter	Omega F2004
8	TWHC	Cold water to WH	Cold water supply to water heater	Type T therm.	Immersion thermocouple
9	TWH	Hot water from WH	Hot water line from water heater	Type T therm.	Immersion thermocouple
10	TWCO	CREWH outlet temperature	CREWH outlet water temperature	Type T therm.	Immersion thermocouple
11	TWOM	Mixed temperature	Outlet of mixing valve	Type T therm.	Immersion thermocouple
12	TWHH	Hot water line temperature	HW line inlet to mixing valve	Type T therm.	Immersion thermocouple
13	TWC	CREWH cold water inlet temp	CREWH cold water Inlet temperature	Type T therm.	Immersion thermocouple
14	EREF	Refrigerator Energy	At refrigerator	Watt-hour meter	Rochester

Short term measurements of refrigerator and freezer temperatures will be completed using HOBO temperature loggers. The short term monitoring will last a minimum of one week.

Post-monitoring will log indoor/outdoor temps, CREWH/condenser energy on 15-minute intervals; all other data will be logged on 2-second intervals during DHW flow intervals.

5. Data Analysis

For both pre- and post-monitoring we will have datasets with both 15-minute summary data and 2 second interval data during kitchen hot water draws. From this data we can derive energy use characteristics on kitchen hot water draws, hot water volume wasted until hot water temperature reaches 100°F, and hot water waiting times.

Data will be downloaded daily via modem. The data will be stored in comma-delimited ASCII format and will be analyzed to provide summary statistics characterizing performance.

The primary values that need to be calculated in order to compare the CREWH to the baseline unit are:

Pre-monitoring:

Energy delivered to the supply hot water line at the water heater, QWH, and energy delivered at the end use point, QEU, are defined as shown below:
:

QWH = Ffix*8.33*(TWH-TWC)

QEU= Ffix*8.33*(Tfix-TWC)

Where,
Ffix = fixture hot water flow (either kitchen sink or dishwasher)
Tfix = hot water temperature at the fixture where flow is occurring

For each draw, a distribution efficiency can be calculated as defined by the ratio of QEU to QWH. Total flow volume, volume of water above 100°F, and waiting time to achieve 100°F will also be calculated.

Post-monitoring:

Energy delivered by water heater, QWH:
QWH= FHW*8.33*(TWH-TWC)

Energy out of CREWH, QC:
QC= FCR*8.33*(TWCO-TWC)

Total energy delivered at end use point, QEU:
QEU= Ffix*8.33*(Tfix-TWHC)

Note: FKD must be calculated for the CREWH testing. The flow meter from the dishwasher line in the base case must be moved for use in the CREWH outlet line or the hot water supply line at the mixing box due to a limitation in the number of high speed

channels on the datalogger. We can calculate the following flows based on the three measured flows:

FKD = FHW + FCR – FKS
Total flow from mixing box = FHW + FCR
Cold water flow into CREWH = FCR

6. Reporting

Reporting for Task 2.1.4 ("Develop, Install, and Monitor a Second Prototype") includes documenting the design process for the second prototype and reporting on the field performance of the unit. Prior to the field test, we will perform limited lab testing on the unit to verify basic performance characteristics. These results will also be including in the Task 2.1.4. report. We will focus on the hot water energy savings characteristics of the CREWH, the reduction in water wasted, CREWH's impact on waiting times, and overall efficiency. Full-year MICROPAS runs will be completed to assess the impact of reduced kitchen internal gains on space conditioning loads based on pre and post-CREWH monitored refrigerator energy use.

APPENDIX C:

Focus Group Report

COMBINED REFRIGERATOR ELECTRIC WATER HEATER FOCUS GROUPS:

SUMMARY REPORT

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January 26, 2005

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1. BACKGROUND AND OBJECTIVES

This report summarizes the results of two focus groups conducted by Energy Market Innovations, Inc. to support the development of the Combined Refrigerator and Electric Water Heater (CREWH), an energy efficient refrigerator design under development by the Davis Energy Group (DEG) with financial support from the California Energy Commission (CEC).

This focus group research is part of the development process for the CREWH, and is intended to solicit market feedback on this potential product. Information gleaned from this research will be used to inform and refine subsequent CREWH development and commercialization strategies undertaken by DEG.

Two focus groups were undertaken, one comprised of each of the following groups:

- **Builders and Contractors** – market actors who would potentially play a role in the selection, specification, and/or installation of a CREWH unit; and

- **Owners of new homes** – market actors who have recently been involved in selecting appliances and furniture for a new home, and who fit the characteristics of people likely to consider purchasing a CREWH unit.

A more detailed description of the CREWH is provided below, followed by a review of research objectives that guided this project.

1.1 Product Description

The CREWH incorporates a nine gallon polyethylene tank with immersed refrigerant condenser and load side heat exchangers. The tank was designed to fit into the mechanical space under a standard refrigerator. Heat from the refrigerator is transferred from a copper refrigerant condensor coil to water in the heat exchanger tank. The tank water transfers heat to the load side heat exchanger located in the tank. Kitchen hot water loads preferentially draw water from the CREWH tank to a mixing valve which mixes a small amount of hot water from the hot water line to the water heater. (This draws water from the hot water tank shortening the hot water wait time at the kitchen fixtures.) If the CREWH tank temperature is too low, the valve draws water exclusively from the water heater line. . A diagram of CREWH can be found in this document's appendix.

In designing the CREWH, Davis Energy Group expected that the following features would be of interest to potential purchasers:

- Faster delivery of hot water to the kitchen fixtures

- Energy savings through reduced water heater load

- Energy savings through improved refrigerator efficiency

- Reduced summer heat gains from the refrigerator

The focus groups offered the opportunity to explore these benefits, uncover possible additional benefits of the device, and identify other issues that are likely to influence product purchase decisions.

1.2 Research Objectives

The overall objective of this research was to provide DEG with candid feedback from both consumers and builders/contractors regarding the viability of a CREWH unit in the marketplace. Within this framework, DEG identified specific issues on which feedback was desired. A moderator's guide was constructed reflecting these research issues, and included the following:

- **Homebuyer Attitudes Related to Utility Cost** – Background information from attendees related to the overall importance and level of consumer concern regarding home energy and water costs. Discussions of this topic helped to identify where energy costs fall relative to other home ownership costs, and provided a context for subsequent feedback.

- **Homebuyer Awareness and Interest in Efficient Appliances** – Building upon overall importance of energy costs, we explored consumer interest and awareness of energy efficient appliances, focusing on the influence of specific product attributes on perceived value.

- **Homebuilder Perception of Recirculating Pumps and Tankless Water Heaters –** Both devices, currently sold in the CREWH target market, are potential competitors to CREWH. This portion of the discussion explored homebuilder opinions regarding the current and potential market for these devices and set the context for exploring the market potential of CREWH

- **Hot Water Use And Wait Time** – One of the potentially significant benefits of the CREWH is reduced wait time for hot water at faucets that are distant from a storage hot water heater (i.e., kitchen, bathroom). The focus group therefore sought to explore whether this is an issue for homeowners and, if so, the significance of the inconvenience and what steps were taken to address it.

- **Response to Product** – Information was provided on the product, including pictures and a brief technical explanation of product design. Initial impressions were then solicited from homebuilder and homebuyer perspectives, including concerns that came to mind and potential benefits as seen from a consumer perspective.

- **Interest in the Product** – Following a discussion of initial responses, we reviewed in more detail (1) homebuilder interest in offering and installing CREWH and (2) homebuyer interest in obtaining CREWH.

- **Suggestions for Improvement** – Recommendations were solicited that would improve the design of the product and meet consumer needs.

- **Suggestions for Marketing** – Recommendations were solicited for introducing and promoting the product within the marketplace.

The issue areas as specifically defined for each focus group are listed in Table 1-1, below.

Table 1-1: Issue areas by Focus Group

CREWH Focus Group Topics	
Homebuilders	**Homebuyers**
Perceived Homebuyer Attitudes Related to Utility Costs	Homebuyer Attitudes Related to Utility Costs
Perceived Homebuyer Interest in Efficient Appliances	Homebuyer Interest in Efficient Appliances
Hot Water Use and Wait Time	Hot Water Use and Wait Time
Response to Product	Response to Product
Builder and Contractor Interest in the Product	Homebuyer Interest in the Product
Suggestions for Improvement	Suggestions for Improvement
Suggestions for Marketing	Suggestions for Marketing

1.3 Report Organization

Within this report, we provide a summary of each focus group. This summary parallels, approximately, the structure and flow of each group as it occurred. At the end of each section, we provide a summary of recommendations provided by the participants that relate to the overall CREWH design and the ways in which such a product may best be marketed. Finally, we provide a summary of market issues based upon the feedback and insights provided in these focus groups.

2. BUILDERS AND CONTRACTORS FOCUS GROUP FINDINGS

2.1 Focus Group Composition

Since the installation of a CREWH unit requires the installation of additional plumbing that is best done during the initial construction of a home, the new home construction market is considered a primary target market for this technology. Moreover, since the units are likely to be more costly than other refrigerators, it is assumed that early adopters will be owners of higher-end homes. As such, the first of the two focus groups was comprised of individuals involved in the design, specification, and construction of newer, high-end homes in the Sacramento area. The group included eight people from different companies that complete a significant amount of work in new residential construction in the Sacramento area. Seven of the eight participants work for companies specializing in residential construction, including two purchasing managers, one purchasing manager and contractor, three purchasing agents, and one vice president. The remaining participant is an estimator and supervisor for a plumbing company. While none of the participants in this group had participated in the Zero Energy Home program, each of the residential construction companies represented participates in utility energy efficiency programs run by the Sacramento Municipal Utility District (SMUD). Participants were also pre-screened for awareness of domestic hot water recirculation systems, a possible competing product to CREWH.

Table 2-1: Homebuilder Focus Group Attendee List

Name	Company Type	Title	Zero Energy Home Builder?
Stacy C.	Homebuilder	Purchasing Manager	No
Jim H.	Homebuilder	Purchasing Agent	No
Dana M.	Plumbing	Purchasing Manager and Contractor	N/A
Ron M.	Homebuilder	Estimator and Supervisor	No
Lynn O.	Homebuilder	Purchasing Agent	No
Patrick S.	Homebuilder	Purchasing Agent	N/A
Greg N.	Homebuilder	Vice President	No
Mike V.	Homebuilder	Purchasing Manager	No

2.2 Perceived Homebuyer Attitudes Related to Utility Costs

To better understand the importance of energy costs among the homebuyers that builders consider within their target markets, we first discussed homebuyer attitudes toward utility costs. Builders reported that, based upon their experience, consumers are concerned about utility costs, and that there is some consumer interest in options that will assist them in lowering their utility bills. Significantly, these builders also noted that, especially in some jurisdictions where water is quite costly (*e.g.*, Elk Grove, water costs appear to be a greater concern for customers than the cost of electricity.

- "It isn't the gas or the electric to heat the water. It's getting to be the cost of the water."

- "We see more options being picked up for some of the tankless [water heaters] and some recirculating [pumps] they were talking about in the past. But [the options] vary from area to area."

2.3 Homebuilder Perception of Recirculating Pumps and Tankless Water Heaters

To enhance the discussion of the viability of CREWH in the new construction market, homebuilder group members were prescreened to ensure awareness of recirculating water pumps, a potential market competitor to CREWH. Additionally, all members had familiarity with a secondary potential competitor, point-of-use (POU) tankless water heaters which provide instantaneous hot water at the tap. While some of the homebuilders have installed the POU tankless water heaters, their future viability is expected to be limited by a provision of Title 24 of the California Energy Code that penalizes electric resistance water heating.

Builders offer recirculating pumps and point-of-use tankless water heaters to homebuyers as devices to reduce the wait time for hot water, particularly for homes with significant distance between the water heater and water outlets. While currently there is not a large demand for these devices, some builders offer recirculating pumps as standard in higher end homes and as an option in other homes. The primary application of these devices is in master bathrooms, but the devices are also used in kitchens.

One participant noted that, while recirculating pumps do provide hot water more quickly, as currently designed they do not yield energy savings.

- "It's [recirculation pump] such a waste because you are heating the water 24/7 as opposed to on demand hot water, which a tankless unit just does. It just runs right through and gets hot."

One builder, noting upcoming changes in the state energy code, felt that there will be a decline in the market for storage water heaters, stating:

§ "I think the Title 24 changes coming in to affect this year will produce big changes with the 26-watt kitchen lights and all that. I think that's going to make the home builders think twice about using tank heaters."

Finally, group members noted that energy efficient appliances have to compete with other optional features which homebuyers may find more attractive:

§ "We will put it [recirculation pump] in as a standard in higher-end homes. But everything you can always get as an option."

§ "We do it [recirculation pump] as a feature on our more expensive products like he was saying. On some jobs we did it as optional. But it's not a very popular option."

§ "It makes a big difference whether it's a one story or two. On some larger lots we build a one story and the master bath is maybe 90 feet from the water heater. So we put one in automatically."

Statements from others in the builders group illustrate that these and other devices compete for the homebuyers' attention with more visible home options:

§ "I don't think there is really any price point [for recirculating pumps.] I think that it's just a matter of being low on [homebuyers'] priority lists. People would rather have a granite counter top in the kitchen."

§ "People want their friends to walk in and say, 'Oh my god your counter tops are beautiful. Your carpet is gorgeous. Look at all your Travertine tile. Look at your $20,000 Sub-Zero Wolff package kitchen.' I mean that's what they want. They buy a Mercedes for the same reason. They want to be seen in it. They want their friends to drive by. Conspicuous consumption is what we are all about. And you know if you put a three cornered star in front of that thing you might be able to do something with it. But I don't know."

2.4 Hot Water Use and Wait Time

When asked whether or not the perceived hot water wait time to be an issue among new home purchasers, homebuilders reported that this is indeed an issue. Importantly, however, this issue is perceived as being of greatest importance in the bathroom rather than in the kitchen. While this concern is directly related to the obvious issue of comfort, it is also related to a perceived cost of wasted water and energy associated with waiting for hot water.

§ "We have found that [the kitchen] is the second most important place to have the hot water [recirculation pump.] We do the Grundfos. We put the valves in the master and one in the kitchen."

§ "I think it [water efficiency] is a big reason especially in the Elk Grove area with the Elk Grove Water District. The fees are so high. People are talking about having to run their hot

water for—however long—two minutes, three minutes, whatever before it gets hot. Then they get a $700 water bill."

§ "Typically your kitchen is near your garage. And typically your water heater is in your garage. So it's not a common complaint [about kitchen hot water] but it does happen on occasion."

§ "I would say it's more of a complaint in your master bathroom, which tends to be in the back of the house."

§ "You are not bathing in the kitchen. That's the big thing…I mean you could still wash dishes. Using warm or cold even."

2.5 Response to Product

The group was provided with a diagram, photos, and verbal description of a CREWH (copies of this diagram and the photos are included as the appendix to this report). The initial responses were ones of curiosity regarding the amount and temperature of hot water it would be able to provide. The group then discussed product durability, liability and installation logistics:

§ "How big is the tank?

§ "How many gallons of hot water is this going to be putting out in let's say an hour or twenty minutes? The time it takes to use the kitchen faucet and do the dishes?"

§ "I think you've got a good theory but I think you have some challenges in engineering. And I understand the theory there. I'm not totally convinced that the refrigerator discharges enough energy to heat this as it keeps heating over and over again. But it's possible. But I think from a builder's standpoint you are up against some challenges. Like dollars and practicality. But I think the theory is something that they could work if it was engineered."

Hot Water Temperature

The hot water generated by the CREWH, as designed, will be hot but not scalding in temperature. When asked if this would be an issue, specifically, the group did not see the need for the water temperature at the sink to be hot enough to sanitize dishes:

§ "Nobody is going to use it for 140 at the faucet."

§ "Sanitizing-wise, what is it supposed to be 140?"

§ "A dishwasher uses 140 for that [sanitizing]. It makes it hot to get grease and butter and stuff off of plates, which is not hot enough [to sanitize.]"

Long-term Performance Issues

Some builders were concerned about longer-term issues, such as the performance of CREWH over time, or changes related to home resale:

§ "You know the demand placed on that tank contracting and expanding all the time could lead to some issues down the road with failure of the tank [in the refrigerator]."

§ "Well if you've got hard water over time. The softener builds up inside there [heat exchange coils] and you lose the efficiency of the heating."

§ "I don't know that you would recognize the benefits that soon, if ever. What if you sell the house and they want the fridge and whatever. If the tank goes to pot on you in a couple of years you just never know. I don't know."

Expense of Installation

Regarding installation, builders felt that plumbing for this would be a relatively inexpensive, but noted that plumbing logistics would force a decision to install CREWH early in the construction process:

§ "It [the cost] varies though if you have a kitchen sink and you have a little bit of counter space in the refrigerator at the end or if you have a kitchen sink here and the refrigerator is at the other side of the kitchen. Sink in the island. Two dishwashers in the island. It could be as a little as $150."

§ "It's not that much because you are not running additional waste lines. If you running a home run [it would cost more.] If you are using a standard system, maybe a hundred bucks at the most."

§ "You would have to get the plumbing in for the system early in the construction process."

§ "If it was really close to the sink it would be a real slam-dunk. You could do it all at trim like a dishwasher. It wouldn't be much at all. It, just hook it through the back of the cabinets."

Installation Liability

Most significantly, this group was concerned about potential liability issues related to the installation of the appliance, with builders citing possible contractor liability for damage due to improper installation:

§ "Just being a devil's advocate I don't know what your target market is but, as a builder, we would be very, very reluctant to offer something like this and we offer refrigerators per se. But we don't sell them because of the liability of the leaking. If something leaks, we buy the floor, we buy the walls, and we've bought the mold. We buy everything.

§ "It's disastrous. The reason I'm bringing this up is that we recently replaced a hardwood floor to the tune of $22,000 for a $375 water filtration system that we sold somebody. That was a really good business move for us."

§ "Another possible leak. On a wood floor in this case here where your liability. We all get sued for everything, everyday now. If the roofer makes a mistake, if the plumber gets called in cause of water. I would be scared of that from, in tank water heater ten to fourteen

years in a water heater. If you just got the newest of tanks, what have you, ten to fourteen years and they are cracking and then we put in a new floor in."

2.6 Builder and Contractor Interest in CREWH

Many in the group indicated that their interest in the product was limited, stating that they avoid installation of refrigerators and other appliances in general. Reasons for their limited interest include: (1) appliances other than "built-ins" are not a core part of their business; (2) builders are hesitant to install a product they view as unproven; (3) there is perceived risk of premature product failure due to the hot water tank failing before the refrigerator; and (4) product style and selection may be very limited and restrict consumer options.

Appliance Sales Not Part of Core Business

Builders noted that, while they will sometimes sell appliances to consumers, they are not motivated to do so because of the cost of "hand-holding" consumers through the decision-making process. Representative quotes include:

§ "We'll sell some people refrigerators, but if you look at the price you are going to pay for that refrigerator it's going to be nearly double than if you go down to Best Buy, or Frye's. I mean we are going to make you really think about that purchase."

§ "People bring it with them. They already own it. Do they want to buy another one? And when they buy a house. They always say will wait maybe do it in a few years."

§ "It [a built-in refrigerator] is a higher-end product and people are not going to split hairs over $6,000 when they are buying an $800,000 house. They just want it done and something like that we'll take every precaution necessary to make it work. But in terms of $350,000 - $450,000 price point we are not even going to touch a refrigerator."

Unproven Value

Two of the builders in the group indicated that they would be hesitant to recommend or install a CREWH because it is unproven in terms of performance and value:

§ "We're an 86 year old company and we are that way for a reason. We are extremely conservative. I don't think we would offer this product for a couple of years to let the bugs worked out of it. And let somebody else buy some hardwood for awhile. And I'm not saying that we wouldn't eventually go there but we are very rarely on the cutting edge of products and systems when it's talked about for a long term on a house."

§ "I think anytime you can conserve water, conserve energy, especially as we move in to the future --- are fewer and it's a great idea. But I don't think that we would. This isn't something that we would be trying to push on our homeowners. Because we are trying to tout so many other energy efficient products that are tried and true…"

§ "You have some challenges from a builder's standpoint there that are pretty tough to overcome. And you've got to realize too it's just a kitchen faucet there. It's not one of the biggest complaints we get."

§ "You could solve the engineering challenge with this, but builders here are going to be reluctant to offer this --- until it's been tried and proven."

Product Failure

Contractors focused on the potential for tank or connection failure:

§ "If we as builders could get away from offering an icemaker line, I bet we would. Because that is the only connection in the house that the buyer deals with on a regular basis other than maybe the washing machine. At least you can see the washer. But that one. If he puts his fridge in the day he moves. And think about it the copper line nine times out of ten is a compression fitting. If it moves just a tiniest little bit. It's going to drip."

§ "My refrigerator at home is getting close to fifteen years old. I hate to necessarily have to replace it [a refrigerator] because of a tank."

§ "It's the connections that I see. I know you have one hose or however tubing line now. What would you have? Just have three? You would have a hot water in and cold water in and a hot water out. So you would have three lines running out the back of the refrigerator when you'd connect up. And then you put the refrigerator back in and it's bad enough now with one hose."

§ "Even if the appliance leaked. You could probably ----. If you could sue anyone you want too. If the appliance leaked go talk to GE. It's their appliance. We don't have anything to do with it. We don't repair it. We don't touch it. But if the connection failed and we were installing it boy we are right there in the chain of liability. And here's another thing to throw out. If it leaks, a couple of drips a day. Nothing big. You don't notice it for six months. All of a sudden you pull it out there and you got black mold all over the back wall. Cause it's hot, dirty, and it's wet."

Limited Product Selection

In those cases where homebuyers want to purchase a new refrigerator, group members indicated that buyers would not want to be limited in their selection:

§ "The other thing you have to think about too is the woman's perspective on this. Is she going to buy the house? Is she going to be stuck one with one refrigerator style."

§ "If all the women liked one refrigerator it would be at Circuit City. But there are $1800 refrigerators out there and who wants a bottom freezer who wants a top freezer who wants a double door. Who wants this?"

2.7 Suggestions for Improvement of CREWH

Feedback was solicited on ways that the CREWH could be modified or otherwise improved for acceptance in the marketplace.

Solutions to Minimize Potential for Leakage

Some group member offered engineering solutions for reducing the possibility of leakage, and for making the connection more visible to enable buyers to watch for leakage. Another noted that it would be important that the device be one that could be installed quickly:

§ "You would really need to come up with a connection system for the ends of the hoses that would be a quick disconnect. Foolproof. Aircraft quality."

§ "If you had those connections to the appliance upfront maybe behind the access panel. That would be half a solution. Then they are going, typically the connection in the wall is behind the refrigerator. I mean there is probably a better way to do it. But I don't think you want both of those connections in the back of the refrigerators."

§ "And it's got to be built so that he can put it in fifteen minutes. It can be a three-hour process to put it all together."

Interest in Hot Water at Refrigerator

While initial suggestions from the focus group focused initially on strategies for limiting the possibility of leaks and leak damage from the additional plumbing connection, the conversation then transitioned toward the possibility of modifying CREWH to be a refrigerator accessory, providing hot water from a spout in the refrigerator door:

§ "Not that there would be a lot of demand for it. But is there consideration for just being a hot water dispenser on a refrigerator? Like a cold water dispenser, a hot water one?"

§ "That would be neat because you are getting ice water out of there all the time, why not get hot water?"

§ "And it frees up an extra hole on the sink, which the plumbers always love. So they can put another soap dispenser or a lotion dispenser or whatever."

§ "Like I said they want their friends to be going, "Ooh! Wow! That's neat when they walk in. Showing them a hot water tank isn't going to blow their shoes off."

§ "So the more benefits you can generate. Now you just went from one to three. You went from just the kitchen sink to the dispenser to the refrigerator to the dishwasher. Now you've got three functions of this unit, which lends itself to an energy package for lack of a better term. Here is our normal appliance package but here's the energy package and this is what the energy package can do for you."

2.8 Suggestions for Marketing

Group members felt that the device could be marketed effectively as a feature of a high-end refrigerator line, preferably as an in-door, instant hot water source instead of as a device for heating water for use at the kitchen sink. However, one felt that the initial market would be limited to homebuyers that were particularly interested in energy and water efficiency. Others felt that it could it sell if bundled with other appliances as part of an energy efficiency package.

The group also noted that, due to plumbing logistics, a homebuyer would need to commit to having this feature early in the construction process. Members also felt it was important to recognize that CREWH would be competing with other options considered by the Homebuyer.

Group members felt that a point of purchase utility rebate would be a good way to boost consumer interest in the product.

Builders also described the product supply chain for appliances installed in new homes, and indicated the importance of working with large appliance manufacturers and large builders to have the product installed in new homes. One suggested partnering with a major distributor that enters purchase contracts with major home builders.

- "If this refrigerator is just presented as a freestanding product with nothing else, or no other line of appliances to go with it. If your salesman comes in to my office and says hey we've got this fridge we want you to put in to the marketing program then no way."

- "But again I think if it were me I would still target the built-in model as the strategy to carry this thing in to the market with. Just because of the cost that's going to be involved."

One participant felt that the initial market would be consumers who are particularly aware and concerned about energy efficiency, and that the market for additional options was currently limited by a tight market:

- "I would submit that that's going to be your target audience at first. Somebody who is savvy enough to want to recognize the benefit of that system. Because it's going to be expensive. There is going to be added cost. With the affordability being a problem then it is right now in California. If people who are squeaking in to their very first home or even their second home. Are they going to want to go out and spend a couple of grand, $500 for a new fridge if they don't have to? Like you said. The builder can't afford to do this as a standard. And how many home built buyers are going to spend $3,000 for this upgrade."

- "Not if it doesn't come in a Sub-Zero or a Thermador or a Kitchen-Aid or Viking."

Builders also discussed the current practice of bundling various construction options to appeal to specific customer groups, and suggested that such a device could be included as part of an energy efficiency package:

§ "You package the options that make it more attractive to the buyer. And this is what basically all our appliance packages are just that. When we sell we don't just sell them a monogram dishwasher and all the standard other stuff. We sell them a Monogram package and everything matches. So this would lend itself very well to an energy 'package.'"

Builders noted that CREWH would have to be an early cutoff option due to the need for additional plumbing:

§ "And then I think, which is going to be first, are the builders going to make provisions in selling the house to accommodate this or is this going to be on the market and then the builders [have to accommodate for it.] If it's a very common appliance then builders can plumb the house. But I think the refrigerator has to have a hot water dispenser on the door with a hot water tap that can be tied in to what is it on the back like with cold water that comes in to it or not. It can feed the dishwasher, kitchen faucet or whatever. But you just can't come out of the chute with a new refrigerator designed while the builders [haven't plumbed] the house that way."

One group member felt that homebuyers would be hesitant to purchase this option because it competes with options they would be considering:

§ "That would have to be an early cutoff option. And a lot of times buyers are hesitant to spend all their money right up front because they get in to the process and they want to see what they've got left over in their budget and then say okay. We've got an extra couple of hundred bucks I guess you can have this surround sound speakers you want or whatever the case may be. The cutoff factor is going to be a problem."

Homebuilder group members felt that rebates for plumbing for CREWH installation, and for the CREWH itself, would aid in market acceptance:

§ "I would envision particularly if PG&E or somebody had a rebate for this. It would maybe be a rebate to have the house built to have this plumbing in this way so it could be hooked up if somebody had this kind of refrigerator, if it was in the market and available."

§ "I believe PG&E does give rebates when you buy certain items with energy ---. I think you could offset some of the cost of that with the --- like that. I don't know exactly how much but it is. But you know they offer things like that. They are pretty good. Municipalities do [offer rebates] as well."

Two of the group members discussed the importance of working with large manufacturers and homebuilders to get CREWH market share:

§ "Keep something else in mind when you are approaching the big builders is that a lot of us, and I'm sure you guys are the same way have contracts with existing appliance suppliers. I know we do. Well there are a lot of rebates and national regional contracts with every product that's made that's in the house."

§ "You offer the builder a substantial rebate to offer it as a standard. Just to get some market share and get some exposure for the product. A bigger builder is probably one you are going to want to approach to do that."

2.9 Summary

Because CREWH is likely to require the support of designers, builders and contractors, attitudes and opinions expressed in this group could significantly influence a homebuyer's purchase decision regarding CREWH. The following issues surfaced as the most significant in terms of their potential impact on homebuilder acceptance of CREWH.

§ Water and energy costs are of moderate concern among new homebuyers, but to date these issues have not a significant influence on sales of non-required energy efficiency appliances and measures.

§ Larger, higher-end new homes have provided a limited market for recirculating hot water systems, which reduce hot water wait times. Builders feel that expansion of markets for these devices are possible.

§ Builders and contractors were concerned about potential liability from CREWH installations, due to potential for leakage. Similar concerns were not expressed regarding installation of the potentially competing products, tankless water heaters or recirculating pumps.

§ Builders felt that CREWH may not fare well as a new home option. The group noted three limiting factors. The first is a general downturn in homebuyer purchases of "add-on" options in recent years. The second is availability of competing options that are more visually appealing or add more comfort or convenience. The third is competition with proven energy efficiency devices that are currently on the market.

§ Builders felt that CREWH could succeed if the system was completely incorporated into a higher-end refrigerator, adding the hot water dispenser to the cold water and ice dispensers. Builders noted that this would reduce builder and contractor liability for the product, and fit into the existing supply chain for new home items.

3. HOMEBUYER FOCUS GROUP FINDINGS

3.1 Focus Group Composition

In order to assess potential consumer interest in CREWH, we recruited a focus group comprised of individuals who were considered to be similar to the target market for this product: purchasers of mid- to higher-end homes (i.e., valued at more than $350,000) who are likely to place significant value on minimizing hot water wait time. The resulting group of eleven people was comprised of recent purchasers of higher-end homes with kitchens located more than 20 feet from a storage water heater (a proxy for likelihood of experiencing delays in hot water), representing a potential market for the CREWH technology. A summary of participant attributes is provided in Table 3-1.

Table 3-1: Homebuyer Focus Group Attendee List

Name	Home Value at Time of Purchase (Q6)	Homebuilder (Q7)	Development / Community Name (Q7 cont.)	Distance From Kitchen Sink to Water Heater (Q8b)	Age (Q9)	Marital Status (Q10)	Employment Status (Q11)	Ethnicity (Q12)	Income (Q13)
Renee F.	$450-500K	Elliott Homes	Silverado Arbor	100 Feet	42	Married	Homemaker	Caucasian	$100,000-$150,000
Amber F.	$450-500K	Forecast	Woodcreek	30 Feet	27	Married	Homemaker	Hispanic	$75,000-$100,000
Seth P.	$500-550K	Cresleigh	Cresleigh Springs	60 Feet	33	Married	Full Time	Caucasian	$50,000-$75,000
Walter G.	$600K+	Morrison	Silvergate	40 Feet	44	Married	Full Time	Asian	$150,000+
Andrea A.	$450-500K	Renaissance	Park at Natomas	35 Feet	34	Married	Homemaker	Caucasian	$75,000-$100,000
Michael W.	$450-500K	KB Homes	Westlake	20 Feet	27	Married	Full Time	Asian	$75,000-$100,000
Steven W.	$450-500K	Cresleigh	Cresleigh Springs	40-50 ft.	35	Married	Full Time	Asian	$75,000-$100,000
Mike F.	$450-500K	JMC	Windsong	100 Feet	44	Married	Part Time	Caucasian	$75,000-$100,000
Branka P.	$500-550K	Wincrest	Saratoga	20 Feet	40	Married	Full Time	Caucasian	$75,000-$100,000
Peter L.	$450-500K	Lennar-Renaissance	Monterey	95 Feet	48	Married	Full Time	Caucasian	$100,000-$150,000
Greg F.	$500-550K	Lennar-Renaissance	Somerset	90 Feet	36	Married	Full Time	Caucasian	$150,000+

3.2 Homebuyer Attitudes Related to Utility Costs

In order to assess participant experiences with utility costs, consumers were first asked to rank the importance of energy efficiency in their home using a one to ten scale, where ten indicated high importance. While most of the participants gave ratings of seven and eight out of ten, two indicated that the energy costs in their new homes were actually less than they had anticipated:

§ "We moved from the Bay Area, and we thought too that the bills are going to be expensive, but they are way less expensive."

§ "I was scared moving into a much bigger house, [especially] about the bills, heating and air conditioning. But they were probably 50 percent or less. It's great."

3.3 Homebuyer Awareness of and Interest in Appliance Efficiency

Homebuyers named various features of their homes that they consider energy efficient, but none named more than one energy efficient feature. Features mentioned included Smart Vent (a nighttime ventilation system), dual zone heating, skylights and recirculation pumps. In describing these measures, participants tended to discuss attributes other than energy and water savings, referring instead to increased comfort, product technology and other benefits and features. Further, while recirculating devices can be used to save energy, neither of the participants with recirculation pumps in their home is using the controls necessary to operate the device efficiently. All homebuyers had purchased refrigerators from retailers rather than homebuilders. While many report looking for the "energy savings" sticker when shopping for refrigerators and other appliances, it appears from comments that amenities such as large appliance size and in-door water and ice delivery were more significant in influencing refrigerator purchases .

Illustrative quotes about energy efficiency measures:

§ "We have dual zone, so the upstairs and downstairs has their own heater and air conditioner so I think that helps."

§ "One feature we have is a huge skylight, so it's always bright and we don't have to turn on the lights all the time."

§ "One of the features that I think helps us a lot is the Smart Vent that we have."

§ "Our house has low e-glass—the energy efficient glass. I also have sun screens in the back of the house which gets most of the exposure, and that drastically improves the energy in the summertime."

§ "[The recirculation pump] has a timer that's connected to the hot water heater. And it goes through all the plumbing in the house for the hot water. So what happens is this hot water in the pipes 24 hours. You turn on the faucet, you hardly wait 1 or 2 seconds and the hot water is right there."

§ "It [the recirculating pump] is the best thing that's ever happened, because we had the same problems [delay in delivery of hot water] in our other homes, and it was a nightmare."

§ "It is constantly circulating, 24 hours a day. You can put it on a timer if you want to save a little bit more energy. To come on at 6:00 to 9:00 in the morning, and then to come on

again in the evening. You can put it on a timer if you want. It has that facility, but we leave it on 24 hours."

None of the homebuyers indicated purchasing appliances through their builder, with all naming "big box" stores (Home Depot, Fry's, Lowe's and Sears) as the source for appliance purchases. The majority of the participants own side-by-side refrigerators, and four mentioned crushed ice and ice water as "front door" features. Two noted the relatively high cost of purchasing appliances through the builder:

§ "It's more expensive."

§ "The [appliance] upgrades are expensive."

3.4 Hot Water Use and Wait Time

The majority of participants reported that they were inconvenienced by the wait for hot water in the bathroom, the kitchen, or both places. Some participants were also moderately concerned about the amount of water wasted while waiting for hot water. Factors noted by consumers as contributing to the delay in hot water included (1) the distance from the water tank and (2) cold winter temperatures. Various members also reported being frustrated by low or fluctuating water temperatures at the kitchen tap and the dishwasher.

The selected quotes indicate the level of inconvenience caused by hot water delay:

§ "In terms of hot water it's terrible, in the wintertime especially, to turn on the kitchen faucet, which is the furthest spot from the hot water heater, and wait, and wait for hot water. There must be a better system out there to improve circulation of hot water that builders should be offering homeowners."

§ "Forever. We just run it. When I go to take a shower, I turn on both my husband's and my sink, and the shower, and just let it run for 3 minutes, maybe 4 or 5 minutes."

§ "Especially in the mornings. That's when it takes the longest. In the evening, maybe about two minutes."

§ "It's probably the most annoying thing about the house."

§ "Maybe because it's colder during the winter, so it takes longer. So, I tend to run my dishes, and do all my wash in the evening, if I'm going to take up more warm or hot water, it's not a long wait. We take our showers in the evenings. I don't take them in the morning, it's too cold."

Two participants expressed some concern regarding water waste resulting from the wait time for hot water:

§ "Seriously, my husband and I get so irritated, because we're on a water meter. Not that water is that expensive, I was kind of scared going to a meter, coming from Sacramento, but

it's worked out to be actually less to be metered versus non metered. But we're kind of freaked out about it…I'm always saying, 'turn the water off, turn the water off,' but you have to be that way."

§ "I don't think it's wasting as much water as we thought too, because it's still a meter, you're going uh oh, but in terms of energy, a hot water heater's got to fire up again, and it's got to be a system other than your circulating system that's circulating the hot water, and you have hot water, there's got to be a better system out there."

One noted availability of hot water as an issue despite his use of a recirculating pump:

§ "I have the circular [recirculating pump], but the problem, for some reason, in our house, when we turn in on, my water is not hot enough. When I turn it off, I get hot water. I get it fairly quickly. I don't know why. When I turn it off, I get water which is more hot, which is what I like."

Several noted that low or fluctuating water temperature at the kitchen tap was a frustration:

§ "Yeah, and then as I'm washing dishes, you know you turn on the water to rinse, it'll be cold again. So, I'll have to warm it up, and move it back to rinse the dish. It's really bad, like she said; it was like the first thing that we noticed about the house upon move in – why are we waiting so long for hot water? It just seems like it's talked about all the time."

§ "The kitchen is the longest wait, because it's the furthest point from the hot water heater. If you run your dishwasher, the water in the dishwasher is cold because it's filling up with cold water so your dishes aren't as clean. It's just not energy efficient; it's not effective at all. I have to turn on the water in the kitchen and probably wait 3 to 5 minutes as well.""

§ I just turn it on to rinse in the other half of the sink. But it'll be cold."

§ "It's amazing how fast it [the water temperature drop] happens."

§ "I think I leave the water on when I wash them, the whole time; I don't think I ever shut it off. Is that bad?"

3.5 Homebuyer Interest in CREWH

Participants were introduced to the CREWH concept and shown pictures of a prototype installation. The initial response of homebuyers was guarded, and focused on product cost, installation issues, and energy savings. However, they felt that if these issues could be addressed, they would be interested.

Homeowners expressed a qualified interest in CREWH, noting that a new homebuyer would consider the product in relation to other, more visible options. They also discussed the resale value of CREWH, and the possibility of plumbing the home for later installation of CREWH.

The group also discussed the concept of CREWH as a device that provides hot water at the refrigerator door. Women in the group, three of whom were full-time homemakers, saw it as a feature that would be helpful in food and drink preparation. They showed greater interest in the device than did the men. Various members raised issues about hot water safety.

The moderator suggested an additional cost of $500 for this feature. The group was generally favorable to this amount, but some participants were tentative due to concerns about cost-effectiveness, and to interest in competing options. One member felt it would be an improvement over the recirculating pump.

Initial Questions

Some illustrative examples:

§ "How much more would it be then the usual ones that we buy?"

§ "Installation, plumbing it in. It doesn't sound like someone who is a weekend warrior guy could do. It's not just like hooking up the automatic water ice maker was challenging enough. So that would be my question, installation, are there installers, what is the cost of installation on top of the cost of the unit itself, and then overall savings. I'm a number guy; I'd have to see the numbers of what the savings would be."

§ "Did the homebuilders feel like they could put it in?"

§ "Already pre-plumbed for that. You sell the home three years later and get an older home on 3 acres that is not pre-plumbed, can you go out and fix it yourself or how much does it cost to hire a plumber to do it."

§ "Is it available in a size that I want?"

Concern about Potential Leakage

Homebuyers did express some concern about possibility of leakage from the CREWH:

§ "I'm thinking about my husband, he's big on aesthetics, and how things are working and safety also. He would be asking what is the chance that the five gallons leak on the hardwood floor."

§ "I didn't think about it, but she brought up a good point."

§ "What's the chance of all that water ending up on the floor?"

Perceived Benefits

Group members discussed the benefits of CREWH:

§ "It's a wonderful idea, because I stand at the refrigerator and my toes are all hot. I'm going man this heat has got to be used for something. So whoever came up with the idea is brilliant, but, the efficiency would be my question."

Three participants described reduced wait time for water as a convenience that would be appreciated by parents:

§ "It's a convenience to have my kids wash their hands instead of saying 'Dad, it's cold.'"

§ "…While you're holding them up."

§ "I don't have to hold them up, just hear them complain. Yeah, just turning that hot water on to do the dishes and having to stand there for like it's literally three minutes if not longer."

Value Relative to Other Options

The following representative quotations address the need for CREWH to compete with other building options:

§ "I don't see it as a major feature that is going to sell my home or make it the better home next to the house next door that's the same home. It's not like an upgrade of tile or crown molding or hardwood floors or a swimming pool. It's not going to…it would not sway me to buy the home or if the home was on the market. If it was an option in a new residential development, then it'd be something that I'd seriously take a look at, same as wiring surround sound, crown molding, or tile, but then again, it's whatever my wife says goes, I'm just along for the ride."

§ "Yes, because this is our second new home and doing upgrades, obviously the builder, that's where their bread and butter is. It's not just buying the home with standard stuff, it's when you start adding crown molding or tile, or this or that, that when they make their money. As a consumer or home buyer, my bank is only so wide. I can only say ok we're going to do tile, and we're going to upgrade our counter tops or whatever, then you get to, ok, what about this option."

Value of Energy Efficiency Savings

Homebuyers expressed a desire to have assurance that CREWH would yield energy savings:

§ "Sometimes when you buy new refrigerator, they have the energy efficiency label, [indicating] how much you can save in one year. Maybe they could do something like that, how much energy you could save with that gizmo."

§ "I also think that numbers would be good. Why…for example I bought an energy efficient washer and it's amazing, and I'm looking for those things."

§ "The same with these, that's what you've got to [show] them. You pay up front, but you're going to get it back later."

§ "That's what the consumer needs to know."

§ "And they're much more expensive then the regular, but you save in the long run."

Resale Value

Group members were also concerned about the resale value of the CREWH when a home is sold:

§ "Cosmetically, is it going to help in the re-sale of your home? Those are the things that I would take to look at, but again I need those hard numbers to decide. If it's a $100 upgrade, it's not such a big deal…"

§ "If I sell the home, will they say hey everyone check this out, hot water!"

One respondent found value in having the house plumbed so that there would be the option for later CREWH installation:

§ "I also think that just having the option if you have this upgrade put in your house, you wouldn't have to buy this fridge right away, but if you wanted to later on, it's all set up to do that."

Hot Water from Refrigerator

After discussing the CREWH in their current configuration, the idea of configuring the CREWH to provide hot water from the refrigerator door was presented. While many had lukewarm opinions about the CREWH as a device for heating water at the kitchen tap, several changed their mind about the product when this option was presented:

§ "Yes, it changes mine."

§ "It would definitely change that for me too. I would love that feature. I love the hot water on the water jugs, the water tank at work or whatever."

§ "I used to live in Japan…and they have what's called a hot pot. What you do, is you put water in there, it's usually made for to make tea, but they have a feature where there is temperature gages, so you can make it, I forgot what the temperature is, it's not in Fahrenheit, it's in Celsius but, for children's bottles, so if they had something like that in refrigerators [it would be good]."

The women appeared more interested in the CREWH in this configuration than were the men. Women also asked about the possibility of having a water filter added as a feature:

§ "As a woman, and I use a lot of hot water with the cereals and stuff, and I've got kids, and mine are 9, 10 and 13, that would be a better seller then if it was just what you were talking about."

§ "If it would go through a filter as well, that would help. For example I use the water from the refrigerator to cook and for bottles and stuff like that."

§ "I have to heat it all the time because it's really cold. And that's the downside about it, what I don't like about it. It would be nice if I could get warm water, filtered."

Men were more hesitant about CREWH, with several indicating that it wasn't a device they would use, but one that they might agree to if their spouse was interested:

§ "I'm still trying to figure this out. I go [to the refrigerator to] get a glass of water or pop."

§ "But women are the ones that make those final decisions."

§ "If we're debating over a $100 over the fridge that has this and the one that doesn't, I'm saying spend the $100 so that I can get home."

§ "And I guess men and women think differently, so men might see it as efficient, but women might see it as more convenient."

One participant felt that CREWH wouldn't work in her community as an instant hot water device due to water quality issues:

§ "That feature wouldn't work well in Elk Grove and Laguna because a lot of those homes out there were forced to get a soft water system. We need to boil water we use that, we never use the water or the ice either. Just because it's filtered, it's not, it still tastes different. It's not the same way."

Safety Concerns

Some participants expressed safety concerns related to possible scalding from the hot water:

§ "If would have to be labeled in maybe a red for hot."

§ "You'd have to have a lock on it to for little kids."

Participants were asked whether they would pay an additional $500 for a refrigerator with this feature. While some felt this would be reasonable, other indicated that the feature would be competing with other building features, and that they would have to be convinced of its cost-effectiveness:

§ "That's not bad at all."

§ "That's not bad, but I would have to agree with Steven, I'd have to see what the savings is on – show me what the savings is. If it's $500, it's going to save me a $100 a year, in 5 years, I'd make my money back, that's how I'd kind of look at it."

§ "Waiting for the hot water is an inconvenience, it's kind of a pet peeve, but the lighting in my kitchen is terrible so I'm doing all new lighting, and I would do that because it's a direct effect all the time, compared to winter time."

§ "So I'd rather have hot water coming especially straight from the fridge and than from this recycling [recirculating] thing, I don't like it."

3.6 Suggestions for Improvement

As previous comments suggest, homeowners strongly favored CREWH as a device that would be provide hot water from a tap in the refrigerator door. Additionally, some participants felt that the ability to adjust the temperature would be an important feature:

§ "And if you had to adjust it, if you could make ones that you could adjust, is it going to be on the back of the fridge, can you get easy access to it."

§ "If you had a temperature adjustment, if you go up to 160 or whatever you were talking about."

3.7 Suggestions for Marketing

Participants felt that first time buyers would not be interested in this appliance. However, one participant felt that it could succeed as part of an energy package for new homes.

The following comments relate to the potential interest of first time homebuyers:

§ "I don't think they are going to be able to sell it to the first time home buyer."

§ "No, because they won't know how long it takes for the hot water, they won't know that it'll take five minutes, or three minutes."

The following participant felt that it would have value if packaged with other energy efficiency features:

§ "That [an energy efficiency package option] would be awesome. That would be something in the option package for the representative to tell me. Because I wouldn't think that, but to say ok now you are going to get hot water in 15 seconds compared to three to five minutes would be huge for me in the wintertime. But just in terms of energy efficiency and not wasting and being able to recapture and reuse that wasted heat is a great idea."

3.8 Summary

This group represented the target market for CREWH. In discussing this product it became clear that the CREWH purchase decision would be one of a series of home construction and home furnishing decisions. The following issues surfaced as having the greatest potential impact on homebuyer acceptance of CREWH.

§ While the findings indicate that water and energy savings are valued, the group indicated that other options are likely to be selected on the basis of visual appeal, comfort or convenience.

- Homebuyers, rather than builders or contractors, made the final decisions on new home appliances. Homebuyers selected and purchased their refrigerators at large chain stores, and some noted that they do look at the "energy savings" sticker when purchasing appliances. Members felt that for CREWH to be widely accepted it would need to be available in various refrigerator styles.

- Participants were concerned with the wait for hot water in the master bathroom as well as in the kitchen. While two homeowners did have recirculating water pumps to reduce the wait for hot water, neither was satisfied with the performance of those devices. Further, neither was operating the device in a way that would yield energy savings.

- Homeowners liked the idea of CREWH reducing wait time for hot water in the kitchen. This seems particularly true for the parents of young children, who liked the idea of reducing their children's wait time for hot water.

- As with the homebuilders group, homeowners raised concerns about potential leakage.

- Homeowners were most interested in CREWH as a device for delivering hot water at the refrigerator door. While there was some concern about potential scalding from hot water, participants, particularly homemakers, felt that it would be a convenience for preparing hot beverages and some foods.

- Participants placed the value of CREWH in comparison with other optional features, and indicated that other features may be favored for visual appeal, convenience, or comfort.

- Homeowners also expressed various concerns related to performance and acceptance of CREWH over the long term. This includes the ability to reinstall CREWH in a new home, the resale value of CREWH, and the option for disabling the water heating feature of the CREWH if the feature is no longer desired or feasible.

4. SUMMARY OF MARKET ISSUES

Market actor beliefs and behavior provide the raw material for shaping market strategy. While the previous sections report on these beliefs and behaviors, this section suggests ways apply this information in shaping the product and consumer opinion to increase the market potential of CREWH.

This section first presents product features and benefits of CREWH, as seen by homebuilders and homebuyers. This is followed by a discussion of key market barriers that must be addressed in future CREWH development and marketing efforts.

4.1 Desired Feature and Benefits

Certain product features and benefits stand out as important to build on in CREWH marketing and development efforts. Because marketing and development should address the concerns of both builder and homebuyer, the following tables present these features and benefits from the perspectives of each group. Most of the features and benefits identified by one group were also selected by the other. The builder perspective tends to reflect a focus on “no surprises” -- with known cost, quick installation and limited liability. The homebuyer perspective reflects the longer term, with interest in amenities related to attractiveness, operation, and reliability.

Desired Features	
Builders and Contractors	**Homebuyers**
Leak-proof, or leak- evident	Leak-proof
"Installer Friendly" - Designed for installation in 15 minutes or less	"Installer Friendly" - Low added construction cost; ability to uninstall or disable
Fast hot water from refrigerator only	Fast hot water from refrigerator and kitchen tap
Available as a "built-in" appliance	Available as a "built in" and in other styles
Safeguards against scalding	Safeguards against scalding
Homebuilder rebate	

Desired Benefits	
Builders and Contractors	**Homebuyers**
Reliability - Limited or no liability for product installation	Reliability - Safe, with no breakdowns
Low installation cost	Low cost-to-value
Increased revenue (for "built-ins")	Increased value of convenience

4.2 Key Market Barriers

- **Builders and contractors are unlikely to push the market for CREWH.** Appliance marketing, sales and installation are not a core part of their business. However, manufacturer or energy program rebates could change this.

- **CREWH, as now conceived, is not favored by builders due to liability concerns about water damage.** Technical fixes suggested include making water connections visible , so leaks would be detectable; and having CREWH be a refrigerator-only hot water device, with no connections to the water heater or the sink area.

- **Builders and plumbers would be willing to pre-plumb for a CREWH, which is a relatively simple and inexpensive task.** The group suggested that energy programs could compensate for CREWH pre-plumbing.

- **New homebuyers prefer other amenities over the CREWH.** The product would have to compete with items providing more tangible benefits in terms of comfort, convenience, visual appeal or dollar savings.

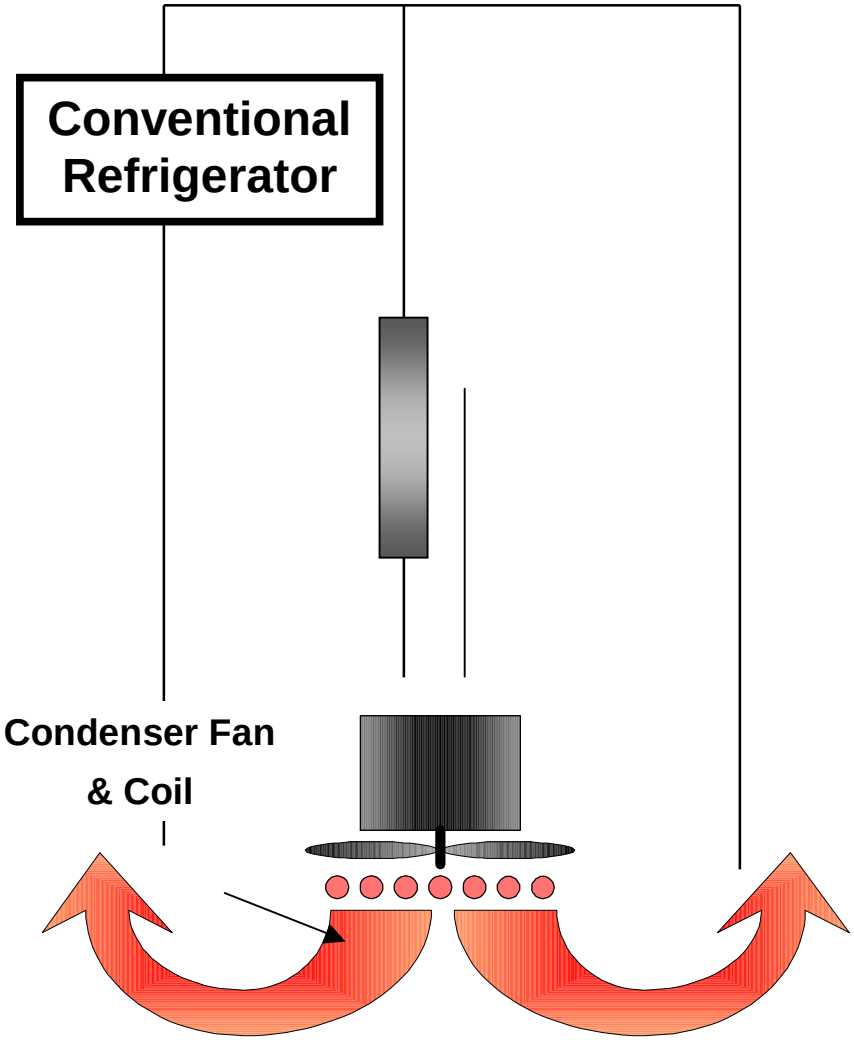
- **The builders group noted competition in the "fast hot water" market.** Recirculating hot water systems are currently being installed in some Sacramento area homes. These devices provide fast hot water at the tap, and some of the systems may provide energy savings.

- **Both groups felt that CREWH should feature a hot water dispenser**. Both groups felt this would add convenience and style. Further, builders felt that a self-contained CREWH could reduce the potential for water damage, and possible contractor liability. Both groups thought a hot water dispenser should include safeguards to prevent scalding.

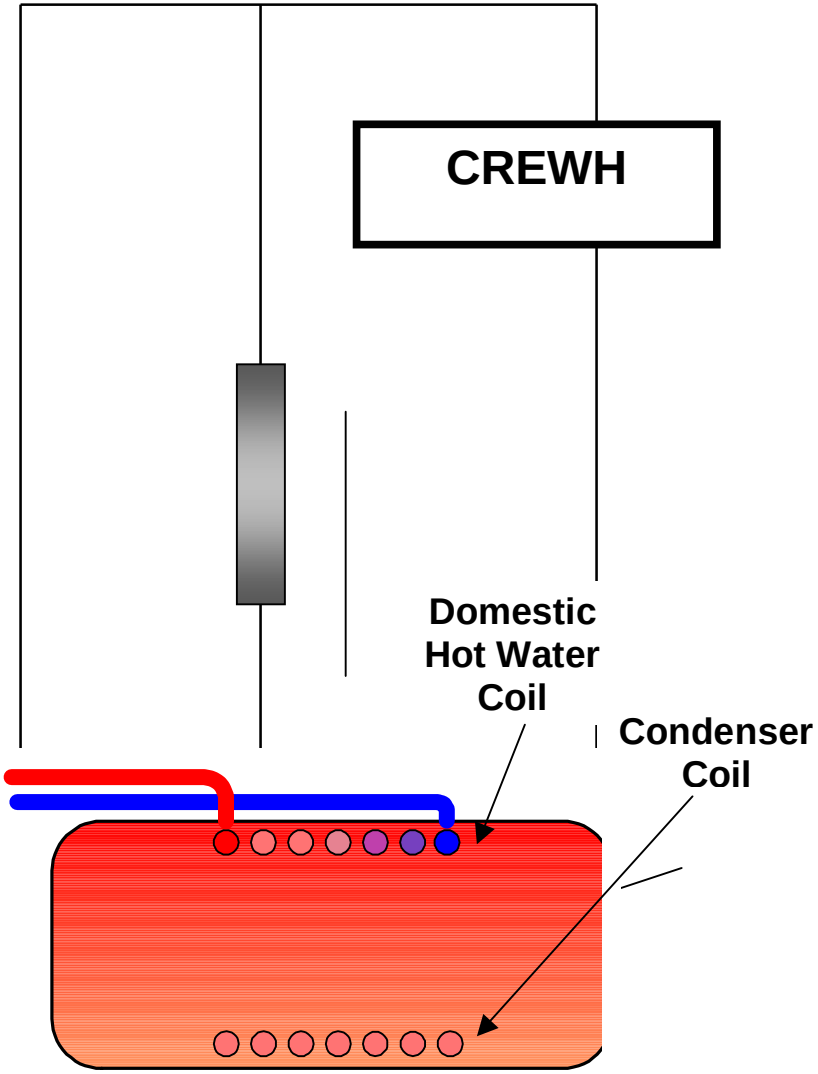
- **Both groups felt that, to maximize product acceptance, CREWH should be available in various refrigerator styles, and should be featured in various kitchen suites.** Refrigerator appearance, size and function are likely to be the factors driving product purchase.

- **Homebuyers are concerned about limited portability of a CREWH.** This includes the ability to reinstall a CREWH in another home, ability to resell a CREWH, and to disable a CREWH if desired.

APPENDIX A: FOCUS GROUP DISPLAY MATERIALS



Refrigerator waste heat discharged to kitchen



Refrigerator waste heat used to heat domestic water

CALIFORNIA
ENERGY
COMMISSION

Safety Analysis and Testing of a Heat Pump Water Heater Condensate Recovery System

Project Final Report

TECHNICAL REPORT

JULY 2005
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Abstract

With support from the California Energy Commission Public Interest Energy Research (CEC PIER) Program, the Department of Energy through Oak Ridge National Laboratory, and Enviromaster International (EMI) of Rome, New York, staff employed at TIAX designed, developed, and successfully tested a market-optimized heat-pump water heater (HPWH). The unique characteristics of the HPWH allow it to be installed in any location a conventional electric water heater is installed. No provisions for ventilation or condensate drainage are required. While developing the HPWH, the staff of TIAX also conceived and developed a prototype of a patented condensate recovery system (CRS) for use with a heat-pump water heater. As condensate forms on the evaporator of the HPWH it is collected in a condensate pan located below the evaporator. The condensate is gravity fed to the condensate recovery system, heated to a point of boiling and then is injected it into the hot water tank of the HPWH. The system is technically proven, however, the regulatory issues are still unresolved.

Safety Analysis and Testing of a HPWH Condensate Recovery System

Final Report

Report to:
California Energy Commission

December 19, 2002

CEC Contract No. 400-00-038

TIAX, LLC
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Reference TIAX No. 74426

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- California Energy Commission PIER Program (Contract No. 500-98-028)
- Department of Energy (DOE)
- DOE Oak Ridge National Laboratory
- DOE National Energy Technology Laboratory
- Enviromaster International

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Preface

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

The PIER Program, managed by the California Energy Commission (Commission), annually awards approximately $62 million annually 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:

- Building 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 Safety Analysis and Testing of a Heat Pump Water Heater Condensate Recovery System. This report completes the Condensate Recovery System project under the Synergistic Water Heating Technologies Program, conducted by TIAX, LLC under subcontract to the Davis Energy Group of Davis, California. This project contributes to the Building End-Use Energy Efficiency program Area.

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.

Executive Summary

With support from the California Energy Commission Public Interest Energy Research (CEC PIER) Program, the Department of Energy through Oak Ridge National Laboratory, and Enviromaster International (EMI) of Rome, New York, staff employed at TIAX[1] designed, developed, and successfully tested a market-optimized heat-pump water heater (HPWH)[2]. The unique characteristics of the HPWH allow it to be installed in any location a conventional electric water heater is installed. No provisions for ventilation or condensate drainage are required.

While developing the HPWH, the staff of TIAX also conceived and developed a prototype of a patented condensate recovery system[3] (CRS) for use with a heat-pump water heater. As condensate forms on the evaporator of the HPWH it is collected in a condensate pan located below the evaporator. The condensate is gravity fed to the condensate recovery system, heated to a point of boiling and then is injected it into the hot water tank of the HPWH. The system is technically proven, however, the regulatory issues are still unresolved.

1 Project Objectives

The overall objective of this project was to obtain laboratory evidence supporting the safety of injecting sterilized condensate from a residential HPWH into the water storage tank. We were specifically interested in the potability of the water that is injected into the HPWH storage tank and subsequently delivered to the point-of-use. The project objectives required to accomplish this were:

1. Perform a preliminary hazard analysis to identify key water-quality concerns, such as biological, volatile organic compounds (VOCs), particulate, surface contaminants, and others.
2. Prepare a test plan to address the contaminants identified in the previous objective.
3. Fabricate a prototype CRS and test apparatus.
4. Conduct the CRS safety tests.
5. Recommend the next steps based on the results of our testing.

This report addresses all five project objectives. In this report, we describe the hazard analysis, the test plan, fabrication of the test apparatus, safety testing, and finally recommend next steps.

In this work, we use a prototype CRS

[1] TIAX LLC is the former Arthur D. Little Technology and Innovation business
[2] U.S. Patents 5,906,109 and 5,946,927
[3] U.S. Patents 6,199,395 and 6,257,002

2 Preliminary Hazard Analysis

We completed a preliminary hazard analysis to assess the risk level of incorporating the condensate recovery system into a heat-pump water heater. We recommended that we test the following three potential contaminants in the laboratory:

- Paints and Aerosols,
- Gasoline, and
- Mold and Mold Waste

This section of the report details how the potential contaminants were selected, how the contamination barriers reduce the risk, and the process we followed to complete the preliminary hazard analysis. The hazards associated with the mechanical and electrical safety issues are outside the scope of this project. However, during the prototype development, mechanical and electric standards were addressed in the design.

The first step in the process was identifying the hazard potential associated with those contaminants that a HPWH may be exposed in a typical installation. Contaminants that are airborne (e.g. dust or aerosols) are drawn through the HPWH fans and evaporator and may collect on the evaporator fins and eventually drop into the condensate pan. Likewise, the condensation present on the evaporator fins may draw in condensable vapors and/or chemicals that may be soluble in water. Once the contaminants are in the condensate pan they will either eventually be drawn through condensate recovery system or evaporate (in the case of a dry pan). Through the process of a literature review, use of experts, and a brainstorming session we identified numerous potential contaminants. These were grouped into four major families: Airborne, Household, Material (from the HPWH), and Biological. The hazard potential levels were assigned to each based on the estimated source availability and associated health risks.

The condensate recovery process was evaluated to assess the likelihood of the potential contaminants passing through the CRS. Seven potential contamination barriers were identified: solubility of the contaminant in condensate, the design of the HPWH hood, an air-filter, a drain-screen, a carbon filter, the sterilization by the CRS, and the dilution of the condensate in the water tank. The mitigating effect of each barrier on the potential contaminants was assessed and the contamination potential was determined.

Using a hazard analysis-screening tool developed specifically for this work, we assessed the potential contamination risk level associated with each contaminant. We determined the potential contamination risk level based on the contaminant's hazard potential and contamination potential.

3 Test Plan

We developed a test plan for the safety testing of the CRS that describes the instrumentation, test facility, data analysis and the details of four tests: a baseline test, a paint test, a gasoline test, and a mold test. The baseline test allowed us to determine the potability of the condensate without any intentionally introduced contaminants. For the

paint test, we filled the room containing the HPWH with spray paint and measured the contaminants making their way from the air into the condensate exiting the CRS. Similarly for the gasoline test we exposed the HPWH to gasoline vapors and measured the contaminants. When testing the mold and mold toxins we proposed performing the test in a two step process. In the first step we performed a bench test in which mold is heated in water to 150°F for 100 seconds. If the mold is not deactiviated in the first test, we proposed to perform a second test in which mold spores are placed in the evaporator pan of the HPWH and allowed to flow into the CRS.

4 Fabrication of Test Apparatus

Because the CRS is still under development, a production version of the device is not available. Therefore, we fabricated a prototype CRS and the test apparatus. The fabrication consisted of installing a HPWH, CRS, and associated instrumentation into a test chamber as specified in the Test Plan. We also designed and fabricated a carbon filter that would be incorporated into the test rig only if deemed necessary based on initial test results. We fabricated and installed a condensate receptacle for collecting the condensate after passing through the CRS. We also verified that the CRS operated properly, both before and after installation into the HPWH.

5 Safety Tests

We performed a baseline test, a paint test, a gasoline test, and a mold test. These tests were performed as described in the Laboratory Test Plan[4]. A summary of the results is presented in the table below.

Summary of Laboratory Test Results

Test Type	Measured Level (μg/l)		Applicable Limit (μg/l)a	Potable at exit of CRS?	Potable when diluted in tank?
Baseline Test	Toluene	ND	1000	YES	YES
	Ethyl Benzene	ND	700		
	Xylene	ND	10000		
Paint Test	Toluene	380	1000	YES	YES
	Ethyl Benzene	56	700		
	Xylene	320	10000		
Gasoline Test	Toluene	3.6	1000	NO[c]	YES[c]
	Ethyl Benzene	ND	700		
	Xylene	ND	10000		
	MTBE[b]	100	13		
Mold Test (Lab Simulation)	No growth of mold in water or on filter		Deactivation of mold and toxins	YES	YES

ND: Not detected
[a] Except for the MTBE level, all limits are defined in the EPA Primary Drinking Water Standard
[b] State of California Primary Drinking Water Standard
[c] When the 100 μg/l is considered with the dilution effect of the tank, the concentration is reduced to 1.25 μg/l, which is less than California standard of 13 μg/l.

[4] Safety Analysis and Testing of a HPWH Condensate Recovery System – Laboratory Test Plan, report to CEC, Feb 12, 2002

The contaminant levels in the baseline test, paint test, and gasoline test were all below the prescribed EPA limits. However, the level of MTBE found in the condensate exiting the CRS exceeds the level allowed by the State of California Department of Health Services (DHS). While this is of some concern, there are three mitigating factors:

1. The level of MTBE, once diluted in the storage tank of the HPWH, was far below the regulated level.
2. The State of California expects to completely phase out MTBE from its gasoline supply by the end of 2003 and, therefore, will no longer be a contamination source.
3. The EPA concludes that keeping the concentration below 20 to 40 μg/L will likely avert any unpleasant taste and odor effect and provides a margin of safety that is equivalent to other regulated contaminants.

The mold tests showed that with the operating conditions of the CRS any mold or mold toxins would be rendered inactive during the CRS process. Because the test results showed that the water was potable in all cases without the installation of a carbon filter, we did not test with a carbon filter in place (consistent with the approach outlined in the Laboratory Test Plan).

6 Recommended Next Steps

Following the safety testing of the CRS we recognize there a number of activities that ought to be completed before the commercialization of the CRS is likely. While the CRS is technically proven and the safety of the device has been demonstrated (relative to drinking water), market barriers remain. Completing the following activities will help to move the CRS from prototype to product (in no particular order):

1. Work with regulatory groups to make certain the design complies with applicable national mechanical and building codes.
2. Contact companies (individuals) that are engaged in and approved to test water treatment devices for the state of California and have them review and test the CRS integrated with the HPWH.
3. Perform an additional design iteration to integrate the CRS into the HPWH and incorporate design-for-manufacture features that enable commercial production.
4. Develop a focus group of consumers to determine the reaction of consumers to the product and idea of injecting condensate from the air into their water.
5. Demonstrate the product in a field-test to determine energy impacts and provide more information regarding the safety of the device.
6. Review potential carbon filter designs and determine if there is a cost-effective filter that could be incorporated into the CRS.
7. Developing an education program to increase the understanding of the system.

Chapter 1 - Introduction

With support from the CEC PIER Program (Contract No. 500-98-028), the Department of Energy through Oak Ridge National Laboratory, and Enviromaster International of Rome, New York, the staff of TIAX has designed, developed, and successfully tested a market-optimized heat-pump water heater (HPWH). The unique characteristics of the HPWH allow it to be installed in any location a conventional electric water heater is installed. There are no provisions for ventilation or condensate drainage required.

The staff of TIAX has developed a prototype of a patented condensate recovery system[5] (CRS) for use with a heat-pump water heater. Condensate forms on the evaporator of the HPWH and is collected in a condensate pan located below the evaporator. The condensate is gravity fed to the condensate recovery system, heated to a point of boiling and then is injected it into the hot water tank of the HPWH. The system is technically proven, however, the regulatory issues are still unresolved.

There are other alternatives to the CRS. The preferred option of condensate disposal is to drain the condensate from the evaporator pan into a local drain. With this option, there is no energy impact, however, not all installations have a drain available. Another option is to re-evaporate the condensate back into the atmosphere using an electric resistance-heating element placed in the lower portion of the evaporator pan. There are disadvantages to this type of disposal, this includes the additional energy required to evaporate the condensate and the elimination of any dehumidification benefits. Another possibility is to use the T&P drain line (which is exhausted outdoors) as a drain, either as a gravity drain or in combination with the CRS where gravity is not available). This option has not been explored and may violate the accepted plumbing codes.

1 The Market-Optimized Heat Pump Water Heater

With a combination of Department of Energy and internal support, the staff of TIAX has invented, developed and laboratory tested a market-optimized Heat Pump Water Heater (HPWH) that costs less relative to current Heat Pump Water Heaters. In addition, the HPWH installs in the same manner as a conventional electric water heater (with no provisions for ventilation or condensate drainage required).

Under California Energy Commission PIER Project 500-98-028, TIAX and EMI, its manufacturing partner, are refining the design of the market-optimized Heat Pump Water Heater, conducting a laboratory-based durability test, and conducting a 20-unit field test in California. In addition, ORNL is completing an 18-unit national field test of the HPWH with the support of various utilities throughout the United States. With the support of the New York Energy Research and Development Agency, EMI is

[5] U.S. Patents 6,199,395 and 6,257,002

fabricating 500 units for a test in the New York City area. EMI expects to commercially offer the HPWH in the first quarter of 2003.

2 The Condensate Recovery System Prototype Development

In addition to the continued development of the HPWH, we have developed and tested a prototype CRS. This work was funded through a contract with the Department of Energy and managed by the National Energy Technology Laboratory (NETL). The goal of the DOE/NETL work was to conduct a preliminary assessment of the regulatory issues, develop and fabricate a prototype, and perform functional and durability tests on the prototype. The key advantages, relative to the re-evaporation of condensate into the ambient air (the current condensate disposal method), are:

- Less energy is consumed,
- The dehumidification benefit of the heat-pump water heater is retained; and
- There is less chance of creating moisture problems when the heat-pump water heater is installed in enclosures (such as utility closets).

The results of the Department of Energy/NETL project clearly demonstrated technical viability. A prototype CRS has been successfully demonstrated in the laboratory through a number of functional tests. In addition, two durability tests were successfully completed. One of the tests rapidly cycled the CRS, completing over 5000 cycles. The other test was a mock-up of the CRS as installed in a HPWH (placed inside the exterior jacket of a conventional electric water heater). The manufacturing cost was reasonable.

3 CRS Prototype Design

The design and operation of the CRS is simple by nature. A conceptual drawing of the CRS is shown in Figure 1.1. The CRS heats the condensate within a vessel of fixed volume. A float valve at the inlet of the vessel and a check valve on the outlet maintain the pressure within the vessel. As the heat is applied, the pressure rises until the pressure slightly exceeds the pressure of the water tank (enough to overcome the pressure drop through the check valve). At that point, a portion of the condensate flashes to vapor and the condensate is subsequently injected into the water tank. The vessel cools and the process begins again.

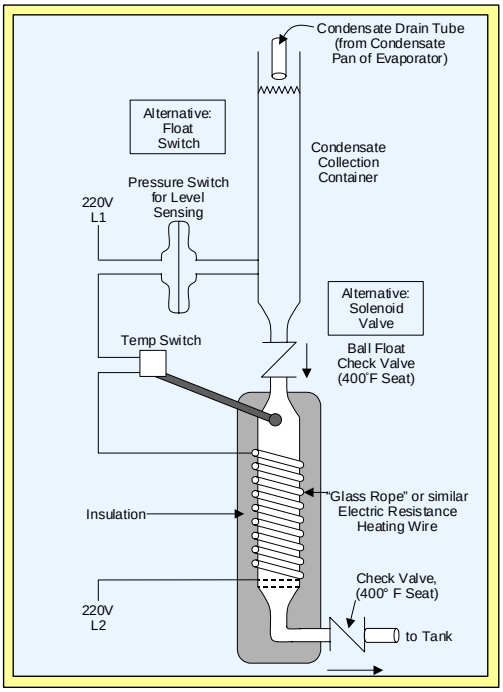

Figure 1.1: Conceptual Drawing of CRS

4 Condensate Generation

The generation of the condensate and the path it takes to reach the water heater tank is important to understanding the potential hazards associated with the CRS. Air is drawn into the HPWH through an air-filter and then passes through the evaporator coil containing the refrigerant from the HPWH. As the air passes over the cold evaporator, it cools to a point in which the water vapor in the air stream condenses onto the coils. The condensate then drains from the evaporator into the drain pan located directly below the evaporator. It is this condensate that may contain potential contaminants. After passing through the coil, the air is exhausted back into the surroundings of the water heater.

The evaporator pan is sloped slightly so that the condensate drains to the location of a drain nipple. A tube is attached to the drain nipple and runs downward into the condensate recovery system. At the point where the tube is attached to the underside of the pan, a standard wire mesh screen, like that in a faucet, prevents any solid particles from passing into the CRS.

The current prototype CRS design does not include a carbon filter. However, as an option, we may include a carbon filter placed between the drain pan and the CRS. The carbon filter would enable the CRS to remove volatile organic chemicals (VOC) that may be found in the condensate. If, testing, we found that an unacceptable level of VOCs passed through the CRS, we could test a carbon filter. In this case, all the condensate would pass through the carbon filter before entering the CRS.

The CRS process injects the condensate into the storage tank of the HPWH, approximately two fluid ounces of condensate per cycle. The CRS is designed to complete a cycle as often as every 15 minutes, if required, to provide a throughput capacity of ½ lb. per hour. The condensate that is collected in the CRS is heated to the onset of vaporization, and then injected into the water heater tank.

The preliminary investigation carried out under the NETL contract uncovered no significant regulatory issues. However, more work is needed to ensure that regulatory issues are not a serious barrier. This project supplies experimental evidence showing that the injection of sterilized condensate into the water storage tank does not introduce significant health risk to household occupants. These data can then be used to demonstrate to regulatory agencies that the CRS is safe and should be permitted for use with the HPWH. (Pursuing regulatory issues is beyond the scope of this project.)

Chapter 2 - Preliminary Hazard Analysis

The preliminary hazard analysis was completed in three steps as shown in Figure 1.2 and as described below:

1. Assess the hazard potential of those contaminants judged to have the highest probability of being present in the environment of a HPWH.

2. Assess the contamination potential of each contaminant; e.g., the probability of the contaminant passing through the CRS and into the potable water supply, resulting in a sufficiently high concentration to warrant concern.

3. Established the contaminant risk level of each contaminant by considering the hazard potential of the contaminant along with it's contamination potential.

We realize this process is subjective and relies on internal expertise and judgement in the assessments of hazard potentials, contamination potentials, and overall risk. However, we are confident that this process provides a reasonable and realistic selection of the hazards that impose the most risk to the use of the CRS in the HPWH. The following sections discuss this process in greater detail.

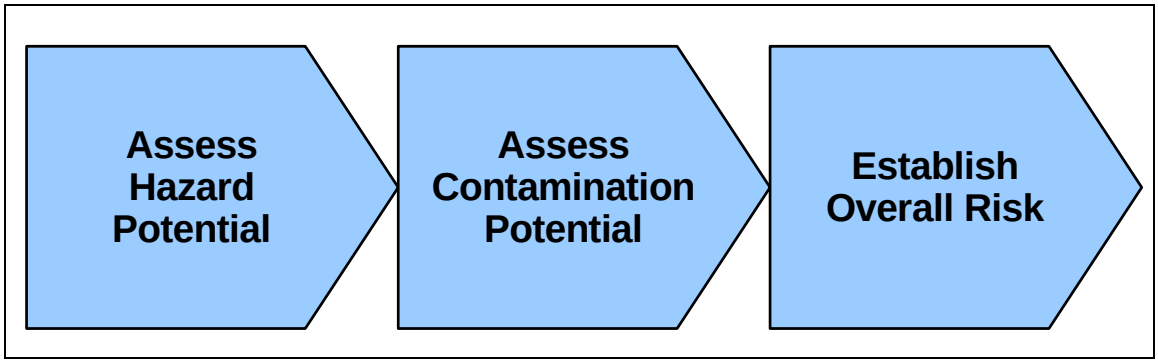

Figure 1.2: Preliminary Hazard Analysis Program Approach

1 Assessment of Hazard Potential

The first step in the development of the preliminary hazard analysis was to determine the hazard potential of all the potential contaminants. We identified those contaminants that we judged a HPWH would most likely be exposed to in a typical installation. Once the potential contaminants were identified, we determined their hazard potential. The hazard potential took into account both the probability of a contaminant being present and its associated health risk.

1.1. Identifying the Potential Contaminants

We developed an initial list of contaminants using the National Primary Drinking Water Regulations from the Environmental Protection Agency[1] as a reference. Using our engineering judgement and common sense, we selected some of the contaminants from this list that had the greatest probability of being present in the condensate. The resulting list is shown in Table 1.1 along with the allowable exposure limits and some of the potential sources for the contaminants.

Table 1.1: Initial List of Potential Contaminants (from EPA Drinking Water Standards)

Type	Contaminant	Limit (mg/L)	Potential Sources
Inorganic Chemicals	Antimony	0.006	electronics, solder
	Asbestos	7 million fibers/L	asbestos insulation or cement
	Cadmium	0.005	galvanized pipe, batteries, paint
	Copper	1.3	plumbing systems
	Lead	0.015	plumbing systems
Organic Chemicals	Benzo(a)pyrene	0.0002	water storage tanks
	Di(2-ethylhexyl)adipate	0.4	PVC plumbing systems
	Tetrachloroethylene	0.005	leaching from PVC pipes
	Vinyl Chloride	0.002	leaching from PVC pipes
Radionuclides	Beta particles and photon emitters	4 millirems / year	Naturally occurring, some man-made deposits
Micro-organisms	Legionella	99.9% killed/inactivated[2]	naturally occurring in water systems, multiplies in heating systems

Using the initial list as a starting point, we held a brainstorming session with some of TIAX's hazard analysis, water treatment, and appliance experts. A diverse group of potential contaminants and their possible sources were identified. Rather than focus on the specific chemicals, we expanded the list to consider the types of contaminants that were likely to be present (i.e., paints, plastics, cleaners, etc.). The final list of identified potential contaminants is presented in Table 1.2.

Table 1.2: Final List of Potential Contaminants

Airborne	Household	Material	Biological
◆ Laundry Lint ◆ Dust ◆ Pollen ◆ Mold Spores ◆ Sawdust ◆ Asbestos ◆ Radon Gas ◆ Carbon Monoxide ◆ Residue from HPWH air filter	◆ Moth Balls ◆ Rat Poison ◆ Gun Powder ◆ Dark Room Chemicals ◆ Household Cleaners ◆ Household Solvents ◆ Gasoline (MTBE) ◆ Paint Thinners ◆ Paint/Aerosols ◆ Pesticides ◆ Fertilizers ◆ Mercury ◆ Lead ◆ Weld/Solder/Brazing	◆ Plastics filings ◆ Plastics leaching ◆ Refrigerant and oil ◆ Metal filings ◆ Corrosion products ◆ Cleaning Solvents	◆ Mold & Mold Waste ◆ Insects & Spider ◆ Vermin (waste) ◆ Viruses ◆ Cat/Dog Hair (dander) ◆ Legionella ◆ Fungi ◆ Cryptosporidium ◆ Giardia ◆ Coliform ◆ Pseudomonas

[1] As specified in 40 CFR Ch. 1. See http://www.epa.gov/safewater/mcl.html for general information.

The potential contaminants were organized into four families, Airborne, Household, Material, and Biological. The potential airborne contaminants consisted of either particles found in the air (dust), or gases potentially present in the air. The potential contaminants listed within the Household Family were those that were thought to be commonplace in a residential environment. The Material Family consisted of all the contaminants potentially introduced from the interior of the HPWH itself. Finally, the Biological Family contained the potential contaminants associated with living organisms. In some instances there is overlap (such as pollen being both an airborne and biological contaminant), but the families only provide a way of organizing the contaminants, so there is no impact on the final analysis.

1.2. Establishing the Definition of the Hazard Potential

Upon identifying the potential contaminants, we assessed the hazard potential associated with each contaminant. The hazard potential describes the potential for harm for each contaminant to which the HPWH and CRS may be exposed. The hazard potential takes into account the magnitude of the health risk associated with the contaminant and the likelihood of the contaminant being present in the HPWH environment. The hazard potential level is presented graphically in Figure 1.3, with the definition of the source availability and potential health risk defined below.

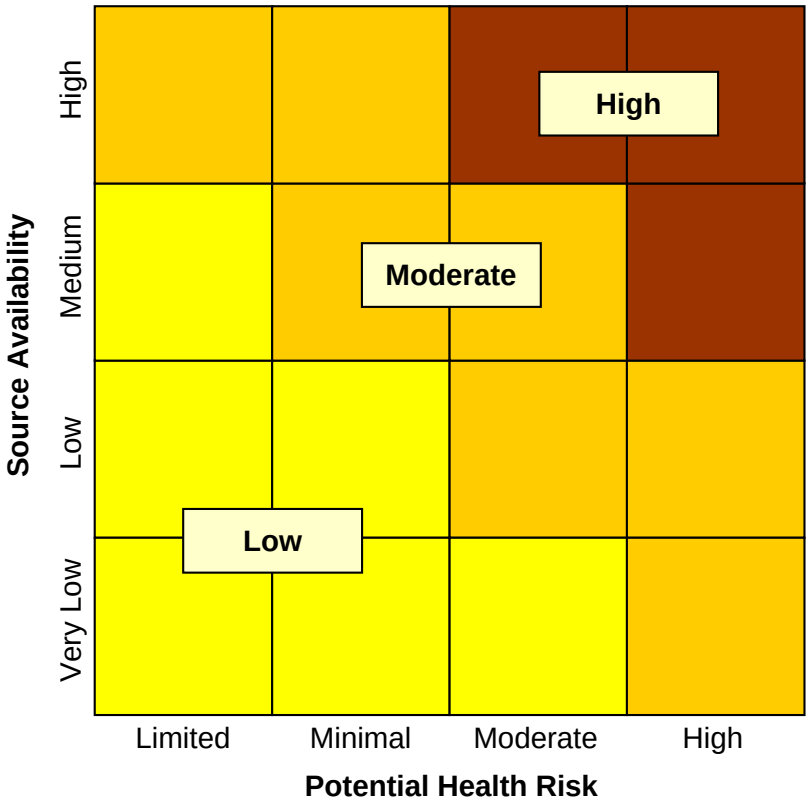

Figure 1.3: Graphical Presentation of Hazard Potential Level

Source Availability

Source Availability describes the probability of a particular contaminant being in the area of the installed HPWH. Thus, the probability of the contaminant being introduced to the CRS at any point in it's lifetime. The levels and descriptions of the levels are presented in Table 1.3.

Table 1.3: Definition of Source Availability

Source Availability Level	Description
High	Usually present and common in households
Medium	Likely to be present in most households
Low	Not likely to be present
Very Low	Rarely found in households

Potential Health Risk

The potential health risk describes the risk associated with exposure to a particular contaminant. These effects can be acute, or chronic. An example of an acute effect would be a poisoning having immediate health repercussions. Contaminants that have acute effects are considered to have high hazard potential if severe reaction results from exposure, such as death, and lower levels of potential as effects decrease in severity. The cause of a chronic effect could be repeated exposure to a carcinogen that leads to cancer after many years. Chronic effects are judged on the severity of the effect on a person that is repeatedly exposed to the contaminant. Most of the contaminants that are considered here have only an acute effect.

Table 1.4: Definition of Potential Health Risk

Health Risk Level	Description
High	Very severe acute or chronic effects (leading to death)
Moderate	Serious acute or chronic effects (permanent damage)
Minimal	Minor acute or chronic effects
Limited	Affects a limited segment of the population to a minor degree

1.3. Assessment of the Hazard Potential

Source availability and potential health risk ratings were assigned to each of the previously identified potential contaminants and are discussed in detail below. Based on the levels assigned to each potential contaminant the hazard potential was determined. The results of this analysis are presented in Table 1.5.

Table 1.5: Hazard Potential of the Potential Contaminants

Family	Source	Source Availability	Potential Health Risk	Hazard Potential
Airborne	Laundry Lint	High	Minimal	Moderate
	Dust	High	Minimal	Moderate
	Pollen	High	Limited	Moderate
	Mold Spores	High	Limited	Moderate
	Sawdust	Medium	Minimal	Moderate
	Asbestos	Very Low	High	Moderate
	Radon Gas	Low	High	Moderate

Family	Source	Source Availability	Potential Health Risk	Hazard Potential
	Carbon Monoxide	Low	High	Moderate
	Residue from filter	Medium	Minimal	Moderate
Household	Moth Balls	Medium	Moderate	Moderate
	Rat Poison	Medium	Moderate	Moderate
	Gun Powder	Low	Minimal	Low
	Dark Room Chemicals	Low	Moderate	Moderate
	Household Cleaners	High	Moderate	High
	Household Solvents	High	Moderate	High
	Gasoline (MTBE)	High	Moderate	High
	Paint Thinners	Medium	Moderate	Moderate
	Paint/Aerosols	High	Moderate	High
	Pesticides	Medium	Moderate	Moderate
	Fertilizers	High	Limited	Moderate
	Mercury	Low	High	Moderate
	Lead	Low	High	Moderate
	Weld/Solder/Brazing	Low	Minimal	Low
Material	Plastics filings	Low	Minimal	Low
	Plastics leaching	Low	Minimal	Low
	Refrigerant and oil	Low	Minimal	Low
	Metal filings	Low	Minimal	Low
	Corrosion products	Low	Moderate	Moderate
	Cleaning Solvents	Low	Moderate	Moderate
Biological	Mold & Mold Waste	Medium	Moderate	Moderate
	Spiders & Insects	Medium	Minimal	Moderate
	Vermin (waste)	Low	Moderate	Moderate
	Viruses	Low	Moderate	Moderate
	Cat/Dog Hair (dander)	Medium	Minimal	Moderate
	Legionella	Medium	High	High
	Fungi	Medium	Moderate	Moderate
	Cryptosporidium	Low	Moderate	Moderate
	Giardia	Low	Moderate	Moderate
	Coliform	Medium	Minimal	Moderate
	Pseudomonas	Medium	Minimal	Moderate

Using our intuition, common sense and engineering judgement we assessed the availability of each source. In determining the health risk, we interviewed professionals in the field, performed some literature reviews, and examined specific Material Safety Data Sheets (MSDS). The assignment of levels to each of the contaminants is discussed below.

Airborne

Laundry lint, dust, pollen, mold spores, and sawdust all have a high source availability, as most of these contaminants are present in indoor air at some level. However, these contaminants have a limited and/or minimal health risk.

Carbon dioxide, radon and asbestos are all contaminants with a high health risk. However, given the high public level of awareness and current methods of construction (insulation materials and mechanical ventilation), we judged these contaminants to have a

low source availability. Therefore, these contaminants have only a moderate hazard potential.

Household

Most of the contaminants found in the Household Family are readily available and commonly found in the household at one time or another. However, in general, the contaminants have a moderate health risk, thus creating only a moderate hazard potential. However, of particular concern are the household cleaners, household solvents, paints/aerosols, and gasoline because they have a high hazard potential due to the combined high source availability and the moderate health risk.

Household Cleaners and Solvents

We studied material safety data sheets (MSDS) of some common household cleaners and solvents and found that many of the chemicals were considered corrosive and toxic[3]. Thus we assigned a moderate health risk. Combined with a high level of source availability (based on our judgment), we determined the household cleaners and solvents had a high potential hazard level.

Paints/Aerosols

Some of the paint/aerosol products that were examined were latex paint, oil-based paint, spray paint, and lubricating oils. We examined typical product labels and studied their MSDS to identify some common chemical constituents. Toluene, Xylene and Ethyl benzene are chemicals found in these products and for which there exist EPA drinking water standards. The health hazard was estimated to be moderate based on the health hazard data, obtained through MSDS of the paints investigated and our judgment of source availability. The data sheets indicated health hazards such as breathing problems, damage to lungs and nervous system, headaches, nausea and vomiting.

Gasoline

A review of the MSDS for gasoline revealed that there are similar types of chemicals found in gasoline as there are in the paints and aerosols. Thus we assigned gasoline a moderate health risk. Because the potential exists for an open container of gasoline to exist in any residence, the source is assumed high.

Material

Most of the contaminants identified in the Material family have a low hazard potential. This is mainly because there is little risk of the contaminants being present in the HPWH after manufacturing and inspection. There is also a low potential for the refrigerant and oil to be present in the condensate. The HPWH typically has only a 16 oz. charge of refrigerant. Any refrigerant leak (and oil) from the evaporator coil, would significantly impact

the HPWH would , the refrigerant woulIf the evaporator were to develop a leak, thIn the case of the refrigerant and oilIn addition, the health risk associated with the contaminants is only minimal to moderate.

[3] According to the National Fire Protection Ratings for Health they rank 3 on a scale of 0 to 4 (0 having no unusual reaction and 4 being fatal with a short exposure). The NFPA ratings may be found at http://www.orcbs.msu.edu/chemical/nfpa/nfpa.html.

Biological
Many HPWH are installed in secluded, usually dark and sometimes damp locations. This type of environment attracts many of the biological contaminants we identified, including spiders, insects, and mold. For this reason, many of the biological elements are assigned a medium source availability. However, the health risk is generally judged to be minimal, resulting in a hazard potential of moderate. The exception is Legionella, which we examined in greater detail along with mold, mold waste, and the pathogens.

Legionella
Legionella are of concern because they can cause Legionnaires Disease, which can be fatal. Thus, Legionella is assigned a high health risk. Legionella are present in natural water sources and thrive in water heating systems that range in temperature from 95°F to 115°F. At temperatures greater than 120°F they begin to die off. Because some people may keep their water heater at the lower temperatures, we assume the source availability is medium.

Mold and Mold Waste
Research shows that filters in HVAC systems may have problems with mold and mold waste if not changed or cleaned periodically. Thus we assessed a medium source availability for the mold and mold waste. The key health hazards identified were allergic reactions and other respiratory problems. We assessed a moderate health risk and consequently a moderate potential hazard.

Pathogens
The key pathogens (harmful bacteria, viruses and microorganisms) investigated for which EPA has set standards are Cryptosporidium, Giardia , coliforms and enteric viruses such as hepatitis A, rotavirus, polio and echo viruses. Cryptosporidum, Giardia, and the viruses have animal and fecal waste as the primary source for contamination of water. Thus a very-low source availability was assigned along with a moderate health risk. We assessed a higher source availability for the coliforms as they may be found in the atmosphere and also since carbon filters (which we may install) could harbor these bacteria. However, coliforms by themselves are not harmful and only indicate the presence of other potentially harmful pathogens. Thus, they have a moderate hazard potential (due to the other pathogens that may be present).

2 Assessment of the Contamination Potential

The second step in the preliminary hazard analysis process was assessing the contamination potential for each contaminant. The probability of the contaminant passing through the CRS is encompassed in the contamination potential. The first step in determining this potential was identifying the mechanisms by which the contaminants would be present in the CRS. The second step was to identify those barriers we believed would decrease the probability of the contaminants passing through the CRS. Following that, we assessed the mitigating effects these barriers had on each of the potential contaminants.

2.1. The Mechanisms for Potential Contamination

There are at least five mechanisms for potential contaminants to get into the CRS. They are:

- Contaminants may dissolve in the water vapor of the atmosphere or in the condensate on the evaporator coil or in the condensate pan,
- Chemicals may condense on the evaporator as the evaporator cools the vapor below the saturation temperature,
- Particles entrained in the air may either stick to the evaporator coil or drop into the condensate pan,
- Biological contaminants may grow in the condensate pan or other components of the HPWH,
- Corrosion may occur within the HPWH.

2.2. Identifying the Contaminant Barriers

We identified a number of contaminant barriers that would inhibit the passing of the contaminants into the condensate and ultimately into the residential hot-water system. These include:

- the solubility of the contaminant in the water vapor present in the air;
- use of a rounded shroud for the HPWH that prevents stacking of potential contaminant sources on top of the HPWH;
- the air-filter on the HPWH that filters the air passing over the evaporator coil;
- a screen placed in the condensate pan drain;
- a carbon filter designed into the CRS (if necessary);
- the thermal sterilization process that occurs within the CRS; and
- the dilution effect due to the injection of the condensate from the CRS into the storage tank.

Figure 1.4 highlights some of the contaminant barriers provided by the HPWH and CRS. This section discusses in greater detail the contaminant barriers that we identified.

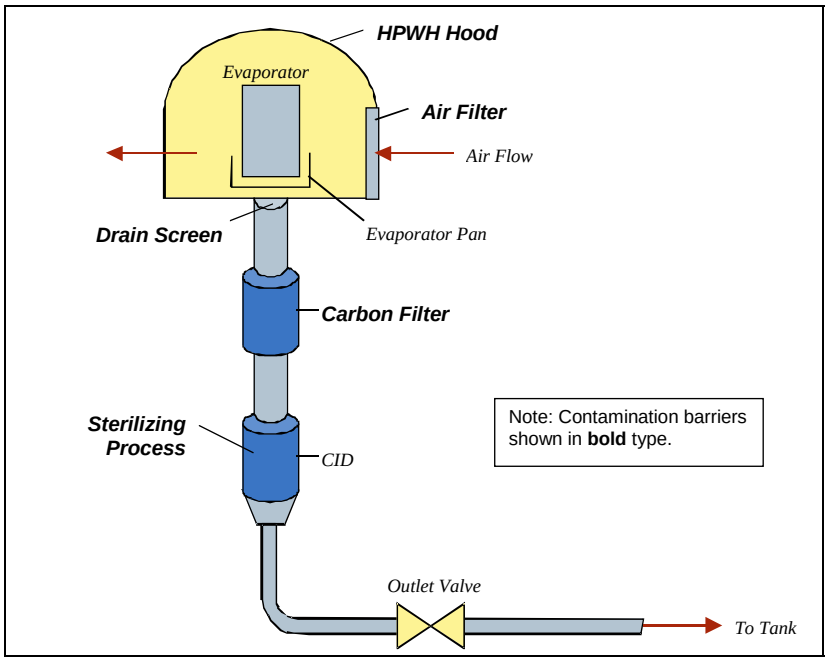

Figure 1.4: Contamination Barriers

Solubility

The solubility of the chemical contaminants in question will play a large role in the possibility of the contaminant being present in the condensate. If the substance is not soluble in the water vapor of the atmosphere, or has a very low solubility, the probability of that substance being present in the CRS is remote. This physical property will eliminate many potential contaminants from consideration as hazards.

Although a contaminant is not necessarily soluble in the water vapor, it is possible for a chemical contaminant to condense out of the atmosphere onto the evaporator coil. It is also feasible to assume that some airborne particles would land on or stick to the moist evaporator coil. In both of these cases the potential exists for the condensate on the evaporator coil to wash these contaminants away and carry into them into the CRS. If this is the case, the solubility of the contaminant cannot be considered a barrier of the CRS.

HPWH Hood Design

The current HPWH shroud is a clamshell design with two-pieces that join to form a flat top. The purpose of the shroud is to protect the heat-pump components (compressor, evaporator, and controls) that are attached to the top of the water tank. However, the current embodiment of the shroud potentially provides an additional storage shelf for common household items. For this reason, we believe a rounded hood may prevent anything from being stored on top of the water heater and, therefore, reduce the possibility of anything spilling directly into the evaporator pan. The physical barrier of the shroud also helps to ensure that only water condensed from the air will be present in the evaporator pan and subsequently in the CRS.

Air Filter
The air filter is effective in keeping any large airborne particles such as hair and particles of dust from coming into contact with the evaporator or evaporator pan. The design of the shroud is such that there is little leakage and most of the air must pass through the air filter before entering the shroud.

Drain Screen
The screen will prevent any solid particles that are within the rounded hood from entering the CRS. These are items that have most likely come from one of the heat pump system components (plastic flakes, metal filings, etc.).

Carbon Filter
If, in the testing of the CRS, it became necessary to add a carbon filter to reduce the concentration of volatile organic chemicals entering the potable water system, we would install a carbon filter between the evaporator drain pan and the CRS. One of the objectives of the testing was to determine whether a carbon filter is even needed.

The carbon filter would be comprised of a granular activated carbon (GAC) filter. A carbon filter is capable of removing different organic substances from water by absorption, and they are widely used in water purification processes. As water passes over the granular carbon surfaces, organic materials adhere to the surface of the carbon, and thereby are removed from the condensate. The top layers of carbon would absorb the majority of the contaminants in the condensate at first, which means that the condensate contacts cleaner carbon, as it gets further through the filter. This would happen until the filter is saturated with organic contaminants and has to be replaced.

The carbon filter would also act as a particulate filter. Whatever particles passed through the drain screen would also have to pass through the carbon filter's granular carbon bed.

The filter would be specifically designed to capture the particular contaminants that are deemed to pose the greatest threat. It would be designed for maximum service time, which would minimize the frequency the filter will need to be changed. The specific design and selection of the carbon filter (if necessary) is out of the scope of this project.

Sterilization Process
Once enough condensate is collected within the CRS, a stainless steel float seals the device and the heating process begins. Heat is added to the condensate via an electric resistance heater wrapped around the outside of the CRS. The condensate temperature and the heating time depend on the pressure in the storage tank, which may range anywhere from 20 to 120 psia, depending on the municipal water supply pressure. During the performance testing of the CRS, we found the heating time for the condensate to be approximately 3 minutes, reaching a maximum temperature of about 375°F. The condensate stayed above 212°F for about 1 minute. A typical profile of the heating and subsequent cooling of the CRS is presented in Figure 1.5.

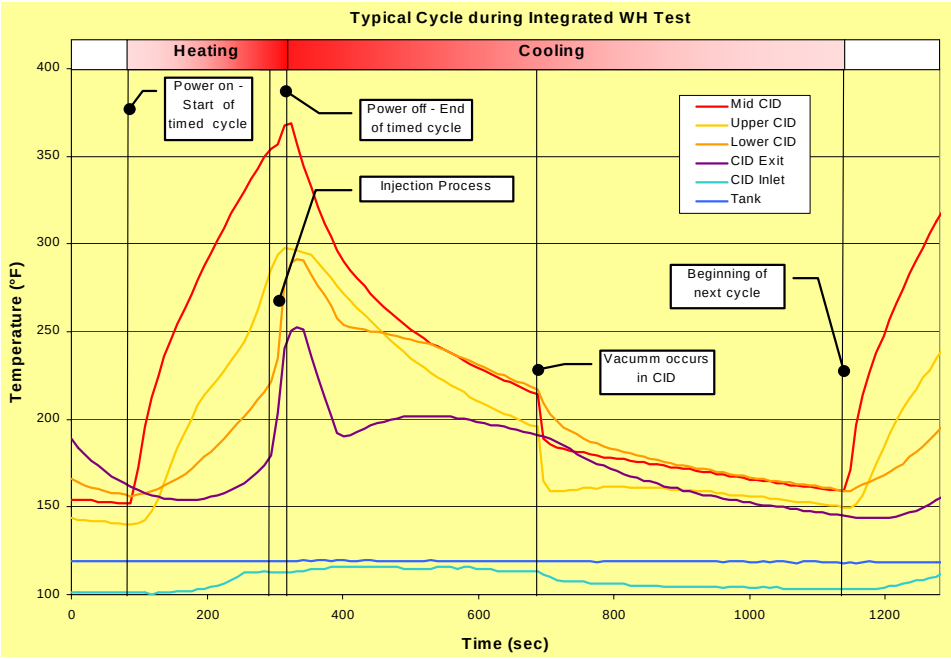

Figure 1.5: Typical Heating Cycle for the CRS

These temperature conditions exceed those suggested by Federal Emergency Management Agency (FEMA) for the purification of water [2]. However, depending upon the level of sterilization needed (kill ratio), the duration and temperature varies. For instance, it is common to sterilize medical equipment at a temperature of 250°F for 15 minutes. Nonetheless, the heating of the condensate within the CRS will provide some sterilization, although the exact amount remains unknown.

Dilution

The CRS injects approximately two ounces of water into the HPWH storage tank during each cycle. The CRS is designed to complete as many as four cycles per hour if required based on the condensate formation rate. The HPWH has an average heating rate of approximately 3200 Btuh. Hence, in one hour's time the HPWH can heat approximately 42 lbs. of water. With very moist conditions (80°F / 50% RH), the CRS will inject approximately 0.5 lb. of condensate during that same hour. Therefore, the condensate, when injected into the storage tank, is diluted at rate of about 1 to 80.

2.3. Defining the Contaminant Potential Levels

The contamination potential describes the probability of a contaminant being present in the condensate after it has passed through all contamination barriers. Each barrier has a different level of effectiveness against each potential contaminant. The contamination potential indicates the mitigation effect of the combined barriers. The contamination potential levels are defined in Table 6.

[2] The Federal Emergency Management Agency recommends bringing water to a rolling boil for at least one minute. For more information see their website at http://www.fema.gov/r-n-r/waterf.htm

Table 6: Definition of Contamination Potential

Contamination Potential Level	Description
High	The contaminant barriers have little mitigating effect on the particular contaminant. If present in the HPWH environment, it will most certainly pass through the CRS.
Medium	The contaminant barriers have some mitigating effect on the particular contaminant. If present in the HPWH environment, the concentration of the contaminant is reduced.
Low	The contaminant barriers are effective in removing the contaminant or reducing the concentration to a small amount.
Very Low	The contaminant barriers completely remove the contaminant or reduce the concentration to an insignificant level.

2.4. Assessment of the Contamination Potential

We developed a semi-qualitative method to assess the contamination potential for each identified contaminant. The results are presented in Table 1.6 below. Column A and B list the family and specific contaminant. In Columns C-H list the contaminant barriers. The solid-black dots in these columns signify that the barrier has some mitigating effect on that particular contaminant (although the exact amount was not necessarily known). The contamination potential was evaluated for a CRS without a carbon-filter (Column I). Column J denotes whether the carbon filter (if in place) has any mitigating effect on the contaminant. The contamination potential for the CRS with a carbon filter is presented in Column K. The assessment of the contamination potential is discussed in greater detail in the text following the table.

Table 1.6: Contamination Potential of the Potential Contaminants

A	B	C	D	E	F	G	H	I	J	K
Family	**Source**	**Solubility**	**Rounded Hood**	**Air Filter**	**Drain Screen**	**Sterilization**	**Dilution Effect**	**Contamination Potential Without Carbon Filter**	**Carbon Filter**	**Contamination Potential With Carbon Filter**
Airborne	Laundry Lint		λ	λ	λ		λ	Low	λ	Very Low
	Dust		λ	λ	λ		λ	Low	λ	Very Low
	Pollen		λ	λ			λ	Low	λ	Very Low
	Mold Spores		λ	λ		λ	λ	Low	λ	Very Low
	Sawdust		λ	λ	λ		λ	Low	λ	Very Low
	Asbestos		λ	λ	λ		λ	Very Low	λ	Very Low
	Radon Gas	λ					λ	Low	λ	Very Low
	Carbon Monoxide						λ	Medium	λ	Low
	Residue from filter	λ			λ		λ	Low	λ	Very Low
Household	Moth Balls	λ	λ		λ		λ	Very Low		Very Low
	Rat Poison	λ	λ				λ	Very Low	λ	Very Low
	Gun Powder	λ	λ		λ		λ	Very Low	λ	Very Low
	Dark Room Chemicals		λ				λ	Low	λ	Very Low
	Household Cleaners	λ	λ				λ	Low	λ	Very Low
	Household Solvents	λ	λ				λ	Low	λ	Very Low
	Gasoline (MTBE)		λ				λ	Medium	λ	Low
	Paint Thinners		λ				λ	Medium	λ	Low
	Paint/Aerosols		λ				λ	Medium	λ	Low
	Pesticides		λ				λ	Low	λ	Very Low
	Fertilizers		λ				λ	Low	λ	Very Low
	Mercury		λ				λ	Low		Low
	Lead	λ	λ				λ	Low		Low
	Weld/Solder/Brazing	λ					λ	Low	λ	Very Low
Material	Plastics filings	λ					λ	Low	λ	Very Low
	Plastics leaching						λ	Low	λ	Very Low
	Refrigerant and oil	λ					λ	Low	λ	Very Low
	Metal filings				λ		λ	Low	λ	Very Low
	Corrosion products				λ		λ	Low	λ	Very Low
	Cleaning Solvents						λ	Very Low	λ	Very Low
Biological	Mold & Mold Waste					λ		Medium		High[1]
	Spiders & Insects		λ	λ	λ	λ		Very Low	λ	Very Low
	Vermin (waste)		λ		λ	λ		Very Low	λ	very low
	Viruses					λ		Low		Low
	Cat/Dog Hair (dander)		λ	λ	λ			Very Low	λ	Very Low
	Legionella					λ		Very Low		Very Low
	Fungi					λ		Very low		Very low
	Cryptosporidium					λ		Very low		Very low
	Giardia					λ		Very low		Very low
	Coliform					λ		Very low		Very low
	Pseudomonas					λ		Low		Low

[1] The addition of a carbon filter actual increases the chance of mold growth.

Airborne
The airborne particles will be readily controlled by most of the contamination barriers. The air filter will serve as the first line of protection against these particles, as they will likely be suspended in the air being pulled in by the evaporator fan. The physical obstruction of the drain screen and the carbon filter will also serve as protective elements against the particle contamination.

Household
The rounded hood will discourage storage of household chemicals on or above the HPWH. This will prevent spillage of household chemicals directly into the condensate pan. However, the contaminants are also soluble in water and or are condensable vapors. Therefore, it is highly probable that if these chemicals are present in the HPWH environment, they will enter the CRS. In this case, there are effectively two mitigating factors: the dilution effect and, if present, the carbon filter.

Material
The chemicals that are leached from the materials may enter the CRS, but the impact is lessened by the dilution of the condensate. If the carbon filter is in place, there is almost no chance these contaminants will be present at any significant level.

Biological
The heat sterilization of the condensate is the largest contributing factor to reducing the contamination potential of the biological contaminants. Because the CRS must always heat the condensate to above 212°F (in order to inject the condensate), the contamination potential is reduced significantly by the heat sterilization. Also, the physical barriers of the hood, air-filter, and drain screen are important for removing the insects, dust, pollen, hair, etc.

Mold and mold waste have only medium contamination potential without the carbon filter. According to biological experts at TIAX, mold begins to be destroyed at 150°F and is completely destroyed when it is exposed to a temperature of 250°F for a small amount of time. While we don't know to what extent the sterilization barrier may destroy the mold, we assume it will contribute to reduction of mold entering the storage tank. In addition, the dilution of the mold and mold waste reduces the contamination potential. It is important to note that placement of the carbon filter may actually increase the growth of mold within the CRS. Therefore, if a carbon filter is installed, the contamination potential increases to high level.

While Legionella is considered by many to be dangerous, it can be readily controlled through sterilization, as the bacteria begin to die at 120°F. Temperatures above 140°F are considered a fast death range[6]. The heating of the condensate in the CRS will certainly raise the temperature of the water above 140°F, so the Legionella bacteria should be controlled by the system. Thus, a very low contamination potential is estimated.

[6] Legionnaires Disease Pathogenicity And Design Considerations, Department Of Aerobiological Engineering, Pennsylvania State University, http://www.engr.psu.edu/ae/wjk/wjkl.html

3 Assessment of the Potential Contaminant Risk Level

Each potential contaminant was assessed to determine the Potential Contaminant Risk Level associated with the use of the CRS in the HPWH system. The risk is viewed from the standpoint of the residential end-user. The Potential Contaminant Risk Level combines the probability of an event occurring (Contamination Potential) with the significance of the event (Hazard Potential). A graphical representation of the risk level is presented in Figure 1.6.

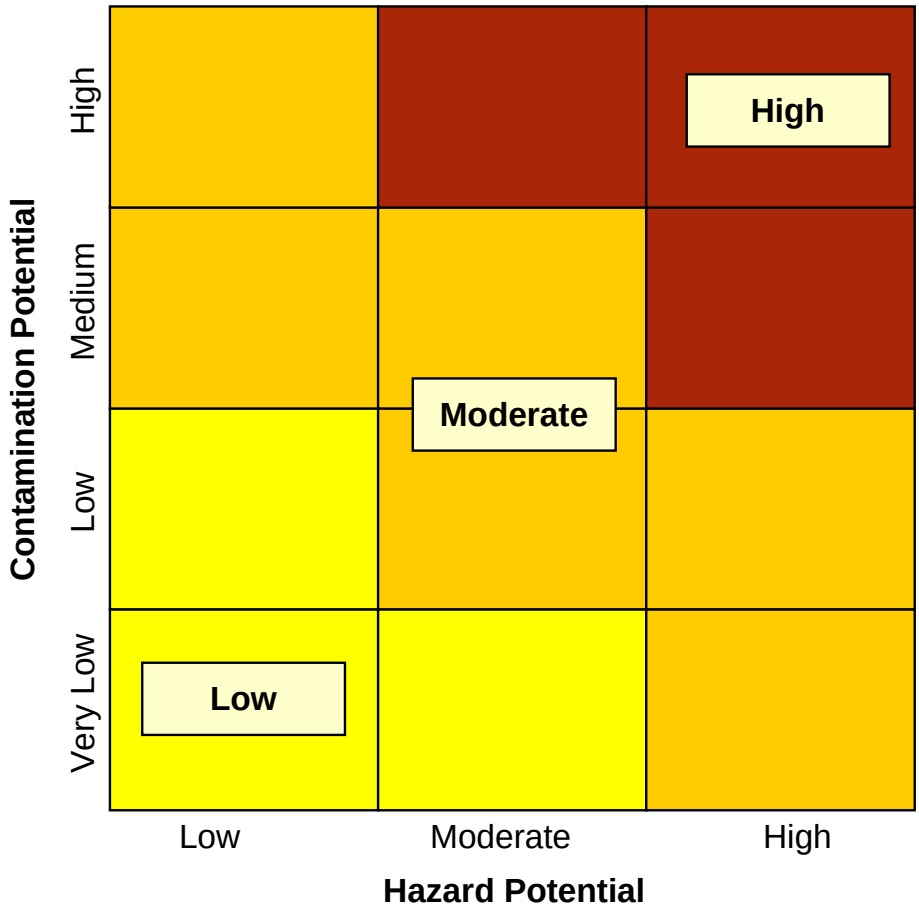

Figure 1.6: Graphical Presentation of the Potential Contaminant Risk Level

The contaminant risk level enabled us to judge which contaminants needed further examination and testing under Task 2 of this project. As with the contamination potential, we evaluated the potential contamination risk level with and without a carbon filter in the CRS. Table 1.7 presents the results of the assessment. The assessment of the potential risk is discussed in detail below.

Table 1.7: Potential Contaminant Risk Levels

Family	Source	Hazard Potential	Contamination Potential without Carbon Filter	Contaminant Risk Level without Carbon Filter	Contamination Potential with Carbon Filter	Contaminant Risk Level
Airborne	Laundry Lint	Moderate	Low	Moderate	Very Low	Low
	Dust	Moderate	Low	Moderate	Very Low	Low
	Pollen	Moderate	Low	Moderate	Very Low	Low
	Mold Spores	Moderate	Low	Moderate	Very Low	Low
	Sawdust	Moderate	Low	Moderate	Very Low	Low
	Asbestos	Moderate	Very low	Low	Very Low	Low
	Radon Gas	Moderate	Low	Moderate	Very Low	Low
	Carbon Monoxide	Moderate	Medium	Moderate	Low	Moderate
	Residue from filter	Moderate	Low	Moderate	Very Low	Low
Household	Moth Balls	Moderate	Very Low	Low	Very Low	Low
	Rat Poison	Moderate	Very Low	Low	Very Low	Low
	Gun Powder	Low	Very Low	Low	Very low	Low
	Dark Room Chem.	Moderate	Low	Moderate	Very Low	Low
	Household Cleaners	High	Low	Moderate	Low	Moderate
	Household Solvents	High	Low	Moderate	Low	Moderate
	Gasoline (MTBE)	High	Medium	High	Low	Moderate
	Paint Thinners	Moderate	Medium	Moderate	Low	Moderate
	Paint/Aerosols	High	Medium	High	Low	Moderate
	Pesticides	Moderate	Low	Moderate	Very Low	Low
	Fertilizers	Moderate	Low	Moderate	Very Low	Low
	Mercury	Moderate	Low	Moderate	Low	Low
	Lead	Moderate	Low	Moderate	Low	Low
	Weld/Solder/Brazing	Low	Low	Low	Very Low	Low
Material	Plastics filings	Low	Low	Low	Very Low	Low
	Plastics leaching	Low	Low	Low	Very Low	Low
	Refrigerant and oil	Low	Low	Low	Very Low	Low
	Metal filings	Low	Low	Low	Very Low	Low
	Corrosion products	Moderate	Low	Moderate	Very Low	Low
	Cleaning Solvents	Moderate	Very Low	Low	Very Low	Low
Biological	Mold & Mold Waste	Moderate	Medium	Moderate	High	High
	Spiders & Insects	Moderate	Very Low	Low	Very Low	Low
	Vermin (waste)	Moderate	Very Low	Low	Very low	Low
	Viruses	Moderate	Low	Low	Low	Low
	Cat/Dog Hair	Moderate	Very Low	Low	Very Low	Low
	Legionella	High	Very Low	Moderate	Very Low	Moderate
	Fungi	Moderate	Very low	Low	Very low	Low
	Cryptosporidium	Moderate	Very low	Low	Very low	Low
	Giardia	Moderate	Very low	Low	Very low	Low
	Coliform	Moderate	Very low	Low	Very low	Low
	Pseudomonas	Moderate	Low	Low	Low	Low

Airborne

In our judgement, all of the airborne contaminants have a low level of potential risk and do not need any further examination. The potential risk levels are all moderate or below without the carbon filter and nearly all are low with the carbon filter.

Household
There are two contaminants that have a high potential contamination risk level, gasoline and paint/aerosols. Both have a high hazard potential signifying a high probability of being present in the HPWH environment and posing some health risk to the user. While the assessment shows the carbon filter is effective in reducing the risk associated with these two contaminants, we recommend testing in a laboratory environment.

The objective of the laboratory test was to understand how effective the CRS system was in reducing the concentration of each contaminant. Although the dangerous chemicals in the contaminants are similar, the physical mechanisms by which they reach the CRS differ. The airflow through the unit would potentially contain particles of paint and aerosols that could then drop out onto the evaporator coil and be picked up by the condensate that forms on the coil. Because the gasoline vapor is soluble in water vapor, it will likely be present in the condensate that forms on the evaporator coil and drain into the CRS. The laboratory tests take into consideration these two different mechanisms.

Material
Most of the material contaminants have a low level of potential risk with or without the carbon filter in place, so further testing or examination does not seem justified.

Biological
Mold and mold waste are the only contaminants that exhibit a high level of potential risk. This high risk level is associated with the carbon filter and is mainly due to the potential for mold growth within the filter itself. We don't know whether the eventual design of the CRS will include a carbon filter. However, knowing how effective the CRS sterilization process is in destroying the mold is necessary if the carbon filter is eventually incorporated into the design. Therefore, we recommend that we test the CRS using mold as a biological contaminant.

Chapter 3 - Test Plan

This chapter of the report describes the testing objectives, the planned test matrix, a general description of the tests, and the results that we expected. The details of the testing procedures used for the tests are presented in Appendix A.

1 Technical Approach

The two objectives in the testing of the condensate recovery system (CRS) were:

1. Determine if the condensate passing through the CRS was potable for a baseline case where there were no contaminants intentionally introduced into the environment.
2. Determine if the condensate passing through the CRS exceeded the limits of the National Drinking Water Standards (NDWS)[7] given an environment with a predetermined level of contamination.

In order to assess the potential need and effectiveness of a carbon filter, we designed the test to evaluate its benefits and drawbacks. We completed the second objective using a CRS without a carbon filter installed. If we had found the contaminant levels exceeded the allowable limits, we would have installed a carbon filter in-line between the evaporator drainpan and the CRS vessel to determine its effectiveness. We could then use the information gained from the testing in subsequent design iterations of the CRS and to demonstrate the safety of the CRS to regulators.

In these tests, we are only concerned with the potability of the condensate that passes through the CRS as defined by the primary standards of the EPA. Therefore, the testing does not include testing to evaluate compliance with the EPA's secondary standards. The secondary standards are non-enforceable guidelines[8] for odor and taste.

The mold and mold spores are not regulated by the NWDS. Therefore, we assumed that if the mold and mold spores were completely deactivated in the testing we would have sufficient evidence to claim the condensate as potable.

Use of the information gained for further design work or regulatory approval efforts was beyond the scope of the current assignment.

[7] As specified in 40 CFR Ch. 1. See http://www.epa.gov/safewater/mcl.html for general information.
[8] States may choose to adopt these or even more stringent requirements in defining potable water.

2 Testing Matrix

The following contaminants were selected for testing in the preliminary hazard analysis (Chapter 2):

- Spray paint (aerosol)
- Gasoline vapor
- Mold and mold waste products

We identified these contaminants as having a high level of risk for contamination (on a scale of very low to high) in the Preliminary Hazard Analysis Report.

3 Testing Approach

We executed the tests as presented in the flow diagram shown in Figure 3.1. First, we tested the CRS with the baseline conditions (i.e., no intentional introduction of contaminants). Secondly, we tested the spray paints and gasoline with the CRS without the carbon filter. If we had found the contaminants in the condensate exceeded the allowable limits, we would perform further tests with the carbon filter installed.

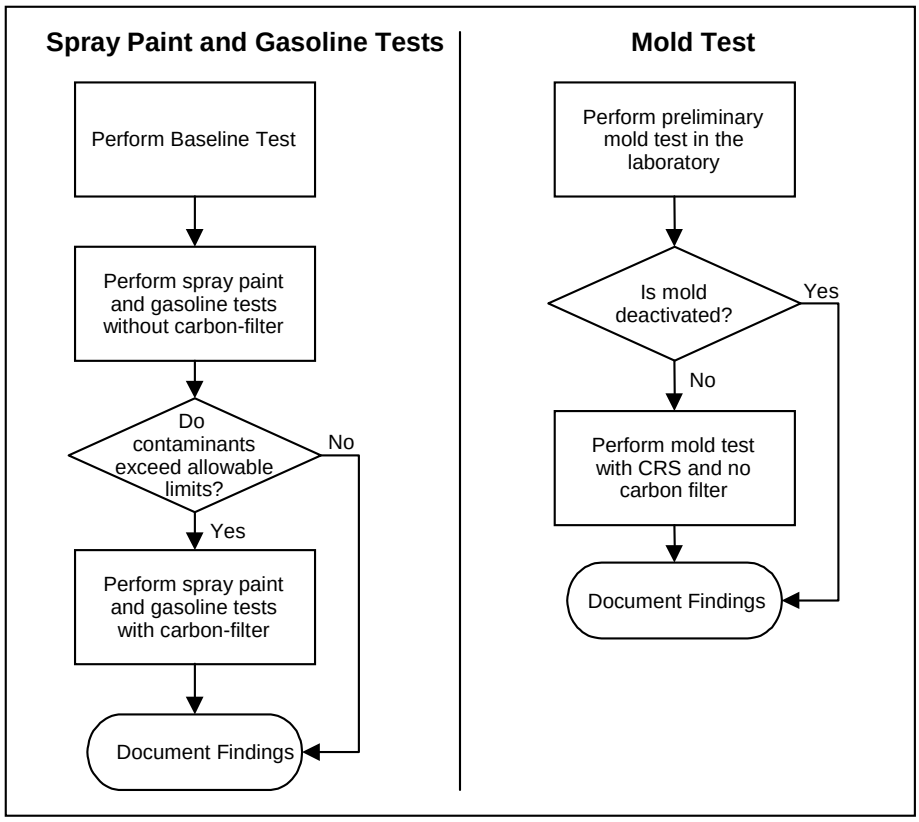

Figure 3.1: Test Approach

Concurrently, we performed a preliminary test for the mold in the laboratory. If we found that the mold was deactivated and toxins (mold waste) were rendered harmless, we would not perform additional mold tests. Otherwise, we would test the mold using the CRS, but without the carbon filter. We did not plan to use the carbon filter in this test because it may have temporarily prevented mold and mold waste from reaching the CRS. In the long term, however, the carbon filter has the potential to act as a source for the mold and mold waste, thus it could reach the CRS unimpeded.

The following subsections discuss the general purpose of each step and outline the procedures we followed. Detailed testing procedures, test conditions, and methods are presented in Appendix A.

Baseline Conditions

We wanted to determine if the condensate, generated by the HPWH and subsequently passing through the CRS, was potable. We defined environmental conditions that would allow the HPWH to generate the maximum expected condensate flow rate. We believe this was a worst-case condition that results in the maximum amounts of contaminants being entrained by the condensate. We used an environmental chamber to establish an ambient condition of 80°F and 50% RH. In previous work, we have used these conditions to represent the design conditions for generating condensate[9]. We did not intentionally introduce any contaminants to the environment for the baseline case.

We continually drew water from the HPWH to ensure that the heat pump operated continuously. We collected the condensate after passing through the CRS, but before it had entered the water tank. Once the test was complete, we had a testing lab analyze a sample of the condensate collected to determine its potability.

We did not expect any contamination in the baseline test and expected the water to be potable.

Spray Paints

We wanted to simulate conditions in a house where the HPWH would be exposed to high levels of spray paints (for example, the garage or basement of a house where someone may be spray painting and exposure limits for the chemicals of concern are reached).

After review of the material safety data sheets (MSDS) for typical spray paint[10], Toluene, Xylene and Ethyl Benzene were identified as chemicals commonly present in spray paint and that are regulated by the EPA's NDWS. The exposure limits enforced by OSHA and the standards set by EPA for these chemicals are presented in Table 3.1.

[9] Fabrication and Laboratory Test Report, Report to the California Energy Commission, Contract No. 500-98-028, by Arthur D. Little, 1999.
[10] Krylon Decorator paints, Material Safety Data Sheets

Table 3.1: Exposure Limits and EPA Standards

Chemicals	PEL[a] (ppm)	TWA[b] (mg/m^3)	STEL[c] (ppm)	MCL[d] (ppm)
Toluene	100	375	150	1
Xylene	100	435	150	10
Ethyl-benzene	100	435	125	0.7

[a] Permissible Exposure Limits (PEL)
[b] Time Weighted Average (TWA)
[c] Short Term Exposure Limits (STEL)
[d] Maximum Contaminant Level (MCL)

We performed the experiment in a controlled environment where we were able to maintain relatively constant temperature and humidity over the test duration. We ran one test to test for all three chemicals by choosing a paint that had all three chemicals as components. We sprayed the paint in the environment to achieve the exposure limits for the chemical with the least percentage by weight amongst the three chemicals. This ensured that the exposure limits for the other chemicals were also met or exceeded. We let the HPWH run under these conditions for approximately six hours; the time that it took the HPWH to heat a full tank of cold water.

We collected the condensate and tested it for the chemicals identified in Table 3.1 to determine if the contamination levels are within the EPA limits. If the EPA NWDS were exceeded, we would have repeated the tests with the carbon filter installed as explained above. The details of the experimental conditions and testing procedure are presented in Appendix A.

Gasoline

We wanted to simulate conditions where the HPWH is exposed to gasoline vapors; for example, in a garage where a gasoline container is kept open for an extended period on a hot day.

The chemicals identified in gasoline for which we found EPA drinking water standards are Toluene, Xylene, Ethyl Benzene (see Table 3.1) and Benzene (see Table 3.2). We didn't find any standards for MTBE through EPA. However, the California Department of Health Services (DHS) has a standard for MTBE of 0.013 mg/L[11]. We compared the MTBE levels found in the condensate with this standard.

Table 3.2: Exposure Limits and EPA Standards for Benzene

Chemicals	PEL[a] (ppm)	MCL[b] (ppm)
Benzene	10	0.005

[a] Permissible Exposure limits
[b] Maximum Contaminant Level (NWDS)

[11] MTBE in California Drinking Water, Feb 4 , 2002, (http://www.dhs.ca.gov/ps/ddwem/chemicals/MTBE/mtbeindex.htm), EPA expects to have standards by 2010

As with the spray paint test, we performed the experiment in a controlled environment where we maintained the temperature and relative humidity over the test duration. We introduced gasoline vapors in the environment by placing an open container of gasoline on a raised platform near the evaporator inlet. We let the HPWH run for six hours in this environment. We limited the amount of gasoline introduced to the test chamber so that, even if all the gasoline were evaporated, the concentration in the test chamber would be less than half the lower flammability limit.

We collected the condensate and tested it for the chemicals identified. We compared the contamination levels with the available EPA standards to determine if they were within the EPA limits. We expected the contamination from gasoline vapors to be within the EPA limits. However, if they were found to exceed the limits, we would have performed further tests with the carbon filter as explained above. Appendix A presents details of the ambient conditions and testing procedure for gasoline.

Mold and Mold Waste

To test for mold and the toxins present in the mold waste, we performed a preliminary test in the microbiology lab at TIAX. The purpose of the preliminary test was to determine whether mold spores of *Stachybotyrs chartarum* were effectively eliminated when exposed to heated water (below the boiling point of water) for a short period of time. If the mold spores were found active after the preliminary test, we would have performed an additional test in which mold and mold waste were introduced to the CRS and tested *in-situ*.

Preliminary Test

From previous work[12], we knew the temperatures within the CRS remained above 150°F for at least 100 seconds between the initial heating and final injection of the condensate. We exposed the mold spores to these conditions in a laboratory bench-top experiment to determine if they were killed. We also examined if the mold by-products were rendered non toxic. The detailed testing procedure and experimental details are presented in Appendix A.

Based on discussions with our biology experts, we expected that the 150°F temperature would deactivate the mold and render the by-products non-toxic.

CRS Test

If we had found the temperature of the preliminary test was ineffective in deactivating the mold, we would have simulated conditions where mold and mold waste had formed in the evaporator pan due to the presence of moisture over extended periods of time.

We planned to introduce a substantial amount of mold spores and the mold waste (by-products) of *Stachybotrus* in the pan, to simulate the adverse situations. We would run the HPWH for one hour and let the mold pass through the CRS and then collect the condensate. The condensate would have been tested in the microbiology lab to examine if

[12] *Heat Pump Water Heater Condensate Disposal System*, Report to National Energy Technology Laboratory, Contract No. DE-FC26-99FT40652, Arthur D. Little, 2001

the mold spores were killed and if the mold by-products were rendered non toxic. Appendix A presents the detailed procedure and experimental details for the test.

We expected that we would not need to perform the CRS test, but that if we did that the sterilization process in the CRS would have deactivated all the mold spores and render the by-products non-toxic..

Chapter 4 - Fabrication of Test Apparatus

This chapter of the report describes the fabrication of the test apparatus including the test facility, the carbon filter and the condensate receptacle.

1 Heat Pump Water Heater and Test Chamber

We received a HPWH from EMI, and installed it within the test chamber. We configured the test chamber as detailed in the Test Plan (Appendix A). Figure 4.1 shows the schematic of the test chamber and the heat pump water heater. A photograph of the HPWH installation and test chamber configuration is shown in Figure 4.2.

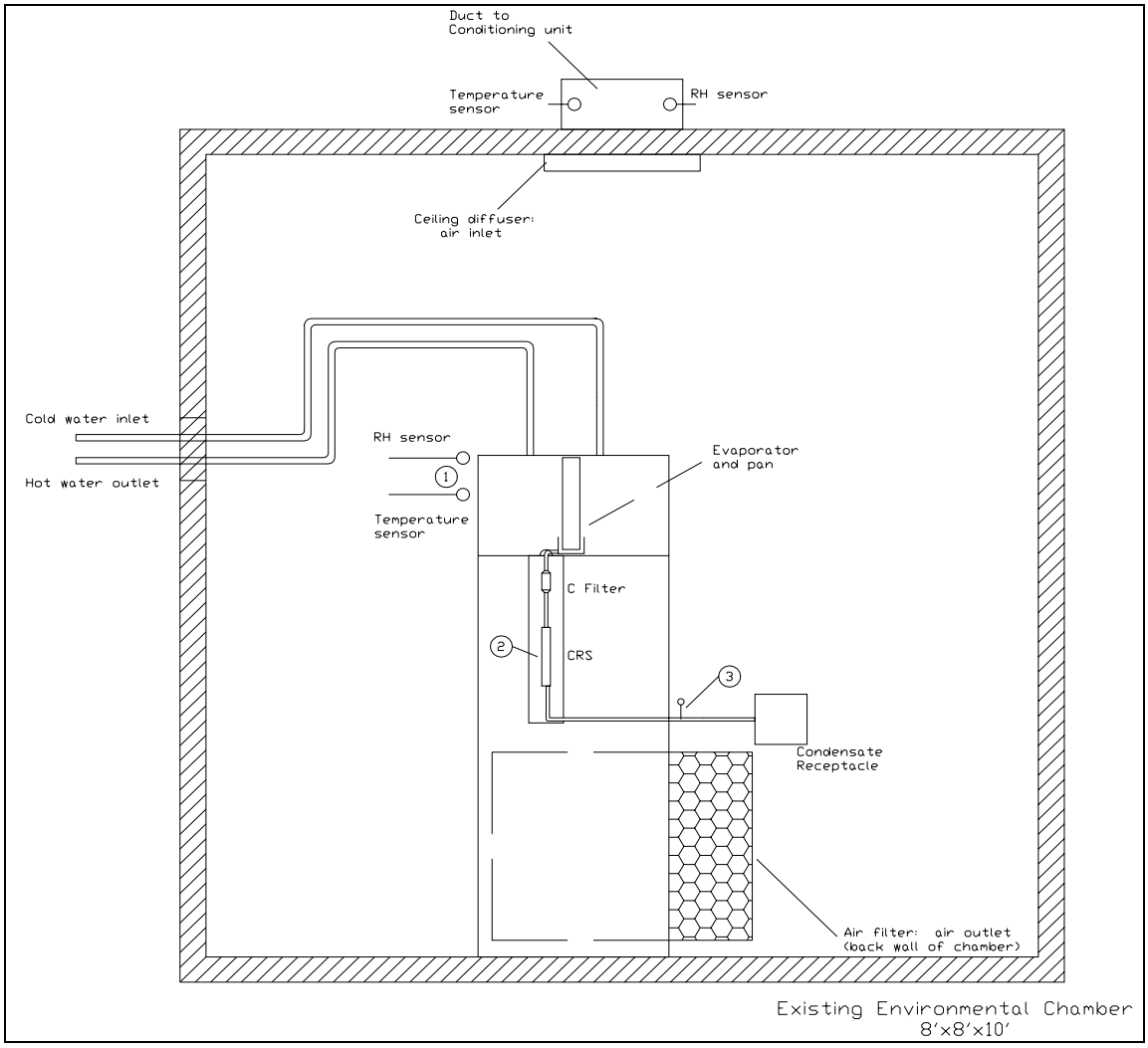

Figure 4.1: Heat Pump Water Heater and Test Chamber

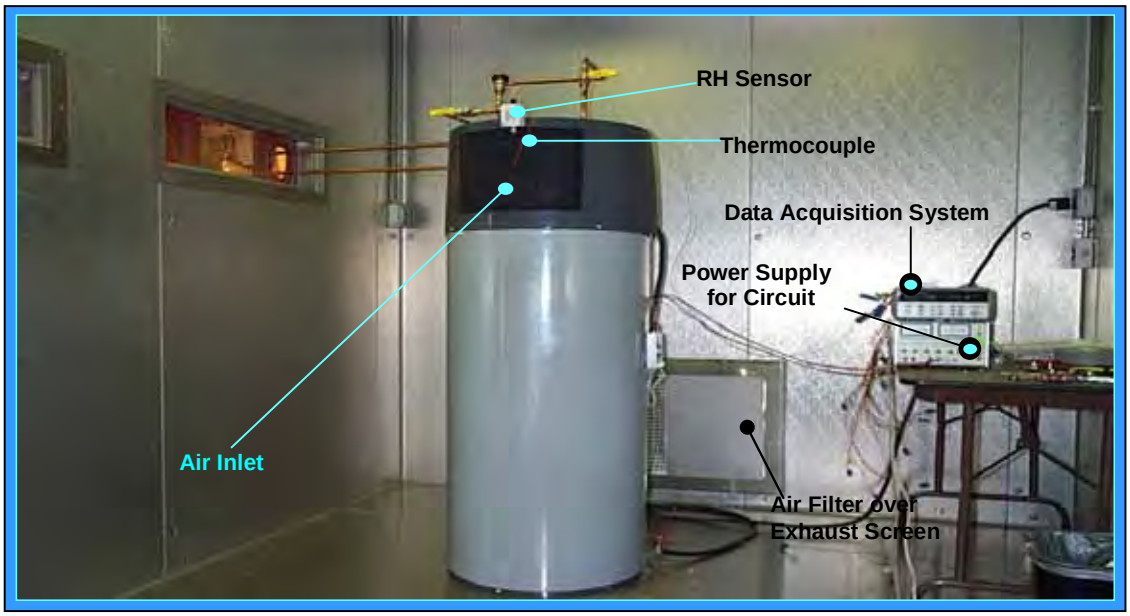

Figure 4.2: Heat Pump Water Heater within the Test Chamber

2 Installation of the Condensate Recovery System (CRS)

The CRS was installed in the HPWH as shown in schematic in Figure 4.3 and the photograph in Figure 4.4. The evaporator pan, tubing, level sensor, CRS vessel, and the hardware necessary for installation are indicated in the picture. We made a cut out in the exterior jacket of the HPWH storage tank to install the CRS. The cutout is approximately 18 by 2.25 by 2.25 inches and cleared of all insulating materials. Steel bands were used to hold the CRS next to the water tank. We placed thermal mastic between the CRS vessel and the HPWH water tank to enhance heat transfer during the cool-down period of the CRS cycle. The control circuit that uses the level sensor to operate the CRS was attached below the cutout. (In the production version we envision integrating the control logic into the HPWH's microprocessor control board).

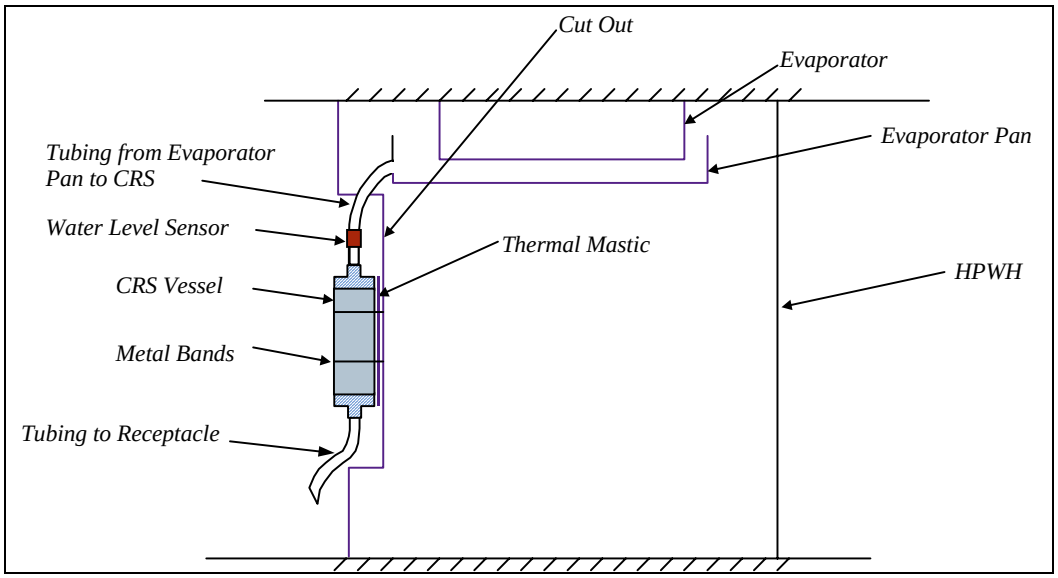

Figure 4.3: Schematic of CRS Installation

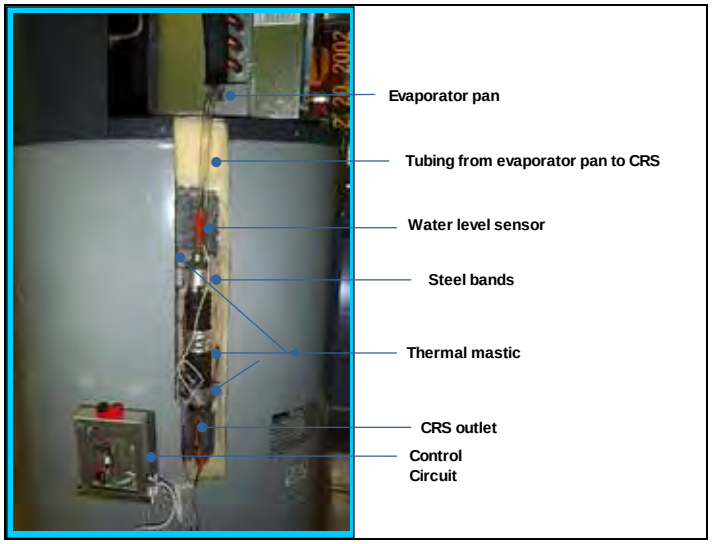

Figure 4.4: CRS Installed in the HPWH

3 Carbon Filter

Because of the very low flow rate in the present application and the size restrictions, we did not find any suitable off-the-shelf carbon filters. We, therefore, designed a carbon filter assembly for the sole purpose of testing the CRS with a carbon filter, if those tests were necessary. If we decide that a carbon filter is required in the system, then a production version will need to be designed. (Design of a carbon filter for the CRS was beyond the scope of the current assignment.) The filter medium selected for testing was granular activated carbon (GAC). We used a 2.5” length of 1” diameter copper tubing, capped on each end with 1” to 0.5” reducers that connect to the plastic tubing. Inside each of the reducers was a round, wire-mesh screen to hold the GAC in place. During assembly, we brazed the reducer and the copper tubing together, put the screen in place

and filled the tubing with GAC. Finally we put the second reducer in place and brazed it in place. A schematic of the filter (exploded view) is seen in Figure 4.5. The carbon filter assembly as installed is shown in Figure 4.6.

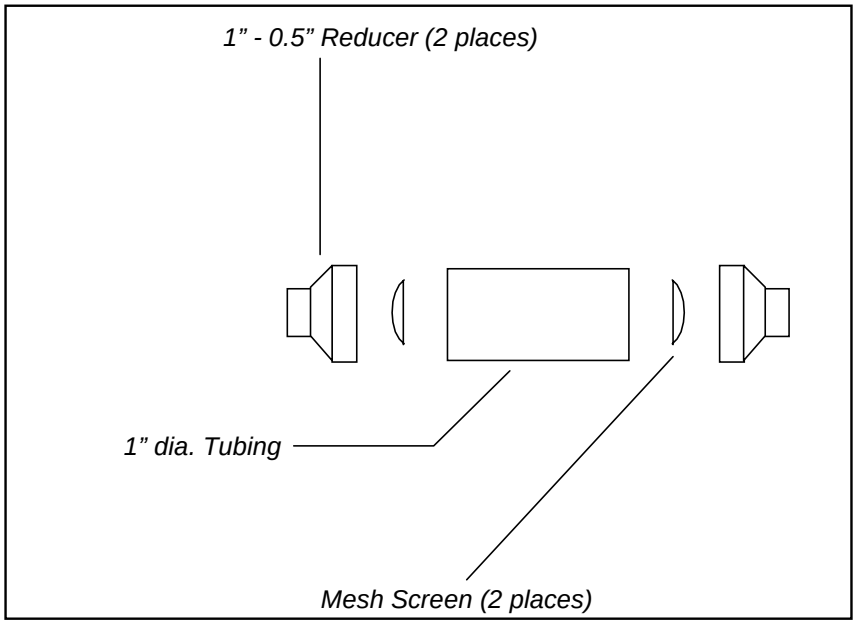

Figure 4.5: Schematic of Carbon Filter (Exploded View)

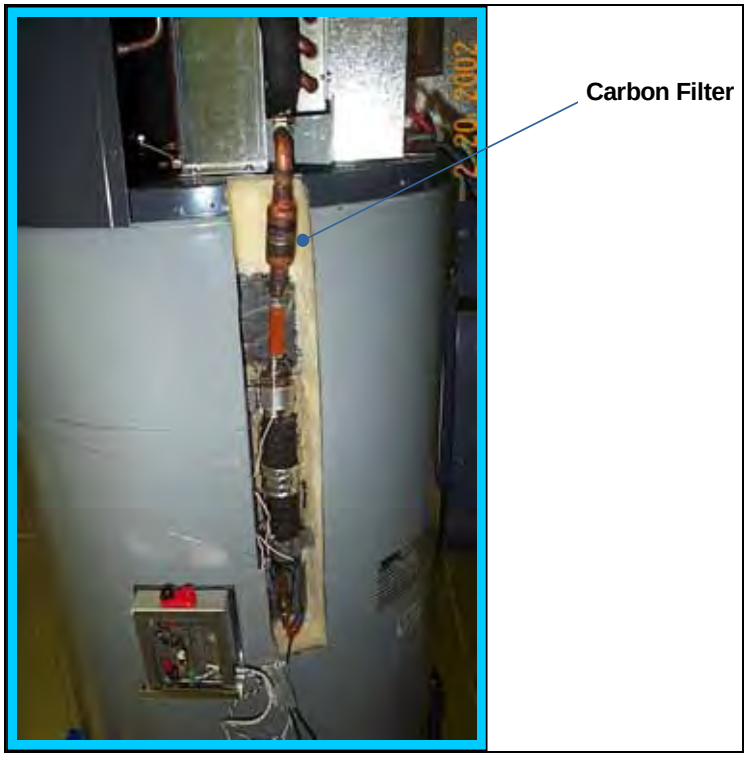

Figure 4.6: CRS Installed with Carbon Filter

4 Condensate Receptacle

The condensate receptacle played two roles in the CRS testing. The first was to simulate the back pressure that is present when the outlet of the CRS is connected to the water heater tank, and the second was to collect condensate for analysis. To achieve these two goals, the receptacle includes an inlet tubing connection, a pressure relief valve, an air hose connection (used for initial pressurization), a pressure gauge, and a two-way ball valve. The condensate that leaves the CRS passed through plastic tubing and into the receptacle, which was pressurized to 20 psi (using the air hose and plant air). Once a test was completed, the pressure was relieved and the ball valve was opened to collect the condensate for analysis.

We fabricated the receptacle from a 16” length of 3” diameter pipe, with 1/8” thick plates welded on the ends. We welded all components into place. Figure 7 shows a photograph of the receptacle.

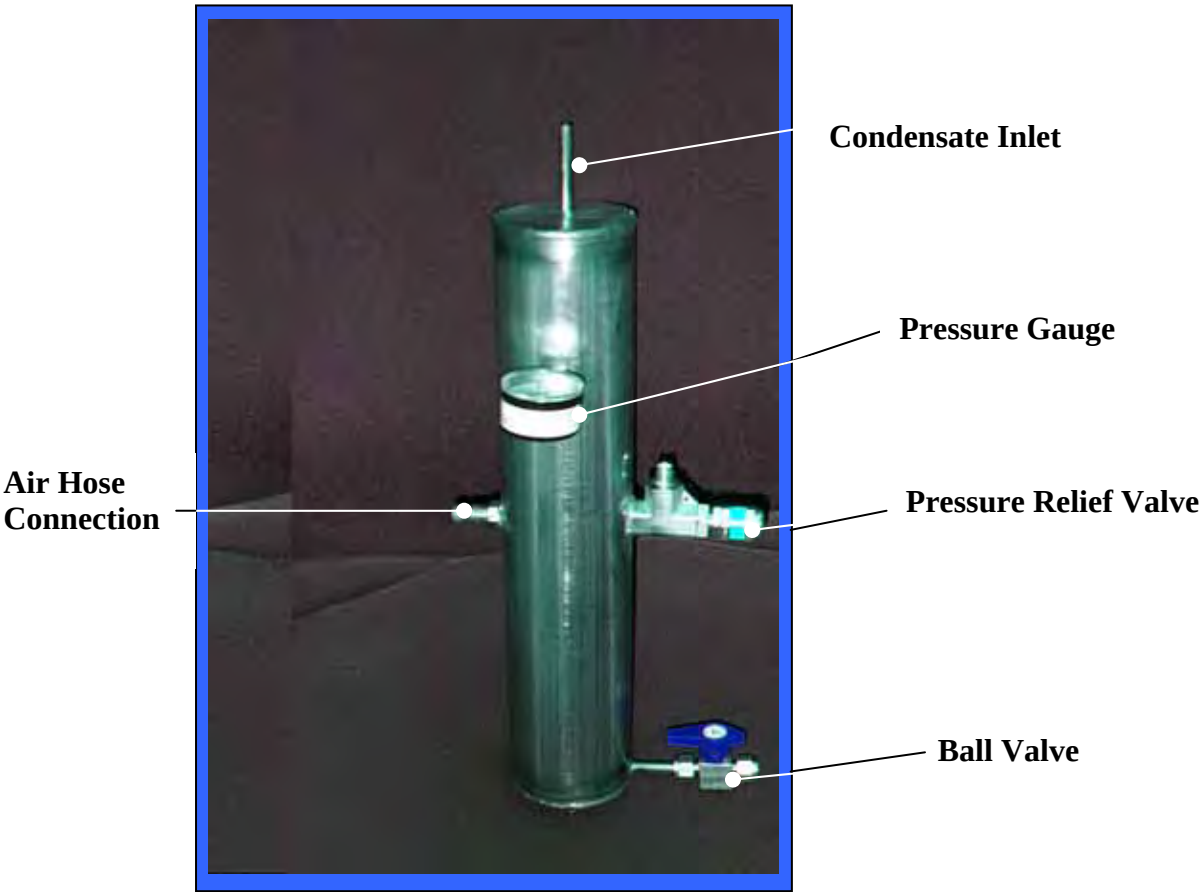

Figure 4.7: Condensate Receptacle

5 Operational Verification of CRS

Before initiating the testing of the CRS as described in the Laboratory Test Plan, it was necessary to confirm that the CRS was operating properly. We performed two separate

tests, the first on the bench top, the second with the CRS in the HPWH. The tests confirmed that the CRS was operating properly.

5.1. Bench-Top Operational Verification Test

We set up the CRS test with a constant supply of water, simulating the condensate under worst-case conditions, and allowed it to operate continuously for several hours. We recorded the temperatures at the top, middle, and the bottom of the vessel. The test apparatus is shown in Figure 4.8.

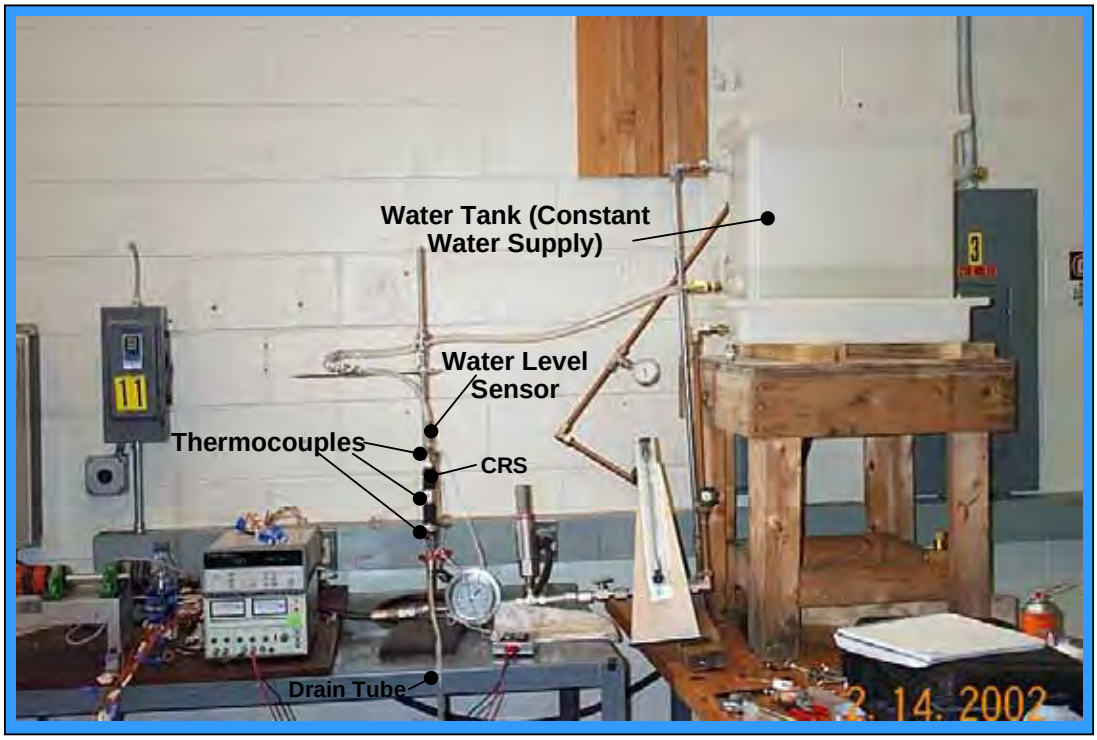

Figure 4.8: Bench-Top CRS Test Set Up

The test spanned a little more than four and half-hours. Figure 4.9 shows the results of the test. The data are consistent over the duration of the test. This repeatability and consistency is also seen in a comparison of two individual cycles of the CRS (Figure 4.10 and Figure 4.11). The cycle shown in Figure 4.10, is taken from the first half-hour of operation. The cycle shown in Figure 4.11, is taken from the last half-hour.

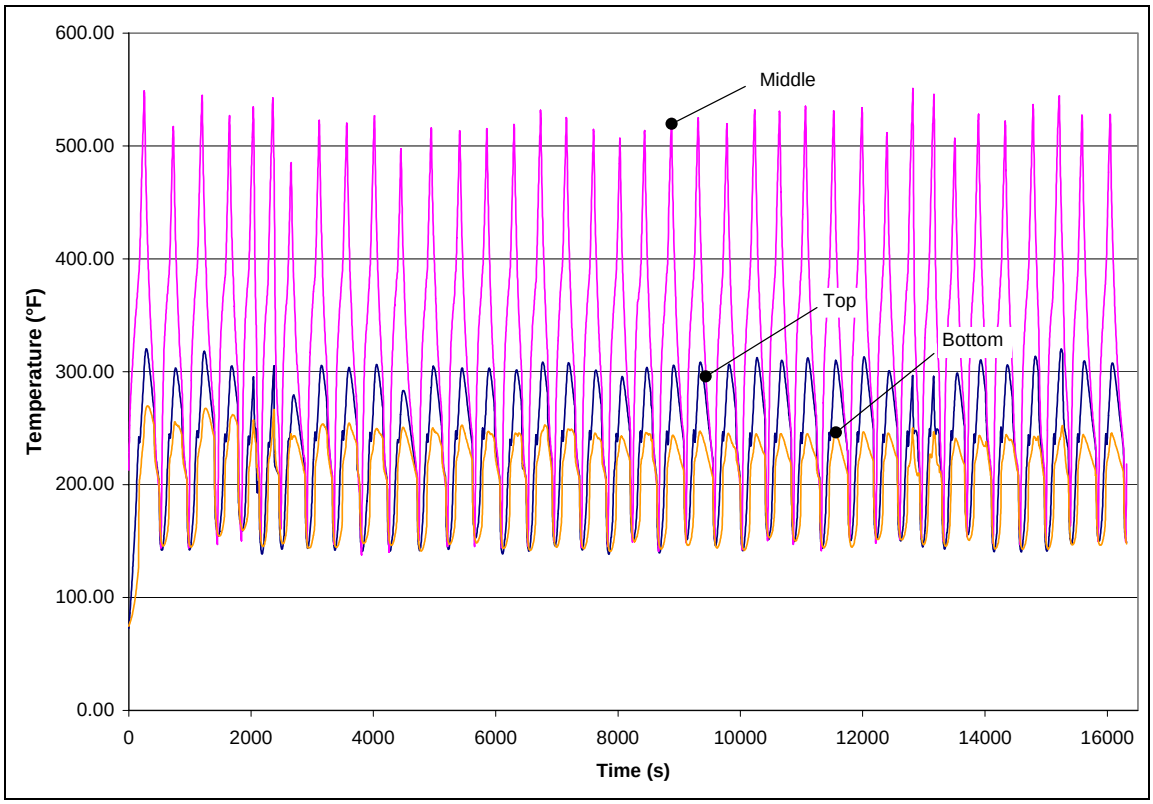

Figure 4.9: CRS Bench-Top Test Results

The temperature and cycle times are comparable to the results found in previous laboratory testing sponsored by the National Energy Technology Laboratory (NETL)[13]. The results are compared in Table 4.1. The temperature ranges from both tests are nearly the same. The heating cycle time in the current test is slightly improved, which is indicative of better heat transfer to the interior and higher energy efficiency relative to the previous test.

Table 4.1: Comparison of Bench-Top Results

Parameter	Previous Test[13]	Bench-TopTest
Heating time (sec.)	230 - 250	200 - 225
Vessel Top Temperature (°F)	280 - 320	280 - 320
Vessel Bottom Temperature (°F)	260 - 300	240 - 280

The consistency of the cycle and comparable results suggests that the CRS was operating properly. However, we performed an installed operational test to confirm the proper operation.

[13]Heat Pump Water Heater Condensate Disposal System, Final Report presented to National Energy Technology Laboratory (NETL), May 24, 2002

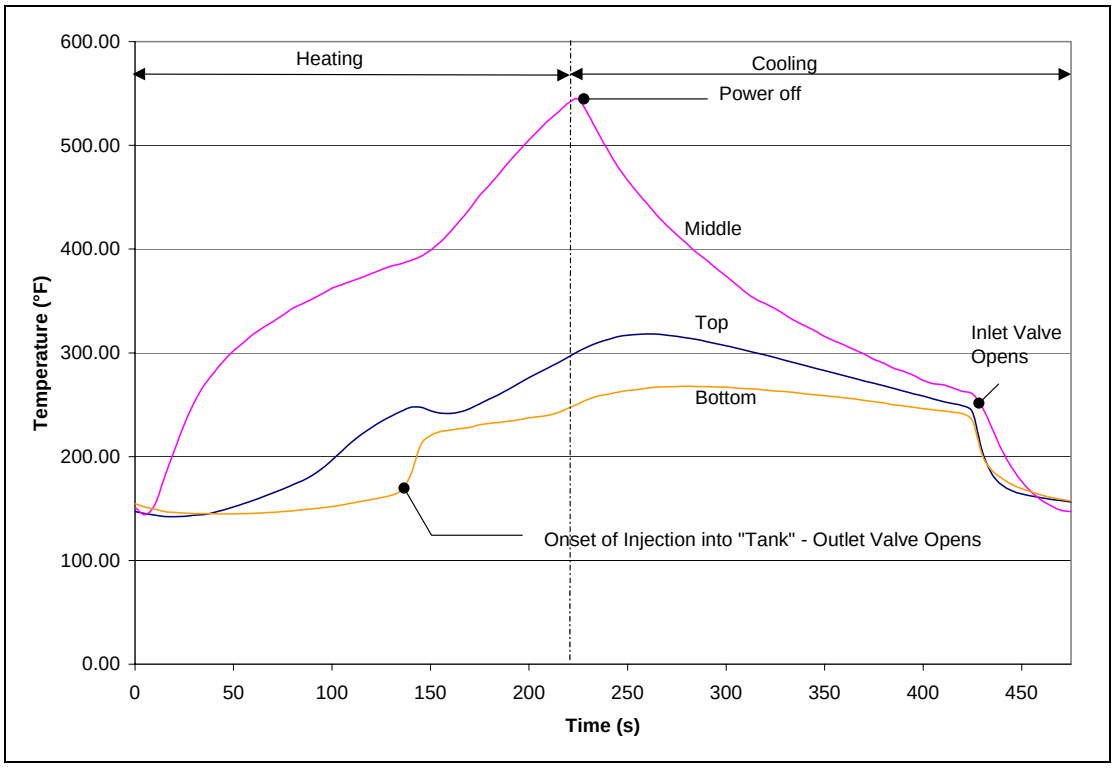

Figure 4.10: CRS Bench Top Test (Cycle Data Early in Test)

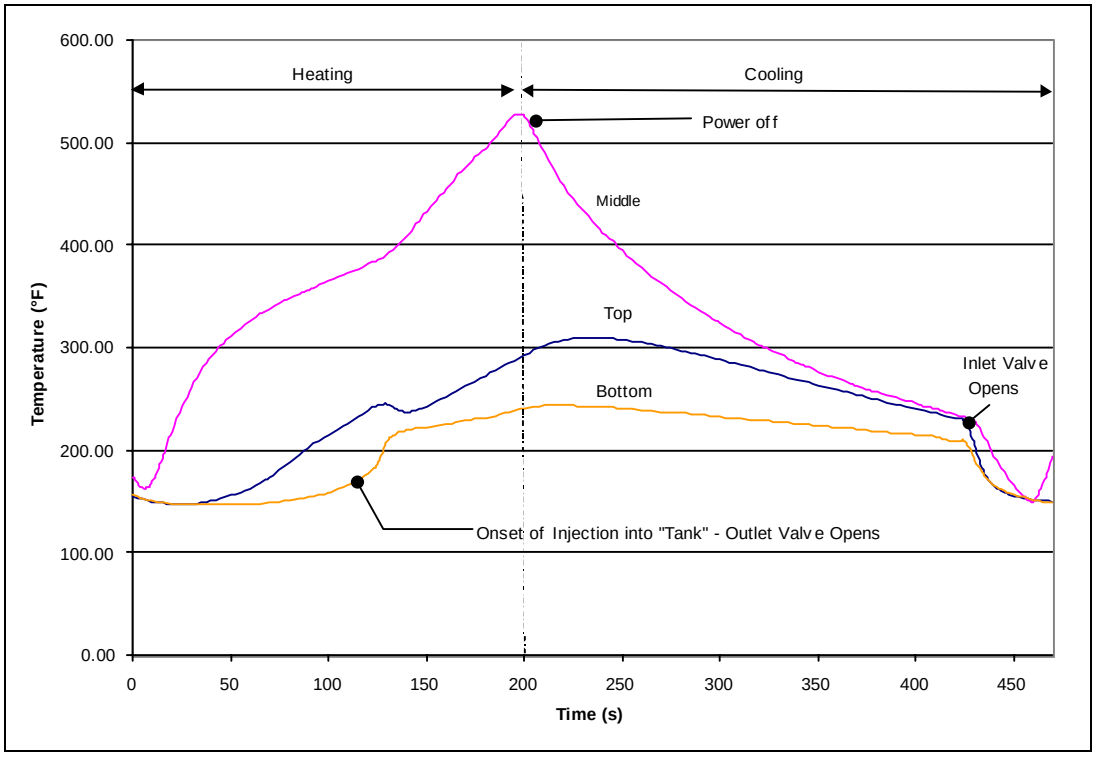

Figure 4.11: CRS Bench-Top Test Results (Cycle Data Late in Test)

5.2. Operational Verification Test Installed in the HPWH

We connected the CRS to the HPWH as described in Section 2 without the carbon filter installed. We introduced sufficient water into the evaporator pan to ensure that we would have a sufficient number of cycles to test the continuous operation of the CRS. Figure 4.12 shows the test results.

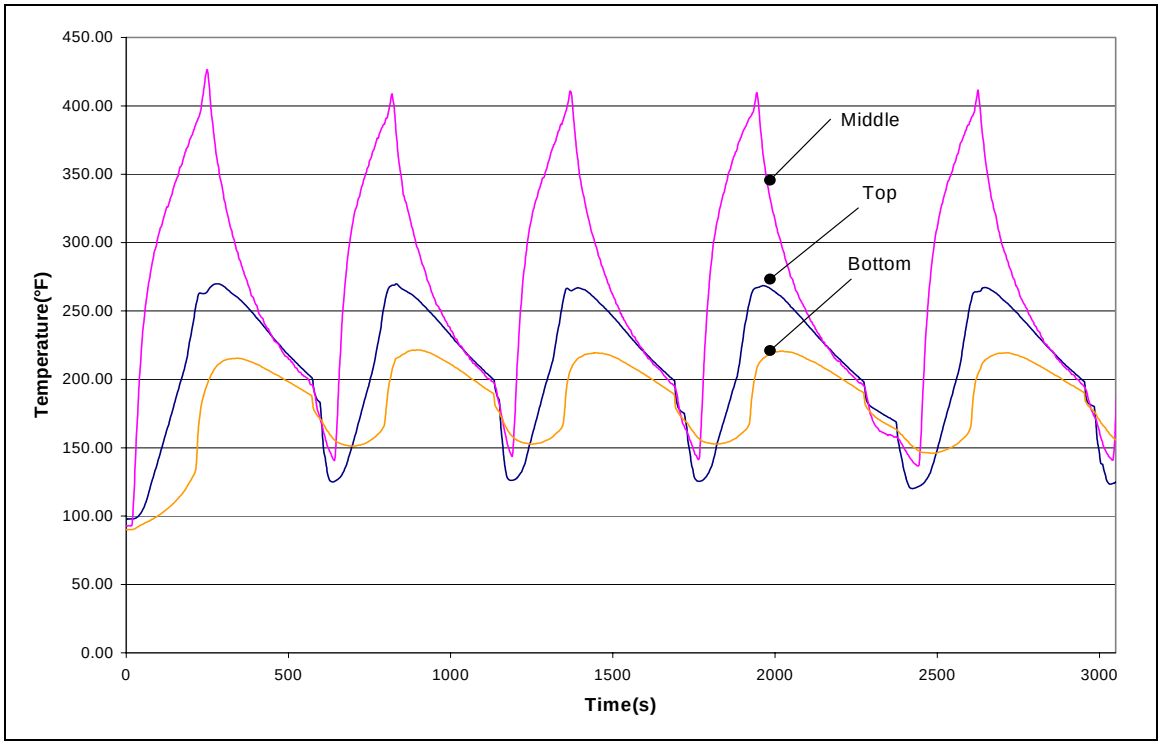

Figure 4.12: Operational Verification Test – CRS Installed in HPWH – Results

As was found in the bench-top tests, the CRS performed consistently during the test. The results also compared well with the previous NETL test results. The CRS temperatures and cycle times are compared with the previous test in Table 4.2. The CRS operated for 50 minutes, during which time it completed five cycles, resulting in an average cycle time of about 10 minutes. Thus, the throughput is estimated at 0.75 lb/hr, higher than the estimated 0.5 lb/hr found in the previous NETL test. The results of this test confirm the proper operation of the CRS when installed in the HPWH.

Table 4.2: Comparison of Installed Tests

Parameter	Previous Test[13]	Installed Test
Heating time (sec.)	220	175
Top Temperature (°F)	280 - 320	260
Bottom Temperature (°F)	240 - 260	220

Chapter 5 - Safety Testing

We performed the following safety tests of the CRS: a baseline test, paint test, gasoline test, and mold test. The tests were performed in accordance with the Test Plan. The following sections describe the test conditions, procedures, and results. It was not necessary to test the CRS with a carbon filter installed because the concentrations of the contaminants did not exceed the applicable levels identified in the test plan.

1 Baseline Test

In preparation of the baseline tests, the evaporator pan and the condensate receptacle were cleansed thoroughly with water. We set the temperature of the environmental chamber to 80°F and the relative humidity to 50%RH. We allowed the HPWH to operate until the condensate in the evaporator pan just crested above the plastic tube inlet that led to the CRS. We began recording data and allowed the HPWH to operate for an additional hour and a half. During this time, the CRS cycled five times. The chamber remained at an average temperature of 82.4°F and 50% RH. All of the condensate that passed through the CRS was collected in a condensate receptacle. Once the test was complete, two 40-ml samples were taken from the condensate in the condensate receptacle and sent to an outside laboratory for analysis (the second sample was for back-up purposes).

An independent, third-party, laboratory tested the condensate sample using the standard test for potable water as specified in EPA 524.2. Appendix B contains the results from the laboratory. Table 5.1 summarizes the results of the laboratory analysis. Two chemicals were detected in the condensate of the baseline test, Styrene and Methylene Chloride. However, their levels were below the contamination limits set by the EPA. No other chemicals were detected. From this, we conclude that the condensate exiting the CRS is potable for the baseline condition.

Table 5.1: Baseline Test Results (Detected Chemicals)

Chemical	Measured Levels (μg/L)	EPA Limits (μg/L)	Potable?
Styrene	2.6	100	Yes
Methylene Chloride	3.4	5	Yes

Although the EPA contamination limits were not exceeded during the baseline test, we were curious about the source of the styrene and methylene chloride. To determine the background levels of the chemicals in the testing environment, we performed an 'ice bath' test to gather condensate directly from the environment without requiring the condensate to pass through the evaporator of the HPWH or the CRS. We used a beaker filled with ice and placed it in a glass pan. The water vapor present in the environment

condensed on the outer surface of the beaker and collected in the pan. We took two 40 ml samples from the condensate collected in the pan and sent them to the laboratory for analysis (again, one sample being for backup).

Table 5.2 summarizes the results for the ice bath test. Based on these results, we conclude that environmental chamber in which the HPWH and CRS are located in has a small background level of styrene and methylene chloride. In addition, we can virtually rule out the HPWH or CRS as sources for these contaminants because the background level and level measured during the first test were nearly the same.

Table 5.2: Ice Bath Test Results (Detected Chemicals)

Chemical	Measured Levels (μg/l)	EPA Limits (μg/l)	Potable?
Styrene	2.1	100	Yes
Methylene Chloride	2.4	5	Yes

2 Paint Test

In preparation for the paint test, we set the temperature of the environmental chamber to 80°F and the relative humidity to 50%RH. We filled the HPWH with cold water. We allowed the HPWH to operate until the condensate in the evaporator pan just crested above the plastic tube inlet that led to the CRS. We made sure that the CRS was functioning properly by observing a few cycles of the CRS before introducing the paint. We turned off the environmental chamber conditioning system and closed the door before spraying paint into the chamber to avoid contaminating the chamber conditioning system. The temperature in the room dropped to about 60 °F and relative humidity increased to about 55% while the chamber conditioning system was shut off[14].

We sprayed through a small outlet at the side of the chamber and closed the outlet after spraying the paint. Per the Laboratory Test Plan, we sprayed 262.1 grams of paint. After spraying the paint, we let the paint dissipate throughout the environmental chamber for about an hour.

After the paint had settled, we turned the environmental chamber back on. The temperature and humidity quickly stabilized to about 83 °F and 49 % RH. The test was concluded after the HPWH finished heating the cold tank of water to about 135°F and the compressor shut off (approximately 5-1/2 hours).

We collected all of the condensate that passed through the CRS in the condensate receptacle. The CRS completed seven cycles after the paint had been sprayed. After mixing the condensate thoroughly in a beaker to ensure uniformity, we collected two 40-ml samples and sent them to a testing agency for analysis. The condensate sample was tested using the standard test for potable water as specified by EPA Method 524.2. The results from the testing agency are attached in Appendix B.

[14] This is expected because the HPWH removes heat from the air and condensed water vapor and transfers it to the storage tank through the vapor compression cycle.

Table 5.3 summarizes the results for the Paint Tests. We found that the limits of the three chemicals identified in the hazard analysis[15] as being potential hazards were below the limits allowed by EPA. We conclude that the condensate exiting the CRS is potable for the paint test.

Table 5.3: Paint Test Results

Chemicals	Measured Levels (μg/l)	EPA Limits (μg/l)	Potable?
Toluene	380	1000	YES
Xylenes(total)	320	10000	YES
Ethyl Benzene	56	700	YES

3 Gasoline Test

In preparation for the gasoline tests, we drained and dried the evaporator pan. We then ran the HPWH and generated fresh condensate to fill the evaporator pan until the condensate started flowing through the plastic tube into the CRS. We ran a few cycles to remove any residue from the paint tests. We threw away the condensate collected in the condensate receptacle and flushed the condensate receptacle thoroughly with running water before re-installing it.

Per the Laboratory Test Plan, we placed about 90 ml of gasoline[16] in a large open container above and in front of the HPWH air inlet[17]. We simulated a hot day by setting the temperature of the chamber to 100°F with 50% RH. The HPWH was emptied of hot water to start the test with a cold tank of water. The HPWH operated while exposed to the gasoline vapor and hot environment. The test was terminated when the HPWH heated the tank of water to about 135°F and the compressor shut off (approximately 6 hours). The measured average temperature and humidity during the test period were approximately 99°F and 44% RH.

We collected all the condensate that passed through the CRS in the condensate receptacle. The CRS cycled about 30 times during the test. After mixing the condensate thoroughly in a beaker to ensure uniformity, we collected two 40-ml samples and sent them to a testing agency for analysis. The condensate sample was tested using the standard test for potable water as specified by EPA Method 524.2. The results from the testing agency are attached in Appendix B.

Table 5 summarizes the results. As seen from the table, we found that the limits of all the chemicals of concern were below the allowable EPA limits.

[15] Safety Analysis and Testing of a HPWH Condensate Recovery System – Preliminary Hazard Analysis, report to CEC, date Feb 6 2002.
[16] For Safety purposes, we verified that the amount of gasoline introduced into the chamber was not sufficient to reach the flammability limits for gasoline even if all the gasoline evaporated.
[17] The density of the gasoline vapor is greater than that of air. In order to ensure the gasoline vapor was exposed to the HPWH evaporator it was necessary to put the container in front and above the inlet to the evaporator.

Table 5.4: Gasoline Test Results

Chemical	Measured Levels (μg/l)	Applicable Limits (μg/l)	Potable?
Toluene	3.6	1000	YES
Xylene	ND	10000	YES
Ethyl Benzene	ND	700	YES
Benzene	ND	5	YES
MTBE	100	13	--

Although there are no current EPA standards for MTBE, the EPA Method 524.2 tests for MTBE. The testing agency found the level of MTBE in the sample we provided at 100 μg/L. The maximum contaminant level of MTBE allowed by the State of California Department of Health Services' (DHS) Primary Drinking Water Standard is 13 μg/L[18]. While the amount of MTBE found in the sample exceeds the level regulated by the State of California, there are three mitigating factors to consider:

1. The level of MTBE, once diluted in the storage tank of the HPWH, is far below the regulated level.

2. The State of California expects to completely phase out MTBE from its gasoline supply by the end of 2003 and, therefore, will no longer be a contamination source.

3. The EPA concludes that keeping the concentration below 20 to 40 μg/L will likely avert any unpleasant taste and odor effect and provides a margin of safety that is equivalent to other regulated contaminants.

When the dilution effect of the HPWH storage tank (1:80)[19] is considered, the MTBE level is reduced to 1.25 μg/l. The diluted concentration level is lower than the California standard by a factor of 10. However, it is uncertain whether regulatory agencies would define the water source as the exit of the hot water tank or the exit of the CRS. One could consider the CRS as a "water treatment device" as defined by California Code[20]. However, because the CRS is also integral to the HPWH, there could be reason to consider the entire HPWH as a "water treatment device". In the future, this subject will require further investigation, understanding and clarification.

In March of 2002, California Governor Gray Davis issued an executive order that extended the phase-out of MTBE by one year. With this order, the complete phase-out of MTBE from the California gasoline supply will be completed by no later than December

[18] Title 22 of the California Code of Regulations, Primary Drinking Water Standards
[19] Safety Analysis and Testing of a HPWH Condensate Recovery System – Preliminary Hazard Analysis, Report to CEC, Jan 22 , 2001
[20] California Health and Safety Code Section 116825(a): "Water treatment device" means any point of use or point of entry instrument or contrivance sold or offered for rental or lease for residential use, and designed to be added to the plumbing system, or used without being connected to the plumbing of a water supply intended for human consumption in order to improve the water supply by any means, including, but not limited to, filtration, distillation, adsorption, ion exchange, reverse osmosis, or other treatment "Water treatment device" does not include any device that is regulated pursuant to Article 12 (commencing with Section 111070) of Chapter 5 of Part 5.

31, 2003. Even if the CRS were introduced by 2003, the risk of the CRS being exposed to gasoline containing MTBE is low.

The EPA currently does not regulate MTBE in its primary drinking water standards. The EPA is studying the possibility of including MTBE within the secondary drinking water standard, based on taste and odor. The EPA has stated that, at concentration levels between 20-40 μg/L, there is little likelihood of negative health effects[21].

4 Mold Test

We performed the preliminary test for mold as described in the Laboratory Test Plan. Two samples were generated, one serving as a control, and the other to determine the effectiveness of heating that would occur in the CRS in deactivating the mold. The tests were performed in the microbiology lab at TIAX[22].

Initially, we placed 100 ml of deionized water into a glass beaker. One ml of the mold organism[23] was then added to the beaker. A control sample was taken from the beaker prior to heating and tested for mold and mold growth.

Next, to test if the mold and the toxins were rendered inactive by the heating process, the beaker was placed on a heating plate and heated to a temperature of 150°F. After maintaining the beaker water temperature at 150°F for 100 seconds, the water was tested for mold growth.

The mold growth testing procedure was identical for both the heated and unheated water. Some of the water was filtered through a 0.22 μm filter. The filtered water, unfiltered water and the filter were all tested for mold growth. The filter was placed in a petri dish enriched with potato dextrose growth media and allowed to incubate for 48 hours at 37°F. 1 ml samples of the filtered and unfiltered water were each placed on two growth media, namely potato dextrose agar and blood agar growth media. The absence of any colonial growth on the potato dextrose sample would indicate that mold was rendered inactive. The absence of hemolysis[24] on the blood agar sample would indicate that the toxins were deactivated.

Table 5.5 shows the results for the mold tests. The control samples, i.e., the samples of the unheated water, showed that there was mold growth on the filter and hemolysis in the unfiltered water, indicating that both the mold and toxins were active. However, after heating there was no growth on the filter, or hemolysis in the unfiltered water, indicating that both the mold and toxins were rendered inactive.

[21] EPA MTBE FAQs Drinking Water on the internet at http://www.epa.gov/mtbe/water.htm
[22] At the time of the tests, this laboratory was owned by Arthur D. Little.
[23] Stachybotrys - (Source: ATCC 9182 (typically used in water testing))
[24] Stachybotrys produces a toxin which lyses blood cells. This process is called hemolysis. The absence of hemolysis indicates that the toxin is deactivated.

Table 5.5: Mold Preliminary Test Results

Test	Heated Water	Unheated Water (Control)
Filter – Potato Dextrose	No Growth	Growth
Filtered Water – Dextrose	No Growth	No Growth
Unfiltered Water – Potato Dextrose	No Growth	Growth
Filtered Water – Blood Agar	No Hemolysis	No Hemolysis
Unfiltered Water – Blood Agar	No Hemolysis	Hemolysis

During a typical CRS cycle, the condensate is heated to a minimum temperature of 150°F and remains at or above 150°F for at least 100 seconds before being injected into the HPWH storage tank. The results of the preliminary tests show that the mold and mold toxins are deactivated when exposed to a temperature of 150°F for 100 seconds. Therefore, we conclude that the CRS will deactivate any mold or mold toxins that are present in the condensate prior to being injected into the HPWH storage tank.

Chapter 6 - Recommended Next Steps

Following the safety testing of the CRS we recognize there are a number of activities that ought to be completed before the commercialization of the CRS is likely to move forward. While the CRS is technically proven and the safety of the device has been demonstrated (relative to drinking water), market barriers remain. Completing the following activities will help to move the CRS from prototype to product (in no particular order):

1. Work with regulatory groups to make certain the design complies with applicable national mechanical and building codes.

2. Contact companies (individuals) that are engaged in and approved to test water treatment devices for the state of California and have them review and test the CRS integrated with the HPWH.

3. Perform an additional design iteration to integrate the CRS into the HPWH and incorporate design-for-manufacture features that enable commercial production.

4. Develop a focus group of consumers to determine the reaction of consumers to the product and idea of injecting condensate from the air into their water.

5. Demonstrate the product in a field-test to determine energy impacts and provide more information regarding the safety of the device.

6. Review potential carbon filter designs and determine if there is a cost-effective filter that could be incorporated into the CRS.

7. Develop an education program to increase the understanding of the system.

1 Regulatory Groups

There are two regulatory groups that are involved with the codes and regulations that impact the condensate recovery system. The first is the group that produces the International Mechanical Code (IMC). Relative to the CRS, the IMC ensures that proper methods are used for HVAC equipment condensate disposal. The code that applies to the CRS focuses on proper disposal of the condensate in order to protect equipment and buildings from harm, i.e., condensate draining onto a roof and puddling, or sewer gases entering the equipment (room) through a direct connection to the sewer. It is in our opinion that, while the IMC will probably want to review the CRS, they will be hard-pressed to find any specific reason to disallow it under the current code.

The second regulatory group is responsible for the International Plumbing Code (IPC). The IPC focuses on protecting the potable water systems from contamination. Within the

code the most troubling section facing the development of the condensate recovery system is found in Section 602.2 and is as follows:

> *Only potable water shall be supplied to plumbing fixtures that provide water for drinking, bathing or culinary purposes…Unless otherwise provided in this code, only potable water shall be supplied to all plumbing fixtures.*

Because of this project, we have preliminary evidence showing that the condensate exiting the CRS will be potable. However, we will want to discuss with the IPC what other data and/or evidence they would need to show that the safety of the potable water system is not compromised.

2 Water Treatment Device Testing

Under California law, the CRS may be considered a water treatment device and therefore require compliance with the California Health & Safety Code. According to the code, the Department of Health Services determines the criteria and procedures for certification of these devices. The certification is intended for devices that provide supplemental treatment of municipally treated water. However, because the CRS is a unique application where potable condensate is introduced to the municipal water system, the Department may want to consider its certification. The Department may accept certification issued by another state, an independent testing organization, or the by federal government as long as the certification program meets the requirements of the California Code. Additional study and dialogue with the Department of Health Services would be beneficial.

3 Additional Design Iterations

We have developed and technically proven the design of the prototype CRS. In addition, the safety of the device, relative to drinking water, has been demonstrated. The next logical step in the commercialization of the CRS is to perform an additional design iteration to integrate the CRS into the HPWH and incorporate design-for-manufacture features that enable commercial production. Incorporating the control logic into the HPWH microprocessor based control board is still needed. Some more design work to define how the CRS integrates into the HPWH would be beneficial. There are a number of areas where we could improve the manufacturability of the CRS. This may make it more palatable for manufacturers. These improvements include using an extruded vessel with welded caps, developing a method for incorporating the electric heater, eliminating the use of plastic threaded parts, and re-designing the float for higher-volume production.

4 Focus Groups

Throughout the development of the CRS we have observed some hesitation to the idea of injecting condensate into people's hot water storage tank. It would be beneficial to study the reasons in further detail in order to understand what it is exactly that makes consumers apprehensive. We may also want to see how the reaction varied if we downplayed the function of the CRS and focused on the other features and benefits of the

HPWH with the CRS. Perhaps if we present it as a small (or non-) issue, people will not react as negatively to the concept. There are many issues revolving around the consumer acceptance of the CRS and it would be helpful to develop a couple of focus groups to study the issues further.

5 Field Testing

The HPWH is currently being tested in a number of California field installations with support of the PIER program (CEC Contract 500-98-028). In addition, the Oak Ridge National Laboratory is completing a field test of 18 units located throughout the nation. EMI (the HPWH manufacturer) has also begun ramping up production to support a field test of nearly 500 units in the New York area. The units that are currently in the field have been operating constantly for as little as 2 months and for as long as 1.5 years.

It may be possible to leverage the current field installations and their respective data in a field test of the CRS. Knowing how each HPWH operates at each site would allow us to select the most appropriate sites for testing of the CRS. We would ideally select sites where the condensate generation rate is high. Although it may also be of interest to select a site or two where there was little condensation to see how the lack of operation affected the performance of the CRS. We could then swap out the selected existing HPWHs with new HPWHs having the CRS.

6 Carbon Filter Design

Although the preliminary safety tests demonstrate that there is no need for the carbon filter, there still remain some questions in consumers' minds about the inherent safety. We estimate the manufactured cost of the CRS to be approximately $20. If there were a way to incorporate a carbon filter into the CRS design without increasing the costs by more than around 10% it may be worth considering further. By providing the additional protection, the consumer would perhaps be more willing to accept the HPWH with an integrated CRS. We believe that reviewing potential carbon filter designs and determining if there were a cost-effective method for incorporating the filter into the CRS is a worthwhile activity and should be included as a next step.

7 Education Program

As mentioned previously, people tend to hesitate at the idea of taking condensate from the air and injecting it into the water. This hinders the commercialization effort in two ways. First, the consumer is hesitant to purchase equipment that seems unsafe. Secondly, the manufacturers, distributors, and retailers are unwilling to invest the time and/or energy required to move the technology forward due to the risk that the consumer will not purchase the equipment. Furthermore, they want to limit their exposure to any potential lawsuits from consumers who may allege damages due to using the CRS.

We recommend that an education program be developed to educate not only the end-user of the technology, but also the parties along the distribution chain. This would include the HPWH manufacturer(s) (current and potential), distributors, retailers, installers,

building owners, city building inspectors, etc. During the development of the CRS, we have had an opportunity to describe to numerous people how the CRS operates. Once we have explained what processes occur in taking water from the air and injecting it to the tank, people have generally been far more amenable to the idea.

Appendix A - Test Procedures

The information presented in this appendix describes the detailed test procedure for the CRS tests, including a brief description of the test facility, the measurement and instrumentation required, and finally the detailed testing procedures.

1 Test Facility

Figure A.1 presents the schematic of the test set up. The environmental chamber has controls to regulate the humidity and temperature. We will connect the HPWH to the building plumbing system (but not plumb the CRS to the HPWH).

The air in the environmental chamber is circulated in a closed loop through an air conditioning system. We do not want to contaminate the AC system with any spray paint, so we will place a high-density air filter at the air outlet of the chamber.

We will cut a rectangular section in the outer casing of a new HPWH and install the CRS, as indicated in Figure 4.3. We will use thermal mastic (thermally conductive paste) for thermal contact with the HPWH tank, which hastens the cooling of the CRS.

We will connect the outlet of the CRS to a condensate receptacle and install it as indicated in Figure A.1 to collect the condensate, rather than inject it into the HPWH. The condensate receptacle will maintain a back-pressure of approximately 20 psig on the CRS (similar to well water pressures and corresponding to the lowest, i.e., worst case, pressure). We will relieve the pressure after the tests are complete and collect the condensate.

Table A.1 presents the details of the instrumentation. The instrumentation is also indicated in Figure A.1.

Table A.1: Instrumentation

No.	Measurement	Instrumentation
1	Relative humidity and temperature of the environmental chamber	Relative humidity sensor and temperature sensor
2	Temperature of the CRS	T Type thermocouple
3	Temperature of Condensate	T Type thermocouple
	Weight of the spray paint can (before and after spraying)	Weighing Scale

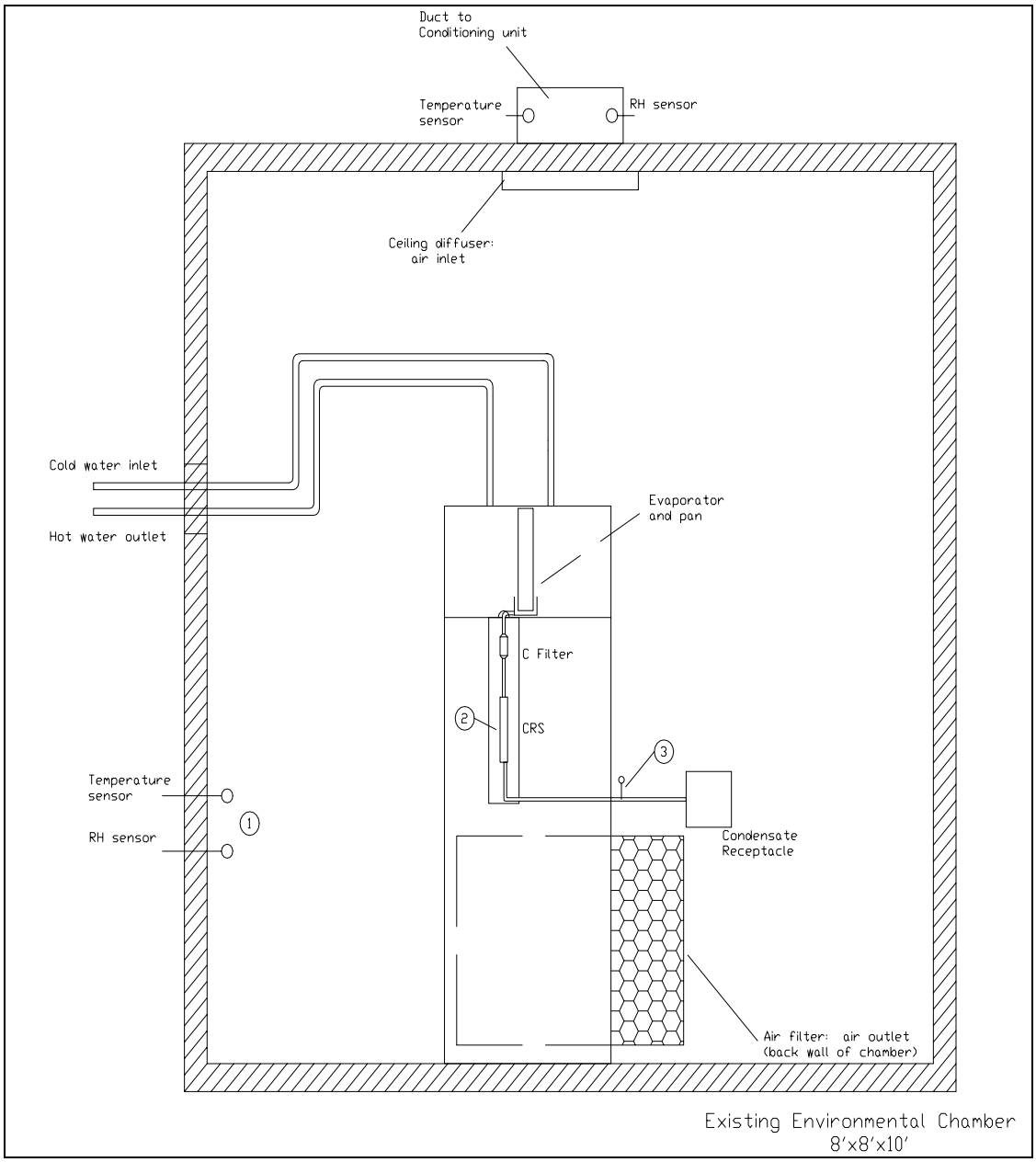

Figure A.1: Test Facility Setup

2 Test Procedures

The following section presents the detailed testing procedure for the baseline, spray paints, gasoline, and mold tests.

Baseline Test

Table A.2 presents the conditions for the baseline test.

Table A.2: Conditions for Baseline Test

Ambient Conditions	Duration
80°F±5°F, 50%+10% RH	1 hr

We will execute the following steps in carrying out this test:

1. Start the environmental chamber and set the chamber to the conditions in Table A.2.
2. Start the HPWH and let it run for 1 hour.
3. Collect the condensate from the condensate receptacle after 1 hour and send it to a testing agency to test for potability.

Spray Paint

We want to simulate conditions where the HPWH is running in the basement of a house where spray painting occurs.

Table A.3 presents the exposure limits of the chemicals under investigation and the amount of the chemical that must be present in the chamber to reach those exposure limits (volume of the chamber = 18.1 m^3). We expect that the spray paint particles will dissipate and some will settle on the floor and the walls of the chamber (which we will protect with paper). However, we expect the chemicals of interest will stay suspended in the air for some time due to their volatility.

Table A.3: Exposure Limits

Test	Chemical	Exposure limit – TWA(mg/m^3)	Amount of chemical needed to reach Exposure Limit (gms)
1	Toluene	375	6.8
2	Xylene	475	7.9
3	Ethyl-benzene	475	7.9

Table A.4 presents the calculation details for determining how much of the spray paint we will need to spray to achieve the desired exposure limits. As shown, Ethyl Benzene is only 3 percent by weight of the spray paint, the least of the three chemicals. Therefore, we will need to spray at least 77% of the can to achieve the exposure limit of Ethyl Benzene that we desire. In doing so, we will exceed the exposure limits set forth by the EPA for the other chemicals and will have to evaluate the results accordingly.

Table A.4: Calculation Details for Determining the Amount of Spray Paint

Test	Paint Type[a]	Chemicals	Weight in the spray can (%)	Percent of paint can to be sprayed
1	Decorator Paint 3 – Bright Gold	Toluene	26	8
		Xylene	15	15
		Ethyl Benzene	3	77
[a]Krylon Paints, www.krylon.com (MSDS obtained from the manufacturer)				

We will execute the following steps to carry out the paint test:

1. Run the environmental test chamber to establish the initial ambient conditions of 80°F±5°F and 50 %±10%. RH.
2. Run the HPWH for about a half an hour before spraying the paint to ensure the formation of condensate has begun as indicated by flow from the condensate pan into the CRS.
3. Turn the environmental chamber off before spraying the paint.
4. Shake the spray can thoroughly as per instructions and weigh it before spraying.
5. Spray in short bursts, frequently weighing the can to achieve the desired weight after spray painting (77 % of can as per Table A.4)
6. Let the paint settle and dissipate for half an hour.
7. Start the environmental chamber after the half an hour.
8. Switch off the HPWH 6 hrs after spraying the paint.
9. Collect the condensate and send a sample to a testing agency to test for contamination and potability.
10. Flush the HPWH by running it for half an hour before starting the next test.

Gasoline

Table A.5 presents the ambient conditions and the duration for the gasoline test. We will use regular unleaded gasoline for the test. We will simulate a hot day, which would cause the evaporation rate to be high.

Table A.5: Ambient Conditions for Gasoline Test

Ambient Conditions	Duration
100°F±5°F, 50%±10%RH	6 hrs

We will limit the amount of gasoline introduced to the test chamber such that, even if all the gasoline were evaporated, the concentration in the test chamber would be less than half the lower flammability limit. Table A.6 presents the details of the calculation in that shows the allowable volume of liquid gasoline is 98 ml. We will limit the amount of liquid gasoline we use to 50 ml ± 1 ml to maintain a safety of factor of two.

Table A.6: Calculation Details for Gasoline

Lower Flammability Limit (% by volume)	Allowable Volume of Gasoline Vapors in Chamber (m^3)	Allowable Mass of Gasoline (gms)	Allowable Volume of Liquid Gasoline (ml)
1.3	0.023	69	98

We will execute the following steps for the gasoline test:

1. Set and run the environmental chamber at the conditions specified in Table A.5.
2. Place an open container of gasoline with 50 ml ± 1 ml on an elevated platform directly in front of and slightly above the inlet to the HPWH (gasoline vapor is denser than air).
3. Run the HPWH in this environment for six hours.
4. Collect the condensate and a sample to a testing agency to test for contamination and potability.
5. Flush the HPWH by running it for half an hour before starting the next test.

Tests with Carbon Filter

As explained above, if the tests without the carbon filter are found to exceed the allowable contamination levels after considering the dilution effect in the HPWH tank, we will perform tests with the carbon filter in place. We will place the carbon filter as shown in Figure A.1: Test Facility Setup. The spray paint and gasoline test procedures with the filter are identical to the above procedures.

Mold and Mold Waste Test

We will perform the preliminary test for the mold and mold waste by growing the mold (and subsequently the mold waste) in the laboratory prior to performing the tests. Initial, we will perform the preliminary test. If we find the mold is not deactivated in the preliminary test, we will then perform the CRS test. Biosafety level two controls will be employed throughout the tests.

Preliminary Test

We will execute the following steps for the preliminary mold test:

1. Grow approximately 10 million-log phase colony forming units (cfu) organisms in 10 mls of fungal media prior to the execution of the preliminary test.
2. Heat de-ionized water to 150°F (66°C) in an insulated beaker.
3. Place 1 ml of the organisms into the de-ionized water.
4. Wait 100 seconds.
5. Immediately filter the 100 mls of water through a 0.22-µm filter.
6. Place the filter in a petri dish on a pad that has been enriched with growth media.
7. Incubate for 48 hours at 37°C to determine if the mold and mold waste is inactivated.

Mold Test with the CRS

If we find that the mold spores are not killed in the laboratory simulation, we will perform a test with the CRS.

We will execute the following steps for the mold test with the CRS:

1. Grow approximately 10 million-log phase colony forming units (cfu) organisms in 10 mls of fungal media prior to the execution of the test.
2. Set and run the environmental chamber at 80°F±5°F and 50%±10%RH.
3. Run the HPWH for half an hour to ensure condensate has started collecting in the evaporator as indicated by flow from the condensate pan into the CRS.
4. Introduce the mold solution into the evaporator pan. Let the HPWH run for 2 hours to allow ample time for the mold to flow from the evaporator pan into the CRS

5. Collect all the condensate and have it analyzed at the microbiology lab at TIAX.
6. Clean the evaporator pan and the CRS using support from the microbiology lab at TIAX

The microbiology lab at TIAX will support us throughout this testing to ensure that the necessary safety precautions are taken in handling the mold spores.

3 Data Analysis

The collected condensate in each of the runs will be sent to a testing agency for analysis. Knowing the contamination levels of the condensate, we will calculate the corresponding contamination levels that we would expect to find in the storage tank by applying a dilution rate of 1 to 80. The dilution rate is based on the HPWH heating a cold tank of water (45 gallons) over approximately a six hour period with ambient conditions of 80°F and 50%RH.

We will compare the calculated contamination level to the EPA maximum contamination levels (MCL) for the contaminants found in the condensate to confirm that the levels are below the MCL.

Appendix B - Laboratory Test Results

This appendix provides the test reports for the samples taken during the safety and hazard testing. The tests results are presented as received from the independent testing laboratory. Following the test results are the results from the mold tests that were performed in the TIAX laboratories.

1 Laboratory Test Results

TOXIKON CORPORATION
15 WIGGINS AVENUE
BEDFORD, MA 01730
TEL: (781) 275-3330

March 22, 2002

Ankur Rupani
Arthur D. Little
Acorn Park
Cambridge, MA 02140
TEL: (617) 498-6042
FAX (617) 498-7213

RE:

Order No.: 0203239

Dear Ankur Rupani:

Toxikon received 2 samples on 03/21/02 for the analyses presented in the following report.

Unless noted in the report, there were no problems with the analyses and all data for associated QC met EPA or laboratory specifications.

If you have any questions regarding these test results, please feel free to call.

Sincerely,

Paul Lezberg

Certifications: MA: MA 064, NH: 204099D and 204099E, ME: MA064, RI: 55, VT: MA064, TN: MA064
NY: 10778, NC: 286, PA 68-461, CT: PH 0563, NJ: 59538, MD: 185

Toxikon **Date:** *22-Mar-02*

CLIENT: Arthur D. Little
Project:
Lab Order: 0203239

Work Order Sample Summary

Lab Sample ID	Client Sample ID	Collection Date	Date Received
0203239-01A	EVAPORATOR		03/21/02
0203239-02A	ICE SIMULATION		03/21/02

Toxikon **Date:** *22-Mar-02*

CLIENT:	Arthur D. Little	**Client Sample ID:**	EVAPORATOR
Lab Order:	0203239	**Tag Number:**	
Project:		**Collection Date:**	
Lab ID:	0203239-01A	**Matrix:**	AQUEOUS

Analyses	Result	Limit	Qual	Units	DF	Date Analyzed
PURGEABLE ORGANIC COMPOUNDS		**E524.2**				Analyst: **SP**
1,1,1,2-Tetrachloroethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,1,1-Trichloroethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,1,2,2-Tetrachloroethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,1,2-Trichloroethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,1-Dichloroethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,1-Dichloroethene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,1-Dichloropropene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,2,3-Trichlorobenzene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,2,3-Trichloropropane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,2,4-Trichlorobenzene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,2,4-Trimethylbenzene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,2-Dibromo-3-chloropropane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,2-Dibromoethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,2-Dichlorobenzene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,2-Dichloroethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,2-Dichloropropane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,3,5-Trimethylbenzene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,3-Dichlorobenzene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,3-Dichloropropane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
1,4-Dichlorobenzene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
2,2-Dichloropropane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
2-Chlorotoluene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
4-Chlorotoluene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
4-Isopropyltoluene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Benzene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Bromobenzene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Bromochloromethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Bromodichloromethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Bromoform	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Bromomethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Carbon tetrachloride	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Chlorobenzene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Chloroethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Chloroform	ND	0.60		µg/L	1	03/21/02 11:08:00 PM
Chloromethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
cis-1,2-Dichloroethene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
cis-1,3-Dichloropropene	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Dibromochloromethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Dibromomethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM
Dichlorodifluoromethane	ND	0.50		µg/L	1	03/21/02 11:08:00 PM

Qualifiers:

ND - Not Detected at the Reporting Limit
J - Analyte detected below quantitation limits
B - Analyte detected in the associated Method Blank
* - Value exceeds Maximum Contaminant Level
S - Spike Recovery outside accepted recovery limits
R - RPD outside accepted recovery limits
E - Value above quantitation range

Toxikon **Date:** *22-Mar-02*

CLIENT:	Arthur D. Little	**Client Sample ID:**	ICE SIMULATION
Lab Order:	0203239	**Tag Number:**	
Project:		**Collection Date:**	
Lab ID:	0203239-02A	**Matrix:**	AQUEOUS

Analyses	Result	Limit	Qual	Units	DF	Date Analyzed
PURGEABLE ORGANIC COMPOUNDS		**E524.2**				Analyst: **SP**
1,1,1,2-Tetrachloroethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,1,1-Trichloroethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,1,2,2-Tetrachloroethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,1,2-Trichloroethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,1-Dichloroethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,1-Dichloroethene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,1-Dichloropropene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,2,3-Trichlorobenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,2,3-Trichloropropane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,2,4-Trichlorobenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,2,4-Trimethylbenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,2-Dibromo-3-chloropropane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,2-Dibromoethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,2-Dichlorobenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,2-Dichloroethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,2-Dichloropropane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,3,5-Trimethylbenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,3-Dichlorobenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,3-Dichloropropane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
1,4-Dichlorobenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
2,2-Dichloropropane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
2-Chlorotoluene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
4-Chlorotoluene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
4-Isopropyltoluene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Benzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Bromobenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Bromochloromethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Bromodichloromethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Bromoform	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Bromomethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Carbon tetrachloride	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Chlorobenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Chloroethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Chloroform	ND	0.60		µg/L	1	03/21/02 11:46:00 PM
Chloromethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
cis-1,2-Dichloroethene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
cis-1,3-Dichloropropene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Dibromochloromethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Dibromomethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Dichlorodifluoromethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM

Qualifiers:
ND - Not Detected at the Reporting Limit
J - Analyte detected below quantitation limits
B - Analyte detected in the associated Method Blank
* - Value exceeds Maximum Contaminant Level
S - Spike Recovery outside accepted recovery limits
R - RPD outside accepted recovery limits
E - Value above quantitation range

Toxikon **Date:** *22-Mar-02*

CLIENT:	Arthur D. Little	**Client Sample ID:**	ICE SIMULATION
Lab Order:	0203239	**Tag Number:**	
Project:		**Collection Date:**	
Lab ID:	0203239-02A	**Matrix:**	AQUEOUS

Analyses	Result	Limit	Qual	Units	DF	Date Analyzed
PURGEABLE ORGANIC COMPOUNDS		**E524.2**				Analyst: **SP**
Ethylbenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Hexachlorobutadiene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Isopropylbenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
m,p-Xylene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Methyl tert-butyl ether	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Methylene chloride	2.4	0.50		µg/L	1	03/21/02 11:46:00 PM
n-Butylbenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
n-Propylbenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Naphthalene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
o-Xylene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
sec-Butylbenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Styrene	2.1	0.50		µg/L	1	03/21/02 11:46:00 PM
tert-Butylbenzene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Tetrachloroethene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Toluene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
trans-1,2-Dichloroethene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
trans-1,3-Dichloropropene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Trichloroethene	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Trichlorofluoromethane	ND	0.50		µg/L	1	03/21/02 11:46:00 PM
Vinyl chloride	ND	0.50		µg/L	1	03/21/02 11:46:00 PM

Qualifiers:

ND - Not Detected at the Reporting Limit
J - Analyte detected below quantitation limits
B - Analyte detected in the associated Method Blank
* - Value exceeds Maximum Contaminant Level
S - Spike Recovery outside accepted recovery limits
R - RPD outside accepted recovery limits
E - Value above quantitation range

TOXIKON
15 Wiggins Ave., Bedford, MA 01730
Telephone: (781) 275-3330
Fax: (781) 275-7478

Hb Lime

CHAIN OF CUSTODY RECORD

WORK ORDER #: 02-03-239
DUE DATE : 03-22-2002

COMPANY: Arthur D Little
ADDRESS: Acorn Park, Cambridge MA 02140
PHONE #: (617) 498-6042 FAX #: (617) 498-7213
P.O. #: 422494
PROJECT MANAGER: RICHARD WILLIAMS
PROJECT ID/LOCATION:

SAMPLE TYPE: 1. WASTEWATER, 2. SOIL, 3. SLUDGE, 4. OIL, 5. DRINKING WATER, 6. WATER (DW/MW/SW), 7. OTHER (SPECIFY)
CONTAINER TYPE: P - PLASTIC, G - GLASS, V - VOA

ANALYSES: 524 Analysis

TOXIKON #	SAMPLE IDENTIFICATION	SAMPLE TYPE	CONTAINER SIZE	CONTAINER TYPE	CONTAINER #	SAMPLING DATE	SAMPLING TIME	PRESERVATIVE	524 Analysis	SPECIAL INSTRUCTIONS/ COMMENTS
1	Evaporator			V	2			HCL	X	
2	Ice simulation			V	2			HCL	X	

SAMPLED BY:	DATE: - - / TIME: -	QUOTATION #:	
RELINQUISHED BY:	DATE: - - / TIME: - -	RECEIVED BY:	DATE: - / TIME: - -
RELINQUISHED BY:	DATE: - - / TIME: - -	RECEIVED FOR LAB BY:	DATE: 03-21-02 / TIME: 16-00 -
METHOD OF SHIPMENT		COOLER TEMPERATURE	

✱ 1 Day ✱
☑ RUSH ..... BUSINESS DAY TURN AROUND
☐ ROUTINE

Sample disposal information
Are there any other known or suspected contaminants in these samples other than those listed above?
Yes ____ No ____ If Yes, 1st Known _____

ASAP

TOXIKON CORPORATION
15 WIGGINS AVENUE
BEDFORD, MA 01730
TEL: (781) 275-3330

March 29, 2002

Ankur Rupani
Arthur D. Little
Acorn Park
Cambridge, MA 02140
TEL: (617) 498-6042
FAX (617) 498-7213

RE:

Order No.: 0203305

Dear Ankur Rupani:

Toxikon received 1 sample on 03/27/02 for the analyses presented in the following report.

Unless noted in the report, there were no problems with the analyses and all data for associated QC met EPA or laboratory specifications.

If you have any questions regarding these test results, please feel free to call.

Sincerely,

Paul Lezberg

Certifications: MA: MA 064, NH: 204099D and 204099E, ME: MA064, RI: 55, VT: MA064, TN: MA064
NY: 10778, NC: 286, PA 68-461, CT: PH 0563, NJ: 59538, MD: 185

Toxikon

Date: *29-Mar-02*

CLIENT: Arthur D. Little
Project:
Lab Order: 0203305

Work Order Sample Summary

Lab Sample ID	Client Sample ID	Collection Date	Date Received
0203305-01A	ARTHUR D. LITTLE	03/27/02	03/27/02

Toxikon **Date:** *29-Mar-02*

CLIENT:	Arthur D. Little	**Client Sample ID:**	ARTHUR D. LITTLE
Lab Order:	0203305	**Tag Number:**	
Project:		**Collection Date:**	03/27/02
Lab ID:	0203305-01A	**Matrix:**	DRINKING WATER

Analyses	Result	Limit	Qual	Units	DF	Date Analyzed
PURGEABLE ORGANIC COMPOUNDS		**E524.2**				Analyst: **SP**
1,1,1,2-Tetrachloroethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,1,1-Trichloroethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,1,2,2-Tetrachloroethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,1,2-Trichloroethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,1-Dichloroethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,1-Dichloroethene	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,1-Dichloropropene	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,2,3-Trichlorobenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,2,3-Trichloropropane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,2,4-Trichlorobenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,2,4-Trimethylbenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,2-Dibromo-3-chloropropane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,2-Dibromoethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,2-Dichlorobenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,2-Dichloroethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,2-Dichloropropane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,3,5-Trimethylbenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,3-Dichlorobenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,3-Dichloropropane	ND	25		µg/L	50	03/28/02 6:46:00 PM
1,4-Dichlorobenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
2,2-Dichloropropane	ND	25		µg/L	50	03/28/02 6:46:00 PM
2-Chlorotoluene	ND	25		µg/L	50	03/28/02 6:46:00 PM
4-Chlorotoluene	ND	25		µg/L	50	03/28/02 6:46:00 PM
4-Isopropyltoluene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Benzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Bromobenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Bromochloromethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
Bromodichloromethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
Bromoform	ND	25		µg/L	50	03/28/02 6:46:00 PM
Bromomethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
Carbon tetrachloride	ND	25		µg/L	50	03/28/02 6:46:00 PM
Chlorobenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Chloroethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
Chloroform	ND	25		µg/L	50	03/28/02 6:46:00 PM
Chloromethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
cis-1,2-Dichloroethene	ND	25		µg/L	50	03/28/02 6:46:00 PM
cis-1,3-Dichloropropene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Dibromochloromethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
Dibromomethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
Dichlorodifluoromethane	ND	25		µg/L	50	03/28/02 6:46:00 PM

Qualifiers:
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J - Analyte detected below quantitation limits
B - Analyte detected in the associated Method Blank
* - Value exceeds Maximum Contaminant Level
S - Spike Recovery outside accepted recovery limits
R - RPD outside accepted recovery limits
E - Value above quantitation range

Toxikon **Date:** *29-Mar-02*

CLIENT:	Arthur D. Little	**Client Sample ID:**	ARTHUR D. LITTLE
Lab Order:	0203305	**Tag Number:**	
Project:		**Collection Date:**	03/27/02
Lab ID:	0203305-01A	**Matrix:**	DRINKING WATER

Analyses	Result	Limit	Qual	Units	DF	Date Analyzed
PURGEABLE ORGANIC COMPOUNDS		**E524.2**				Analyst: **SP**
Ethylbenzene	56	25		µg/L	50	03/28/02 6:46:00 PM
Hexachlorobutadiene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Isopropylbenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
m,p-Xylene	200	25		µg/L	50	03/28/02 6:46:00 PM
Methyl tert-butyl ether	ND	25		µg/L	50	03/28/02 6:46:00 PM
Methylene chloride	ND	25		µg/L	50	03/28/02 6:46:00 PM
n-Butylbenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
n-Propylbenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Naphthalene	ND	25		µg/L	50	03/28/02 6:46:00 PM
o-Xylene	120	25		µg/L	50	03/28/02 6:46:00 PM
sec-Butylbenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Styrene	ND	25		µg/L	50	03/28/02 6:46:00 PM
tert-Butylbenzene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Tetrachloroethene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Toluene	380	25		µg/L	50	03/28/02 6:46:00 PM
trans-1,2-Dichloroethene	ND	25		µg/L	50	03/28/02 6:46:00 PM
trans-1,3-Dichloropropene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Trichloroethene	ND	25		µg/L	50	03/28/02 6:46:00 PM
Trichlorofluoromethane	ND	25		µg/L	50	03/28/02 6:46:00 PM
Vinyl chloride	ND	25		µg/L	50	03/28/02 6:46:00 PM

Qualifiers:

ND - Not Detected at the Reporting Limit
J - Analyte detected below quantitation limits
B - Analyte detected in the associated Method Blank
* - Value exceeds Maximum Contaminant Level
S - Spike Recovery outside accepted recovery limits
R - RPD outside accepted recovery limits
E - Value above quantitation range

TOXIKON CORPORATION
15 WIGGINS AVENUE
BEDFORD, MA 01730
TEL: (781) 275-3330

April 02, 2002

Ankur Rupani
Arthur D. Little
Acorn Park
Cambridge, MA 02140
TEL: (617) 498-6042
FAX (617) 498-7213

RE: GASOLINE SAMPLE

Order No.: 0203350

Dear Ankur Rupani:

Toxikon received 1 sample on 03/29/02 for the analyses presented in the following report.

Unless noted in the report, there were no problems with the analyses and all data for associated QC met EPA or laboratory specifications.

If you have any questions regarding these test results, please feel free to call.

Sincerely,

Douglas Shealy for P.L

Paul Lezberg

Certifications: MA: MA 064, NH: 204099D and 204099E, ME: MA064, RI: 55, VT: MA064, TN: MA064
NY: 10778, NC: 286, PA 68-461, CT: PH 0563, NJ: 59538, MD: 185

Toxikon **Date:** *02-Apr-02*

CLIENT: Arthur D. Little
Project: GASOLINE SAMPLE
Lab Order: 0203350

Work Order Sample Summary

Lab Sample ID	Client Sample ID	Collection Date	Date Received
0203350-01A	GASOLINE SAMPLE		03/29/02

Page 1 of 1

Toxikon **Date:** *02-Apr-02*

CLIENT:	Arthur D. Little	**Client Sample ID:**	GASOLINE SAMPLE
Lab Order:	0203350	**Tag Number:**	
Project:	GASOLINE SAMPLE	**Collection Date:**	
Lab ID:	0203350-01A	**Matrix:**	DRINKING WATER

Analyses	Result	Limit	Qual	Units	DF	Date Analyzed
PURGEABLE ORGANIC COMPOUNDS		**E524.2**				Analyst: **XL**
1,1,1,2-Tetrachloroethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,1,1-Trichloroethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,1,2,2-Tetrachloroethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,1,2-Trichloroethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,1-Dichloroethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,1-Dichloroethene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,1-Dichloropropene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,2,3-Trichlorobenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,2,3-Trichloropropane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,2,4-Trichlorobenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,2,4-Trimethylbenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,2-Dibromo-3-chloropropane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,2-Dibromoethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,2-Dichlorobenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,2-Dichloroethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,2-Dichloropropane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,3,5-Trimethylbenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,3-Dichlorobenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,3-Dichloropropane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
1,4-Dichlorobenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
2,2-Dichloropropane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
2-Chlorotoluene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
4-Chlorotoluene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
4-Isopropyltoluene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Benzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Bromobenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Bromochloromethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Bromodichloromethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Bromoform	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Bromomethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Carbon tetrachloride	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Chlorobenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Chloroethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Chloroform	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Chloromethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
cis-1,2-Dichloroethene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
cis-1,3-Dichloropropene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Dibromochloromethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Dibromomethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Dichlorodifluoromethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM

Qualifiers: ND - Not Detected at the Reporting Limit

J - Analyte detected below quantitation limits

B - Analyte detected in the associated Method Blank

* - Value exceeds Maximum Contaminant Level

S - Spike Recovery outside accepted recovery limits

R - RPD outside accepted recovery limits

E - Value above quantitation range

Toxikon **Date:** *02-Apr-02*

CLIENT:	Arthur D. Little	**Client Sample ID:**	GASOLINE SAMPLE
Lab Order:	0203350	**Tag Number:**	
Project:	GASOLINE SAMPLE	**Collection Date:**	
Lab ID:	0203350-01A	**Matrix:**	DRINKING WATER

Analyses	Result	Limit	Qual	Units	DF	Date Analyzed
PURGEABLE ORGANIC COMPOUNDS		**E524.2**				Analyst: **XL**
Ethylbenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Hexachlorobutadiene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Isopropylbenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
m,p-Xylene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Methyl tert-butyl ether	100	2.5		µg/L	5	04/01/02 11:32:00 PM
Methylene chloride	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
n-Butylbenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
n-Propylbenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Naphthalene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
o-Xylene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
sec-Butylbenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Styrene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
tert-Butylbenzene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Tetrachloroethene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Toluene	3.6	2.5		µg/L	5	04/01/02 11:32:00 PM
trans-1,2-Dichloroethene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
trans-1,3-Dichloropropene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Trichloroethene	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Trichlorofluoromethane	ND	2.5		µg/L	5	04/01/02 11:32:00 PM
Vinyl chloride	ND	2.5		µg/L	5	04/01/02 11:32:00 PM

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ND - Not Detected at the Reporting Limit
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R - RPD outside accepted recovery limits
E - Value above quantitation range

Page 2 of 2

Toxikon **Date:** *02-Apr-02*

CLIENT: Arthur D. Little
Project: GASOLINE SAMPLE
Lab Order: 0203350

CASE NARRATIVE

The sample could not be analyzed at a lower dilution due to the presence of MTBE.

TOXIKON
15 Wiggins Ave., Bedford, MA 01730
Telephone: (781) 275-3330
Fax: (781) 275-7478

CHAIN OF CUSTODY RECORD

WORK ORDER #: 02-03-350
DUE DATE: ~~03-29-2002~~ 04-02-02

COMPANY: Arthur D Little
ADDRESS: Acorn Park, Cambridge MA 02140
PHONE #: (617) 4986042 FAX #: (617) 4912453
P.O. #:
PROJECT MANAGER: Richard Williams
PROJECT ID/LOCATION:

SAMPLE TYPE: 1. WASTEWATER, 2. SOIL, 3. SLUDGE, 4. OIL, 5. DRINKING WATER, 6. WATER (GW/MW/SW), 7. OTHER (SPECIFY)
CONTAINER TYPE: P - PLASTIC, G - GLASS, V - VOA

ANALYSES: 524.2 (MTBE)

TOXIKON #	SAMPLE IDENTIFICATION	SAMPLE TYPE	CONTAINER SIZE	CONTAINER TYPE	CONTAINER #	SAMPLING DATE	SAMPLING TIME	PRESERVATIVE	524.2 (MTBE)	SPECIAL INSTRUCTIONS/ COMMENTS
1	Gasoline Sample			V	2			HCL	X	

SAMPLED BY:	DATE: - - / TIME: - -	QUOTATION #:	
RELINQUISHED BY:	DATE: - - / TIME: - -	RECEIVED BY:	DATE: - - / TIME: - -
RELINQUISHED BY:	DATE: - - / TIME: - -	RECEIVED FOR LAB BY:	DATE: 03-29-02 / TIME: 12-00
METHOD OF SHIPMENT		COOLER TEMPERATURE	

☑ RUSH ..... BUSINESS DAY TURN AROUND
☐ ROUTINE

Sample disposal information
Are there any other known or suspected contaminants in these samples other than those listed above?
Yes ____ No ____ If Yes, 1st Known _____

2 Mold Test Results

Table B.1 shows the results of three tests, which were performed as controls for the mold preliminary tests. Stachybotrys was grown and the water was not heated for these tests. As expected there was growth in the broth and in the water. Also, toxins were not deactivated in these tests as the water was not heated, indicated by the observation of hemolysis.

Table B.1 Controls for Mold Preliminary Tests

Type	Mold Growth (Potato Dextrose Agar Growth Media)	Mold Growth (Blood Agar Growth Media)	Toxins
Stachybotyrs in broth	G	G	H
Unfiltered water control	G	G	H
Filtered water-control	G on filter, NG in water	NG	N/H
G-growth, NG-no growth, N/H-no hemolysis, H-hemolysis			

CALIFORNIA
ENERGY
COMMISSION

Evaluation of Residential Hot Water Distribution Systems by Numeric Simulation

Project Final Report

TECHNICAL REPORT

JULY 2005
CEC-500-2005-111-A3

Arnold Schwarzenegger, *Governor*

Prepared By:
Davis Energy Group
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Davis, CA
Contract No. 400-00-038

Prepared For:
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B. B. Blevins
Executive Director

DISCLAIMER

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

Abstract

This “Evaluation of Residential Hot Water Distribution Systems by Numeric Simulation: Project Final Report” attachment is a document produced by the Synergistic Water Heating and Distribution Technologies (SWHDT) program, funded by the California Energy Commission’s Public Interest Energy Research (PIER) Program.

The goal of the Hot Water Distribution Systems project was to simulate and compare the energy and water performance, economics, and barriers to use of various domestic hot water distribution systems in new and existing California residences, and to evaluate the potential statewide impact of the use of more efficient hot water distribution systems. Heat loss from distribution piping affects overall energy use, water consumption, and homeowner waiting time at the end use points. A new numerical model, developed using LabVIEW, was used to estimate the heat loss or gain from insulated and non-insulated hot water pipes. This model permitted the evaluation of a wide range of options and alternatives (>250 scenarios were studied).

Preface

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

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million 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
- Energy Systems Integration

What follows is an attachment to the final report for the Synergistic Water Heating and Distribution Technologies program, Contract Number 400-00-038, conducted by Davis Energy Group. This project contributes to the PIER Building End-Use Energy Efficiency program. This attachment, "Evaluation of Residential Hot Water Distribution Systems by Numeric Simulation: Project Final Report" (Attachment 3), provides supplemental information to the program final report.

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.

Evaluation of Residential Hot Water Distribution Systems by Numeric Simulation

Final Report – March 2004

Synergistic Water Heating Technologies Program
Element 3 - Efficient Hot Water Distribution

Final Deliverable for:
Project 3.1 - Evaluation of Alternative Hot Water Distribution Systems
Task 3.1.2 "Simulate Potential Energy Savings, Perform Cost-Benefit Analyses, and Identify Market Barriers of Alternative New Systems",
Task 3.1.3 "Conduct Analysis of Existing Domestic Hot Water Distribution Systems", and
Task 3.1.4 “Evaluate Potential Impact”

Prepared for:
Davis Energy Group, Inc., and California Energy Commission
Under:
Work for Others Agreement ERD-01-2048 and Energy Commission Contract No: 400-00-038

Authors:
Robert Wendt, Co-Principal Investigator
Evelyn Baskin, Co-Principal Investigator
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Oak Ridge, Tennessee 37831-6285
Managed by
UT-Battelle, LLC
for the
U.S. DEPARTMENT OF ENERGY
Under contract DE-AC05-00OR22725

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1. Executive Summary

The goal of this project was to simulate and compare the energy and water performance, economics, and barriers to use of various domestic hot water distribution systems in new and existing California residences, and to evaluate the potential statewide impact of the use of more efficient hot water distribution systems.

Methodology

A new numerical model, developed using LabVIEW, was used to estimate the heat loss or gain from insulated and non-insulated hot water pipes. Heat loss from distribution piping affects overall energy use, water consumption, and homeowner waiting time at the end use points. This model permitted the evaluation of a wide range of options and alternatives (>250 scenarios were studied).

Two draw cycles (use patterns) were investigated. The first assumed that each individual draw was a "cold start", i.e. the water had reached the ambient temperature surrounding the pipe before each use. This pattern represents a "worst case" for potential water and energy waste. The second was a "clustered use" which had individual draws clustered in the early morning and late afternoon/evening, thereby retaining some hot water between draws. This pattern represents the likely "best case" regarding water and energy waste. Actual residential water use patterns vary between these extremes.

The economic implications of the various distribution systems and options were based on an analysis of expected utility cost savings. The average utility cost of ten California cities was used in the analysis (Gas: $.638/therm, Electric: $.116/kWh, and Water: $.85/HCF or 100 cu ft). The construction costs of the various distribution systems and options were developed from cost data provided by a major plumbing contractor based in southern California. The results shown in all tables in this report that reflect costs are based on the utility costs shown above. While these costs change over time, the relative ranking of the distribution system options to each other will not change unless the rate of escalation for utilities varies significantly from the rate of construction cost escalation.

New construction and existing housing were studied. The housing characteristics used for new construction included five examples that ranged from a four bedroom, 2½ bath, 3080 ft^2 single family detached home down to a one bedroom, one bath, 580 ft^2 apartment. The existing residences evaluated included a three bedroom, two bath, 1100 ft^2 single family home and a four bedroom, 2½ bath, 1960 ft^2 single family home. The characteristics used for new and existing hot water systems were typical of standard California practice

The following changes to conventional trunk and branch distribution systems were evaluated:

- Compare alternative piping materials used in conventional trunk and branch systems.
- Relocate water heater to a more central location.
- Add insulation to the various piping materials in standard system configurations.

The following alternative new home distribution systems were evaluated:

- Demand-actuated recirculating pump and controls in a conventional trunk and branch

system using the cold-water line for the return.

- Continuous recirculating system with a dedicated return line for larger residences.
- A parallel-pipe system with a manifold located near the water heater and ½" piping from the manifold to each individual fixture.

The following scenarios were evaluated for existing housing:

- Retrofit existing conventional system with a demand recirculation system and controls, using the cold water line for the return.
- Replace existing conventional system in kind and evaluate the impact of pipe materials and insulation.
- Replace existing conventional system with a parallel-pipe system with a manifold located near the water heater and ½" piping from the manifold to the individual fixtures.

Results

According to the model results, the pattern of energy and water waste performance among the scenarios for new construction was fairly consistent for all the single family detached houses studied. However, the results varied significantly with the water use pattern (cold start or clustered) that was assumed.

Table 1.1 shows the simulated results for the hot water distribution systems and parameters evaluated for a three-bedroom, two bath home, using a clustered (least wasteful) hot water use pattern. Demand and continuous recirculation systems waste the least water, while demand recirculation and a central water heater location waste the least energy for this set of assumptions. Changing the use pattern to cold start (most wasteful) significantly improved the performance of the parallel pipe/manifold system relative to the other systems, placing it just behind the demand recirculation systems. Continuous recirculation systems waste the most energy of all the systems. This consistently occurred among all houses and use patterns studied. Results for existing housing also showed the benefit of the demand recirculation system as a retrofit option.

The waiting time for hot water (105°F) to arrive at the faucet or shower is a primary factor in the evaluation of system performance by homeowners. The waiting times associated with the various scenarios studied for one of the houses are reflected in Table 1.1. All systems had "reasonable" typical waits (<30 seconds), but demand and continuous recirculation systems and the parallel pipe systems had shorter maximum waiting times. If a cold start use pattern is assumed, the typical waiting time for the various conventional systems increase significantly while the other systems remain about the same.

The construction costs of the various distribution systems for one of the houses studied are also reflected in Table 1.1. The use of CPVC piping, parallel pipe systems (PEX), and a centrally-located water heater all resulted in lower construction costs than the typical copper trunk and branch system. The continuous recirculation systems had the highest construction cost.

Table 1.1 Hot Water Distribution Systems and Parameters Evaluated for New Construction Home, Three Bedrooms, Two Baths, 2010 ft^2, Using a Clustered (*Least Wasteful*) Hot Water Use Pattern. Note: Using a cold start (*Most Wasteful*) use pattern increases (depending on the system/option evaluated) water waste by 25% to >600% and energy consumption by 60% to >600% above that shown in the table. The "better" options in each category are highlighted in **red** below. Results for the other houses studied are in Appendix A.

System/Option Evaluated	Construction Cost[a]	Wait Time for HW (Sec.)		Annual Water Waste (Gallons)	Annual Energy Waste ($)	
		Typical	Maximum		Electric @$0.116/kWh	Gas @$0.683/therm
Conventional, Attic, Copper - Central Water Heater	$1,450	5	40	1404	35.16	11.04
Conventional, Attic, CPVC - Central Water Heater	**$1,087**	5	39	1428	**34.08**	**10.68**
Conventional, Attic, Copper	$1,271	5	99	2352	58.80	18.36
Conventional, Attic, Copper – Insulated	$1,552	5	99	2340	58.32	18.24
Conventional, Attic, CPVC	**$866**	5	95	2292	55.08	17.16
Conventional, Attic, CPVC – Insulated	**$1,147**	5	95	2292	55.08	17.16
Conventional, Slab, Copper	$1,556	54	109	10140	273.00	85.20
Conventional, Slab, Copper – Insulated	$1,838	4	102	2304	60.12	18.72
Conventional, Slab, CPVC	**$1,086**	50	98	9204	224.04	69.96
Conventional, Slab, CPVC - Insulated	$1,368	5	98	2304	55.80	17.40
Demand Recirculation, Attic, Copper	$1,880	5	**9**	**924**	**26.52**	**8.28**
Demand Recirculation, Slab, Copper	$2,447	4	**8**	**792**	**26.40**	**8.28**
Demand Recirculation, Attic, CPVC	$1,475	5	**9**	**936**	**24.36**	**7.68**
Demand Recirculation, Slab, CPVC	$1,978	4	**8**	**840**	**22.80**	**7.08**
Parallel Pipe, Attic, PEX	**$1,226**	11	36	2352	60.48	18.84
Parallel Pipe, Slab, PEX	$1,443	19	38	3432	89.16	27.84
Continuous Recirculation, Attic, Copper – Insulated [b]	$2,559	5	**9**	**924**	146.16	45.60
Continuous Recirculation, Slab, Copper – Insulated [b]	$2,861	4	**8**	**792**	426.60	133.20
Continuous Recirculation, Attic, CPVC – Insulated [b]	$1,965	5	**9**	**936**	157.80	49.32
Continuous Recirculation, Slab, CPVC – Insulated [b]	$2,185	4	**8**	**840**	389.40	121.56

a. Construction Costs are for the distribution system only as paid by the homeowner (see Section 4.2)
b. The total annual pumping power cost for these systems will add $87.60/yr. to both gas and electric totals shown above.

Projected Impact on California

The impact of applying more efficient alternative hot water distribution systems on California's overall residential energy and water consumption was estimated for the period beginning 3 to 5 years after initiation of the recommended Implementation Plan, (see Section 6.2). The more efficient systems selected for the new construction projection had both lower or equal initial cost and superior water and energy performance than the conventional systems as currently installed. For this reason a penetration rate of 100% was assumed for new construction in the state (150,000 units/year). For systems in existing California housing with excessive waiting periods (3 million units), a 10% per year penetration rate for retrofit demand recirculation systems was assumed until the market was saturated. The penetration rate for all replacement systems in existing housing (11 million units) was assumed to be an on-going 0.1% per year.

The projected annual savings in water and energy for both new and existing California homes are shown below. Projected savings in each case are given as a range reflecting the difference between the cold start and clustered water use assumptions, but actual savings are likely to be between these extremes. The projected annual savings assumes that the program to facilitate and encourage the use of more efficient systems outlined in Section 6.2 has been underway for 3 to 5 years and has reached its maximum impact level.

Projected Annual Savings	Water, 10^6 gallons	Natural Gas, 10^9 Btu	Electric, MWh
Each year	850 to 2,670	470 to 1,450	24,200 to 74,800
Total after 10 yrs	8,500 to 26,700	4,700 to 14,500	242,000 to 748,000

Using data from the California Urban Water Conservation Council on per person water consumption in the San Francisco Bay Area (www.nrdc.org/greengate/water/residentialf.asp), the potential annual savings from using alternative hot water distribution systems would equal the total annual water consumption of between 8,000 and 27,000 California homes. Using water consumption rates from areas with significant irrigation demands could lower the impact measured in homes by 50%. DOE's Energy Information Agency, Residential Energy Consumption Survey [DOE/EIA-0314(90)] data for typical household energy consumption shows a potential annual saving due to use of improved distribution systems comparable to the total annual energy consumption of between 7,000 and 22,000 California homes.

Conclusions

The simulation results from this study provided the following conclusions:

Continuous recirculation systems add substantial construction cost as well as operating cost and energy waste when compared to any other system. Although they minimize wait times for hot water and water waste, continuous recirculation systems should not be installed due to their high cost and energy waste.

Adding a demand recirculation pump and controls increases conventional system costs by about $600 but reduces operating cost, waste and wait times. Wait times can be similar to continuous recirculation systems, with the added benefit that water and energy wastes are significantly reduced compared to conventional systems. Demand recirculation systems can be installed in both new construction and retrofit housing.

For the segment of the new construction market that is sensitive to first cost (i.e. most production homes), centrally locating the hot water heater cuts wait times and waste for a modest cost increment.

Parallel pipe distribution systems may also offer an attractive alternative for some house designs and distribution system layouts. These systems are less costly to install than conventional systems and can reduce wait times to acceptable levels, however, the energy and water savings of parallel pipe systems are sensitive to hot water use patterns. When modeled assuming clustered hot water draws, parallel pipe systems use similar amounts of water and energy as conventional systems and offer no advantage with regard to waste. When the cold start use pattern is modeled, parallel pipe systems perform better than conventional systems.

Recommendations

While detailed recommendations will vary with the specific house some general recommendations can be made.

For Policymakers:

- Gather field data to better understand what hot water distribution systems have been and are being installed in the state and how these systems perform. Specific issues of interest include: actual system performance, impact of insulation on under-slab systems, and hot water use patterns of a broad sample of homeowners.
- Remove barriers to the use of CPVC and PEX piping when appropriate quality and durability can be demonstrated.
- Utilize field data to validate the results of the model used in this report and other hot water distributions system simulation models.
- Incorporate the validated results into the next round of Title 24 building standards revisions (2008); publish best practices recommendations to builders and plumbers in the interim.
- Consider ways to encourage the use of centrally located hot water heaters.
- Consider ways to encourage installation of demand recirculation and parallel pipe systems, when warranted.
- Educate builders and the public about the consequences of locating distribution systems below floor slabs and the benefits of alternative locations.
- Consider banning continuous (uncontrolled) recirculation systems.

For Residential Designers, Builders, and Plumbers:

- Consolidate bathrooms and other hot water consuming activities in the same areas to take advantage of clustered uses of hot water.
- Consider centralizing the location of water heaters to minimize the length of piping between the fixtures and the water heater(s).
- Consider locating hot water distribution piping in the attic for single story homes without basements and interstitial space between floors for multistory homes.
- Do not oversize hot water piping. Use code permitted minimums. Bigger isn't better.
- Layout systems with all hot water pipe runs as short as possible to reduce energy and water waste, and the wait for hot water.
- Consider installing a demand recirculation system in lieu of a continuous recirculation system if waiting time and water waste are an issue.
- Consider installing CPVC or PEX plastic piping in lieu of copper when appropriate quality and durability can be demonstrated.

For New and Existing Homebuyers:

- Time how long it takes for hot water to arrive at the "most important" fixtures, such as the master bath's shower. This should be done several hours after any previous uses. Is this waiting time acceptable?
- Note the distance between the water heater and the furthest hot water consuming fixture. Note or ask about the pipe material used, pipe insulation provided, and where the system is located.

2. Project Purpose

This project was an element of the Synergistic Water Heating Technologies Program of the California Energy Commission's (Energy Commission's) Public Interest Energy Research (PIER) Program. The Oak Ridge National Laboratory (ORNL), under a contract with Davis Energy Group, accomplished the work.

Objective

The objective of this project was to evaluate the performance and economics of various domestic hot water distribution systems in representative California residences. While the greatest opportunities for improved efficiency occur in new construction, significant improvements can also be made in some existing distribution systems.

Specific objectives of the project tasks were:

- Simulate potential energy savings of, perform cost-benefit analyses of, and identify market barriers to alternative new systems.
- Simulate potential energy savings of, perform cost-benefit analyses of, and identify market barriers to maintenance, repair, and retrofit modifications of existing systems.
- Evaluate potential impact of adopting alternative hot water distribution systems and report project findings.

Project Outcome

The outcome of this project is to provide homeowners, homebuilders, systems suppliers, municipal code officials and utility providers (both electric and water/sewer) with a neutral, independent, third party, cost-benefit analysis of alternative hot water distribution systems for use in California. The results will enable these stakeholders to make informed decisions regarding which system is most appropriate for use.

Performance Metrics

The information from this project is intended to be used by the target audience to increase the utilization of technologies that have significant energy reduction, cost or other benefits. The performance metric used in evaluating the project's ability to meet its impact goals will ultimately be the number of alternative systems installed in new and/or existing housing in California. This metric can be measured by surveying residential plumbers to assess how their hot water distribution system practices have changed over time as a result of this information. Impact on existing homes can also be determined by surveying both plumbers and homeowners. The impact of improved hot water distribution systems can also be measured through "before and after" monitoring of existing residences, and by "side-by-side" monitoring of similar new residences with and without distribution system improvements. These follow-on performance evaluations are not within the scope of this project.

3. Methodology

3.1 Simulation Model for Hot Water Distribution Systems

A numerical model for residential hot water distribution systems was developed that allows analysis of various types of pipe, with and without insulation. The pipe segments may be exposed to a convective environment with known conditions (either forced or natural convection), buried in attic insulation, or buried beneath a floor slab in the soil. The distribution system model is Windows-based and versatile. The model used in this project was developed by Keith A. Woodbury, PhD., University of Alabama, and Evelyn Baskin, PhD., ORNL in conjunction with other related hot water distribution systems studies sponsored by the U.S. Department of Energy at ORNL.

The model simulates one-dimensional energy transport in the axial direction of the piping system with lateral heat losses to the pipe wall. The temperature distribution in the pipe wall and insulation is computed using two-dimensional calculations, coupled to the one-dimensional pipe solution through a heat transfer coefficient. Mathematically the problem can be described as follows (see Table 3.1 for definition of symbols). In the pipe, the (axial) temperature distribution of the fluid will be governed by

$$\dot{m}c_p \frac{\partial T}{\partial x} + \rho c_p A_{cs} \frac{\partial T}{\partial t} + p q''_{loss} = k A_{cs} \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

Here p is the perimeter and A_{cs} is the cross sectional area of the inner surface of the pipe, and k, c_p, and ρ are properties of the fluid. The heat loss from the fluid to the pipe wall will be modeled via a heat transfer coefficient as

$$q''_{loss} = h(x,t)\big(T(x,t) - T_s(x,t)\big) \qquad (2)$$

where $T_s(x,t)$ is the temperature of the inner surface of the pipe. The temperature distribution in the pipe and insulation can be computed from the solution of the two-dimensional heat conduction equation in radial coordinates:

$$\rho c_p \frac{\partial T_p}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr \frac{\partial T_p}{\partial r} \right) + k \frac{\partial^2 T_p}{\partial x^2} \qquad (3)$$

where the radial variation in k must be retained (to allow for insulation over the pipe) but the axial variation in k is being ignored. $T_p(r,x,t)$ is the solution for the temperature in the pipe and/or insulation, and the temperature $T_s(x,t)$ in equation 2 is simply the value of T_p at the pipe inner radius:

$$T_s(x,t) = T_p(r_0, x, t) \qquad (4)$$

The boundary condition on equation 3 is convection to a known reference temperature, where r_2 is at the outside boundary of the pipe:

$$-k\left.\frac{\partial T}{\partial r}\right|_{r_2} = h(T_p(r_2, x, t) - T_\infty) \qquad (5)$$

Equation 2 is used to couple the solution for $T_p(r,x,t)$ to that for $T(x,t)$.

Table 3.1 Symbol Definitions for Equations in Section 3.1 (listed in order of use)

$\dot{m}$	Mass flow rate
C_p	Heat capacity at constant pressure
T	Temperature of fluid
x	Linear distance in axial direction of pipe
ρ	Density
A_{cs}	Cross sectional area of pipe
t	Time
p	Perimeter of pipe
q''_{loss}	Heat flux (energy per unit time per unit area)
k	Thermal conductivity
h	Convective heat transfer coefficient (heat flux per unit temperature)
r	Radial dimension normal to pipe's axial dimension

Piping systems surrounded by a large layer of attic insulation, or soil, are treated in the model as a finite radial thickness of the external material. This is basically the same as if the pipe (with or without pipe insulation) is further insulated with a thickness of attic insulation (piping buried beneath attic insulation), or soil (piping buried in soil underneath the slab).

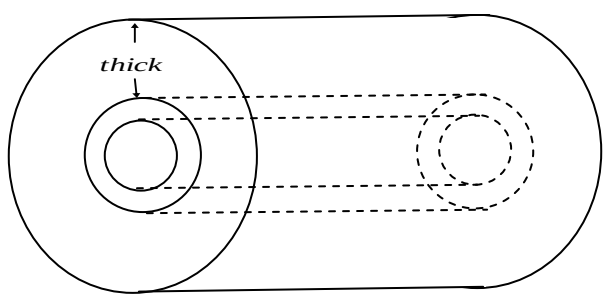

Figure 3.1 Soil or attic insulation material of thickness *thick* surrounding pipe/insulation

In Figure 3.1, the layer of surrounding material is characterized by a thickness parameter, *thick*, and this thickness of material is assumed to surround the pipe. The outer surface of the composite cylinder is assumed to be subjected to a convective/radiative boundary condition. It is assumed that the simulation time is much shorter than the time it would take the temperature on the outside of this large cylinder of added material to be change substantially during the simulation. Therefore, the solution will not be affected if one surface of the large cylinder is modeled by convective heat transfer and the others are semi-infinite (as in the case

of a buried pipe) or if one surface has convection/radiation to a lower temperature than the other (as for attic insulation). The outer radius boundary of the composite cylinder is assumed to be at a constant temperature during the operation of the hot water system. Both the constant temperature that is assumed and the radius of the material are user inputs. There are two options used to determine when no water is flowing in the piping. The value input for the flow rate determines which of the following options is selected:

- If the flow rate is specified as zero, then a simulation of the system will be performed with pure conduction. The initial fluid temperature is taken as that of the environment. This approach treats the pipe as a fin on the water heater and heat from the water heater flows down the pipe to determine the total heat loss by the water heater through the pipe system when it is not in use.
- If the flow rate is specified as any value less than zero, this signals the program to perform a special computation in which the initial fluid temperature is set equal to the supply temperature and the heat loss during the cool-down is computed also as pure conduction simulation.

When there is no flow in the pipe, a new heat transfer coefficient accounting for the heat conduction from the fluid to the pipe was developed by using a correlation based on an analytical solution for heat conduction in a solid cylinder that is subjected to a step increase in temperature at its surface. This heat transfer coefficient is applied to all piping configurations and heat loss is computed using the conduction equation (#3) above plus the new heat transfer coefficient.

During flow conditions all of the above equations are used. For time periods between clustered draws (hot water uses), calculations are performed as a no flow cool down of water in the piping. The no flow cool down temperature is used as the pipe and/or insulation temperature in the subsequent draw in the cluster. During hot water use, the soil surrounding the pipe or the attic insulation surrounding the pipe is penetrated by heat to a small depth and this same depth is affected during cool down. Since the depth is not large, it is not used when the cool down piping temperature is calculated for the subsequent cluster draw.

The model solves for the temperature distribution in the water, pipe, and insulation along the length of the pipe as a function of time using a finite element technique capable of modeling various piping configurations, the entire piping layout, and hot water use events. Flow conditions can be specified for comparatively short time periods; therefore many draw patterns can be modeled. The simulation can be used to do comparative studies, such as establishing the heat loss differences between insulated and non-insulated piping and calculating the effect of various pipe diameters on the outlet water temperature.

The simulation requires the following data to compute the heat loss and outlet water temperature: the pipe parameters (length, inside diameter, and wall thickness); the pipe and insulation properties (thermal conductivity, specific heat, and density); the water flow rate; the insulation thickness; and the distribution system location (soil & attic—indicate “thick” cylinder condition and crawl space—still air). The program accepts input as Excel files.

Table 3.2 is an example of an input file showing several events of two pipe sections each, in no particular order of event. Actual files have events for a complete day of water usage. Pipe

and insulation property data are automatically selected based on pipe and insulation type as specified in Table 3.2. For each additional section, five additional columns on the right of the Table are required. If the pipe section is not insulated, the insulation thickness ($S1_{ins-th}$, $S2_{ins-th}$) is set to zero. There is a limit of 50 sections per event - the evaluated houses varied between 2 and 3 sections. There is no limit on the number of events. It is assumed that all the sections in one event have the same pipe material and/or piping insulation type (this is independent of surrounding insulation.).

The computer time needed for the calculation for each event depends on the number of sections, the diameter and length of the pipe section and the specified time step (~1 second) and maximum simulation time (specified by the user, usually less than 3 minutes--time taken for the water to reach 105°F). At the end of the simulation, the results are tabulated in a tab-delimited ASCII file. Figures 3.2 through 3.4 show a series of screens from input through the completion of a computational run. Note that the piping diagram shown for each type of system is just a sample representing a particular type of system (e.g., trunk and branch). The program does not draw a diagram whose dimensions match those of the particular system that is being modeled. Table 3.3 shows an example of an output file.

Table 3.2 Sample input File (S1 = pipe section 1, d = diameter, L = length, T amb = Ambient temperature, Ins-th = insulation thickness, Sur-th = surface thickness)

Event	Flowrate (gpm)	Sections	$Pipe_{material}$	$Pipe_{Type}$	$Material_{sur}$	$Location_{sur}$	$Pipe_{Insulation}$	$S1_d$	$S1_L$	$S1_{Tamb}$	$S1_{Ins\text{-}th}$	$S1_{Sur\text{-}th}$	$S2_d$	$S2_L$	$S2_{Tamb}$	$S2_{ins\text{-}th}$	$S2_{Sur\text{-}th}$
MBR shower	2.25	2	Copper	M	Mineral Fiber (loose fill)	Attic	Cellular Polyethylene	3/4	64.5	76	0	6	1/2	14	70	0	0
MBR sink-1	1.25	2	Copper	M	Mineral Fiber (loose fill)	Attic	Cellular Polyethylene	3/4	64.5	76	0	6	1/2	8	70	0	0
MBR sink-2	1.25	2	Copper	M	Mineral Fiber (loose fill)	Attic	Cellular Polyethylene	3/4	64.5	76	0	6	1/2	10	70	0	0
BR2 shower	2.25	2	Copper	M	Mineral Fiber (loose fill)	Attic	Cellular Polyethylene	3/4	37	76	0	6	1/2	13	70	0	0
BR2 shower	2.25	2	Copper	M	Mineral Fiber (loose fill)	Attic	Cellular Polyethylene	3/4	37	76	0	6	1/2	13	70	0	0
BR2 sink	1.25	2	Copper	M	Mineral Fiber (loose fill)	Attic	Cellular Polyethylene	3/4	37	76	0	6	1/2	6	70	0	0
BR2 sink	1.25	2	Copper	M	Mineral Fiber (loose fill)	Attic	Cellular Polyethylene	3/4	37	76	0	6	1/2	6	70	0	0
K sink	2.5	2	Copper	M	Mineral Fiber (loose fill)	Attic	Cellular Polyethylene	3/4	45.5	76	0	6	1/2	9	70	0	0
K sink	2.5	2	Copper	M	Mineral Fiber (loose fill)	Attic	Cellular Polyethylene	3/4	45.5	76	0	6	1/2	9	70	0	0

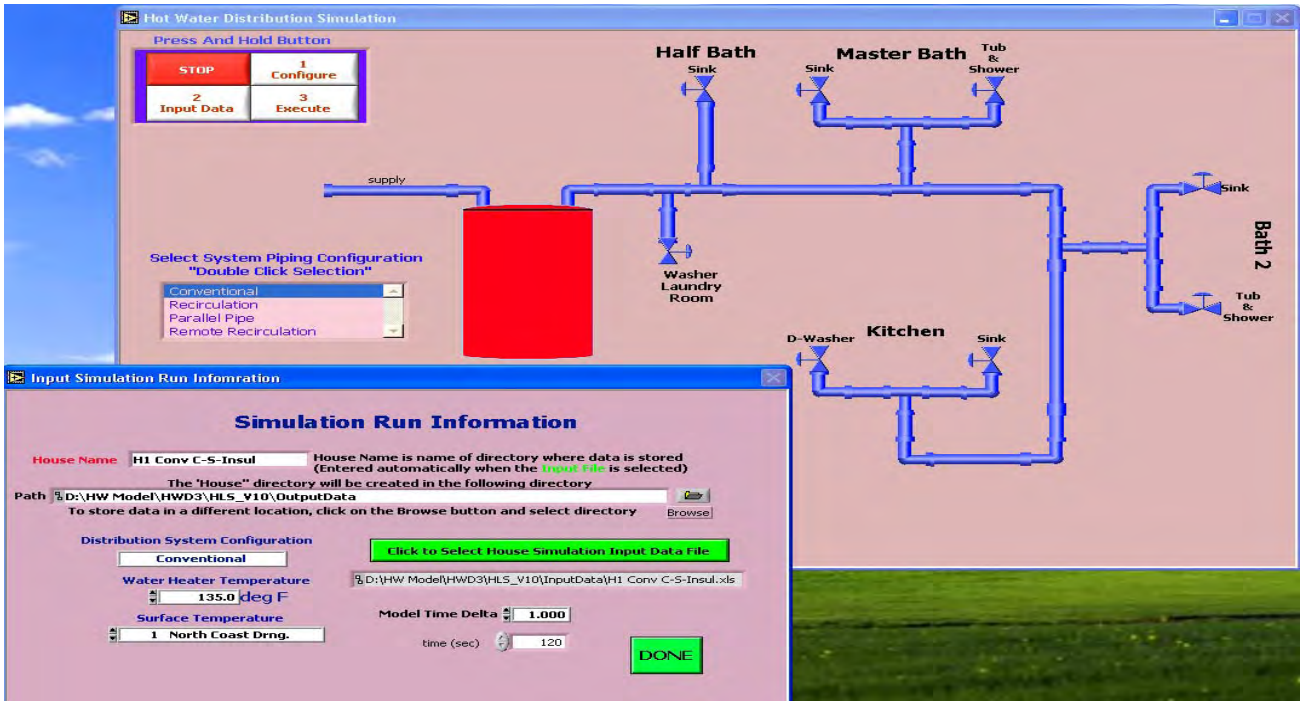

Figure 3.2 Main menu screen, popup menu one—configuration selection, popup menu two—data input/file selection

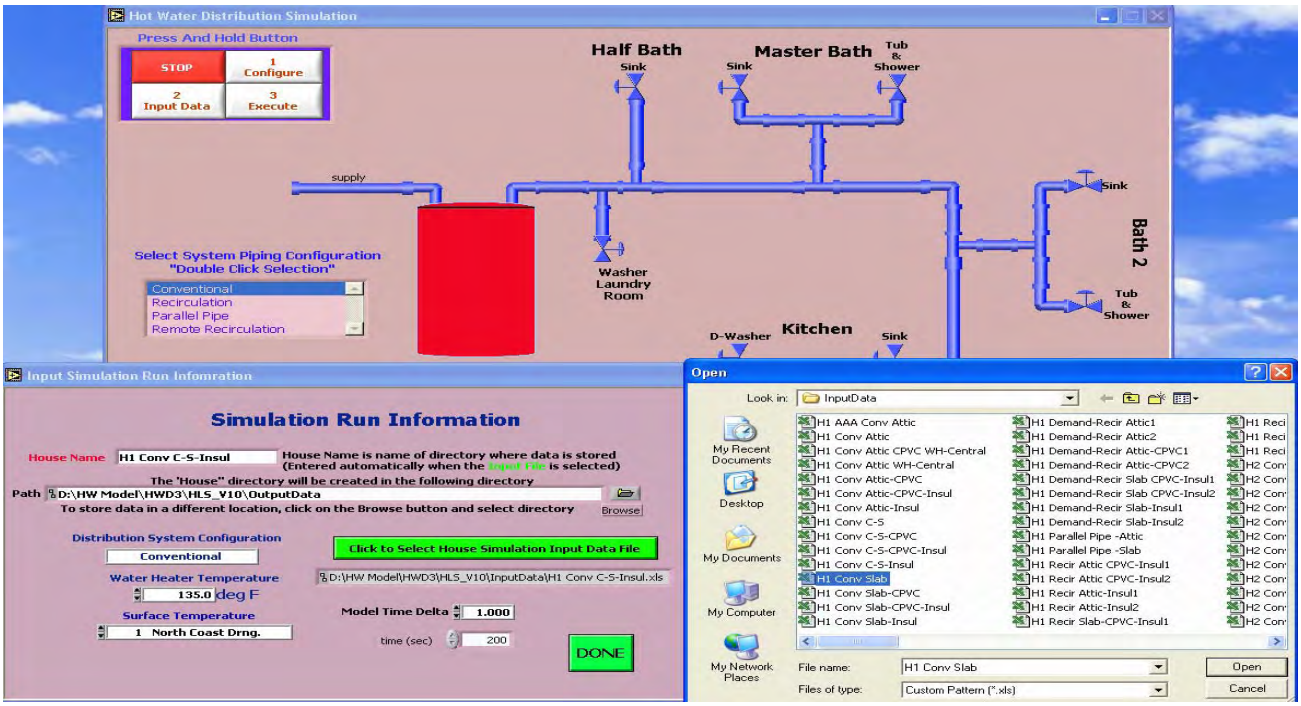

Figure 3.3 Popup open/select data file initiated by clicking green bar on simulation run information menu

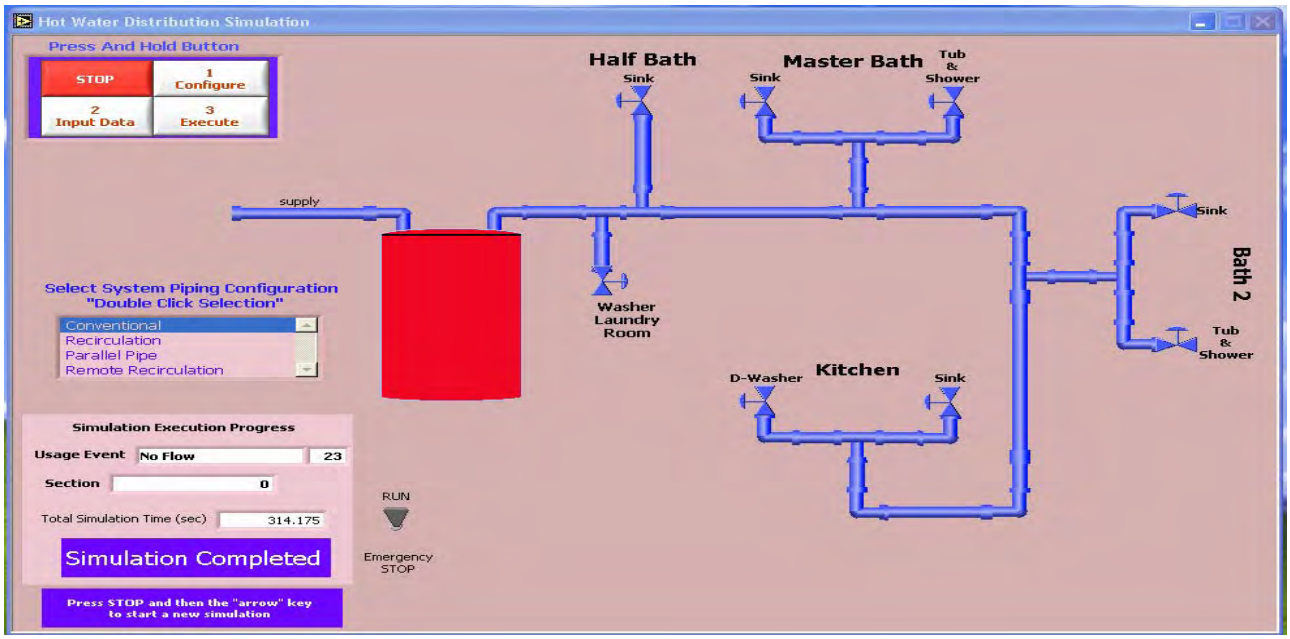

Figure 3.4 Main screen completion menu

Table 3.3 Sample Output Table

Event	Flow rate (GPM)	Time (sec) to reach 105°F	Total Heat Loss (Btu) to reach 105°F	Max Temp (°F)
MBR shower	2.25	70	328	131
MBR sink-1	1.25	109	314	127
MBR sink-2	1.25	111	317	127
MBR sink-1	1.25	109	314	127
MBR sink-2	1.25	111	317	127
BR2 shower	2.25	38	153	133
BR2 shower	2.25	38	153	133
BR2 sink	1.25	63	158	131
BR2 sink	1.25	63	158	131
BR2 sink	1.25	63	158	131
BR2 sink	1.25	63	158	131
BR2 sink	1.25	63	158	131
BR2 sink	1.25	63	158	131
K sink	2.5	39	183	133
K sink	2.5	39	183	133
K sink	2.5	39	183	133
K sink	2.5	39	183	133
K sink	2.5	39	183	133

Assumptions Used for the Numeric Simulations

Based on input from the Project Advisory Committee (PAC), ORNL used the follow assumptions in its analysis of the various hot water distribution systems and options.

- **Average Attic Temperature – 76°F.** This was calculated using the ASHRAE methodology for determining attic temperature related to duct design. We averaged Los Angles and Sacramento to get a statewide average. We believe this temperature is low, but do not have any empirical data from California to suggest another temperature.
- **Average Crawl Space Temperature – 68°F.** This was calculated the same way as the attic temperature.
- **Average Under Slab Temperature – 64°F.** This was calculated the same way as the attic temperature. This is based on average ground water temperatures in California.
- **Shower Flow Rate - 2.25 GPM.** This is based on a review of the Aquacraft hot water studies based on a sample of 10 houses in Washington State over a 14-day period.
- **Bath Faucet Flow Rate - 1.25 GPM.** This is based on a review of the Aquacraft studies.
- **Kitchen and Laundry Faucet Flow Rate - 2.5 GPM.** This is based on recommendations from the Iowa Energy Office for the typical flow of kitchen faucets (2-4 gpm) when filling the sink is desired.

There is little data available on actual hot water usage patterns in California or elsewhere. The project initially computed all houses and system configurations with the assumption that each draw was a "cold start" – meaning that the water had cooled down to the ambient temperature surrounding the pipe before each subsequent use. This approach provided an unambiguous, standard reference point that could be used to compare one system against another.

However, this approach has two significant drawbacks. First, the cold start assumption would only be valid for the first draw of the day, and for other draws during the day when a long enough time elapsed between draws for the water in the piping to go cold. Using such an approach for closely spaced draws would largely negate the effect of insulation around the piping. Second, one of the systems being evaluated is a continuous recirculation system, and there is no such thing (except when the system is first installed and turned on) as a "cold start" for that system.

The cold start approach may overstate the total energy and water waste and tends to discount the value of insulation. An all-cold start use pattern probably represents the "worst case" for potential water and energy waste.

A subsequent decision was made to modify the model to allow approximate calculations of scenarios where draws occurred near each other in time ("clustered"). In these calculations, the extent to which water in the piping cooled down between draws was calculated, rather than assumed. In these cases, a set of draws was assumed in the morning, and then a second set in the evening, with a nine-hour gap between them. This pattern might be typical of a family that spends the middle of the day away from the house. The clustered use represents the likely "best case" regarding water and energy waste.

In the clustered approach, for the first draw of the day (early morning) water in the pipe was assumed to be at ambient temperature. All subsequent draws were based on the calculated temperature of the water remaining in the pipe for each of the segments between the water heater

and the end-use fixture. These cool down temperatures were calculated based on the number of minutes between draws, as shown in Table 3.4. The second cluster of uses occurred nine hours after the first cluster and the water in the pipes had reached ambient temperatures. A similar set of cool down temperatures was calculated for the second cluster of draws and is shown in Table 3.4. After the second cluster, the delay before use the next day was assumed to be sufficient for the water temperatures to reach ambient.

Certain approximations had to be made in calculating the cool down for the clustered draw cases. The most rigorous approach would have been to take the entire profile of temperatures through the water, pipe, insulation and surrounding material (soil or attic insulation) and use these as initial conditions for the calculation of the cooling that occurs between the draws. Time and cost did not permit this much rigor.

The initial set of calculations for clustered draw scenarios produced results that indicated that insulation around the pipe, particularly for under-slab configurations, did not have as large an effect as we would have expected and other studies have suggested. Upon investigation, it was determined that the program had used the average water temperature at the end of a cool down calculation as the initial temperature of the modeled 6 inches of soil. An independent calculation by Dr. Keith Woodbury was made of a particular pipe in soil ("thick") configuration with and without insulation. This calculation showed that, for a 5 minute draw of hot water, the temperature would be elevated from ambient for only a short distance into the soil (less than an inch), and that temperature decays rapidly after the draw ends. Thus, the initial calculations overstated the heat storage in the material surrounding the pipe.

The program was changed so that the initial temperatures for the soil or attic insulation for subsequent draws in a cluster scenario are set to ambient, while the initial temperatures for the water, pipe and, if applicable, insulation, are set equal to the average temperature at the end of the cool down calculation for the time lapse since the previous draw. Ignoring the stored heat in the material around the pipe will somewhat over state the effect of insulation, but because only a small amount of heat is stored and dissipates rapidly, the overstatement should be slight. All of the calculations for cluster draw scenarios contained in this report incorporate this second, more realistic assumption.

The continuous recirculation systems were run at steady state conditions where some of the energy loss was reflected in higher surrounding temperatures. Since the continuous recirculation systems do not revert to ambient temperatures, they should not be compared with the performance of systems under the all cold start assumption. These systems are included in the cluster use tables because comparison between the continuous recirculation systems at steady state and other systems based on clustered use patterns is reasonable. The results of the simulation for both usage assumptions are also provided in Sections 4.1 and 5.1, and Appendix A.

Table 3.4 Description of Clustered Use Events

Event Description	Flowrate (gpm)	Time Before Event (min)	Number of Sections	Section 1 Length (ft)	Starting Temp	Section 2 Length (ft)	Starting Temp
MBR shower	2.25	0	2	64.5	**Tamb**	14	**Tamb**
MBR sink-1	1.25	15	2	64.5	Tnew	8	**Tamb**
MBR sink-2	1.25	15	2	64.5	Tnew	10	**Tamb**
BR2 shower	2.25	20	2	37	Tnew	13	**Tamb**
BR2 shower	2.25	15	2	37	Tnew	13	Tnew
BR2 sink	1.25	15	2	37	Tnew	6	**Tamb**
BR2 sink	1.25	15	2	37	Tnew	6	Tnew
BR2 sink	1.25	15	2	37	Tnew	6	Tnew
K sink	2.5	25	2	45.5	Tnew	9	**Tamb**
MBR sink-1	1.25	540	2	64.5	Tnew	8	**Tamb**
K sink	2.5	15	2	45.5	Tnew	9	**Tamb**
K sink	2.5	15	2	45.5	Tnew	9	Tnew
K sink	2.5	20	2	45.5	Tnew	9	Tnew
K sink	2.5	30	2	45.5	Tnew	9	Tnew
MBR sink-2	1.25	60	2	64.5	Tnew	10	**Tamb**
BR2 sink	1.25	20	2	37	Tnew	6	**Tamb**
BR2 sink	1.25	25	2	37	Tnew	6	Tnew
BR2 sink	1.25	15	2	37	Tnew	6	Tnew

Notes: *Tamb* is when the water temperature equals ambient. *Tnew* reflects the water temperature in the pipe as impacted by the previous draw.

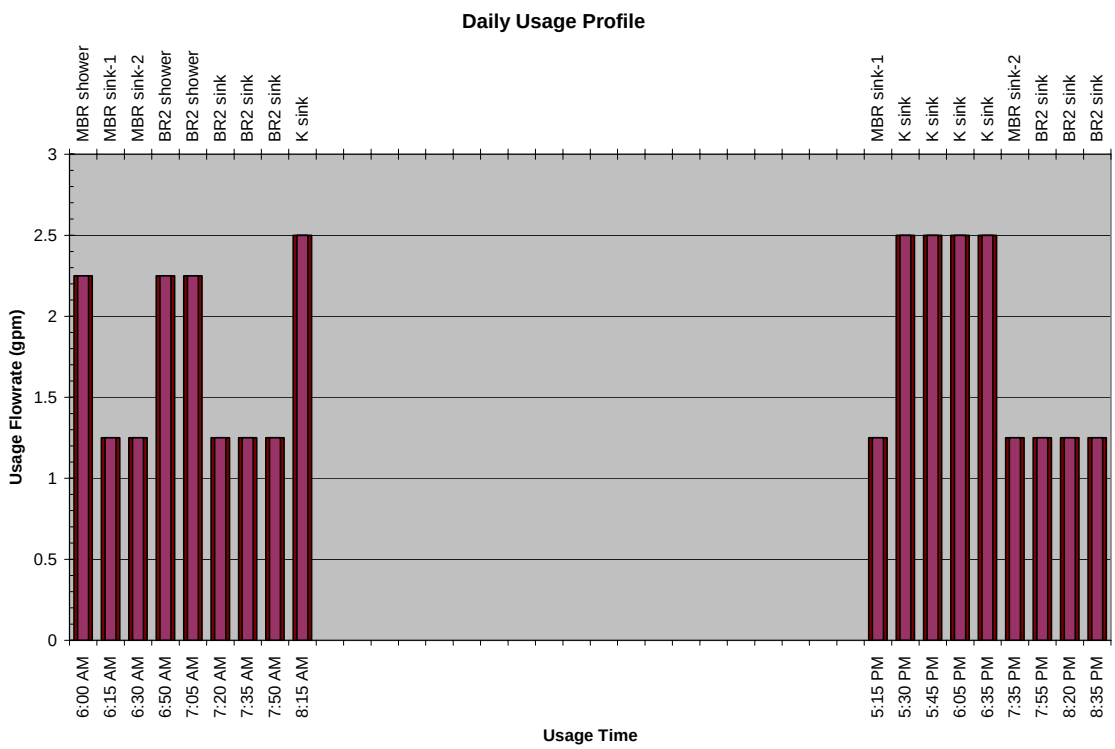

Figure 3.5 Usage profile assumption for test cases (Clustered Draw Cycle)

3.2 Cost-Benefit Analysis Parameters

The benefit of the various alternative systems and options is based on an analysis of utility (electricity, gas, water and sewer) cost savings. Ten California cities were identified to reflect the range of utility costs. These included: Davis, Fairfield, Fresno, Gilroy, Sacramento, San Bernardino, San Diego, San Jose, Stockton, and Tracy. These cities were chosen to represent the climatic and utility costs variations within the most populated portions of the state. Sewage treatment costs in these cities were a fixed monthly charge and therefore not impacted by changes in the amount of wastewater generated. Tracy, CA, which happened to have the average utility costs (water, sewer, electricity, and natural gas) of these cities were selected for use in the analysis. The costs were: electricity $0.11589/kWh, gas $0.68263/therm, water $0.85/HCF (100 cu ft or ~748 gallons).

The costs of the various systems and options for each of the houses analyzed were developed from actual cost data provided by a major plumbing contractor based in California. While these costs may vary in other parts of the state and for other sized contractors, the costs are consistent among the various systems and options, permitting an appropriate comparison to be drawn. The detailed costs for each home are reported in Section 4 (New Construction), and Section 5 (Existing Homes), and Appendix A of this report.

The costs reflected in this study are for the distribution system alone and do not include such items as the water heater, water main connection, fixtures (lavatories, sinks, showers, etc.) and valves. These costs would be the same for all systems. Thus these costs differ from the costs of the complete hot water system that spans from water main to end-use fixtures. By keeping the costs focused on the distribution system alone, one is able to directly determine whether the energy and water savings associated with a particular system adequately offsets any additional cost for the installation of that system.

3.3 Representative Housing for Analysis

3.3.1 New Construction

The following five houses are used as representative of California housing in this study. These houses were being used in the 2005 Title 24 update evaluations and the PAC recommended their use in these simulations.

- House #1 - Single Family, Three Bedroom, Two Bath, One Story, 2010 ft^2
- House #2 - Single Family, Four Bedroom, 2½ Bath, One Story, 3080 ft^2
- House #3 - Single Family, Four Bedroom, Three Bath, Two Story, 2810 ft^2
- House #4 - Apartment, One Bedroom, One Bath, One Story, 580 ft^2
- House #5 - Apartment or Condominium, Two Bedroom, Two Bath, One Story, 960 ft^2

Representative new hot water system characteristics included:

- Gas water heater is located in the garage or an exterior access closet on house perimeter.
- Electric water heater is located in the garage or an interior access closet within the house.
- No particular attention has been paid to the house layout regarding the proximity of hot water consuming devices to each other or the water heater.

- Laundry is located within the house proper.
- Pipe locations are per standard California practice based on type of residence being evaluated, including under the floor slab, or in the attic.

Floor plans and expanded descriptions of the representative new houses (#1 - #5) are found in Appendix A. The floor plans for House #1 also include plumbing layouts for: a conventional distribution system; a continuous recirculation system; a demand actuated recirculation system; and, a parallel pipe manifold system.

3.3.2 Existing Housing (1960/70s Construction Practices)

Representative existing residences evaluated included:

- House #6 - Single Family, Three Bedroom, Two Bath, One Story, 1100 ft^2
- House #7 - Single Family, Four Bedroom, 2½ Bath, Two Story, 1960 ft^2

Representative existing hot water systems evaluated included:

- Same characteristics as "new" except the laundry is located in the garage, and the crawl space is an additional pipe location..

Expanded descriptions and floor plans of the representative existing houses (#6 - #7) are found in Appendix A.

3.4 Hot Water Distribution Systems Evaluated

3.4.1 New Construction

Conventional Trunk and Branch Distribution Systems

The impact on energy and water use/cost and initial installation cost of each of the following cases was determined:

- Change piping materials in the trunk and branch distribution system for all representative residence types, holding everything else constant.
- Relocate the water heater to a more central location thereby shortening the length of the conventional distribution system. Analyze for each of the piping materials.
- Add insulation to each of the piping materials in the trunk and branch distribution systems.

Alternative Distribution Systems

The impact on energy and water use/cost and initial installation cost of each of the following cases was determined:

- Install a demand actuated recirculation pump and controls in an otherwise representative conventional system for single-family detached residences (Houses #1 - #3).
- Replace the representative conventional system with a continuously recirculating system for single-family detached residences (Houses #1 - #3).
- Replace the representative conventional system with a parallel pipe manifold system for all representative residences (Houses #1 - #5).

The results from the use of differing materials and alternative systems in new construction are reported in Section 4 and Appendix A of this report.

3.4.2 Existing Housing

The impact on energy and water use/cost and initial installation cost of each of the following cases was determined:

- Assume an existing, functioning, conventional trunk and branch system. The retrofit involved upgrading this system with the installation of a demand actuated recirculation pump and controls, using the existing cold water line as the return.
- Assume an existing, non-functioning (due to calcification or corrosion failures), conventional trunk and branch system. Replace with the various alternative pipe materials with and without and the addition of insulation.
- Assume an existing, non-functioning, conventional system. Replace with a parallel-pipe manifold system.

The detailed results from the use of the upgrade and replacement options in existing homes are reported in Section 5 and Appendix A of this report.

3.5 Method of Identifying Barriers

A questionnaire (Appendix B) was developed and distributed to a number of plumbing contractors in California. It was also used to guide telephone interviews between ORNL and California plumbing contractors. The questionnaire was designed to identify potential barriers to the use of alternative hot water distribution systems from the viewpoint of the primary party responsible (the plumbing contractor) for their installation and modification. Queries included:

- What are the most important issues to the plumbing contractor?
- What issues does the plumbing contractor believe are the most important to the homeowner?
- How familiar is the plumbing contractor with alternative systems?
- In the contractor's view, what are the barriers (cost, complexity, customer interest, codes, training, reliability, ease of repair) to increased use?

The scope of this project did not permit a statistically significant sampling of the plumbing contractors in California. However, the responses received are believed to give an indication of the barriers to more efficient systems and identify areas worthy of further evaluation by the Energy Commission.

The specific barriers to the use of alternative systems in new and existing applications are reported in Section 4 (New Construction), and Section 5 (Existing Homes) in this report.

4. Alternative New Domestic Hot Water Distribution Systems *(Task 3.1.2)*

4.1 Simulation of Potential Energy and Water Savings

Four hot water distribution system configurations were simulated for each house (#1 - #5). They included: conventional trunk and branch system, parallel pipe manifold system, demand recirculation system, and continuous recirculation system. Variations in distribution system materials, layout and environmental conditions for these simulations included: different pipe materials; with and without pipe insulation; centrally locating the water heater; and locating pipe in the attic, in the crawlspace, and under the concrete floor slab. These are reflected in Tables 4.2 and 4.3 and tables in Appendix A.

Two draw cycles (use patterns) were investigated. The first assumed that each individual draw was a "cold start", i.e. the water had reached the ambient temperature surrounding the pipe before each use. This cold start approach overstates the total energy and water waste and tends to discount the value of insulation in most situations.

In order to bound the effect of actual hot water use patterns on system performance, a second assumption know as "clustered use" was also simulated. This approach had individual draws clustered in the early morning and late afternoon/evening hours as might be expected from a family that spent the middle of the day away from their home. The first draw of the day (during early morning) assumed water in the pipe had reached ambient temperature. The clustered use approach more closely predicts real world energy and water waste.

In addition to these two draw patterns, continuous recirculation systems were modeled at steady-state conditions where some of the energy loss was reflected in higher surrounding temperatures. Comparing simulations of continuous recirculation systems at steady state with simulations of all other systems based on clustered use patterns represents the most realistic approach for the modeling performed.

Simulation results generated for the various systems and options were ranked in order of relative energy use and cost savings. Since the cost savings associated with the various alternatives are based on a specific set of modeling assumptions regarding hot water use (see Table 4.1), system layout, and the environmental conditions around the distribution systems, they should not be viewed as either absolute or directly transferable to another house. However, the trends identified by these simulations are useful in identifying those systems and options that are relatively more efficient and therefore likely to produce actual savings under "real world" conditions.

House #1 simulation results for the cold start draw cycle are shown in Table 4.2 and Figure 4.1; results for the 'clustered am & pm draw cycle' are in Table 4.3 and Figure 4.2. Complete results for Houses #1 - #5 along with hot water distribution system layouts for House #1 and floor plans for Houses #1 - #5 are included in Appendix A. A discussion of the cost-benefit analysis for House #1 follows Table 4.4.

Table 4.1 Sample of Daily Hot Water Use Events with Corresponding Distribution Systems Material & Parameters

Event #	Event	Flowrate (gpm)	# Sections	Pipe Material	Pipe Type	Insul Material	Insul Type	S1 Dia (in)	S1 Length (ft)	S1 amb temp (^{o}F)	S1 insul Thick (in)	S2 Dia (in)	S2 length (ft)	S2 amb temp (^{o}F)	S2 insul Thick (in)
1	MBR shower	2.5	2	Copper	K	Cellular Polyethylene		3/4	64.5	50	0	1/2	14	70	0
2	MBR sink-1	2	2	Copper	K	Cellular Polyethylene		3/4	64.5	50	0	1/2	8	70	0
3	MBR whirlpool	4	2	Copper	K	Cellular Polyethylene		3/4	64.5	50	0	1/2	14	70	0
4	MBR sink-2	2	2	Copper	K	Cellular Polyethylene		3/4	64.5	50	0	1/2	10	70	0
5	MBR sink-1	2	2	Copper	K	Cellular Polyethylene		3/4	64.5	50	0	1/2	8	70	0
6	MBR sink-2	2	2	Copper	K	Cellular Polyethylene		3/4	64.5	50	0	1/2	20	70	0
7	BR2 shower	2.5	2	Copper	K	Cellular Polyethylene		3/4	37	50	0	1/2	13	70	0
8	BR2 shower	2.5	2	Copper	K	Cellular Polyethylene		3/4	37	50	0	1/2	13	70	0
9	BR2 sink	2	2	Copper	K	Cellular Polyethylene		3/4	37	50	0	1/2	6	70	0
10	BR2 sink	2	2	Copper	K	Cellular Polyethylene		3/4	37	50	0	1/2	6	70	0
11	BR2 sink	2	2	Copper	K	Cellular Polyethylene		3/4	37	50	0	1/2	6	70	0
12	BR2 sink	2	2	Copper	K	Cellular Polyethylene		3/4	37	50	0	1/2	6	70	0
13	BR2 sink	2	2	Copper	K	Cellular Polyethylene		3/4	37	50	0	1/2	6	70	0
14	BR2 sink	2	2	Copper	K	Cellular Polyethylene		3/4	37	50	0	1/2	6	70	0
15	BR2 bath tub	4	2	Copper	K	Cellular Polyethylene		3/4	37	50	0	1/2	13	70	0
16	K sink	4	2	Copper	K	Cellular Polyethylene		3/4	45.5	50	0	1/2	9	70	0
17	K sink	4	2	Copper	K	Cellular Polyethylene		3/4	45.5	50	0	1/2	9	70	0
18	K sink	4	2	Copper	K	Cellular Polyethylene		3/4	45.5	50	0	1/2	9	70	0
19	K sink	4	2	Copper	K	Cellular Polyethylene		3/4	45.5	50	0	1/2	9	70	0
21	K sink	4	2	Copper	K	Cellular Polyethylene		3/4	45.5	50	0	1/2	9	70	0
22	Dishwasher	4	2	Copper	K	Cellular Polyethylene		3/4	45.5	50	0	1/2	9	70	0
23	Washer	4	2	Copper	K	Cellular Polyethylene		3/4	21	50	0	1/2	6	70	0
24	No Flow	0	2	Copper	K	Cellular Polyethylene		3/4	64.5	50	0	1/2	14	70	0

Table 4.2 Monthly Water and Energy Waste for House #1 (Cold Start Draw Cycle)

House-1	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu - Central	11	42	43	435	256,948	23,606	0.49	10.80	3.37
Conv Attic CPVC - Central	11	41	42	426	251,851	10,119	0.48	10.08	3.15
Conv Attic Cu	37	60	103	882	521,391	50,105	1.00	22.00	6.87
Conv Attic Cu-Ins	37	60	104	883	522,140	51,092	1.00	22.07	6.89
Conv Attic CPVC	35	57	99	839	496,431	26,163	0.95	20.11	6.28
Conv Attic CPVC-Ins	35	57	99	839	496,431	26,433	0.95	20.12	6.28
Conv CS Cu	37	60	104	892	527,612	58,810	1.01	22.58	7.05
Conv CS Cu-Ins	37	60	104	892	527,612	57,115	1.01	22.52	7.03
Conv CS CPVC	35	57	100	849	501,902	29,741	0.96	20.46	6.39
Conv CS CPVC-Ins	35	57	100	849	501,902	29,494	0.96	20.45	6.39
Conv Slab Cu	38	63	111	932	551,223	114,335	1.06	25.66	8.01
Conv Slab Cu-Ins	37	60	104	884	522,890	79,804	1.00	23.22	7.25
Conv Slab CPVC	36	58	100	862	509,998	35,439	0.98	20.99	6.56
Conv Slab CPVC-Ins	36	58	100	862	509,998	30,818	0.98	20.81	6.50
Demand Recir Attic Cu *	5	6	9	99	58,390	67,669	0.11	4.89	1.53
Demand Recir Slab Cu *	4	5	8	83	48,871	157,283	0.09	8.02	2.50
Demand Recir Attic CPVC *	5	6	9	100	59,140	26,594	0.11	3.31	1.03
Demand Recir Slab CPVC *	4	5	8	85	50,295	38,218	0.10	3.43	1.07
Parallel Attic PEX	12	23	36	314	185,440	20,911	0.36	7.95	2.48
Parallel Slab PEX	12	24	38	324	191,362	26,747	0.37	8.40	2.62

* Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

Table 4.3 Monthly Water and Energy Waste for House #1 (Clustered AM & PM Draw Cycle)

House-1	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu - Central	2	5	40	117	69,334	6,847	0.13	2.93	0.92
Conv Attic CPVC - Central	2	5	39	119	70,458	3,342	0.14	2.84	0.89
Conv Attic Cu	2	5	99	196	115,881	11,435	0.22	4.90	1.53
Conv Attic Cu-Ins	1	5	99	195	115,207	11,145	0.22	4.86	1.52
Conv Attic CPVC	2	5	95	191	113,108	6,200	0.22	4.59	1.43
Conv Attic CPVC-Ins	2	5	95	191	113,108	6,151	0.22	4.59	1.43
Conv CS Cu	3	9	103	410	242,631	22,360	0.47	10.20	3.19
Conv CS Cu-Ins	2	5	102	203	119,854	12,837	0.23	5.11	1.60
Conv CS CPVC	2	8	98	359	212,499	12,196	0.41	8.65	2.70
Conv CS CPVC-Ins	2	5	98	200	118,205	7,305	0.23	4.83	1.51
Conv Slab Cu	32	54	109	845	499,878	90,351	0.96	22.75	7.10
Conv Slab Cu-Ins	2	4	102	192	113,708	16,245	0.22	5.01	1.56
Conv Slab CPVC	28	50	98	767	453,631	31,538	0.87	18.67	5.83
Conv Slab CPVC-Ins	2	5	98	192	113,783	7,076	0.22	4.65	1.45
Demand Recir Attic Cu *	2	5	9	77	45,273	12,030	0.09	2.21	0.69
Demand Recir Slab Cu *	2	4	8	66	39,052	17,997	0.08	2.20	0.69
Demand Recir Attic CPVC *	2	5	9	78	46,397	6,418	0.09	2.03	0.64
Demand Recir Slab CPVC *	2	4	8	70	41,600	7,826	0.08	1.90	0.59
Parallel Attic PEX	2	11	36	196	115,881	15,042	0.22	5.04	1.57
Parallel Slab PEX	9	19	38	286	168,875	24,098	0.32	7.43	2.32
Recir Attic Cu-Ins **	2	5	9	77	45,273	267,509	0.09	12.18	3.80
Recir Slab Cu-Ins **	2	4	8	66	39,052	872,443	0.08	35.55	11.10
Recir Attic CPVC-Ins **	2	5	9	78	46,397	291,240	0.09	13.15	4.11
Recir Slab CPVC-Ins **	2	4	8	70	41,600	790,345	0.08	32.45	10.13

NOTES:

* Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

** Energy supplied to the continuous recirculation system pump is calculated as 755.55 kWh/year or 62.9 kWh/month, which equals approximately $7.30/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

Definitions for Table 4.2 and 4.3:

"Wait Time for Hot Water" is the length of wait in seconds for 105°F water to reach the fixture. Three values are shown: Min. – the shortest wait, Typical – the median wait, and Max. – the longest wait.

"Water Wasted" is the sum of all water wasted down the drain in gallons before temperature at fixture reaches 105°F for all non-batch-load uses and applied only to showers and sinks (i.e., excludes bathtub, dishwasher and clothes washer).

"Energy Loss" includes two terms. As water that has been previously heated by the water heater stands in the pipe between draws, it cools off and looses some energy through the pipe wall. If it cools below a useful temperature, this water is wasted down the drain while the user waits for the water to get hot enough to use. The water down the drain carries with it whatever remains of the energy added to it by the water heater. The first term under this heading, "previously heated water wasted" give the energy lost due to the water sitting in the pipe between draws. The second term, labeled "pipe", is the energy loss during the draw due to heat transfer through the pipe walls to the surrounding environment.

"Water Costs" is the total cost of the water wasted down the drain based on the utility's lowest use rate.

"Energy Costs" for electric water heating is the sum of the BTUs lost in the pipes and the BTUs lost in the water wasted down the drain converted to kWh and multiplied by the utility rate in kWh. It assumes a DOE energy factor (EF) of 0.87 for the electric water heater. For gas water heating, the total BTUs lost are converted to therms and multiplied by the utility rate in therms. It assumes an EF of 0.56 for the gas water heater. The pumping costs for the various recirculation systems are included in the table notes and should be added to the water heating costs to obtain the total cost of operating these systems.

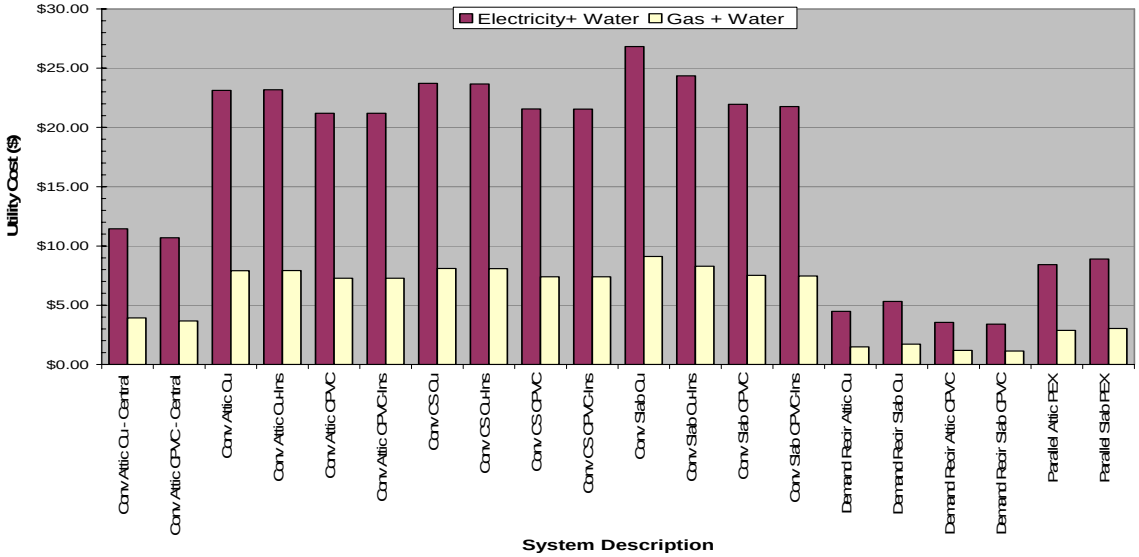

Figure 4.1 – Combined Monthly Water and Energy Waste for House #1 (Cold Start Draw Cycle)

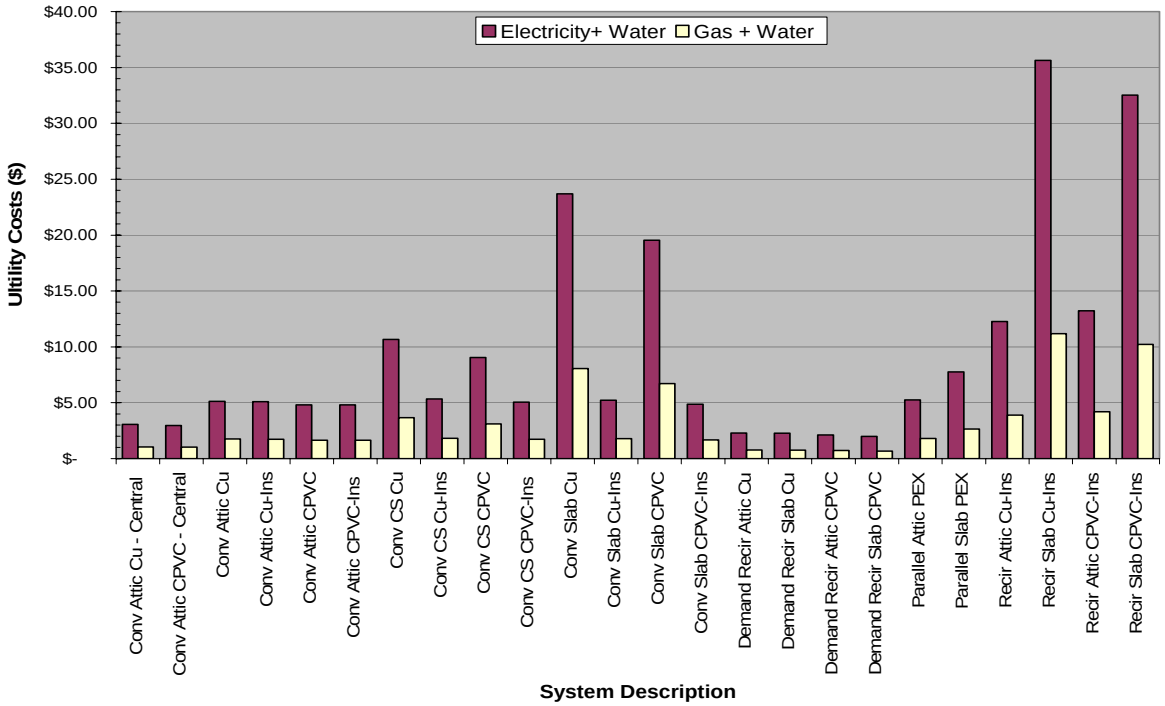

Figure 4.2 – Combined Monthly Water and Energy Waste for House #1 (Clustered AM & PM Draw Cycle)

4.2 Analysis of Cost-Benefit

The potential cost savings (benefits) of the various alternative systems and options for House #1 are shown in Tables 4.2 and 4.3. The potential construction costs, the cost to the homeowner for the various alternative systems and options for House #1 are shown in Table 4.4. The cost-benefit analysis following Table 4.4 compares the estimated construction cost for each of the alternative systems and option with the projected utility cost savings associated with each. Cost-benefit observations and conclusions follow Table 4.4.

Table 4.4 New Hot Water Distribution Systems – Homeowner's Costs

Scenario	New House Type #1
Conventional, Central WH Location, Copper, attic, uninsulated	$1150
Conventional, Central WH Location, CPVC, attic, uninsulated	$787
Conventional, Copper, attic or crawl space, uninsulated	$1271
Conventional, Copper, attic or crawl space, insulated	$1552
Conventional, Copper, under-slab, uninsulated	$1556
Conventional, Copper, under-slab, insulated	$1838
Conventional, CPVC, attic or crawl space, uninsulated	$866
Conventional, CPVC, attic or crawl space, insulated	$1147
Conventional, CPVC, under-slab, uninsulated	$1086
Conventional, CPVC, under-slab, insulated	$1368
Conventional w/ Demand Recirculation, Copper, attic or crawl space, uninsulated	$1880
Conventional w/ Demand Recirculation, Copper, under-slab, insulated	$2447
Conventional w/ Demand Recirculation, CPVC, attic or crawl space, uninsulated	$1475
Conventional w/ Demand Recirculation, CPVC, under-slab, insulated	$1978
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	$1226
Parallel Pipe/Manifold System, PEX tubing, under-slab, uninsulated	$1443
Conventional w/ Continuous Recirculation, Copper, attic or crawl space, insulated	$2559
Conventional w/ Continuous Recirculation, Copper, under-slab, insulated	$2861
Conventional w/ Continuous Recirculation, CPVC, attic or crawl space, insulated	$1965
Conventional w/ Continuous Recirculation, CPVC, under-slab, insulated	$2185

Notes on Table 4.4:

1. Costs shown include Plumbing and General Contractors' OH&P for new construction.
2. Costs for materials and new construction labor provided by Dynamic Plumbing.
3. Costs for under-slab installation are considered to be comparable to attic installation by some plumbers.
4. Costs for Conventional, Central Water Heater Location are for the distribution system alone. They do not include the potentially offsetting additional costs of running additional natural gas distribution lines and providing combustion air and exhaust venting for gas water heaters. For electric water heaters, these costs does not reflect the additional cost (if any) of running 220 V power to the central location.

Cost-Benefit Observations

Based on the data shown in Tables 4.2, 4.3 and 4.4 the following observations can be made about each scenario for House #1. A conventional, copper, uninsulated, system in the attic (common practice in California) is used as the reference point for the cost/benefit analysis.

Scenario	Observation
Conventional, Central WH Location, Copper, attic, uninsulated	Total initial cost higher for gas and less for electric, saves some energy
Conventional, Central WH Location, CPVC, attic, uninsulated	Total initial cost somewhat less for both gas and electric, saves some energy
Conventional, Copper, attic or crawl space, uninsulated	**REFERENCE POINT**
Conventional, Copper, attic or crawl space, insulated	Costs more and saves no additional energy (buried in attic insulation)
Conventional, CPVC, attic or crawl space, uninsulated	Lower initial cost and saves some energy
Conventional, CPVC, attic or crawl space, insulated	Costs less but saves no additional energy compared to uninsulated CPVC (buried in attic insulation)
Conventional, Copper, under-slab, uninsulated	Costs more initially and consumes a lot more energy
Conventional, Copper, under-slab, insulated	Costs more initially and consumes about the same energy
Conventional, CPVC, under-slab, uninsulated	Lower initial cost but consumes more energy
Conventional, CPVC, under-slab, insulated	Costs more initially, saves a little energy
Conventional w/ Demand Recirculation, Copper, attic or crawl space, uninsulated	Costs more initially, saves energy and water, moderate to long payback
Conventional w/ Demand Recirculation, Copper, under-slab, uninsulated	Costs more initially, saves energy and water, moderate to long payback
Conventional w/ Demand Recirculation, CPVC, attic or crawl space, uninsulated	Costs more initially, saves energy and water, reasonable payback (electric)
Conventional w/ Demand Recirculation, CPVC, under-slab, uninsulated	Costs more initially, saves energy and water, reasonable payback (electric)
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	Costs about the same, saves energy and water for “cold start” only
Parallel Pipe/Manifold System, PEX tubing, under-slab, uninsulated	Costs more initially, saves energy and water for “cold start” only
Conventional w/ Continuous Recirculation, Copper, attic or crawl space, insulated	Costs much more initially, consumes more energy, but saves water

Conventional w/ Continuous Recirculation, Costs much more initially, consumes more energy, but saves water
Copper, under-slab, insulated

Conventional w/ Continuous Recirculation, Costs much more initially, consumes more energy, but saves water
CPVC, attic or crawl space, insulated

Conventional w/ Continuous Recirculation, Costs much more initially, consumes more energy, but saves water
CPVC, under-slab, insulated

Cost and Benefit Conclusions

For California (New) House #1 from a *cost/benefit viewpoint*, simulation results showed that distribution systems superior to a conventional system are as follows (in order of greater to lesser benefit):

Assuming a "cold start" use pattern:
1. Conventional w/ Demand Recirculation, CPVC, attic, uninsulated
2. Parallel Pipe/Manifold System, PEX tubing, attic, uninsulated
3. Conventional w/ Centrally Located Water Heater, CPVC, attic, uninsulated

Assuming a "clustered" use pattern:
1. Conventional w/ Centrally Located Water Heater, CPVC, attic, uninsulated
2. Conventional w/ Demand Recirculation, CPVC, attic, uninsulated

The overall ranking of alternative distribution systems compared with the conventional (reference point) systems vary slightly from a cost/benefit viewpoint for the other four new California houses. Generally, however, the rankings for Houses #2 and #3 in this study are similar to that for House #1. The "Conventional w/ Demand Recirculation" and "Continuous Recirculation" distribution systems were not evaluated for Houses #4 and #5 due to their small size (580 ft^2 and 960 ft^2, respectively).

For California (New) House #1 from a *homeowner satisfaction viewpoint* - waiting time for hot water to arrive - simulation results showed that the distribution systems superior to a conventional system are as follows (in order of higher to lesser satisfaction):

Assuming a "cold start" use pattern:
1. Conventional w/ Demand Recirculation, CPVC, attic, uninsulated
2. Parallel Pipe/Manifold System, PEX tubing, attic, uninsulated
3. Conventional w/ Centrally Located Water Heater, CPVC, attic, uninsulated

Assuming a "clustered" use pattern: (1. & 2. are virtually equal)
1. Conventional w/ Continuous Recirculation, CPVC, attic, insulated
2. Conventional w/ Demand Recirculation, CPVC, attic, uninsulated
3. Parallel Pipe/Manifold System, PEX tubing, attic, uninsulated

Note: Tables 4.2 & 4.3 and tables in Appendix A provide the calculated waiting period for hot water to arrive for Houses #1 - #5.

For California House #1 from an *energy and water conservation viewpoint*, simulation results showed that distribution systems superior to the conventional system are as follows (in order of greater to lesser amount of conservation):

Assuming a “cold start” use pattern:
1. Conventional w/ Demand Recirculation, CPVC, attic, uninsulated
2. Parallel Pipe/Manifold System, PEX tubing, attic, uninsulated
3. Conventional w/ Central Water Heater Location, CPVC, attic, uninsulated

Assuming a “clustered” use pattern:
1. Conventional w/ Demand Recirculation, CPVC, attic, uninsulated
2. Conventional w/ Central Water Heater Location, CPVC, attic, uninsulated

Another method of cost evaluation is to annualize the costs of the construction and add them to the annual utility costs to develop a total annualized cost of the system. This methodology permits the direct comparison of systems with differing first costs and differing annual costs. A fifty-year service life was assumed for the distribution systems. The annualized construction costs were therefore 1/50th of the total construction costs. Table 4.5 shows the annualized costs of alternative systems in House #1.

The five lowest cost systems when a clustered use pattern is assumed are highlighted in red. The five lowest costs systems when a cold start use pattern is assumed are highlighted in blue. The impact of the two different use patterns (or draw cycles) is apparent from the fact that only two systems are among the five lowest annualized cost systems under both patterns:

- The conventional CPVC trunk and branch system located buried in the attic insulation and connected to a centrally located water heater is among the better systems under both use patterns.
- The CPVC demand recirculation system located buried in the attic insulation is among the better systems under both use patterns.

Table 4.5 Annualized Costs of Alternative Hot Water Distribution Systems in House #1 Assuming Gas Water Heating

Red highlights - five lowest cost systems for clustered use draws
Blue highlights - five lowest cost systems for cold start draws

System/Option	Water Waste		Energy Waste		Construction Cost		Total Annualized Cost	
	Clustered	Cold Start	Clustered	Cold Start	Total	Per Yr for 50 Yr	Clustered Use	Cold Start Use
Conv Attic Cu - Central	$1.56	$5.88	$11.04	$40.44	$1,450.00	$29.00	**$41.60**	$75.32
Conv Attic CPVC - Central	$1.68	$5.76	$10.68	$37.80	$1,087.00	$21.74	**$34.10**	$65.30
Conv Attic Cu	$2.64	$12.00	$18.36	$82.44	$1,271.00	$25.42	$46.42	$119.86
Conv Attic Cu-Ins	$2.64	$12.00	$18.24	$82.68	$1,552.00	$31.04	$51.92	$125.72
Conv Attic CPVC	$2.64	$11.40	$17.16	$75.36	$866.00	$17.32	**$37.12**	$104.08
Conv Attic CPVC-Ins	$2.64	$11.40	$17.16	$75.36	$1,147.00	$22.94	**$42.74**	$109.70
Conv CS Cu	$5.64	$12.12	$38.28	$84.60	$1,271.00	$25.42	$69.34	$122.14
Conv CS Cu-Ins	$2.76	$12.12	$19.20	$84.36	$1,552.00	$31.04	$53.00	$127.52
Conv CS CPVC	$4.92	$11.52	$32.40	$76.68	$866.00	$17.32	$54.64	$105.52
Conv CS CPVC-Ins	$2.76	$11.52	$18.12	$76.68	$1,147.00	$22.94	$43.82	$111.14
Conv Slab Cu	$11.52	$12.72	$85.20	$96.12	$1,556.00	$31.12	$127.84	$139.96
Conv Slab Cu-Ins	$2.64	$12.00	$18.72	$87.00	$1,838.00	$36.76	$58.12	$135.76
Conv Slab CPVC	$10.44	$11.76	$69.96	$78.72	$1,086.00	$21.72	$102.12	$112.20
Conv Slab CPVC-Ins	$2.64	$11.76	$17.40	$78.00	$1,368.00	$27.36	$47.40	$117.12
Demand Recir Attic Cu	$1.08	$1.32	$8.28	$18.36	$1,880.00	$37.60	$46.96	**$57.28**
Demand Recir Slab Cu	$0.96	$1.08	$8.28	$30.00	$2,447.00	$48.94	$58.18	$80.02
Demand Recir Attic CPVC	$1.08	$1.32	$7.68	$12.36	$1,475.00	$29.50	**$38.26**	**$43.18**
Demand Recir Slab CPVC	$0.96	$1.20	$7.08	$12.84	$1,978.00	$39.56	$47.60	**$53.60**
Parallel Attic PEX	$2.64	$4.32	$18.84	$29.76	$1,226.00	$24.52	$46.00	**$58.60**
Parallel Slab PEX	$3.84	$4.44	$27.84	$31.44	$1,443.00	$28.86	$60.54	**$64.74**
Recir Attic Cu-Ins	$1.08	N.A.	$45.60	N.A.	$2,559.00	$51.18	$97.86	N.A.
Recir Slab Cu-Ins	$0.96	N.A.	$133.20	N.A.	$2,861.00	$57.22	$191.38	N.A.
Recir Attic CPVC-Ins	$1.08	N.A.	$49.32	N.A.	$1,965.00	$39.30	$89.70	N.A.
Recir Slab CPVC-Ins	$0.96	N.A.	$121.56	N.A.	$2,185.00	$43.70	$166.22	N.A.

Costs for Central WH include $300 added for flue, combustion air, and added gas line

4.3 Identification of Market Barriers

Market barriers to the use of alternative hot water distribution systems and options include such factors as cost, code acceptance, reliability/durability, performance, customer's awareness of the alternative, and customer's perception of the alternative. "Customers" - persons involved in choosing the hot water distribution system in a particular residence - include the homeowner, the general contractor, and the plumbing contractor. This study uses input from the plumbing contractor to determine potential market barriers.

Input from Plumbing Contractors

The follow is a summary of the responses received from seven California-based plumbing contractors who are involved in the installation of water distribution systems in new and existing housing. Each was interviewed using the questionnaire in Appendix B. An attempt was made to contact 50+ plumbing contractors in the state, but work schedules, inaccurate contact information, or other reasons precluded additional input. While the number of respondents clearly does not provide a "statistically significant sampling", it does in the opinion of the authors provide useful insight into the contractors' perceptions related to hot water distribution systems.

Questions Asked

Rank the importance of each of the following <u>to you</u> as a Plumbing Contractor (1 = very low to 10 = very high)

Reliability and Durability:	**9**
Low Cost:	**5**
Energy and Water Savings:	**5**

Rank your view of the importance of the following <u>to your customers</u> (1 = very low to 10 = very high)

Length of time before hot water is available at fixture:	**10**
Reliability and Durability:	**9.5**
Initial cost of system affecting the overall home cost:	**9.5**
Adequacy of flow/water pressure:	**6**
Energy and Water Savings:	**5**

Your familiarity with, and use of, Alternative Hot Water Systems

Continuous Recirculation Systems – 80% of the respondents were familiar with and install the systems. These systems are typically not time or temperature controlled. Some time-controlled systems are beginning to be installed, but the temperature controllers are "too new" and are very rarely used. These systems are installed in a very high percentage of new homes over 3000 sq ft (75%-85%) in size. This percentage drops as the square footage of the home decreases, because distribution distances become less and the waiting time for the hot water to get to the fixture is considered acceptable.

On-Demand Recirculation Systems - 80% of the respondents were familiar with the systems, but those interviewed seldom install them in new homes.

Parallel pipe manifold systems (single dead-end hot water lines to fixture from water heater) – 15% (one) of the respondents was familiar with these systems. That firm has not installed them in the past few years.

Point of use heating (for individual fixtures) – The respondents who were familiar with the product observed that they were mainly used in commercial applications. None of the respondents had installed them in residential construction.

Wastewater heat recovery (e.g. GFX) – The respondents were not familiar with the technology and none have installed them.

Observations Based on Response

1) The main drivers in the hot water distribution system selection to the homeowners are, in priority order: time for hot water to arrive at the fixtures, reliability, and cost. The homeowners are very concerned about the waiting time and appear to be willing to pay more to minimize it.

2) Based on comments from new construction plumbing contractors, they are driven mainly by the general contractors' requests, and have little participation in the decision as to what type system is installed. The plumbing contractors are mainly concerned with the reliability and durability to avoid potential callbacks.

3) All of plumbing contractors contacted were familiar with and installed both conventional and continuous recirculation systems. They are not familiar with and do not install parallel pipe/manifold systems, point-of-use water heaters, or waste water heat recovery systems.

4) Continuous recirculation systems are in very high demand for homes of 3000 sq ft and larger, with the demand dropping as the size of the home gets smaller.

5) Conserving water and energy are not considered essential, but are of interest to the homeowner and plumbing contractor.

Barriers to the use of Alternative Systems and Options

Cost – Initial cost is an important factor in entry-level (low-cost) housing, but declines in importance as the size and cost of the home increases. From the questionnaire results, it is apparent that upscale housing owners are willing to pay significantly more for the creature comfort of having hot water immediately available.

Building Code acceptance – This factor is viewed as a "given" by the plumbing contractors. If a system of material is not code approved in their locality, they do not consider it for use. Building code acceptance of plastic (CPVC and PEX) piping in California is mixed. Therefore the use of this lower cost, more energy efficient option is limited. Continuous recirculation systems are mandated in some California communities even though the simulations and cost estimates show that they have higher initial and energy costs than all other alternatives studied in this project.

Reliability/durability – This factor is very important to plumbing contractors. Failures cost the contractor in callback visits and impact their reputation. In general, a material or system has to have demonstrated reliability and durability before it will be considered for use.

Performance – This factor is very important to the homeowner. The distribution system must provide reasonable flow of water, short waiting period for hot water to arrive, and reasonable water and energy costs. Unfortunately, the homeowner will evaluate a systems performance primarily on flow and wait since they will make the direct connection with these factors as they use the system. Energy and water costs are disguised by other uses and are delayed until the utility bill is received by the homeowner, usually well after the actual use of the hot water.

Customer's awareness of alternative distribution systems – This factor impacts the homeowner, general contractor, and plumbing contractor. The general contractor is viewed as the person primarily "calling the shots" when it comes to the decision as to what type of distribution system to install. However, both the plumbing contractor and the homeowner have the potential to impact that decision if they make their input known.

Customer's perception of alternative distribution systems – Again, this factor impacts the homeowner, general contractor, and plumbing contractor. However, the impact of this factor is likely to be shared equally among the three parties. Past experience with similar systems (e.g. plastic piping failure, law suits, publicity, union resistance to use, etc.) can taint the perception held by these decision makers causing them to avoid potentially viable options.

5. Existing Domestic Hot Water Distribution Systems

(Task 3.1.3)

5.1 Simulation of Potential Energy and Water Savings

Viable replacement hot water distribution system configurations and options were simulated for existing houses #6 and #7. When the existing distribution system had failed and needed to be replaced the following options were evaluated: conventional system replacement in-kind, and replacement with a parallel pipe/manifold system. Some of the parameters and conditions were varied including using: different pipe materials, and insulated and non-insulated pipe. In addition, the installation of demand recirculation pump and controls on an existing system was evaluated for when an unacceptable waiting time was the sole issue to be addressed.

Both the "cold start" and "clustered" draw cycles (use patterns) were investigated.

Simulation results generated for the various systems and options were ranked in order of relative energy use and cost savings. Since the cost savings associated with the various alternatives are based on a specific set of modeling assumptions regarding hot water use (see Table 4.1), system layout, and the environmental conditions around the distribution systems, they should not be viewed as either absolute or directly transferable to another house. However, the trends identified by these simulations are useful in identifying those systems and options that are relatively more efficient and therefore likely to produce actual savings under "real world" conditions.

The results of the simulations for House #6 are shown in Tables 5.1 and 5.2. The results for Houses #6 and #7 are also included in Appendix A. A discussion of the simulation results for House #6 follows Table 5.3.

Table 5.1 Monthly Water and Energy Waste for House #6 (Cold Start Draw Cycle)

House-6	Wait Time for HW (Sec)			Water Wasted	Energy Loss From (Btu)		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu	22	59	78	594	351467	33458	0.68	14.82	4.63
Conv Attic Cu Ins	22	59	78	594	351467	34139	0.68	14.85	4.64
	21	56	76	570	337000	16855	0.65	13.62	4.25
Conv Attic CPVC Ins	21	56	76	570	337000	16987	0.65	13.62	4.25
Conv CS Cu	22	60	80	603	356713	38644	0.69	15.22	4.75
Conv CS CPVC	21	57	77	577	341423	18590	0.66	13.85	4.33
Conv CS Cu Ins	22	60	80	603	356713	37939	0.69	15.2	4.75
Conv CS CPVC Ins	21	57	77	577	341423	18564	0.66	13.85	4.33
Demand Recir Attic Cu *	2	3	5	47	27734	55293	0.05	3.22	1.01
Demand Recir CS Cu *	2	3	5	47	27734	62107	0.05	3.49	1.09
Parallel Attic PEX	11	25	33	250	147962	17181	0.28	6.36	1.99
Parallel CS PEX	11	25	34	251	148337	17459	0.28	6.38	1.99

Table 5.2 Monthly Water and Energy Waste for House #6 (Clustered AM & PM Draw Cycle)

House-6	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu	2	4	76	150	88,522	8,856	0.17	3.75	1.17
Conv Attic Cu Ins	2	4	75	149	88,148	8,678	0.17	3.73	1.16
Conv Attic CPVC	2	4	74	149	88,223	4,722	0.17	3.58	1.12
Conv Attic CPVC Ins	2	4	74	148	87,548	4,678	0.17	3.55	1.11
Conv CS Cu	2	18	79	296	175,171	15,121	0.34	7.33	2.29
Conv CS Cu Ins	2	4	79	155	91,446	9,642	0.18	3.89	1.22
Conv CS CPVC	2	12	77	259	153,284	8,112	0.29	6.21	1.94
Conv CS CPVC Ins	2	4	77	157	92,570	5,211	0.18	3.76	1.18
Demand Recir Attic Cu *	2	2	5	37	21,962	6,155	0.04	1.08	0.34
Demand Recir CS Cu *	2	2	5	37	21,962	11,590	0.04	1.30	0.41
Parallel Attic PEX	2	9	30	151	89,197	11,814	0.17	3.89	1.22
Parallel CS PEX	7	18	30	213	126,075	14,570	0.24	5.42	1.69

NOTES: * Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

5.2 Analysis of Cost-Benefit

Tables 5.1 and 5.2 show the potential cost savings (benefits) of the various alternative systems and options for existing California House #6, described in Section 3.3.2 and Appendix A. The potential construction costs to the homeowner for the various alternative systems and options for Houses #6 are shown in Table 5.3. The cost-benefit analysis compares the estimated construction cost for each of the alternative systems and option with the projected utility cost savings associated with each. Cost-benefit observations and conclusions follow Table 5.3.

Table 5.3 Existing Hot Water Distribution Systems – Costs to Homeowner

Scenario	Existing House Type #6
Conventional, Copper, attic or crawl space, uninsulated	$1023
Conventional, Copper, attic or crawl space, insulated	$1217
Conventional, CPVC, attic or crawl space, uninsulated	$702
Conventional, CPVC, attic or crawl space, insulated	$896
Conventional with Demand Recirculation, Copper, attic or crawl space, uninsulated	$694*
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	$944

* Demand recirculation system reuses existing piping system and includes pump and controls only

Notes on Table 5.3:

1. Costs shown include Plumbing Contractors' OH&P only for existing homes.
2. Existing Housing Labor is based on 125% (per R.S. Means) of new construction labor. Costs for materials and new construction labor provided by Dynamic Plumbing.
3. Actual existing housing costs will vary upwards from those shown because of differing field circumstances, the plumbing contractors' view of potential uncertainties, and the need to involve other crafts to open and restore walls to provide access for the plumbers to work. The costs shown above are best viewed a probable minimum costs

Cost-Benefit Observations

Based on the data shown in Tables 5.1, 5.2 and 5.3 the following observations can be made about each scenario for House #6. A conventional, copper, uninsulated, system in the attic (common practice in California) is used as the reference point for the cost/benefit analysis.

Scenario	Observation
Conventional,	**REFERENCE POINT**

Copper, attic or crawl space, uninsulated	
Conventional, Copper, attic or crawl space, insulated	Costs more initially, no energy savings in crawl space
Conventional, CPVC, attic or crawl space, uninsulated	Lower initial cost, saves some energy
Conventional, CPVC, attic or crawl space, insulated	Lower initial cost, no energy savings in crawl space
Conventional with Demand Recirculation, Copper, attic or crawl space, uninsulated	*Not Comparable*, used primarily as retrofit to existing system to reduce waiting, saves energy and water, long payback with gas WH
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	Lower initial cost, lower energy and water (cold start), slightly higher energy and water (clustered start)

Cost and Benefit Conclusions

For California (Existing) House #6 from a *cost/benefit viewpoint*, simulation results showed that the distribution systems superior to a conventional system are as follows (in order of greater to lesser benefit):

Assuming a "cold start" use pattern:
1. Conventional, CPVC, attic, uninsulated
2. Parallel Pipe/Manifold System, PEX, attic or crawl space, uninsulated

Assuming a "clustered" use pattern:
1. Conventional, CPVC, attic, uninsulated

Actual existing housing costs will vary upwards from those shown in Table 5.3 because of differing field circumstances, the plumbing contractors' view of potential uncertainties, and the need to involve other crafts to open and restore walls to provide access for the plumbers to work. It is likely that the installation of a rigid pipe conventional system would require more restoration than the flexible tubing used in the parallel pipe system. This situation could easily reverse the order shown above.

For California (Existing) House #6 from a *homeowner satisfaction viewpoint* - waiting time for hot water to arrive - simulation results showed that the distribution systems superior to a conventional system are as follows (in order of higher to lesser satisfaction):

Assuming a "cold start" use pattern:
1. Replace Existing Conventional w/ Parallel Pipe/Manifold System, PEX, attic, uninsulated

Assuming a "clustered" use pattern:
1. Replace Existing Conventional w/ Parallel Pipe/Manifold System, PEX, attic, uninsulated

The ranking of options to the conventional systems from a cost/benefit viewpoint vary slightly with the specifics of the particular house being evaluated. However, similar results also occurred in House #7.

For California (Existing) House #6 from an *energy and water conservation viewpoint* simulation results showed that distribution systems superior to the conventional system are as follows:

Assuming a "cold start" use pattern:
1. Replace Existing Conventional w/ Parallel Pipe/Manifold System, PEX, attic, uninsulated

Assuming a “clustered” use pattern:
1. Conventional, CPVC, attic, uninsulated

For California (Existing) House #6 from a *reducing the waiting time alone viewpoint* the simulation results showed that the addition of a demand recirculation pump and controls to an existing system is the “best” in all cost and benefit evaluations for both cold start and clustered use patterns.

5.3 Identification of Market Barriers

Refer to Section 4.3 for the identification and discussion of market barriers to the use of alternative hot water distribution systems for new homes. These barriers are by-and-large common to both new construction and existing homes. The exceptions for existing homes include the absence of a general contractor in most of the decisions and the fact that plumbing work is typically done in an occupied residence where disruption of the occupants add another dimension to the decision making process. Another potential barrier to use of some distribution systems is that the unique physical characteristics of the existing house that may preclude the use certain alternative systems and options. These physical characteristics should be viewed as “givens” and not subject to potential mitigation.

6. Evaluate Potential Impact

(*Task 3.1.4)*

6.1 Analysis of Statewide Impact of Successful Implementation

This section evaluates the impact of the application of more efficient alternative distribution systems on overall energy and water consumption at the state level. The evaluation is based on the efficiency of alternatives, their cost effectiveness, and the type and magnitude of barriers to their use that are described earlier in this document. It addresses the impact of alternative domestic hot water distribution systems for new housing and existing housing separately. The impact is projected at the point of maximum potential application (penetration) of the technologies, which is projected to be 3 to 5 years after the initiation of the activities described in Section 6.2 (Implementation Plan).

6.1.1 Alternative New Domestic Hot Water Distribution Systems

Assumptions used in this analysis of the potential impact of applying more efficient hot water distribution systems in California's new construction market:

- An average of ~150,000 homes are built per year in California (source: http://www.californiabuildermagazine.com/admin/files/ca_metrotab.pdf)
- The analysis will use the "best" alternative systems for Houses 1-5 from this report
- The analysis assumes a 100% penetration rate since the "best" alternative systems have both a lower or equal initial construction cost and lower ongoing operating costs. This penetration rate would require the support of an aggressive informational campaign to educate builders, plumber, homeowners, and code officials in the first several years (see Section 6.2).
- Houses 1-5 from this report will be used to represent various types of new housing being built in California (see section 3.3.1, New Construction for house descriptions). The ratio of results will be divided between the five types as follows: #1-30%, 45,000 units; #2-10%, 15,000 units; #3-20%, 30,000 units; #4-10%, 15,000 units; and, #5-30%, 45,000 units.
- Alternative systems are compared with a conventional uninsulated copper distribution system buried in the attic insulation (a current practice) in order to determine potential energy and water savings. Using an under-slab location with uninsulated copper pipe (another current practice) as a reference point would increase the projected energy and water savings by about 300-400%.

Analysis of potential impact:

See Tables 6.1 and 6.2 for the summary of the impacts. The "cold start" use pattern yields the highest impact in terms of water and energy savings while the "clustered" use pattern yields the probable minimum impact. The actual annual water and energy savings is between these extremes, though most likely closer to the savings shown in the clustered use pattern analysis.

Opportunity – House #1. From the assumptions listed above for the new construction market, there are approximately 45,000 units built per year of this type that would benefit from alternative hot water distribution systems. The two most efficient systems identified included: a

conventional CPVC piping system with demand recirculation located in the attic, and a parallel pipe/manifold system with PEX tubing located in the attic. Both systems have acceptable typical waiting periods for hot water to arrive. Using the performance of these alternative systems in 45,000 units of the House #1 type, there is an annual water savings of between 60 and 358 million gallons and an energy savings of between 38,340 and 226,130 MBTUs compared with the current norm.

Opportunity – House #2. From the assumptions listed above, there are approximately 15,000 units per year of this type that would benefit from alternative hot water distribution systems. The two most efficient systems identified included: a conventional CPVC piping system with demand recirculation located in the attic, and a parallel pipe/manifold system with PEX tubing located in the attic. Both systems have acceptable typical waiting periods for hot water to arrive. Using the performance of these alternative systems in 15,000 units of the House #2 type, there is an annual water savings of between 49 and 148 million gallons and an energy savings of between 31,660 and 91,735 MBTUs compared with the current norm.

Opportunity – House #3. From the assumptions listed above, there are approximately 30,000 units per year of this type that would benefit from alternative hot water distribution systems. The three most efficient systems identified included: a conventional CPVC piping system with demand recirculation located in the attic, a parallel pipe/manifold system with PEX tubing located in the attic and a conventional CPVC piping system located in the attic. The first two systems have acceptable typical waiting periods for hot water to arrive. The waiting time for third system is probably marginally acceptable. Using the performance of these alternative systems in 30,000 units of the House #3 type, there is an annual water savings of between 21 and 222 million gallons and an energy savings of between 13,470 and 139,905 MBTUs compared with the current norm.

Opportunity – House #4. From the assumptions listed above, there are approximately 15,000 units per year of this type that would benefit from alternative hot water distribution systems. The most efficient system identified was a parallel pipe/manifold system with PEX tubing located in the attic. This system has an acceptable waiting period for hot water to arrive. Using the performance of this alternative system in 15,000 units of the House #4 type, there is an annual water savings of between 2 and 47 million gallons and an energy savings of between 1,965 and 30,090 MBTUs compared with the current norm.

Opportunity – House #5. From the assumptions listed above, there are approximately 45,000 units per year of this type that would benefit from alternative hot water distribution systems. The two most efficient systems identified included: a conventional CPVC piping system located in the attic, and a parallel pipe/manifold system with PEX tubing located in the attic. The first system has a marginally acceptable waiting period for hot water to arrive while the second system is fully acceptable. Using the performance of these alternative systems in 45,000 units of the House #5 type, there is an annual water savings of between 4 and 73 million gallons and an energy savings of between 1,710 and 50,575 MBTUs compared with the current norm.

Total Potential Impact in New Construction. Combining the impacts of opportunities (Houses #1 - #5) yields a potential total water savings of between 136 and 848 million gallon per year and a potential energy savings of between 87,145 and 538,435 MBTUs per year.

6.1.2 Existing Domestic Hot Water Distribution Systems

Assumptions used in this analysis of the potential impact of applying more efficient hot water distribution systems in existing California homes:

- The total number of existing homes in California is ~11million.
- 25-50% of existing homes have an unacceptable waiting time (>30 seconds) for hot water (source: Larry Acker, Metlund); this translates to 2.75 to 5.5 million existing homes. Assuming 3.0M homes and a market penetration rate of 10% per year yields 300,000 homes per year for ten years. At the tenth year the existing home market will become saturated.
- 0.1% per year of existing homes has a deteriorated distribution system that requires major repair or replacement, or ~11,000 existing homes per year. This percentage is assumed to continue indefinitely.
- Houses 6-7 from this report will be used to represent the existing housing stock in California. The ratio of results will be evenly divided between the two types.
- Alternative systems are compared with a conventional uninsulated copper distribution system located below the crawl space (common in existing homes) in order to determine potential energy and water savings.

Analysis of potential impact:

See Table 6.1 for the summary of the impacts.

Opportunity – Shorten Waiting Time. From the assumptions listed above for existing homes, there are between 2.75 and 5.5 million existing homes that would significantly benefit from the installation of a demand recirculation system to reduce the waiting time for hot water and water waste. With a simple payback at over eight years for gas water heating, this suggests that the dominant factor in installing this option would be the reduced waiting period. This is likely to reduce the implementation by most residents with modest income, therefore, a 1.5 to 3.0 million homes total market for this approach may be more realistic. Using 1.5 million homes and a market penetration rate of 10% per year yields 150,000 homes per year. Using the performance of this technology from houses #6-7 combined, we have an annual water and energy savings of between 695 and 1,780 million gallons and between 451,350 and 1,128,300 MBTU per year over the existing systems. Once market saturation was reached in ten years there would be no further annual savings to be achieved from this opportunity.

Opportunity – Replace Failed Systems. From the assumptions listed above, there are approximately 11,000 existing homes per year that would require the replacement of the existing hot water distribution system. The most likely system to be used for replacement is a parallel pipe manifold system with PEX tubing. It is assumed that the PEX system, which is easier to install in an existing home, would be selected due to its lower total costs (plumbing system and house restoration after installation). Using the performance of this technology from houses #6-7 combined, we have an annual water savings between 12 and 46 million gallons and energy savings between 8,454 and 34,656 MBTU over a replacement in kind of the existing system.

Total Potential Impact in Existing Housing. Combining the impacts of opportunities (Houses #6-#7) yields a total average water savings between 707 and 1826 million gallons per year and an average energy saving between 459,804 and 1,162,956 MBTUs per year during the first ten

years until market saturation of the "shortened waiting time" opportunity was reached. In subsequent years the "replace failed systems" opportunity would continue to increase the total savings with an annual water savings between 12 and 46 million gallons and energy savings between 8,454 and 34,656 MBTU.

Combined New and Existing Housing Impact

Using data from the California Urban Water Conservation Council on per person water consumption in the San Francisco Bay Area, (www.nrdc.org/greengate/water/residentialf.asp) the potential annual savings from using alternative hot water distribution systems would equal the total annual water consumption of between 8,000 and 27,000 California homes. Using water consumption rates from areas with significant irrigation demands could lower the impact measured in homes by 50%. *DOE's Energy Information Agency, Residential Energy Consumption Survey [DOE/EIA-0314(90)]* data for typical household energy consumption shows a potential annual saving due to use of improved distribution systems comparable to the total annual energy consumption of between 8,000 and 24,000 California homes.

The total annual water savings after ten years would equal the total annual water consumption of between 80,000 and 270,000 California homes. The total annual energy savings after ten years would be comparable to the total annual energy consumption of between 80,000 and 240,000 California homes.

Table 6.1 Statewide Impact Assuming Cold Start Water Use Pattern (For New Housing)

House #1 Reference Point: Conventional, CU, In Attic , Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Substitute: Parallel Pipe, PEX, In Attic, Uninsulated	25,000	4.382	109,550	6,816	170
Substitute: Demand Recirc., CPVC, In Attic, Uninsulated	20,000	5.829	116,580	9,384	188
Total MBTU Savings/Year (This House Type)			**226,130**		**358**

House #2 Reference Point: Conventional, CU, In Attic, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Substitute: Parallel Pipe, PEX, In Attic, Uninsulated	5,000	5.591	27,955	8,748	44
Substitute: Demand Recirc., CPVC, In Attic, Uninsulated	10,000	6.378	63,780	10,392	104
Total MBTU Savings/Year (This House Type)			**91,735**		**148**

House #3 Reference Point: Conventional, CU, In Attic, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Substitute: Parallel Pipe, PEX, In Attic, Uninsulated	15,000	4.143	62,145	6,432	96
Substitute: Demand Recirc., CPVC, In Attic, Uninsulated	15,000	5.184	77,760	8,340	125
Total MBTU Savings/Year (This House Type)			**139,905**		**222**

House #4 Reference Point: Conventional, CU, In Attic, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Substitute: Parallel Pipe, PEX, In Attic, Uninsulated	15,000	2.006	30,090	3,132	47
Total MBTU Savings/Year (This House Type)			**30,090**		**47**

House #5 Reference Point: Conventional, CU, In Attic, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Substitute: Parallel Pipe, PEX, In Attic, Uninsulated	20,000	2.145	42,900	3,312	66
Substitute: Conventional, CPVC, In Attic, Uninsulated	25,000	0.307	7,675	264	7
Total MBTU Savings/Year (This House Type)			**50,575**		**73**

Table 6.1 Statewide Impact Assuming Cold Start Water Use Pattern - Continued (Existing Housing)

House #6 Reference Point: Conventional, CU, Crawl Space, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Add: Demand Recirc.to Existing CU Conventional System	150,000	3.666	549,900	6,672	1,001
Substitute: Parallel Pipe, PEX, Attic, Uninsulated	5,500	2.763	15,197	4,236	23
Total MBTU Savings/Year (This House Type)			**565,097**		**1,024**

House #7 Reference Point: Conventional, CU, Interstitial, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Add: Demand Recirc.to Existing CU Conventional System	150,000	3.856	578,400	5,196	779
Substitute: Parallel Pipe, PEX, Interstitial, Uninsulated	5,500	3.538	19,459	4,212	23
Total MBTU Savings/Year (This House Type)			**597,859**		**803**

Total Energy Savings (MBTU) Per Year in California	**1,701,391**
Natural Gas Savings (MBTU) Per Year in California	**1,446,182**
Electricity Savings (MBTU - End Use) Per Year in California	**255,209**
Total Water Savings (Mgals) Per Year in California	**2,674**

Table 6.2 Statewide Impact Assuming Clustered Water Use Pattern (For New Housing)

House #1 Reference Point: Conventional, CU, In Attic , Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Substitute: Conventional with Central WH, PEX, In Attic, Unins	6,750	0.614	4,145	936	6
Substitute: Demand Recirc., CPVC, In Attic, Uninsulated	38,250	0.089	3,420	1,416	54
Total MBTU Savings/Year (This House Type)			**7,564**		**60**

House #2 Reference Point: Conventional, CU, In Attic, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Substitute: Parallel Pipe, PEX, In Attic, Uninsulated	5,000	1.936	9,680	3,024	15
Substitute: Demand Recirc., CPVC, In Attic, Uninsulated	10,000	2.198	21,980	3,420	34
Total MBTU Savings/Year (This House Type)			**31,660**		**49**

House #3 Reference Point: Conventional, CU, In Attic, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Substitute: Demand Recirc., CPVC, In Attic, Uninsulated	30,000	0.449	13,470	696	21
Total MBTU Savings/Year (This House Type)			**13,470**		**21**

House #4 Reference Point: Conventional, CU, In Attic, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Substitute: Conventional, CPVC, In Attic, Uninsulated	15,000	0.131	1,965	132	2
Total MBTU Savings/Year (This House Type)			**1,965**		**2**

House #5 Reference Point: Conventional, CU, In Attic, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Substitute: Parallel Pipe, PEX, In Attic, Uninsulated	45,000	0.038	1,710	84	4
Total MBTU Savings/Year (This House Type)			**1,710**		**4**

Table 6.2 Statewide Impact Assuming Clustered Water Use Pattern - Continued (Existing Housing)

House #6 Reference Point: Conventional, CU, Crawl Space, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Add: Demand Recirc.to Existing CU Conventional System	150,000	1.880	282,000	3,108	466
Substitute: Parallel Pipe, PEX, Attic, Uninsulated	5,500	1.071	5,891	1,740	10
Total MBTU Savings/Year (This House Type)			**287,891**		**476**

House #7 Reference Point: Conventional, CU, Interstitial, Uninsulated					
Strategy	Housing Units/Year	MBTU Savings Unit/Year	Total MBTU Savings/Year	Gals Saved/ Unit/Year	Mgals Water Saved/Year
Add: Demand Recirc.to Existing CU Conventional System	150,000	1.129	169,350	1,524	229
Substitute: Parallel Pipe, PEX, Interstitial, Uninsulated	5,500	0.466	2,563	408	2
Total MBTU Savings/Year (This House Type)			**171,913**		**231**

Total Energy Savings (MBTU) Per Year in California	**546,949**
Natural Gas Savings (MBTU) Per Year in California	**464,906**
Electricity Savings (MBTU - End Use) Per Year in California	**82,042**
Total Water Savings (Mgals) Per Year in California	**843**

6.2 Implementation Plan to Guide Further Energy Commission Activities

This section identifies seven action areas which could materially impact the use of more efficient residential hot water distribution systems within the state. Several action areas (e.g. Plumbing and Building Code Acceptance, Pursue Additional Research,) could be addressed through the Energy Commission working in concert with other groups and agencies since the tasks are national in scope. In the other action areas the Energy Commission could individually accomplish the task (e.g., Title 24 Revisions) or work with others within California to bring about the needed changes (e.g., Educate California contractors and homeowners).

1. Plumbing and Building Code Acceptance of Technologies

The Energy Commission could work with applicable code organizations on revisions that permit the use of non-conventional hot water distribution systems and materials where these have demonstrated the potential to significantly impact the overall distribution systems performance. The Energy Commission could also support efforts to update the current methodology of sizing of plumbing systems to reflect current fixture consumption rates, water use patterns (draw cycles), and the demographics of current California housing.

2. Assessment and Ranking of Technologies by State Building Code (Title 24)

The Energy Commission could develop assessment methodologies that appropriately reflect the performance of non-conventional distribution systems. The Energy Commission could also support efforts to validate and refine current computer simulation models that will contribute to this assessment effort, in particular under-slab installations and those with insulation. Finally, the Energy Commission could implement these assessments in future versions of Title 24 to appropriately credit the better alternative systems and materials. Specific areas in which the conclusions of this study appear to differ with the current draft Title 24 include:

- The insulation of demand "recirculation" systems does not appear warranted regardless of system location.
- The cost/benefit of using insulation on under-slab piping is not compelling, based on simulation results in this study. For a copper pipe distribution system with a gas water heater the simple payback from adding insulation ranged from ~4 years to ~8 years depending on the house being evaluated, and for CPVC pipe the paybacks were longer.
- The Demand Side Management (DSM) factors applied to demand recirculation systems, continuous recirculation, and parallel pipe systems should be adjusted to better reflect each system's performance.

3. Pursue Additional Research Needs

Appendix C contains descriptions of the additional research needed to enhance the knowledge of residential hot water distribution systems. This enhanced knowledge is needed to better understand what the most important energy efficiency and water efficiency issues are and pursue them effectively. This understanding is central to enabling the following areas to be effectively accomplished.

4. Development of Efficient Hot Water Distribution Technologies

This research has shown that more efficient residential hot water distribution system technologies are needed in the marketplace. What follows is a short and unprioritized list of hot water distribution system technologies that may improve residential water and/or energy use efficiencies:

- A high market demand for shortened waiting periods is driving the installation of continuous recirculation systems. Methods to conserve energy while using continuous recirculation systems should be investigated and, where cost-effective, mandated. The primary focus should be on automated controls based on time, temperature, and/or occupancy. Current controls need to be refined and their use mandated.
- Another technology useful for recirculation systems could be to develop significantly more effective pipe insulation materials than those currently available, in order to improve the performance of these systems.
- The current demand control recirculation systems are beginning to evolve from manual actuation to activation by motion sensors. Automating these systems would eliminate a complaint voiced by some that they either forget to activate the systems or don't like the requirement that they do so.
- The tubing size used in the parallel pipe manifold systems is believed to be somewhat oversized for low-flow applications. Development and testing of a ¼" diameter tube may provide still further improvement in efficiency from the use of these systems.
- The integration of effective thermal insulation into the manufacture of tubing such as PEX might reduce the cost of insulating distribution systems and thereby increase the cost effectiveness of this potential conservation strategy.
- Point-of-use electric water heating for remote and low demand locations could be developed to reduce the length of hot water distribution systems and thereby also reduce the waiting period. Combining point-of-use heaters with waste heat recovery devices could make relatively modest capacity units effective in serving showers.

5. Establish a Collaborative Relationship with Water-Related Stakeholders

The Energy Commission should work through California government agencies and other interested residential water system stakeholders such as the Urban Water Conservation Council (CUWCC). Such groups could be coordinated to carry out cooperative research that would ultimately result in one or more Best Management Practices (BMP) being added to the California list of water-related BMPs. A collaborative relationship with a group such as the CUWCC would also benefit the process of addressing the two proposed education and technology acceptance activities that follow.

6. Contractor Education and Acceptance of Technologies

Awareness of efficient alternative hot water distribution systems and materials is mixed at best among the plumbing and general contracting community. . In addition, incentives to change current practices have not been clearly demonstrated and code acceptance varies widely, all of which make adopting alternative distribution systems an impediment to getting the job done. Contractors must have confidence in the performance of any alternative systems or materials because their profitability depends on minimizing "call-backs" to correct defective items. In the

highly competitive residential marketplace, material availability and cost as well as potential labor training requirements and cost impact the contractors' selection process. The Energy Commission should consider collaborating with trade organizations, materials suppliers and others to increase contractor awareness and acceptance of alternative systems and materials.

7. Homeowner Education and Acceptance of Technologies

Hot water distribution system performance is also very important to the homeowner. The distribution system is expected to provide a reasonable flow of hot water within a short time and at reasonable water and energy costs. Unfortunately, homeowners evaluate their distribution system's performance based primarily on flow and wait times, since these factors are immediately evident. The other performance factors of energy cost and water cost are delayed until the utility bills are received, well after the actual use of the hot water. The homeowner is rarely aware of what alternatives are available and how they perform. The Energy Commission could assist in the dissemination of information on the performance of alternative hot water distribution systems and materials. Some possible methods include teaming with utilities and/or municipalities to distribute information to consumers via their utility billing process or using the Energy Commission website to provide tips to homeowners on the topic.

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9. Glossary

Clustered use draw cycle – Assumes that individual hot water draws are clustered in the early morning and late afternoon/evening hours as might be expected from a family that spent the middle of the day away from their home.

Cold start draw cycle – Assumes that the water in the pipe cools down to the ambient temperature surrounding the pipe before each subsequent use as might be expected if hot water uses were separated by many hours.

Continuous recirculation system – A distribution system that has supply and return pipes that form a loop from the water heater. A pump usually near the water heater continuously circulates hot water through the loop. Individual fixtures are served from branches off the loop.

Conventional trunk and branch system – A distribution system that uses one or more larger pipes (trunks) from the water heater to feed a series on smaller pipes (branches) to serve individual fixtures.

CPVC – Chlorinated Poly Vinyl Chloride, one type of rigid plastic pipe of various sizes.

CU – Copper, both rigid pipe and flexible rolled tubing of various sizes.

Demand recirculation system – A conventional trunk and branch distribution system which has a demand actuated pump to transfer "cool" water in the hot water line to the cold water line usually at the fixture that is furthest from the water heater.

DSM – Demand Side Management

EF – U.S. Department of Energy's energy factor for electric and gas water heaters

HWDS – Hot water distribution systems

OH&P – Overhead and Profit, a percentage added to the direct labor and materials costs by contractors

ORNL – Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

Parallel pipe manifold system – A distribution system that locates a manifold near the water heater and provides individual, small diameter, lines from the manifold to each individual fixture.

PEX – Cross-linked Polyethylene, one type of flexible plastic tubing of various sizes.

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Appendix A. - Representative Housing Results

A plan of representative new California houses #1 - #5 are shown in this appendix, along with several different hot water distribution system layouts for the House #1 plan. Plans of representative existing California houses # 6 and #7 are also shown in this appendix. For each of the seven representative California houses (new and existing), construction costs for that house plus charts of Monthly Water and Energy Waste for both a cold start draw cycle and a clustered draw cycle are presented.

The data provided from these computer analyses provides a relative ranking of the various systems and options. Since each is based on a specific set of modeling assumptions regarding hot water use, system layout, and the environmental conditions around the distribution systems, the savings associated with the various alternatives should not be viewed as either absolute or directly transferable to another house. However, trends identified by these simulations are useful in identifying those systems and options that are relatively more efficient and therefore likely to produce actual savings under “real world” conditions. These projected savings should also be verified through field monitoring of actual installations.

Representative Housing Results - New Construction

House #1 – Single Family, Three Bedroom, Two Bath, One Story, 2010 ft^2
This unit represents a typical single story house. It contains a laundry room, one bath with a combined tub and a shower along with two lavatories, and another full bath with a tub/shower and one lavatory. The kitchen includes a sink and dishwasher. The water heater is in the garage. The layout of the house spreads hot water consuming devices throughout the house.

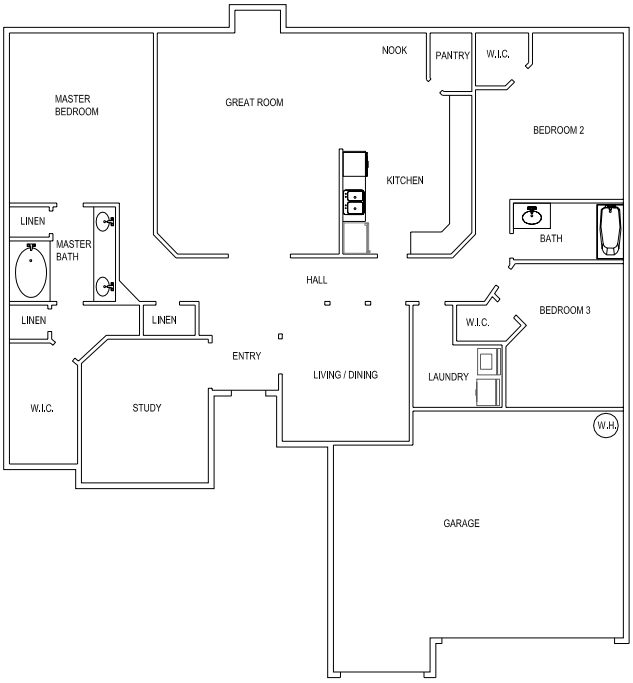

Figure A-1 House #1 - Floor Plan

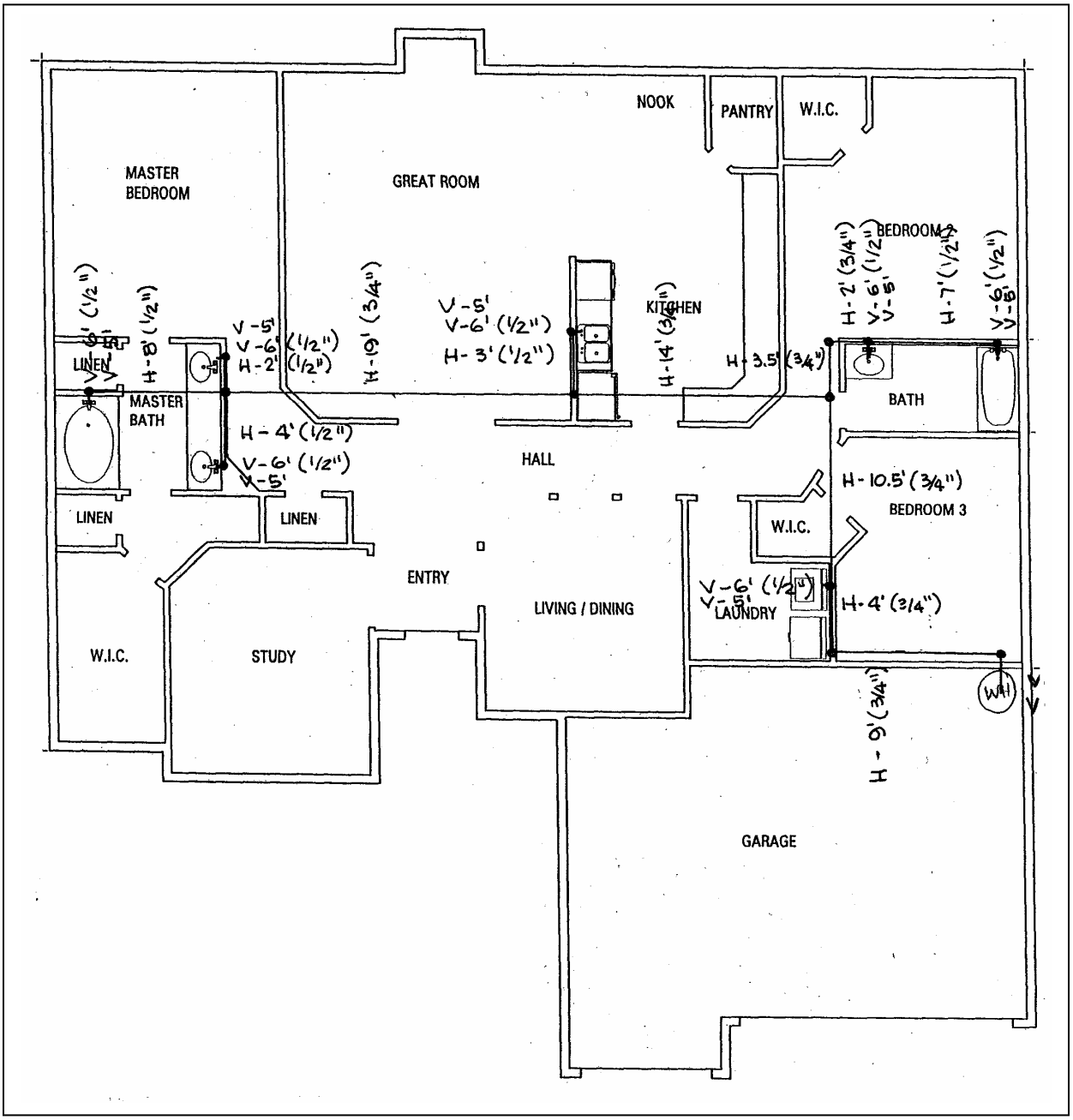

Figure A-2 House #1 - Conventional Distribution System

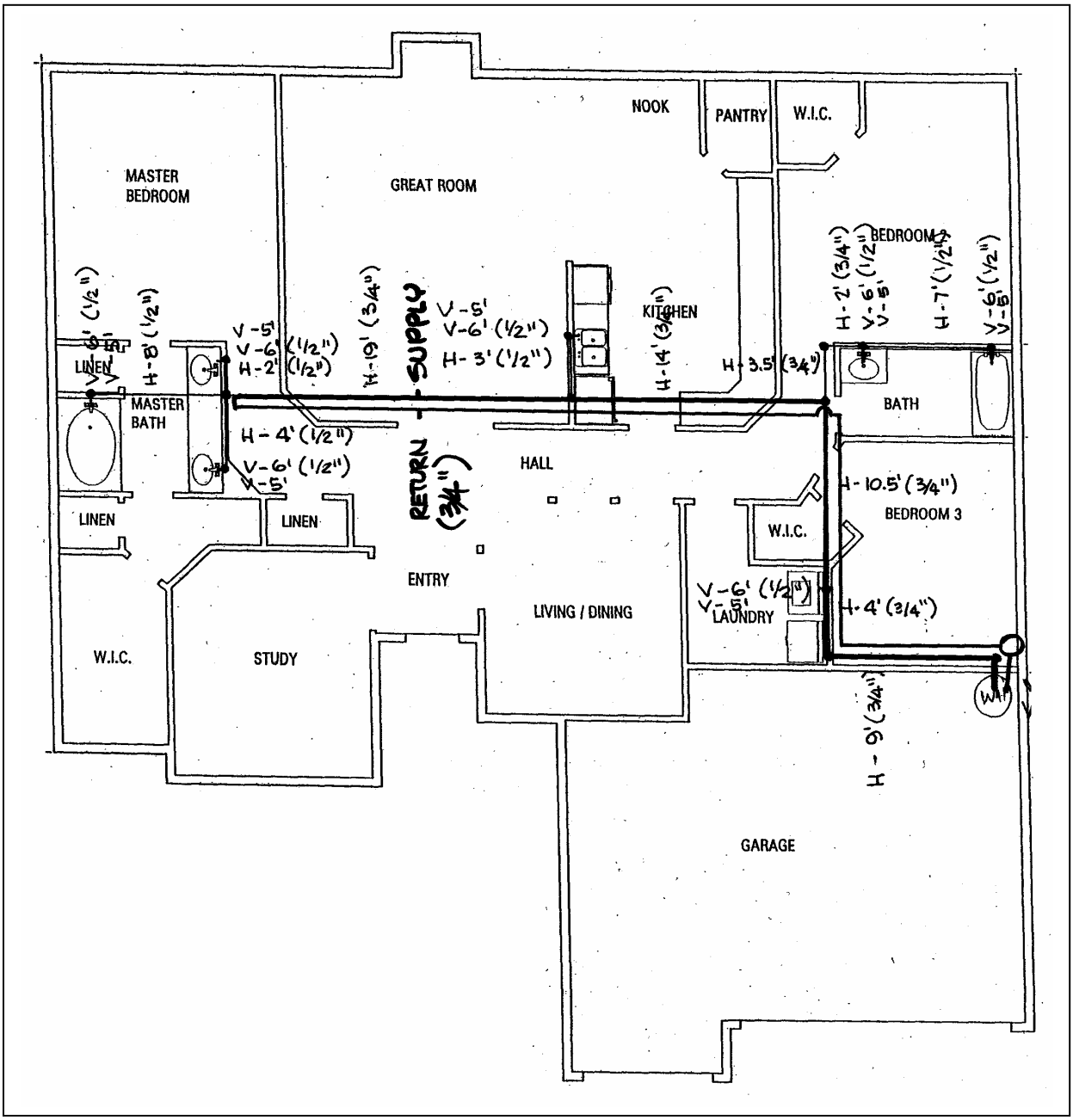

Figure A-3 House #1 - Continuous Recirculation Distribution System

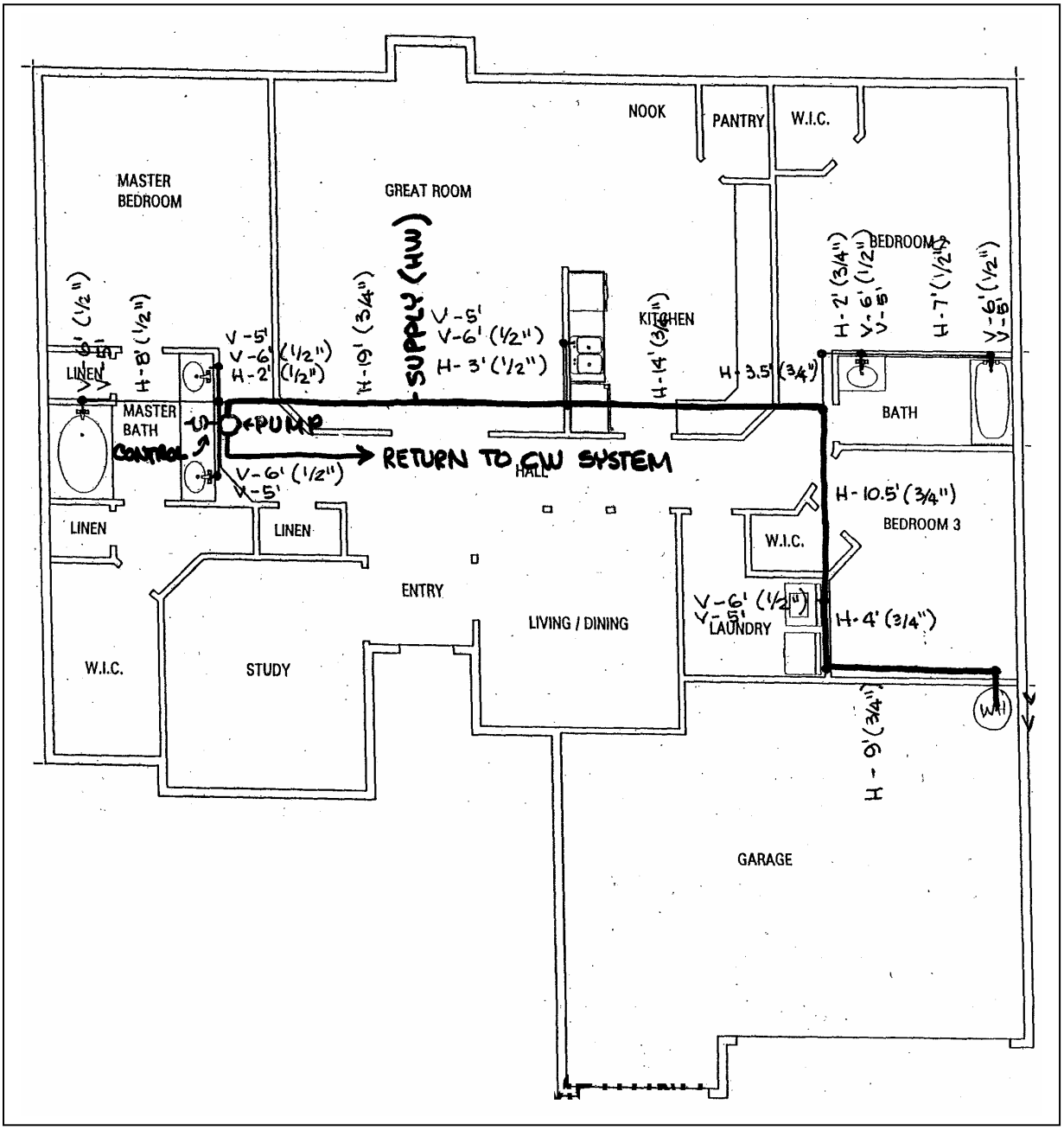

Figure A-4 House #1 - Demand Actuated Recirculation Distribution System

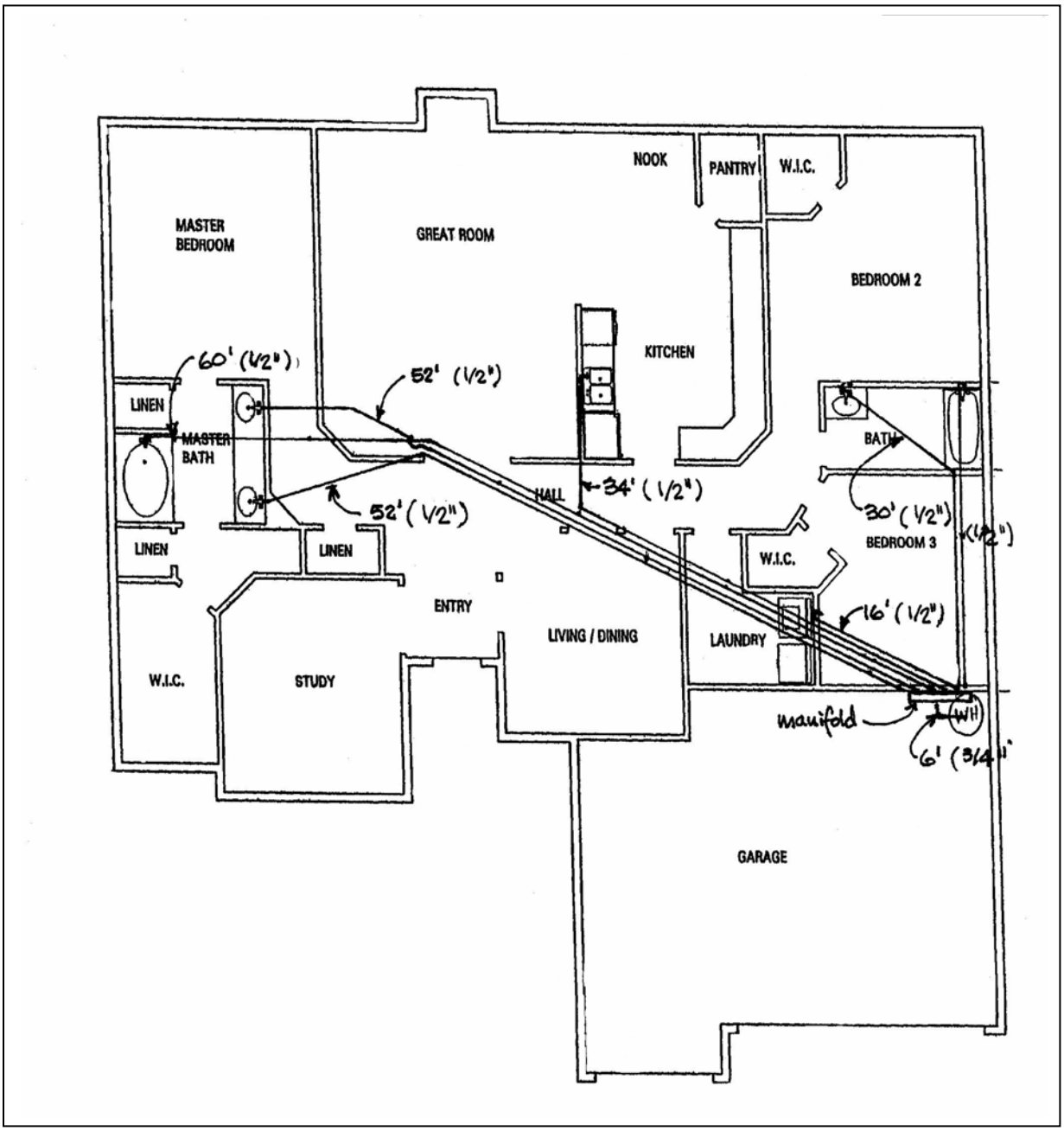

Figure A-5 House #1 - Parallel Pipe/Manifold Distribution System

Table A-1 Construction Costs for House #1

Scenario	Cost
Conventional, Central WH Location, Copper, attic, uninsulated	$1150
Conventional, Central WH Location, CPVC, attic, uninsulated	$787
Conventional, Copper, attic or crawl space, uninsulated	$1271
Conventional, Copper, attic or crawl space, insulated	$1552
Conventional, CPVC, attic or crawl space, uninsulated	$866
Conventional, CPVC, attic or crawl space, insulated	$1147
Conventional, Copper, under-slab, uninsulated	$1556
Conventional, Copper, under-slab, insulated	$1838
Conventional, CPVC, under-slab, uninsulated	$1086
Conventional, CPVC, under-slab, insulated	$1368
Conventional w/ Demand Recirculation, Copper, attic or crawl space, uninsulated	$1880
Conventional w/ Demand Recirculation, Copper, under-slab, insulated	$2447
Conventional w/ Demand Recirculation, CPVC, attic or crawl space, uninsulated	$1475
Conventional w/ Demand Recirculation, CPVC, under-slab, insulated	$1978
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	$1226
Parallel Pipe/Manifold System, PEX tubing, under-slab, uninsulated	$1443
Conventional w/ Continuous Recirculation, Copper, attic or crawl space, insulated	$2559
Conventional w/ Continuous Recirculation, Copper, under-slab, insulated	$2861
Conventional w/ Continuous Recirculation, CPVC, attic or crawl space, insulated	$1965
Conventional w/ Continuous Recirculation, CPVC, under-slab, insulated	$2185

Table A-2 House #1 - Monthly Water and Energy Waste (Cold Start Draw Cycle)

House-1	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu - Central	11	42	43	435	256,948	23,606	0.49	10.80	3.37
Conv Attic CPVC - Central	11	41	42	426	251,851	10,119	0.48	10.08	3.15
Conv Attic Cu	37	60	103	882	521,391	50,105	1.00	22.00	6.87
Conv Attic Cu-Ins	37	60	104	883	522,140	51,092	1.00	22.07	6.89
Conv Attic CPVC	35	57	99	839	496,431	26,163	0.95	20.11	6.28
Conv Attic CPVC-Ins	35	57	99	839	496,431	26,433	0.95	20.12	6.28
Conv CS Cu	37	60	104	892	527,612	58,810	1.01	22.58	7.05
Conv CS Cu-Ins	37	60	104	892	527,612	57,115	1.01	22.52	7.03
Conv CS CPVC	35	57	100	849	501,902	29,741	0.96	20.46	6.39
Conv CS CPVC-Ins	35	57	100	849	501,902	29,494	0.96	20.45	6.39
Conv Slab Cu	38	63	111	932	551,223	114,335	1.06	25.66	8.01
Conv Slab Cu-Ins	37	60	104	884	522,890	79,804	1.00	23.22	7.25
Conv Slab CPVC	36	58	100	862	509,998	35,439	0.98	20.99	6.56
Conv Slab CPVC-Ins	36	58	100	862	509,998	30,818	0.98	20.81	6.50
Demand Recir Attic Cu *	5	6	9	99	58,390	67,669	0.11	4.89	1.53
Demand Recir Slab Cu *	4	5	8	83	48,871	157,283	0.09	8.02	2.50
Demand Recir Attic CPVC *	5	6	9	100	59,140	26,594	0.11	3.31	1.03
Demand Recir Slab CPVC *	4	5	8	85	50,295	38,218	0.10	3.43	1.07
Parallel Attic PEX	12	23	36	314	185,440	20,911	0.36	7.95	2.48
Parallel Slab PEX	12	24	38	324	191,362	26,747	0.37	8.40	2.62

NOTES:
* Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

Table A-3 House #1 - Monthly Water and Energy Waste (Clustered AM & PM Draw Cycle)

House-1	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu - Central	2	5	40	117	69,334	6,847	0.13	2.93	0.92
Conv Attic CPVC - Central	2	5	39	119	70,458	3,342	0.14	2.84	0.89
Conv Attic Cu	2	5	99	196	115,881	11,435	0.22	4.90	1.53
Conv Attic Cu-Ins	1	5	99	195	115,207	11,145	0.22	4.86	1.52
Conv Attic CPVC	2	5	95	191	113,108	6,200	0.22	4.59	1.43
Conv Attic CPVC-Ins	2	5	95	191	113,108	6,151	0.22	4.59	1.43
Conv CS Cu	3	9	103	410	242,631	22,360	0.47	10.20	3.19
Conv CS Cu-Ins	2	5	102	203	119,854	12,837	0.23	5.11	1.60
Conv CS CPVC	2	8	98	359	212,499	12,196	0.41	8.65	2.70
Conv CS CPVC-Ins	2	5	98	200	118,205	7,305	0.23	4.83	1.51
Conv Slab Cu	32	54	109	845	499,878	90,351	0.96	22.75	7.10
Conv Slab Cu-Ins	2	4	102	192	113,708	16,245	0.22	5.01	1.56
Conv Slab CPVC	28	50	98	767	453,631	31,538	0.87	18.67	5.83
Conv Slab CPVC-Ins	2	5	98	192	113,783	7,076	0.22	4.65	1.45
Demand Recir Attic Cu *	2	5	9	77	45,273	12,030	0.09	2.21	0.69
Demand Recir Slab Cu *	2	4	8	66	39,052	17,997	0.08	2.20	0.69
Demand Recir Attic CPVC *	2	5	9	78	46,397	6,418	0.09	2.03	0.64
Demand Recir Slab CPVC *	2	4	8	70	41,600	7,826	0.08	1.90	0.59
Parallel Attic PEX	2	11	36	196	115,881	15,042	0.22	5.04	1.57
Parallel Slab PEX	9	19	38	286	168,875	24,098	0.32	7.43	2.32
Recir Attic Cu-Ins **	2	5	9	77	45,273	267,509	0.09	12.18	3.80
Recir Slab Cu-Ins **	2	4	8	66	39,052	872,443	0.08	35.55	11.10
Recir Attic CPVC-Ins **	2	5	9	78	46,397	291,240	0.09	13.15	4.11
Recir Slab CPVC-Ins **	2	4	8	70	41,600	790,345	0.08	32.45	10.13

NOTES:

* Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

** Energy supplied to the continuous recirculation system pump is calculated as 755.55 kWh/year or 62.9 kWh/month, which equals approximately $7.30/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

House #2 – Single Family, Four Bedroom, 2½ Bath, One Story, 3080 ft^2
This unit represents a larger single-story house than House #1 (by 50%). It contains a laundry room, one bath with a separate tub and a shower stall along with two lavatories, a half bath (lavatory only), and another full bath with a tub/shower and two lavatories. The large kitchen includes a sink and dishwasher. The water heater is in the garage. The house's layout spreads the hot water consuming devices to the four corners of the house.

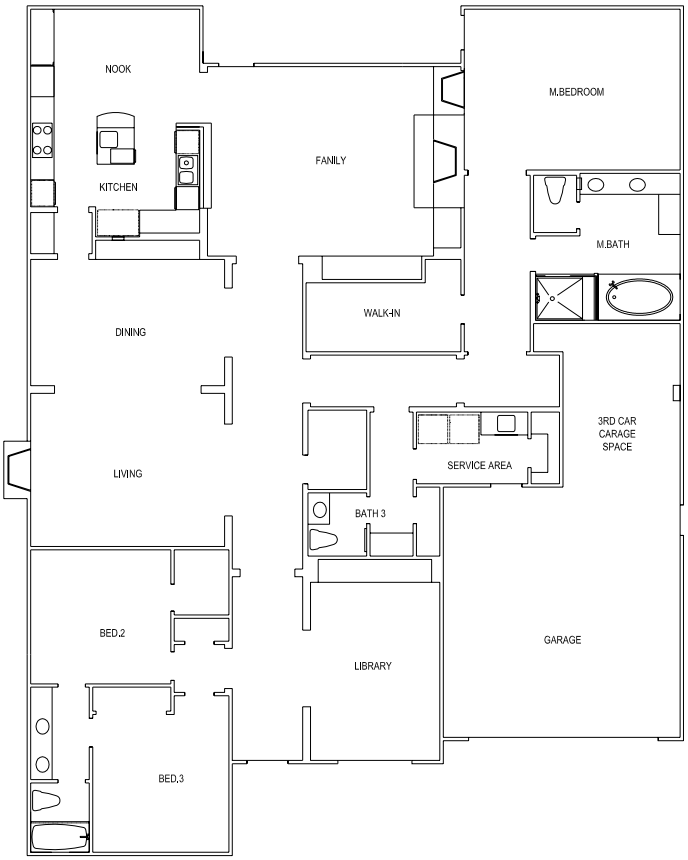

Figure A-6 House #2 – Floor Plan

Table A-4 Construction Costs for House #2

Scenario	Cost
Conventional, Central WH Location, Copper, attic, uninsulated	$1971
Conventional, Central WH Location, CPVC, attic, uninsulated	$1337
Conventional, Copper, attic or crawl space, uninsulated	$1960
Conventional, Copper, attic or crawl space, insulated	$2446
Conventional, CPVC, attic or crawl space, uninsulated	$1306
Conventional, CPVC, attic or crawl space, insulated	$1793
Conventional, Copper, under-slab, uninsulated	$2586
Conventional, Copper, under-slab, insulated	$3072
Conventional, CPVC, under-slab, uninsulated	$1787
Conventional, CPVC, under-slab, insulated	$2199
Conventional w/ Demand Recirculation, Copper, attic or crawl space, uninsulated	$2569
Conventional w/ Demand Recirculation, Copper, under-slab, insulated	$3581
Conventional w/ Demand Recirculation, CPVC, attic or crawl space, uninsulated	$1916
Conventional w/ Demand Recirculation, CPVC, under-slab, insulated	$2808
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	$1578
Parallel Pipe/Manifold System, PEX tubing, under-slab, uninsulated	$2038
Conventional w/ Continuous Recirculation, Copper, attic or crawl space, insulated	$3548
Conventional w/ Continuous Recirculation, -Copper, under-slab, insulated	$4097
Conventional w/ Continuous Recirculation, CPVC, attic or crawl space, insulated	$2707
Conventional w/ Continuous Recirculation, CPVC, under-slab, insulated	$3113

Table A-5 House #2 - Monthly Water and Energy Waste (Cold Start Draw Cycle)

House-2	Wait Time for HW (Sec.)			Water Wasted	Energy Loss Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu - Central	18	35	98	789	466,673	46,409	0.90	19.75	6.17
Conv Attic CPVC - Central	17	34	94	765	452,432	23,852	0.87	18.33	5.72
Conv Attic Cu	10	49	171	1,111	657,210	62,495	1.26	27.71	8.65
Conv Attic Cu-Ins	10	49	171	1,111	657,210	63,592	1.26	27.75	8.67
Conv Attic CPVC	10	48	164	1,070	633,075	31,211	1.22	25.56	7.98
Conv Attic CPVC-Ins	10	48	164	1,070	633,075	31,466	1.22	25.57	7.99
Conv CS Cu	10	50	173	1,123	664,106	72,095	1.28	28.35	8.85
Conv CS Cu-Ins	10	50	173	1,129	667,854	71,267	1.28	28.46	8.89
Conv CS CPVC	10	49	166	1,080	638,546	34,997	1.23	25.92	8.09
Conv CS CPVC-Ins	10	49	166	1,080	638,546	34,782	1.23	25.91	8.09
Conv Slab Cu	10	52	189	1,198	708,555	135,721	1.36	32.54	10.16
Conv Slab Cu-Ins	10	50	173	1,123	664,106	99,622	1.28	29.42	9.19
Conv Slab CPVC	10	49	168	1,089	644,018	40,728	1.24	26.35	8.23
Conv Slab CPVC-Ins	10	49	168	1,088	643,643	36,349	1.24	26.17	8.17
Demand Recir Attic Cu *	6	8	49	241	142,640	91,988	0.27	9.07	2.83
Demand Recir Slab Cu *	5	8	52	246	145,564	200,882	0.28	13.44	4.20
Demand Recir Attic CPVC *	6	9	48	245	144,889	43,292	0.28	7.26	2.27
Demand Recir Slab CPVC *	6	9	52	256	151,560	65,263	0.29	8.37	2.62
Parallel Attic PEX	9	21	52	382	225,916	27,880	0.43	9.77	3.05
Parallel Slab PEX	9	21	56	394	232,887	36,675	0.45	10.39	3.24

NOTES:

* Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

Table A-6 House #2 - Monthly Water and Energy Waste (Clustered AM & PM Draw Cycle)

House-2	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu - Central	2	13	92	377	222,993	22,729	0.43	9.46	2.95
Conv Attic CPVC - Central	2	13	89	355	210,175	11,535	0.40	8.53	2.66
Conv Attic Cu	2	9	114	445	263,244	26,332	0.51	11.15	3.48
Conv Attic Cu-Ins	2	9	114	446	263,918	26,533	0.51	11.18	3.49
Conv Attic CPVC	2	9	110	431	254,849	13,601	0.49	10.33	3.23
Conv Attic CPVC-Ins	2	9	109	430	254,099	13,733	0.49	10.31	3.22
Conv CS Cu	0	32	111	643	380,549	38,185	0.73	16.12	5.04
Conv CS Cu-Ins	2	9	117	455	269,390	29,049	0.52	11.49	3.59
Conv CS CPVC	0	31	102	609	359,936	19,229	0.69	14.59	4.56
Conv CS CPVC-Ins	2	10	112	439	259,646	14,932	0.50	10.57	3.30
Conv Slab Cu	10	49	174	1,108	655,336	116,268	1.26	29.73	9.29
Conv Slab Cu-Ins	2	9	117	450	266,392	39,223	0.51	11.77	3.68
Conv Slab CPVC	2	46	157	978	578,432	42,297	1.11	23.89	7.46
Conv Slab CPVC-Ins	2	10	113	433	255,973	15,462	0.49	10.45	3.26
Demand Recir Attic Cu *	2	7	45	158	93,170	21,829	0.18	4.43	1.38
Demand Recir Slab Cu *	2	7	51	217	128,324	193,741	0.25	12.50	3.90
Demand Recir Attic CPVC *	2	8	44	160	94,669	11,778	0.18	4.10	1.28
Demand Recir Slab CPVC *	2	8	51	223	131,697	84,515	0.25	8.36	2.61
Parallel Attic PEX	2	9	46	193	113,932	14,311	0.22	4.94	1.54
Parallel Slab PEX	8	20	50	348	205,528	31,526	0.39	9.13	2.85
Recir Attic Cu-Ins **	2	19	53	317	187,464	360,666	0.36	21.28	6.65
Recir Slab Cu-Ins **	2	19	52	311	183,866	1,101,737	0.35	50.07	15.64
Recir Attic CPVC-Ins **	2	5	51	203	120,304	374,577	0.23	19.24	6.01
Recir Slab CPVC-Ins **	2	5	51	205	121,053	1,005,310	0.23	43.89	13.71

NOTES:

* Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

** Energy supplied to the continuous recirculation system pump is calculated as 755.55 kWh/year or 62.9 kWh/month, which equals approximately $7.30/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

House #3 – Single Family, Four Bedroom, Three Bath, Two Story, 2810 ft^2
This unit represents a moderately sized two-story house. It contains a laundry room, one full bath with tub/shower, and a moderately sized kitchen with sink and dishwasher on the first floor. The second floor includes two full baths. One bath has a tub/shower and two lavatories. The other bath has both a tub and a shower stall along with two lavatories. The water heater is located in the garage adjacent to the laundry room. The hot water distribution system layout is fairly compact for the area of the unit.

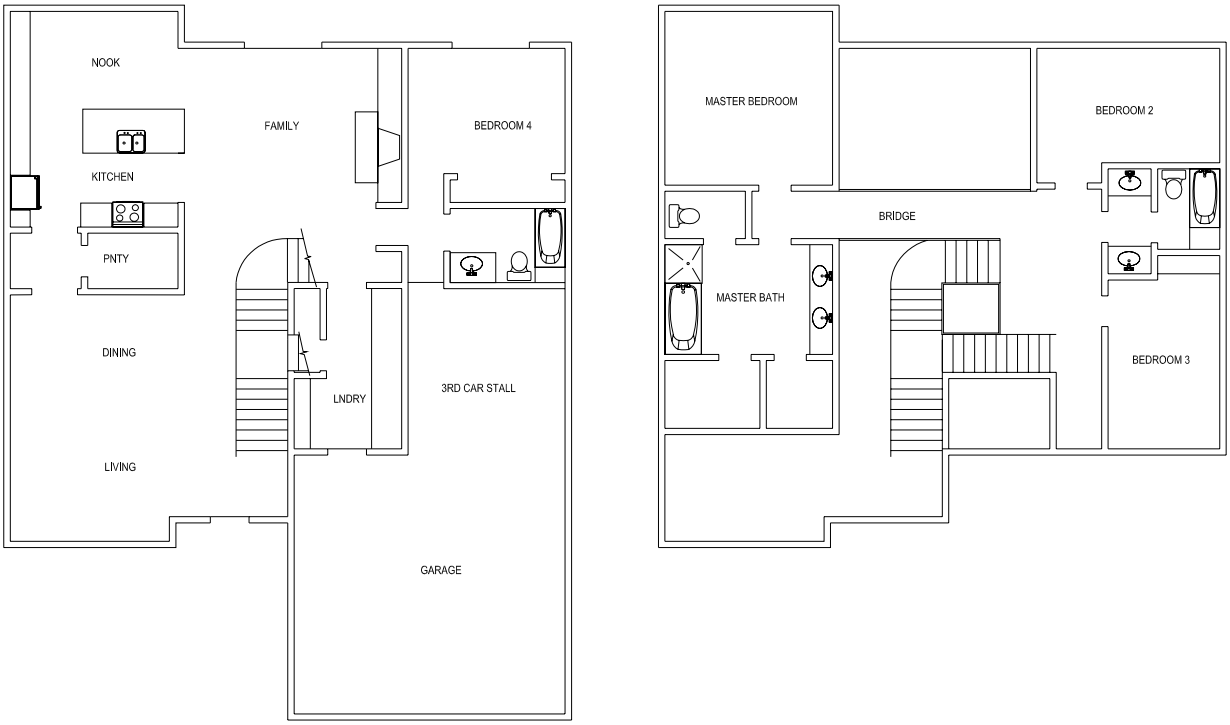

Figure A-7 House #3 - Floor Plan (first floor/left, second floor/right)

Table A-7 Construction Costs for House #3

Scenario	Cost
Conventional, Central WH Location, Copper, attic, uninsulated	$1931
Conventional, Central WH Location, CPVC, attic, uninsulated	$1038
Conventional, Copper, attic or crawl space, uninsulated	$1716
Conventional, Copper, attic or crawl space, insulated	$2103
Conventional, CPVC, attic or crawl space, uninsulated	$1144
Conventional, CPVC, attic or crawl space, insulated	$1531
Conventional, Copper, under-slab, uninsulated	$1896
Conventional, Copper, under-slab, insulated	$2283
Conventional, CPVC, under-slab, uninsulated	$1293
Conventional, CPVC, under-slab, insulated	$1680
Conventional w/ Demand Recirculation, Copper, attic or crawl space, uninsulated	$2326
Conventional w/ Demand Recirculation, Copper, under-slab, insulated	$2892
Conventional w/ Demand Recirculation, CPVC, attic or crawl space, uninsulated	$1754
Conventional w/ Demand Recirculation, CPVC, under-slab, insulated	$2289
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	$1729
Parallel Pipe/Manifold System, PEX tubing, under-slab, uninsulated	$1927
Conventional w/ Continuous Recirculation, Copper, attic or crawl space, insulated	$2978
Conventional w/ Continuous Recirculation, Copper, under-slab, insulated	$3170
Conventional w/ Continuous Recirculation, CPVC, attic or crawl space, insulated	$2249
Conventional w/ Continuous Recirculation, CPVC, under-slab, insulated	$2398

Table A-8 House #3 - Monthly Water and Energy Waste (Cold Start Draw Cycle)

House-3	Wait Time for HW (Sec)			Water Wasted	Energy Loss From (Btu)		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu - Central	22	49	82	709	419,076	39,824	0.81	17.67	5.52
Conv Attic CPVC - Central	21	47	78	729	431,219	21,356	0.83	17.41	5.44
Conv Attic Cu	33	58	101	907	536,232	52,131	1.03	22.65	7.07
Conv Attic Cu-Ins	33	58	101	908	536,982	53,212	1.03	22.72	7.10
Conv Attic CPVC	32	56	97	870	514,420	27,424	0.99	20.85	6.51
Conv Attic CPVC-Ins	32	56	97	870	514,420	27,704	0.99	20.86	6.52
Conv CS Cu	34	59	103	924	546,501	61,208	1.05	23.40	7.31
Conv CS Cu-Ins	34	59	103	925	547,250	59,424	1.05	23.36	7.30
Conv CS CPVC	33	57	98	886	524,239	31,072	1.01	21.37	6.67
Conv CS CPVC-Ins	33	57	98	886	524,239	30,820	1.01	21.36	6.67
Conv Slab Cu	35	62	109	968	572,435	118,562	1.10	26.64	8.32
Conv Slab Cu-Ins	34	59	103	924	546,501	83,684	1.05	24.28	7.58
Conv Slab CPVC	33	57	99	891	526,863	37,016	1.01	21.70	6.78
Conv Slab CPVC-Ins	33	57	99	891	526,863	32,025	1.01	21.51	6.72
Demand Recir Attic Cu *	4	8	33	204	120,379	73,892	0.23	7.51	2.35
Demand Recir Slab Cu *	4	7	32	197	116,256	149,061	0.22	10.29	3.21
Demand Recir Attic CPVC *	4	8	35	212	125,401	30,955	0.24	6.03	1.88
Demand Recir Slab CPVC *	4	8	35	212	125,401	35,023	0.24	6.19	1.93
Parallel Attic PEX	15	24	38	371	219,620	26,512	0.42	9.48	2.96
Parallel Slab PEX	15	24	40	379	224,417	34,381	0.43	9.97	3.11

NOTES

* Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

Table A-9 House #3 - Monthly Water and Energy Waste (Clustered AM & PM Draw Cycle)

House-3	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu - Central	2	5	63	168	99,241	9,775	0.19	4.20	1.31
Conv Attic CPVC - Central	2	5	61	164	96,768	4,928	0.19	3.91	1.22
Conv Attic Cu	2	5	79	187	110,709	10,931	0.21	4.68	1.46
Conv Attic Cu-Ins	2	5	79	187	110,709	10,711	0.21	4.67	1.46
Conv Attic CPVC	2	6	76	184	108,910	5,739	0.21	4.41	1.38
Conv Attic CPVC-Ins	2	6	76	184	108,910	5,699	0.21	4.41	1.38
Conv CS Cu	3	10	83	357	211,375	19,875	0.41	8.90	2.78
Conv CS Cu-Ins	2	6	83	197	116,781	12,058	0.22	4.96	1.55
Conv CS CPVC	2	9	79	327	193,685	11,468	0.37	7.89	2.47
Conv CS CPVC-Ins	2	6	79	192	113,708	6,491	0.22	4.63	1.44
Conv Slab Cu	29	56	100	871	515,020	92,551	0.99	23.41	7.31
Conv Slab Cu-Ins	2	6	82	194	114,682	15,894	0.22	5.03	1.57
Conv Slab CPVC	2	52	92	770	455,655	33,252	0.88	18.82	5.88
Conv Slab CPVC-Ins	2	6	79	192	113,708	6,661	0.22	4.63	1.45
Demand Recir Attic Cu *	3	8	28	173	102,464	17,200	0.20	4.61	1.44
Demand Recir Slab Cu *	3	7	28	167	98,716	24,431	0.19	4.75	1.48
Demand Recir Attic CPVC *	2	4	30	129	76,380	7,850	0.15	3.24	1.01
Demand Recir Slab CPVC *	2	4	30	129	76,380	8,956	0.15	3.29	1.03
Parallel Attic PEX	2	13	35	227	134,545	17,966	0.26	5.87	1.83
Parallel Slab PEX	12	22	37	342	202,005	30,791	0.39	8.97	2.80
Recir Attic Cu-Ins **	2	3	32	99	58,390	189,801	0.11	9.65	3.01
Recir Slab Cu-Ins **	2	3	32	99	58,765	585,618	0.11	25.12	7.84
Recir Attic CPVC-Ins **	2	3	31	101	59,440	186,923	0.11	9.58	2.99
Recir Slab CPVC-Ins **	2	4	32	103	60,939	528,692	0.12	22.98	7.18

NOTES:
* Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.
** Energy supplied to the continuous recirculation system pump is calculated as 755.55 kWh/year or 62.9 kWh/month, which equals approximately $7.30/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

House #4 - Apartment, One Bedroom, One Bath, One Story, 580 ft^2
This unit is representative of small apartments and elderly housing. It contains a small kitchen (with sink and dishwasher) and single bath with a shower stall (no tub). The water heater is located in a closet off the balcony/patio, and there are no provisions for a clothes washer within the unit. While the hot water distribution system layout is compact, the external location of the water heater significantly increases the overall system length.

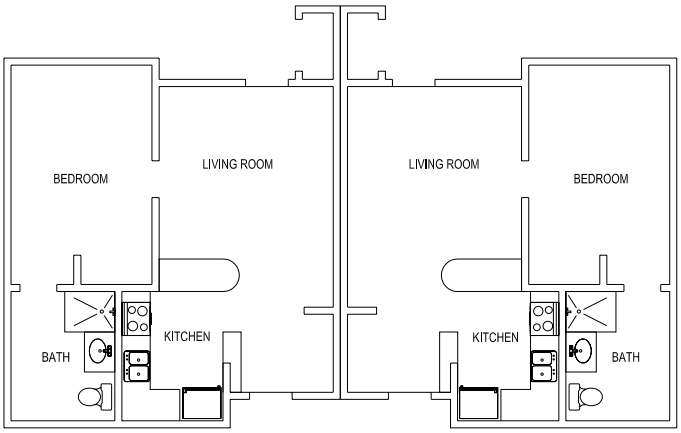

Figure A-8 House #4 – Apartment Floor Plan (two units shown)

Table A-10 Construction Costs for House #4

Scenario	Cost
Conventional, Copper, attic or crawl space, uninsulated	$722
Conventional, Copper, attic or crawl space, insulated	$850
Conventional, Copper, under-slab, uninsulated	$833
Conventional, Copper, under-slab, insulated	$961
Conventional, CPVC, attic or crawl space, uninsulated	$494
Conventional, CPVC, attic or crawl space, insulated	$622
Conventional, CPVC, under-slab, uninsulated	$581
Conventional, CPVC, under-slab, insulated	$692
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	$545
Parallel Pipe/Manifold System, PEX tubing, under-slab, uninsulated	$786

Table A-11 House #4 - Monthly Water and Energy Waste (Cold Start Draw Cycle)

House-4	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu	17	31	58	532	314,439	29,602	0.60	13.25	4.14
Conv Attic Cu-Ins	17	31	58	538	318,186	30,146	0.61	13.41	4.19
Conv Attic CPVC	16	30	56	518	306,418	12,931	0.59	12.29	3.84
Conv Attic CPVC-Ins	16	30	56	518	306,418	12,968	0.59	12.29	3.84
Conv CS Cu	17	32	59	547	323,283	33,421	0.62	13.73	4.29
Conv CS Cu-Ins	17	32	59	547	323,283	33,301	0.62	13.73	4.29
Conv CS CPVC	17	30	57	524	310,091	13,924	0.60	12.47	3.89
Conv CS CPVC-Ins	17	30	57	524	310,091	13,946	0.60	12.47	3.89
Conv Slab Cu	18	32	61	559	330,554	57,488	0.64	14.95	4.67
Conv Slab Cu-Ins	17	31	59	545	322,534	46,154	0.62	14.20	4.44
Conv Slab CPVC	17	31	57	534	315,938	15,192	0.61	12.74	3.98
Conv Slab CPVC-Ins	17	31	57	534	315,938	14,533	0.61	12.71	3.97
Parallel Attic PEX	9	17	30	271	160,480	16,403	0.31	6.81	2.13
Parallel Slab PEX	9	17	31	275	162,729	20,378	0.31	7.05	2.20

Table A-12 House #4 - Monthly Water and Energy Waste (Clustered AM & PM Draw Cycle)

House-4	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu	2	7	29	134	79,228	7,461	0.15	3.34	1.04
Conv Attic Cu Ins	2	7	29	133	78,853	7,330	0.15	3.32	1.04
Conv Attic CPVC	2	7	29	123	72,557	3,238	0.14	2.92	0.91
Conv Attic CPVC Ins	2	7	29	123	72,557	3,238	0.14	2.92	0.91
Conv CS Cu	2	10	51	229	135,670	10,438	0.26	5.62	1.76
Conv CS Cu Ins	2	8	31	138	81,477	7,480	0.16	3.42	1.07
Conv CS CPVC	2	9	50	210	124,426	5,219	0.24	4.99	1.56
Conv CS CPVC Ins	2	8	30	131	77,279	3,452	0.15	3.11	0.97
Conv Slab Cu	20	27	55	486	287,155	40,872	0.55	12.64	3.95
Conv Slab Cu Ins	2	7	31	137	81,102	9,604	0.16	3.49	1.09
Conv Slab CPVC	2	25	53	425	251,626	12,429	0.48	10.16	3.17
Conv Slab CPVC Ins	2	8	30	131	77,279	3,476	0.15	3.11	0.97
Parallel Attic PEX	2	9	27	138	81,776	8,847	0.16	3.49	1.09
Parallel Slab PEX	8	14	29	236	139,792	16,970	0.27	6.04	1.89

House #5 – Apartment or Condominium, Two Bedroom, Two Bath, One Story, 960 ft^2
This unit is representative of mid-sized apartments or condominium units. It contains a modest kitchen (with sink and dishwasher) and two baths, both with tub/shower. The water heater is located in a closet off the balcony/patio, and a closet is provided to permit a small, stacked, clothes washer/dryer unit. The distribution system layout is fairly compact for the area of the unit.

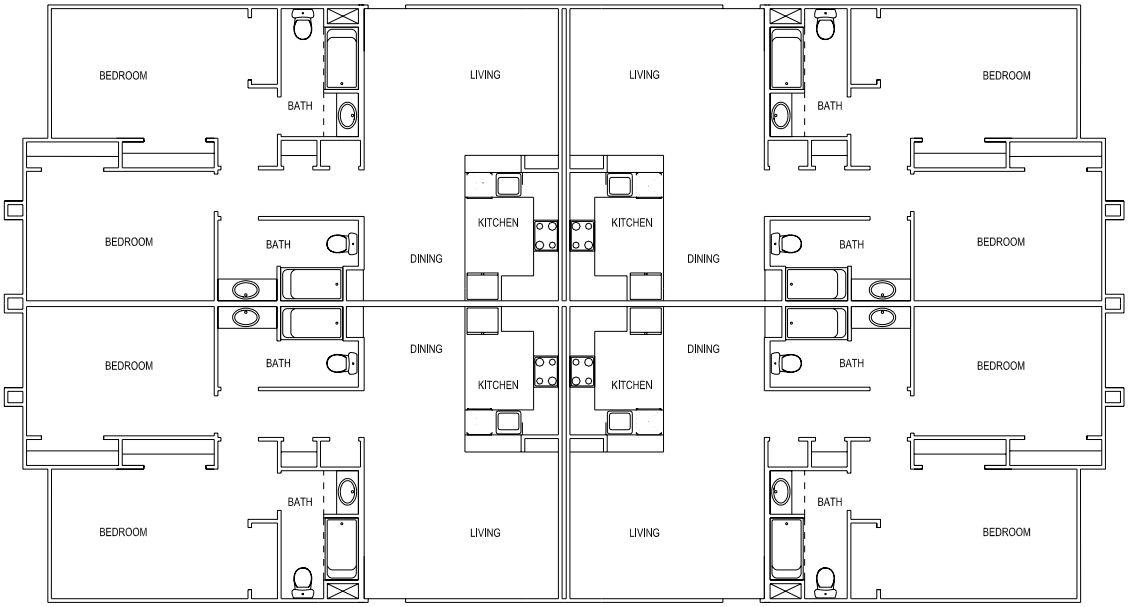

Figure A-9 House #5 – Condominium Floor Plan (four units shown)

Table A-13 Construction Costs for House #5

Scenario	Cost
Conventional, Copper, attic or crawl space, uninsulated	$929
Conventional, Copper, attic or crawl space, insulated	$1098
Conventional, Copper, under-slab, uninsulated	$1063
Conventional, Copper, under-slab, insulated	$1231
Conventional, CPVC, attic or crawl space, uninsulated	$639
Conventional, CPVC, attic or crawl space, insulated	$807
Conventional, CPVC, under-slab, uninsulated	$729
Conventional, CPVC, under-slab, insulated	$897
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	$1040
Parallel Pipe/Manifold System, PEX tubing, under-slab, uninsulated	$1078

Table A-14 House #5 - Monthly Water and Energy Waste (Cold Start Draw Cycle)

House-5	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu	34	37	66	427	252,675	23,928	0.49	10.65	3.33
Conv Attic Cu-Ins	34	37	66	427	252,675	24,361	0.49	10.67	3.33
Conv Attic CPVC	32	35	63	405	239,333	11,639	0.46	9.66	3.02
Conv Attic CPVC-Ins	32	35	63	405	239,333	11,714	0.46	9.66	3.02
Conv CS Cu	34	37	67	431	254,849	27,533	0.49	10.87	3.40
Conv CS Cu-Ins	34	37	68	433	256,348	27,391	0.49	10.93	3.41
Conv CS CPVC	33	36	64	415	245,255	13,156	0.47	9.94	3.11
Conv CS CPVC-Ins	33	36	64	415	245,255	13,154	0.47	9.94	3.11
Conv Slab Cu	36	39	71	455	269,015	52,934	0.52	12.41	3.88
Conv Slab Cu-Ins	34	37	67	431	254,849	38,377	0.49	11.30	3.53
Conv Slab CPVC	33	36	65	417	246,754	15,032	0.47	10.07	3.15
Conv Slab CPVC-Ins	33	36	65	417	246,754	13,780	0.47	10.03	3.13
Parallel Attic PEX	12	12	24	151	89,047	8,774	0.17	3.77	1.18
Parallel Slab PEX	12	12	24	151	89,047	10,619	0.17	3.84	1.20

Table A-15 House #5 - Monthly Water and Energy Waste (Clustered AM & PM Draw Cycle)

House-5	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu	2	4	64	111	65,661	6,308	0.13	2.77	0.87
Conv Attic Cu Ins	2	4	64	110	64,911	6,130	0.12	2.74	0.85
Conv Attic CPVC	2	4	62	108	63,937	3,358	0.12	2.59	0.81
Conv Attic CPVC Ins	2	4	61	107	63,562	3,285	0.12	2.57	0.80
Conv CS Cu	2	18	67	224	132,671	12,674	0.25	5.60	1.75
Conv CS Cu Ins	2	4	67	115	68,210	7,262	0.13	2.91	0.91
Conv CS CPVC	2	17	64	216	127,574	6,653	0.25	5.16	1.61
Conv CS CPVC Ins	2	4	64	111	65,736	3,898	0.13	2.68	0.84
Conv Slab Cu	30	37	70	408	241,282	41,483	0.46	10.90	3.40
Conv Slab Cu Ins	2	4	66	115	67,835	9,595	0.13	2.98	0.93
Conv Slab CPVC	26	34	65	376	222,393	13,375	0.43	9.07	2.83
Conv Slab CPVC Ins	2	4	64	111	65,736	3,959	0.13	2.68	0.84
Parallel Attic PEX	2	12	24	104	61,688	7,080	0.12	2.65	0.83
Parallel Slab PEX	9	12	24	137	80,802	10,092	0.16	3.50	1.09

Representative Housing Results - Existing Housing

House #6 – Single Family, Three Bedroom, Two Bath, One Story, 1100 ft^2
This unit represents a modestly sized existing single story house. The laundry is located in the garage. There is one bath with a tub/shower along with a lavatory. A second bath contains a shower stall and lavatory. The compact kitchen includes a sink, but has no provision for a dishwasher. The water heater is in the garage. The house layout is fairly compact and keeps hot water consuming devices in the same general area of the house.

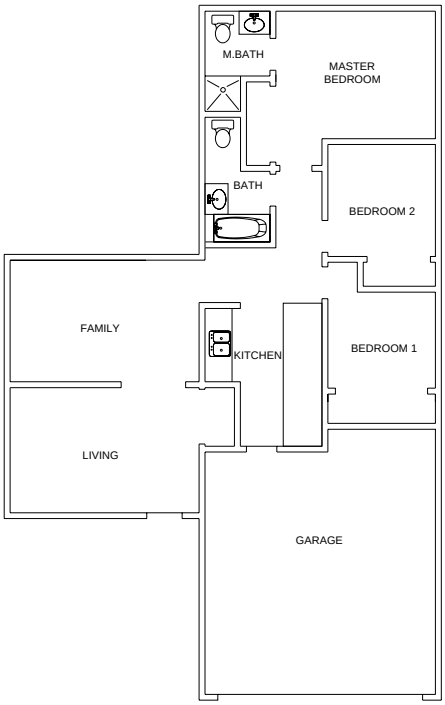

Figure A-10 House #6 – Floor Plan

Table A-16 Construction Costs for House #6

Scenario	Cost
Conventional, Copper, attic or crawl space, uninsulated	$1023
Conventional, Copper, attic or crawl space, insulated	$1217
Conventional, CPVC, attic or crawl space, uninsulated	$702
Conventional, CPVC, attic or crawl space, insulated	$896
Conventional with Demand Recirculation, Copper, attic or crawl space, uninsulated	$694*
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	$944

* Demand recirculation system reuses existing piping system and includes pump and controls only.

Note: Actual existing housing costs will vary upwards from those shown because of differing field circumstances, the plumbing contractors' view of potential uncertainties, and the need to involve other crafts to open and restore walls to provide access for the plumbers to work. The costs shown above are best viewed a probable minimum costs.

Table A-17 House #6 - Monthly Water and Energy Waste (Cold Start Draw Cycle)

House-6	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu	22	59	78	594	351,467	33,458	0.68	14.82	4.63
Conv Attic Cu Ins	22	59	78	594	351,467	34,139	0.68	14.85	4.64
Conv Attic CPVC	21	56	76	570	337,000	16,855	0.65	13.62	4.25
Conv Attic CPVC Ins	21	56	76	570	337,000	16,987	0.65	13.62	4.25
Conv CS Cu	22	60	80	603	356,713	38,644	0.69	15.22	4.75
Conv CS CPVC	21	57	77	577	341,423	18,590	0.66	13.85	4.33
Conv CS Cu Ins	22	60	80	603	356,713	37,939	0.69	15.20	4.75
Conv CS CPVC Ins	21	57	77	577	341,423	18,564	0.66	13.85	4.33
Demand Recir Attic Cu	2	3	5	47	27,734	55,293	0.05	3.22	1.01
Demand Recir CS Cu	2	3	5	47	27,734	62,107	0.05	3.49	1.09
Parallel Attic PEX	11	25	33	250	147,962	17,181	0.28	6.36	1.99
Parallel CS PEX	11	25	34	251	148,337	17,459	0.28	6.38	1.99

Table A-18 House #6 - Monthly Water and Energy Waste (Clustered AM & PM Draw Cycle)

House-6	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv Attic Cu	2	4	76	150	88,522	8,856	0.17	3.75	1.17
Conv Attic Cu Ins	2	4	75	149	88,148	8,678	0.17	3.73	1.16
Conv Attic CPVC	2	4	74	149	88,223	4,722	0.17	3.58	1.12
Conv Attic CPVC Ins	2	4	74	148	87,548	4,678	0.17	3.55	1.11
Conv CS Cu	2	18	79	296	175,171	15,121	0.34	7.33	2.29
Conv CS Cu Ins	2	4	79	155	91,446	9,642	0.18	3.89	1.22
Conv CS CPVC	2	12	77	259	153,284	8,112	0.29	6.21	1.94
Conv CS CPVC Ins	2	4	77	157	92,570	5,211	0.18	3.76	1.18
Demand Recir Attic Cu *	2	2	5	37	21,962	6,155	0.04	1.08	0.34
Demand Recir CS Cu *	2	2	5	37	21,962	11,590	0.04	1.30	0.41
Parallel Attic PEX	2	9	30	151	89,197	11,814	0.17	3.89	1.22
Parallel CS PEX	7	18	30	213	126,075	14,570	0.24	5.42	1.69

NOTES: * Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

House #7 – Single Family, Four Bedroom, 2½ Bath, Two Story, 1960 ft^2
This unit represents a moderately sized existing two-story house. The laundry is located in the garage. There is a ½ bath with a lavatory, and a modestly sized kitchen with sink and dishwasher on the first floor. A second bath containing a tub/shower and lavatory, and a third bath with a shower stall and lavatory is located on the second floor. The water heater is in the garage. The layout is fairly compact and keeps hot water consuming devices in the same general area of the house.

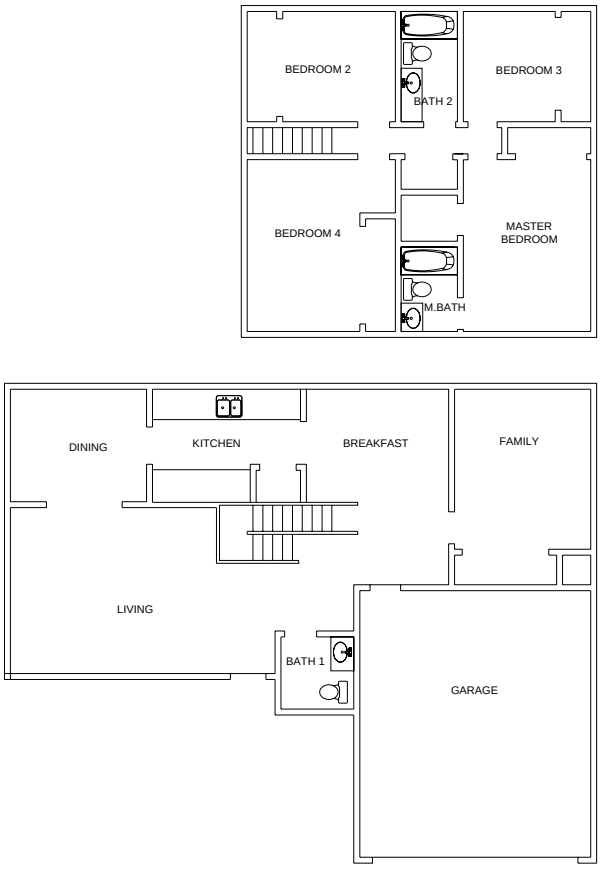

Figure A-11 House #7 – Floor Plan (first floor below, second floor above)

Table A-19 Construction Costs for House #7

Scenario	Cost
Conventional, Copper, attic or crawl space, uninsulated	$1402
Conventional, Copper, attic or crawl space, insulated	$1709
Conventional, CPVC, attic or crawl space, uninsulated	$949
Conventional, CPVC, attic or crawl space, insulated	$1256
Conventional with Demand Recirculation, Copper, attic or crawl space, uninsulated	$694*
Parallel Pipe/Manifold System, PEX tubing, attic or crawl space, uninsulated	$1157

* Demand recirculation system reuses existing piping system and includes pump and controls only.

Note: Actual existing housing costs will vary upwards from those shown because of differing field circumstances, the plumbing contractors' view of potential uncertainties, and the need to involve other crafts to open and restore walls to provide access for the plumbers to work. The costs shown above are best viewed a probable minimum costs.

Table A-20 House #7 - Monthly Water and Energy Waste (Cold Start Draw Cycle)

House-7	Wait Time for HW (Sec.)			Water Wasted	Energy Loss From (Btu)		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv CS Cu	37	51	73	797	471,096	51,334	0.91	20.12	6.28
Conv CS Cu Ins	37	51	73	797	471,096	50,644	0.91	20.09	6.27
Conv CS CPVC	35	49	69	764	452,057	23,744	0.87	18.31	5.72
Conv CS CPVC Ins	35	49	69	764	452,057	23,735	0.87	18.31	5.72
Conv Interstitial Cu	28	51	58	693	409,782	43,089	0.79	17.44	5.45
Conv Interstitial Cu Ins	28	51	58	693	409,782	43,022	0.79	17.43	5.45
Conv Interstitial CPVC	27	49	55	675	399,138	19,276	0.77	16.10	5.03
Conv Interstitial CPVC Ins	27	49	55	675	399,138	19,300	0.77	16.10	5.03
Demand Recir Interstitial Cu *	4	10	51	260	153,584	47,542	0.30	7.76	2.42
Demand Recir CS Cu *	4	10	51	260	153,584	58,439	0.30	8.19	2.56
Parallel Interstitial PEX	15	29	30	342	202,155	25,445	0.39	8.77	2.74
Parallel CS PEX	15	30	30	346	204,404	25,732	0.39	8.86	2.77

Table A-21 House #7 - Monthly Water and Energy Waste (Clustered AM & PM Draw Cycle)

House-7	Wait Time for HW (Sec.)			Water Wasted	Energy Loss (Btu) From		Water Cost ($)	Energy Cost ($)	
	Min	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe	Wasted Water	Electric	Gas
Conv CS Cu	4	15	70	362	214,298	17,894	0.41	8.94	2.79
Conv CS Cu Ins	2	11	70	239	141,216	13,286	0.27	5.95	1.86
Conv CS CPVC	2	16	67	336	198,932	9,297	0.38	8.01	2.50
Conv CS CPVC Ins	2	11	67	225	133,121	6,446	0.26	5.37	1.68
Conv Interstitial Cu	4	14	54	327	193,685	15,609	0.37	8.06	2.52
Conv Interstitial Cu Ins	2	11	54	218	128,774	11,914	0.25	5.42	1.69
Conv Interstitial CPVC	2	13	53	302	178,544	7,903	0.34	7.17	2.24
Conv Interstitial CPVC Ins	2	11	53	206	122,103	5,619	0.23	4.91	1.53
Demand Recir Interstitial Cu *	2	10	51	198	117,156	20,979	0.23	5.32	1.66
Demand Recir CS Cu *	2	10	51	199	117,530	24,168	0.23	5.46	1.71
Parallel Interstitial PEX	10	22	30	293	173,072	20,243	0.33	7.44	2.33
Parallel CS PEX	11	22	30	296	174,946	20,511	0.34	7.53	2.35

NOTES: * Energy supplied to the demand recirculation system pump is calculated as 2.62 kWh/year or 0.22 kWh/month, which equals approximately $0.02/month. This cost should be added to energy cost figures in the last two columns above to get the total energy cost.

Appendix B. – Sample Questionnaire Given to Plumbing Contractors

California Residential Plumbing Systems

Purpose:

The California Energy Commission (Energy Commission) is sponsoring an evaluation of Residential Hot Water Piping Systems in California by Oak Ridge National Laboratory. This study will investigate the energy and water impact as well as the usage and market penetration of different systems. As part of this study, barriers to the utilization of alternative hot water distribution systems are being identified and methods of addressing these barriers proposed. Your input to this questionnaire will enable the project to identify these barriers from the viewpoint of the key participant in the installation and repair processes - you, the plumbing contractor. It will also assist the Energy Commission in evaluating future codes and standards. Participants will receive a copy of the analysis and summary of this survey.

1. Your Firm

Name of Firm_____ Contact Person_____

Address_____ Phone Number_____

_____ E-Mail_____

New Home Construction: Yes____ No_____ Number of houses per year_____

Existing Homes: Yes____ No_____ Number of service calls per Year_____

Your approximate market-share in local area, if known (%): _____

Would you like your firm to be identified in the final report? Yes____ No_____

2. Rank the importance of each of the following <u>to you</u> as a Plumbing Contractor (1 lowest – 5 highest importance)

_____ a. Low Cost

_____ b. Reliability/Durability

_____ c. Local Code Acceptance/Compliance

_____ d. Energy and Water efficiency

_____ e. Other (please specify) _____

_____

3. Rank your view of the importance of the following <u>to your customers</u> for New Home Construction (1 lowest – 5 highest importance)

_____ a. Initial cost of system affecting the overall home cost

_____ b. Durability/Reliability

_____ c. Adequacy of flow (pressure)

_____ d. Length of time before hot water is available at fixture

_____ e. Conserving water

_____ f. Conserving energy

4. Rank your view of the importance of the following <u>to your customers</u> for Existing Homes (1 lowest – 5 highest importance)

_____ a. Time delay between failure and repair

_____ b. Time to fix the problem too long and have to take time off work

_____ c. Cost of repairs/modifications

_____ d. Durability/Reliability

_____ e. Adequacy of flow (pressure)

_____ f. Conserving water

g. Conserving energy

5. Your current practice for Hot Water Systems in new construction

a. Materials (% used) copper_____ PVC_____ CPVC_____ PEX_____ steel_____

Other _____ (material?) _____

b. Location of pipes (%) attic_____ crawl space ____ floor slab ____ between floors____

c. Recirculating systems usage (% installed) on-demand_____ continuous_____

d. Pipe insulation (0 – 100% of installed piping insulated) _____

e. Water heater location (%) garage ____ laundry room ____ utility closet ____ other____

f. Water heater type usage (% installed) ____ gas with storage tank

___ gas instantaneous (no tank) like Rinnia or Takagi ___electric resistance with storage tank

___ heat-pump with storage tank ___ point of use heaters (electric) like EemaX

6. Your familiarity with, and use of, Alternative Hot Water Systems

a. Are you familiar with the following alternative systems (circle yes or no):

- Recirculating systems: On-demand like Metlund D'MAND - yes/no, or
  Continuous full time or time/temp activated - yes/no
- Parallel pipe manifold systems (single dead-end hot lines to fixture from water heater) - yes/no
- Point of use heating (like EemaX for individual fixtures) - yes/no
- Waste water heat recovery (like GFX) – yes/no

b. How did you learn of these systems (mark all that apply)?

Sales people____ Plumbing catalogs____ Trade shows_____ Other _____

c. Do your customers request them or do you market them to your customers (circle request or market)?

d. Do employees attend training or seminars on the alternative systems? Yes___ No____

e. What are the alternative systems you install (mark all that apply)?

Recirculating systems (on-demand _____ continuous_____)

Parallel pipe manifold systems _____

Point of use heating _____

Waste-water heat recovery _____

f. How often are they installed (% of total installations)? New____ Existing ____

Your view of the barriers to increased use of these alternative systems (mark "X" in box for all that apply)

	Recirculating Systems		Parallel Pipe Manifold Systems	Point of Use Heating	Waste Water Heat Recovery
	On-Demand	Continuous			
a. Cost					
b. Complexity of systems					
c. Customer's interest					
d. Code issues					
e. Plumbers training					
f. Reliability					
g. Ease of repair					
h. Other (describe)					

2-18-2002

Appendix C. – Additional Research Needs

The following discussion of hot water distribution system research needs is the result of collaborative discussions between ORNL (Bob Wendt and John Tomlinson), LBNL (Jim Lutz), Energy Commission (Gary Klein), TVA (John Richardson) and others. These discussions were in response to growing interest among various state and federal agencies, utilities, and research organizations in pursuing this topic and were not directly related to this project.

What we know…
Everyone agrees that water is wasted in waiting for hot water to arrive at a fixture. Moreover, everyone agrees that all of the water that is wasted during the wait left the water storage tank at about the set point temperature of the storage tank. We also know that there is great variability in hot water consumption from one house to another and from day-to-day even when we try to account for numbers of persons, ages, season, etc.

What we do not know…

- How many gallons of water are actually wasted while waiting,
- How much embodied energy is lost in the wasted water, and,
- How much energy was lost by conduction/convection to ambient through the pipe walls.

What we know in these areas is based on the projections from largely un-validated models.

Approach to Understanding:
Our difficulty in understanding these losses is caused by several uncertainties: (1) we do not know in any draw whether "hot" water is wasted or put to good use; (2) we do not know the purpose for each draw (i.e. whether for bathing, hand washing, etc.). We feel that future study of hot water distribution systems needs the following elements if it is to provide useful, quantified information:

1) Develop a comprehensive plan or roadmap to guide multiple research projects, using a thorough review of existing information as a starting point.

2) Develop a data acquisition system to measure hot water consumption and patterns of use. Conduct field monitoring of a number of houses through partners in this Program is a core element of this Program. How water is used (and wasted) in homes can be best determined through measurements. This task is to develop the instrumentation and distributed data acquisition system for hot water flow and temperature characterization in the field. The Data Acquisition System (DAS) ideally should employ wireless remote non-intrusive sensors so that installation into houses can be done quickly and without pipe penetrations. Steps include DAS development followed by production of systems for use in the field.

3) Provide field measurements for a large number of "real-world" houses. Characterize each house by occupant number, ages, types of fixtures and appliances (e.g. showers, washing machines). For each house, measurements of H/C flows, flow duration, timing, and H/C delivery temperatures at each fixture will be done for 2-week periods four times a year using the DAS technology developed in (1). Analyze data by draws to determine type of draw (e.g. bath), total water in draw, mixed temperature in draw, flow of hot water in draw before CW was added for tempering.

4) Complete flow/temperature simulation model to analyze piping systems (started at ORNL).

5) Provide controlled laboratory experiments to determine the essential parameters of hot water distribution systems for use in the simulation model. Perform experiments in the laboratory according to the table below. This represents a large number of runs. Leverage work already done by National Association of Home Builders Research Center for the tree and parallel configurations for 2-story layouts. Take temperature, flow and energy data.

6) Calibrate the hot water distribution system model. From flow/temperature and energy measurements in (item 3, above), calibrate the hot water distribution model developed in (item 4, above) for the different piping networks tested.

Pipe	Diameter	Layouts	Surroundings	Draws	Heater
Copper PEX CPVC	0.375” 0.5” 0.75” 1.0”	Straight Tree Parallel Recirculation	Still air Moving air Dry sand Wet sand Concrete Insulated Uninsulated Range of temperature	Range of flows, durations, quiescent periods, operating pressures	NAECA std. gas or electric Instantaneous gas or electric

7) Use the calibrated model to predict energy and water savings for virtually any piping configuration. Exercise the model through analytic studies over a wide range of piping layouts, distances, water consumption patterns, etc. These studies should include the optimization of the various systems including the conventional trunk and branch system.

8) Analyze the impact of varying occupant behavior on different hot water distribution systems. Perform a behavior analysis to determine how customers change how they use water if hot is readily available at fixture.

9) Develop and implement market useful tools. Produce and package information from the model studies that can be used by industry and water and energy utilities to speed hot water delivery to end-uses while at the same time reducing energy and water consumption. Groups such as the American Society of Plumbing Engineers, NAHB, Heating and Piping Magazine, and other trade associations should become involved with the findings.

Appendix D. - Recommendations for Home Designers

Based on the findings of this report the following recommendations are offered for consideration by home designers. The outcome of using these recommendations may vary from the outcomes identified in this report because of variation in house size, layout, and number of occupants, as well as the occupant water use patterns. All of these factors will impact the total energy and water waste from a particular system. The home designer should also note that the quality and performance of a particular material or system may vary among manufacturers and this could impact other performance factors such as cost and durability.

- Consolidate bathrooms and other hot water consuming activities into the same area(s) of the house to minimize overall system length. This could reduce the initial cost of the system and will reduce energy and water waste.
- Consider centralizing the location of water heater to minimize piping trunk lengths. Shorter piping runs to the fixtures will reduce waiting and energy and water waste. This recommendation is primarily applicable to homes that are intended to use electric water heaters. The costs associated with flues, combustion air, and gas piping required by gas water heaters to discount the other benefits.
- Locate plumbing in attic for single story homes and interstitial space between floors for multi-story homes. These locations minimize the energy loss through the pipe and improve access for repair or modification should that ever be required.
- Do not oversize piping. Use code permitted minimums. Bigger isn't better. Some communities will permit "under sized pipe" if adequate flow and pressure can be demonstrated. For large housing developments, it may be worth the effort to obtain approval for downsized piping. Smaller diameter pipe costs less, and reduces energy and water waste as well as the wait for hot water.
- Consider a demand recirculation system in lieu of a continuous recirculation system where waiting times for hot water will be a problem. Demand recirculation systems cost less, and reduce energy and water waste as well as the wait for hot water.
- Consider CPVC or PEX plastic piping in lieu of copper regardless of system type (conventional, recirculation, or parallel pipe) when appropriate quality and durability can be demonstrated for the products in question. This change will reduce the initial cost of the system as well as reduce energy and water waste.

Appendix E. - Recommendations for Plumbing and General Contractors

Based on the findings of this report, the following recommendations are offered for consideration by plumbing and general contractors. The outcome of using these recommendations may vary from the outcomes identified in this report because of variations in house size, layout, and number of occupants, as well as the occupant water use patterns. All of these factors will impact the total energy and water waste from a particular system. Contractors should also note that the quality and performance of a particular material or system may vary among manufacturers and this could impact other performance factors such as cost and durability.

New Homes

- Do not oversize piping. Use code permitted minimums. Bigger isn't better. Some communities will permit "under sized pipe" if adequate flow and pressure can be demonstrated. For large developments in may be worth the effort to obtain approval for downsized piping. Smaller diameter pipe costs less, and reduce energy and water waste as well as the wait for hot water.
- Layout systems with all hot water pipe runs as short as possible. Shorter pipe runs costs less in material, and reduce energy and water waste as well as the wait for hot water.
- Locate plumbing in attic for single story homes and interstitial space between floors for multi-story homes. These locations minimize the energy loss through the pipe and improve access for repair or modification should that ever be required.
- Use the blown-in attic insulation to insulate piping system. Assure complete coverage of pipe with a minimum of 6" of insulation. Do not add foam plastic pipe insulation if the pipes are covered by blown-in insulation because it adds cost and is of no benefit to the energy and water performance of the system.
- Consider CPVC or PEX plastic piping in lieu of copper regardless of system type (conventional, recirculation, or parallel pipe) when appropriate quality and durability can be demonstrated for the products in question. This change will reduce the initial cost of the system as well as reduce energy and water waste.
- Install a demand recirculation system in lieu of continuous recirculation where waiting times for hot water will be a problem. Demand recirculation systems cost less, and reduce energy and water waste as well as the wait for hot water.

Existing Homes

- Install a demand recirculation pump and controls on existing systems if waiting times are excessive. These provide hot water faster and will provide lower utility costs.
- Replace defective existing systems with CPVC or PEX plastic piping in lieu of copper whenever appropriate quality and durability can be demonstrated for the products in question. These will have lower initial costs and somewhat lower utility costs.
- Consider replacing defective existing systems with a parallel pipe/manifold system using PEX tubing. This will have lower initial costs and potentially somewhat lower utility costs.

Appendix F. - Recommendations for Homeowners

Based on the findings of this report the following recommendations are offered to the homeowner. The outcome of using these recommendations may vary from the outcomes identified in this report because of variations in house size, layout, and number of occupants, as well as the occupant water use patterns. All of these factors will impact the total energy and water waste from a particular system.

New Homes:

- Look for houses that consolidate bathrooms and other hot water consuming activities into the same area(s) of the house. These will typically have lower utility costs and shorter waiting period for hot water to arrive at the fixture.
- Look for centralized location of water heater. This also will typically have lower utility costs and shorter waiting period for hot water to arrive at the fixture.
- Inquire into whether the plumbing is located in the attic for single story homes or in the interstitial space between floors for multi-story homes. These distribution systems also will have lower utility costs and will be easier to access than systems built underneath floor slabs should repair or modification ever be needed.
- Request a demand recirculation system rather than a continuous recirculation system. These will have lower initial costs and much lower utility costs. Both save about the same amount of water.
- Request CPVC or PEX plastic piping in lieu of copper whenever appropriate quality and durability can be demonstrated for the products in question. These will have lower initial costs and somewhat lower utility costs.

Existing Homes

- Consider installing a demand recirculation pump and controls on your existing system if waiting times are excessive. These provide hot water faster and will provide lower utility costs. This approach is most beneficial for large houses (>2500 SF) or houses with very long hot water pipe truck lines (>75ft). Houses with electric water heaters are likely to save enough in utilities to pay back the cost of installation in 10-15 years. Smaller houses and ones with gas water heaters would typically not save enough to pay for the system within the expected life of its equipment.
- Replace defective existing systems with CPVC or PEX plastic piping in lieu of copper whenever appropriate quality and durability can be demonstrated for the products in question. These will have lower initial costs and somewhat lower utility costs.
- Consider replacing defective existing systems with a parallel pipe/manifold system using PEX tubing. This will have lower initial costs and for some distribution system layouts potentially reduce utility costs.

CALIFORNIA
ENERGY
COMMISSION

Rapid Radiant Deployment System Development

Project Final Report

TECHNICAL REPORT

JULY 2005
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Preface

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

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million 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
- Energy Systems Integration

What follows is an attachment to the final report for the Synergistic Water Heating and Distribution Technologies program, Contract Number 400-00-038, conducted by Davis Energy Group. This project contributes to the PIER Building End-Use Energy Efficiency program. This attachment, "Rapid Radiant Deployment System Development: Project Final Report" (Attachment 4), provides supplemental information to the program final report.

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.

DAVIS ENERGY GROUP
INCORPORATED

Rapid Radiant Deployment System Development
Final Report

Issued: **August 23, 2004**

Presented To: **Phil Spartz**
California Energy Commission

Contract: **CEC Contract No. 400-00-038**

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Executive Summary

Project Category

The Rapid Radiant Deployment System (RRDS) project was one of four components of the Synergistic Water Heating and Distribution Technologies (SWHDT) Program. SWHDT, funded by the California Energy Commission Public Interest Energy Research (PIER) Program, focused on identification and development of energy saving water heating and heat delivery technologies for California residences.

Project Abstract/Summary

Hydronic radiant floor (HRF) systems offer comfort and energy efficiency benefits, but at current costs are installed only in custom homes. The key RRDS project goal was to develop a lower-cost HRF system suitable for production homes. In the project Davis Energy Group (DEG) developed and successfully prototyped a system that meets cost targets. The key innovations demonstrated in the project include labor-saving modular prefabricated tubing and steel mesh arrays, standardized floor layouts, and lower-cost manifolds; these strategies are expected to reduce HRF installed costs by at least 50%. The project also evaluated "full system" economics and completed a review of occupant comfort preferences, finding higher satisfaction with radiant heating systems than with forced air. Finally, the project evaluated combining this lower-cost radiant floor system with a ductless two-stage evaporative cooler. The resulting economic studies show that the proposed full-year system should have favorable 3 to 7 year initial paybacks vs. forced air for one-story slab-floor California homes. When mature, these full-year systems could have lower installed costs than forced air systems for both one-and two-story homes. The initial cost savings can combine with energy savings of 50-80% for cooling and 15-30% for heating to create "immediate" paybacks. Additional work is recommended to further test the conclusions of this "proof-of-concept" project.

Project Background and Team

Davis Energy Group has been a leader in the engineering of radiant floor heating systems since 1981. Hydronic radiant floor (HRF) systems offer comfort, energy efficiency, and reduced demand benefits in California residences, but at current costs (~\$8/ft^2 installed) find success only in custom homes. This project was organized to evaluate the prospects for implementing HRF systems in the production home market. IPEX, a leading manufacturer of components and thermoplastic pipe products headquartered in Toronto, Canada, joined DEG as a subcontractor in this effort. IPEX played a key role by providing prototype materials, consulting on design, and estimating retooling costs for a preferred tubing system.

Goals and Objectives

The overall goal of the RRDS project was to evaluate the potential for packaging radiant heating (and cooling) components for cost competitive introduction in the production home market. Major objectives associated with specified tasks were to:

1) assess HRF market barriers,
2) develop an optimized RRDS design and fabrication approach,
3) complete a prototype RRDS project,
4) assess occupant preferences between HRF and forced air systems,
5) project RRDS savings potential and overall economics, and
6) identify an optimal RRDS implementation strategy.

Market Barriers

DEG began the project by reviewing market barriers that currently contribute to excluding HRF systems from production homes. The barrier categories identified include: initial cost, construction practices, and market inertia. Major initial cost constraints include radiant hardware costs, installation costs, and redundancy with forced air cooling systems that currently require ductwork. Construction impediments

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include installation time, the danger of tubing puncture, and communications with an additional specialty contractor. Market inertia barriers include the construction market's general reluctance to adopt new technologies, and the fear of leakage.

The study of these market barriers reinforced the project objectives in seeking time and labor-saving advances, as well as helped to identify strategies that can:

1) better protect the tubing during construction,
2) allow installation by contractors already on site and
3) facilitate combination with energy-efficient ductless cooling technologies.

Optimized Technology

After reviewing market barriers and establishing design requirements, DEG and IPEX generated and compared four alternate configurations for a prefabricated tubing/ substrate product. After consultation with the PAC, the team ultimately selected a preferred concept that pre-assembles a unique serpentine tubing arrangement to flat sheets of reinforcing steel mesh. Since the mesh chosen is identical in pattern to the normal slab reinforcement, the product does not require added time for HRF tubing placement at the job site. DEG evaluated methods for rapidly securing the tubing to the mesh, and selected a preferred approach that reduces required labor by 75% compared to current methods. The team also developed a low-cost in-floor radiant tubing manifold system that fully protects components during construction.

To maximize benefits, DEG developed a design that combines space and water heating with efficient cooling. The "full-year" RRDS design includes the modular floor tubing/reinforcing mesh panels plus tubing manifolds, a "combined hydronic" instantaneous gas water heater, and a two-stage evaporative cooler that directly cools the space and can also cool water at night for circulation through the slab tubing. Tubing/mesh panels can be preassembled off-site (or even on-site using a mobile fabrication facility).

Prototype Project

DEG worked with IPEX of Toronto and Pyramid Construction of Davis to design, fabricate, install, and commission a prototype RRDS on a large custom home. After the manifolds were placed, fourteen mesh/tubing panles were assembled off-site and rapidly placed in the waiting foundation. Pyramid's concrete and plumbing subcontractors completed the work, with DEG guidance. The prototype project confirmed the technical viability of the RRDS concept, as well as the speed and quality benefits of the system. The economies and efficiencies of the prototype installation were praised by the experienced construction management and trades participants.

Occupant Preferences

To evaluate HRF system potential in production homes if market barriers are overcome, DEG completed a "satisfaction analysis" among occupants of both radiant and forced air homes. Questionnaire results show a clear preference for radiant heating. 92% of radiant system respondents said they were "very satisfied" with their heating systems, while 86% of forced air responses were equally divided between "very satisfied" and "somewhat satisfied." 100% of radiant respondents said they would recommend their heating system to a friend, relative or co-worker, compared to 78% for forced air.

Economic Results

To evaluate the performance of the full-year RRDS design, DEG simulated base case and "full-year" RRDS systems in six California climate zones for both one and two-story house designs. We then estimated costs under both "current" and "mature market" scenarios. Mature market economics assume a technology has achieved significant production volume and market share. Results indicate significant energy savings potential for the full-year RRDS design. For heating loads, the water heater operates at higher efficiency than conventional equipment, and minimizes standby losses. Full-year space and water heating savings range from 14-31%. In cooling mode the integrated system will satisfy cooling loads

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with an average EER that exceeds 40. Projected cooling savings range from 47-86%. Under current costing assumptions, the full-year RRDS design is projected to offer favorable homeowner economics in eleven of the twelve cases analyzed. Under the mature market scenario, the RRDS system is viable in all cases. The table below shows "bottom line" annual savings considering mortgage and energy costs for five of the six climate zones.

Results: Annual Net Cash Flow Savings for Homeowner

	Current		Mature Market	
Location	One-story	Two-story	One-story	Two-story
Santa Rosa	$130	$21	$266	$270
El Toro	$69	($47)	$205	$202
Riverside	$205	$88	$341	$337
Sacramento	$184	$76	$320	$325
Fresno	$351	$240	$487	$489

Optimal Implementation Strategy

DEG and IPEX evaluated alternative scenarios for implementing the RRDS system. IPEX estimated that a USD $1,276,000) investment would be needed to start manufacturing the preferred figure-8 tubing. This high cost forced the conclusion that conventional rolled tubing should be used initially, to allow near-term RRDS marketing until the market is proven. Other key implementation conclusions include:

- the tubing/mesh sheets and manifold sets should be assembled off-site to minimize costs and interference at the construction site
- plumbers and concrete crews already on site can easily install the RRDS components
- the RRDS configuration should not be vulnerable to damage from fasteners driven into the floor.

Recommendations

Overall, results of this "proof-of-concept" project indicate favorable prospects for the RRDS system. The recommended next steps toward RRDS commercialization are as follows:

1) **Verify Tubing Depth,** working with subcontractors to form and pour a sample slab, test fasteners and saw the slab at regular intervals to measure tubing depth. Create a video for builders, using parts of tape recorded during this project.

2) **Present RRDS to the HRF Industry**, which can immediately benefit from this new technology. The RRDS prototype video and contractor interviews will be valuable in this effort.

3) **Develop RRDS Hardware Center**, working with component suppliers to develop a pre-packaged heat source/valve/control set that minimizes on-site plumbing time and facilitates meeting "mature market" cost targets.

4) **Implement Prototype Projects**, finding "close-to-home" sites where the RRDS/IDEC ductless combination can be implemented in the near future. Install and monitor the systems and gather occupant input. Three candidate projects are immediately available.

5) **Develop a Production Builder Demonstration Project**, working with a selected builder to implement the RRDS/IDEC combination on 30-40 one-story homes in an appropriate climate. Monitor selected units and comparable control homes; provide technical support as needed to all RRDS/IDEC homes. Monitor for a minimum of one year.

Support from governmental agencies and utilities is needed to further advance the RRDS system. Completion of these recommended activities should render a verdict on the potential of the RRDS/IDEC combination to substantially reduce energy consumption and peak demand in new California homes.

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1.0 Background

The Rapid Radiant Deployment System (RRDS) development project was one of four major components of the Synergistic Water Heating and Distribution Technologies (SWHDT) Program. SWHDT, funded by the California Energy Commission Public Interest Energy Research (PIER) Program, focused on identification and development of energy saving water heating generation and delivery technologies for California residences. The overall goal of the RRDS project is to standardize and package radiant heating (and cooling) components for cost competitive introduction in the production home market.

Hydronic radiant floor (HRF) systems offer comfort and energy efficiency and reduced demand benefits in California residences, but at current costs (~\$8/ft^2 installed) find success only in the custom home market. The RRDS project focused on developing HRF systems for production homes; work was organized to address system requirements and concepts, design, fabrication and packaging, installation, overall economics and mass production prospects. Joining Davis Energy Group (DEG) in this effort as a subcontractor was IPEX, a leading manufacturer of thermoplastic pipe and hydronic components for five decades, headquartered in Toronto, Canada. IPEX played a key role in the project by providing prototype materials, consulting on design issues, and estimating retooling costs for a preferred tubing system.

Research progress reports, produced and published on completion of major subtasks throughout the course of work are listed below and included as attachments to this report.

- Prototype Design Report, DEG, October 25, 2002
- Prototype Fabrication and Installation Report, DEG, July 3, 2003
- Production Readiness Plan, IPEX, July 7, 2003; Attachment 3
- Radiant Versus Forced Air Heating Analysis, DEG, January 5, 2004
- Full-Year Economic Evaluation, DEG, March 23, 2004
- Concepts Summary Report, DEG, March 30, 2004

The rapid radiant deployment system (RRDS) developed in this project should simplify and standardize hydronic radiant floor systems and significantly reduce their installed costs. This RRDS will be suitable for use in pressurized, “open loop” combined hydronic applications that eliminate the furnace needed in forced air systems. In addition, it will facilitate application of off-peak evaporatively-cooled water circulated through the RRDS in concrete slabs to reduce cooling loads that less efficient compressor-based cooling systems now must satisfy. In effect, the system can use the thermal mass of the concrete slab to store cooling output from the evaporative cooler. This stored cooling is slowly delivered to the space, without adding moisture to the indoors, by natural heat transfer processes. We expect that the *reduced installed costs* offered by the RRDS will combine with the improved comfort and reduced energy costs of HRF systems to bring them into volume builder market segments. Thus the RRDS will foster more rapid HRF market penetration and accelerated energy and peak demand benefits for California.

2.0 Objectives

Major objectives of the RRDS project, to be accomplished through completion of design development, prototyping, field installation, production, and economics subtasks included:

- Assess HRF market barriers
- Develop optimized RRDS design and fabrication approaches
- Complete a prototype RRDS project
- Project RRDS cooling savings potential and overall economics
- Assess occupant preferences between HRF and forced air systems
- Identify an optimal RRDS implementation strategy

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Each objective was discussed in regular meetings with a Project Advisory Committee (PAC) and the Energy Commission's Program Manager. See section 3.0, Methodology, for a discussion of work to achieve each of these objectives.

3.0 Methodology

3.1 Identify Market Barriers

Our market barrier assessments could be sorted into categories of costs, construction practices, and market inertia. We evaluated key issues in each category to help shape RRDS designs, as follows:

Radiant Systems Costs. Costs of current HRF systems are currently perceived to be too high for production homes, particularly when a parallel forced air system is additionally required for cooling. We examined the following cost barriers:

- Radiant tubing installation cost
- Mechanical and hydronic components cost
- Forced air space cooling cost combined with radiant

Construction Practices. The concrete, plumbing, and HVAC subcontractors for production homes are generally unfamiliar with HRF systems. We examined the following construction trade barriers:

- Most slabs reinforced with rolled steel mesh that is hard to keep flat
- Slow and labor-intensive process attaching tubing to reinforcing mesh
- Floor plate fasteners for interior walls can penetrate on-site radiant tubing
- Building contractors reluctant to add a specialty subcontractor

Market Inertia. The construction industry is slow to change. We examined the following inertial barriers that seem particularly strong in dissuading production builders from offering radiant floors:

- Fear of radiant tube leakage
- Lack of competition among installation contractors

Characterization and impact assessments of these barriers are presented in Section 4.1.

3.2 RRDS Design Requirements and Options

Constraints and Opportunities for Cost Reductions. HRF cost reduction was the major focus of this project. While many radiant floor marketers have developed hardware subassemblies including pumps, valves, and controls, few have pursued the standardized floor arrays proposed in this project. This subtask focused on cost reduction opportunities in the installed tubing component of HRF systems. We identified opportunities for reducing the time and cost associated with placing the reinforcing steel, since integrating tubing and steel in a single product may reduce steel placement costs and thus partially offset the tubing cost. Based on our research we generated a comprehensive set of design requirements for the rapid radiant deployment system (RRDS), as provided in Section 4.2.

After formulating the design requirements, we generated four design concepts for consideration as prototypes. The design concepts, further discussed in reference 1, drew on various tubing and substrate options, and had differing characteristics as to ease and cost of manufacture and shipping, fabrication requirements, ease of installation, and expected performance characteristics of the installed HRF.

The options included prefabricated RRDS tubing arrays of standardized serpentine patterns and circuit sizes that are not constrained to closely follow the outline of individual rooms or exterior walls. These

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circuits would be deployed in arrangements that span more than one room of the home, transiting from room to room beneath the interior walls. This strategy can reduce both up-front detail design time, and tubing layout time. To the extent that tubing arrays could be prefabricated, and could be quickly laid into the prepared slab area, installation time could be greatly reduced.

Standardized tubing arrays could be considered for mass production and distribution, to be stocked as "off the shelf" commodities. Alternatively, RRDS hydronic radiant floor systems could be made-to-order in kits as is common practice for roof truss systems used in the volume production of residential homes. We also considered the possibility of using on-site mobile fabrication equipment.

Preferred Designs. Specific cost saving design objectives for these production-home HRF systems were as follows:

- **Tubing Arrays**
  - Identify preferred tubing array characteristics.
  - Identify the best options for tubing materials (e.g. diameters, extrusion type, other materials besides PEX).
  - Identify the best options for substrate material.

- **Tube Attachment**
  - Identify the preferred means of attaching tubes to substrate
  - Research tying devices used in other industries to determine if they are useful for attaching radiant tube to substrate.
  - Brainstorm other attachment materials.

- **Tube and/or Substrate Location Means**
  - Determine how best to locate or space the substrate and radiant tube in the slab.
  - Research standard construction products used to support or locate steel reinforcing materials during concrete pours.

- **Manifold Systems**
  - Identify the desirable characteristics of manifold systems to be considered for the RRDS.

- **Assembly Jigs**
  - Identify the options for assembly of the RRDS arrays.
  - Identify the desirable characteristics of an RRDS array assembly jig
  - Design and build a prototype jig

The design concepts and objectives were reviewed with Project Advisory Committee members and other industry professionals for added validation and feedback on RRDS product issues. We solicited subcontractor IPEX for input on tying tools and chairs, and to discuss prototype product manufacturing.

3.3 RRDS Prototype

After developing system concepts, the next project task was to implement a prototype system. We considered two prototype options. The first would have installed a relatively smaller “laboratory” version that would test installability of a few standardized components. The second option was to install RRDS in a custom home to be built in a convenient location. We preferred the second option as one that would provide a more realistic test, as it could provide contractor feedback from a full RRDS installation

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experience, and could also allow occupant feedback over an extended time period. Our strategy was to hold the lab prototype as a fallback option if we could not find a willing owner and contractors with an appropriate new home to be built within the project schedule.

Since we knew a local custom homebuilder with a reputation for quality, and with prior experience with radiant floors, we decided first to see whether they had a current client who might be interested in participating in an RRDS prototype project. Fortunately they did, and we were able to proceed with our preferred prototype option. Section 4.3 summarizes the prototype RRDS project including site selection, design, assembly, installation, commissioning, and contractor feedback. Installation videos were recorded as part of the prototyping task.

3.4 RRDS Cooling Savings & Overall Economics

Full-Year RRDS System. A recent E-Source paper (see Reference 8) shows the benefits of applying radiant floor tubing for cooling as well as heating. Integrating radiant floor systems in production homes presents a similar opportunity, to cost-effectively integrate floor tubing with an efficient cooling system to significantly reduce energy costs and on-peak demand. The accompanying challenge is to achieve installed cost targets while demonstrating performance and reliability that are attractive to both homebuilders and homebuyers.

To maximize the benefit of the RRDS system, we developed a design approach that integrates combined hydronic space and water heating with efficient cooling. The key components of the "full-year" RRDS design are:

- the RRDS floor tubing/manifold system
- a "combined hydronic" instantaneous natural gas water heater
- a two-stage evaporative cooler that directly cools the space and can also chill water at night for circulation through the slab tubing (for example, the new "OASys" unit from the Speakman Company[1], an indirect-direct evaporative cooler, or IDEC system).
- integrated controls

Table 1 summarizes the benefits of the full-year RRDS system.

Table 1: Full-Year RRDS Benefits

	Benefits over Conventional Practice
Cooling	• Efficient two-stage evaporative cooler saves 80-90% of cooling energy • Reduces peak demand by cooling slab at night • Cool slab improves comfort
Heating	• More even heat distribution • Higher efficiency heat source • Reduced indoor temperature stratification • Pump has lower parasitic energy use than a blower
Water Heating	• Higher efficiency heat source • Eliminates storage water heater standby losses

[1] See www.speakmancrs.com

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Performance Simulations. To evaluate the performance of this full-year RRDS design, we simulated base case and RRDS systems in six California climate zones (Table 3[2]) for both one and two-story house designs. We evaluated both a typical 1600 ft^2 single-story "starter" home and a 2,600 ft^2 two-story house with 1,600 ft^2 footprint. Envelope inputs were consistent with current Title-24 requirements (R-15 walls, R-38 ceiling, low-E2 glazing). We used MICROPAS6 hourly building simulation software to project hourly space conditioning loads and base case energy use for the two prototypes in each of six climate zones. For the full-year RRDS system, both the first and second floors were independently modeled to disaggregate cooling loads by floor.

System Comparisons. Table 2 compares the characteristics of conventional production home HVAC and plumbing designs with the full-year RRDS design. We assumed conventional equipment efficiencies to be 78% AFUE and 0.60 EF for heating and water heating, respectively. We also conservatively assumed "tight ducts" in the conventional case. Although not yet mandated by Title 24, tight ducts are becoming increasingly commonplace. Finally, we assumed 12 SEER air conditioning consistent with NAECA's 2006 implementation date for an improved air conditioner standard. These assumptions combine to represent the expected performance of a typical new California production home in 2006.

Table 2: Comparison of System Characteristics

	Conventional Practice	**Full-year RRDS**
Heating	78% AFUE furnace, tight attic ducts	0.82 Energy Factor instantaneous gas water heater coupled with RRDS floor heating system
Water Heating	0.60 Energy Factor storage gas water heater	0.82 Energy Factor instantaneous gas water heater shared with heating system
Cooling	12 SEER split system air conditioner, tight attic ducts	Two-stage ductless evaporative cooler with heat exchanger and RRDS diverter valve

Climates. The six California climate zones selected for this study represent approximately 61% of the current projected new home construction in California (see reference 5). The 0.5% ASHRAE summer design temperatures for the six zones are summarized in Table 3. Climate zone 15 (El Centro) is by far the most extreme cooling climate. High temperatures and a long cooling season translate into significant savings potential, but also a challenging environment for maintaining comfort.

Table 3: Climate Zone Summary

Climate Zone	Location	Summer Design Dry Bulb	Climate Characterization
2	Santa Rosa	96°F	N. CA; coastal/transitional
8	El Toro	89°F	LA area; transitional
10	Riverside	102°F	LA area; inland
12	Sacramento	100°F	Central Valley; hot/inland
13	Fresno	101°F	Central Valley; hot/inland
15	El Centro	111°F	S. CA; inland/very hot; low desert

Full-Year RRDS Performance Assumptions. A well-validated hourly radiant floor model is not yet available. Therefore, we conservatively modeled heating at an equivalent level to that of a standard production builder installation (78% furnace, R4.2 insulated attic ducts with 22% leakage). The only credit taken for the radiant system was a 2°F adjustment in daytime thermostat setpoint[3] to reflect higher

[2] See www.energy.ca.gov/maps/climate_zone_map.html

mean indoor temperatures. The forced air case assumes 68°F heating setpoint from 8 AM to 11 PM, while the radiant case assumes 66°F from 6 AM to 10 PM.

RRDS cooling performance was based on monitoring completed for Southern California Edison on an advanced underfloor cooling system installed in a new house in Palm Desert[4]. This system demonstrated the ability of an outdoor "cooling tower" to deliver evaporatively-cooled water through the floor slab at night, when outdoor wet bulb temperatures are most favorable. Since the tower chills water to within a few degrees of the outdoor wet bulb, night operation very effectively cools the floor slab. Monitored performance of this system showed an average indoor cooling rate of 5,700 Btu/hour per 1000 ft^2 of slab floor area, at an average 40 EER. In the current study, we assumed that the full-year RRDS system pre-cools the slab from 10 PM to 6 AM when the prior day's maximum outdoor temperature exceeded 89°F. Slab pre-cooling reduces the peak and total load the IDEC must meet, allowing the IDEC unit to operate at a lower blower speed to meet mid-day loads.

Energy use for the conventional HVAC systems was taken directly from the MICROPAS results. Projected full-year RRDS performance was based on MICROPAS generated loads. Heating results took credit for slightly more favorable thermostat setpoints and a 4% efficiency improvement (78% for the conventional furnace, 82% for the instantaneous gas unit). Cooling energy use was calculated based on the hourly MICROPAS loads reduced by the floor cooling contribution on days exceeding 89°F. The remaining load was met by IDEC cooling[5]. Floor cooling was delivered at an assumed constant 40 EER.

We calculated annual energy cost savings based on current estimates of $.13 per kWh[6] for electricity and $.91 per therm[7].

System Cost Estimates. We developed HVAC and water heater installed cost estimates for the base case system and the full year RRDS system under current and mature market cost scenarios. Sources of cost information included a major HVAC contractor, contractor pricing for key RRDS components, and Davis Energy Group estimates. We made two key assumptions in costing the RRDS configurations. First, in the current market scenario, we assume that the contractor would bid the full-year RRDS system as if he were familiar with the technology and the associated installation issues. Second, R-10 slab edge insulation (a Title 24 requirement for radiantly heated floors) was assigned a $2 per lineal foot cost to the RRDS package. This is lower than the today's $4-$5 cost, but presumes that only a portion of the cost should be recognized as incremental RRDS cost, since the insulation provides comfort and load reduction benefits throughout the year.

Cost Effectiveness Evaluation. We evaluated economics of the full-year RRDS system in terms of the amortized added costs to the homeowner relative to projected annual operating cost savings. Incremental RRDS costs were amortized over a 30-year term at an assumed fixed 6% interest rate. If projected operating cost savings exceed the added mortgage payment, the economics are favorable for the homeowner. This economic analysis did not evaluate tax implications, escalating utility rates, or maintenance and replacement issues with the RRDS system relative to conventional practice.

3.5 Radiant Versus Forced Air Heating - Occupants Satisfaction Analysis

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[3] based on observed equivalent comfort monitoring results
[4] Davis Energy Group, "Coachella Valley Project Final Report", Southern California Edison, December 29, 1995.
[5] IDEC performance was based on 108% effectiveness and 1551 cfm of supply airflow. Energy use estimates were conservative since they were based on full speed fan operation (0.34 Watts/cfm).
[6] see http://www.energy.ca.gov/electricity/current_electricity_rates.html
[7] based on average PG&E rates over the past two years assuming 50% baseline and 50% excess usage.

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The following summarizes work completed in 2003 to assess satisfaction levels among occupants of homes equipped with either hydronic radiant heating or forced air (FA) heating systems. Assessment goals included acquiring satisfaction feedback from thirty or more members of both target populations.

Sample. In early to mid-2002, we prepared and sent questionnaires designed to assess relative customer satisfaction among the two target populations. We initially sent copies to persons positioned to assist in generating responses from the target populations. These included manufacturing, contracting and heating industry association representatives. Due to very low response rates, materials were sent to these persons on three different occasions over several months with unsatisfactory results. Gradually through the summer we managed to fill our quota for the FA population by resorting to various devices including staff networking efforts, neighborhood canvassing, and installing a display at the Davis City Energy Office. We were still less than halfway to our radiant goal entering the last quarter of the year. Fortunately, "WARM FLOORS", a hydronic heating system installer headquartered in Napa, represented by Mike Luttrell and John Chiarella, agreed to join our cause in early fall. After modifying the questionnaire to a form they felt was more customer-friendly, they succeeded in generating enough responses to put us over our radiant population goal (36 total) by mid-November.

Survey Form. We adapted the original questionnaire forms from a format developed in cooperation with a research group for a satisfaction survey of advanced cooling equipment (AC2) in 1998. The WARM FLOORS version was adapted from our original radiant population questionnaire form for their customers in late 2003.

Analysis. Responses for each population were entered in a spreadsheet to facilitate computing totals by question, and the corresponding value of each response total as a percentage of the respective population totals (36 each).

Results. Survey results are discussed in Section 4.5.

3.6 Preferred RRDS Implementation Strategy

In developing a preferred RRDS implementation strategy, we considered tubing manufacturing, array subassembly, and contractor/trade issues. Regarding the tubing, IPEX, a progressive Canadian manufacturer and distributor of plastic tubing, was a subcontractor to the design team. IPEX's role was to participate in the RRDS design development process and to develop a plan for producing the optimal tubing material, to be determined through the design and prototyping process. Because of the specialized nature of the finished product, unique coil configurations, coiling equipment, handling, and packaging, it would be necessary to segregate this PEX extrusion line from mainstream PEX tubing production lines. Thus, the total capital cost includes an extruder, material handling equipment and a separate curing facility. The plan was to estimate capital investment for a single PEX tubing extrusion line including specialized coiling equipment, and PEX curing facility and packaging requirements for the Rapid Radiant Deployment System (RRDS) product line.

A preliminary analysis was performed on the RRDS figure eight coiler design, concluding that the figure eight coiler can be commercialized and automated. For purposes of projecting capital costs, the cost of typical, automated, on-line coiling equipment was used with an allowance for developmental time and additional hardware needed for specialty PEX tubing coils. The time required to develop and employ this coiling system is included in the overall project time line. Results of IPEX production planning are presented in Section 4.6.

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Regarding array subassembly, we evaluated both off-site and on-site prefabrication of RRDS arrays. We also evaluated means to implement the arrays with minimial danger of leakage, and various work allocations among traditional and specialty residential subcontractors. Results of these evaluations are discussed in more detail in Section 4.6.

4.0 Results

4.1 Market Barriers

Extensive studies of current practices and economics of both HRF and forced air systems were completed to characterize the following market barriers:

Radiant System Costs. The major barrier to radiant heating market penetration is that installed costs are currently substantially higher for radiant floor systems than for forced air systems. In most California residential construction markets, forced-air cooling is "standard" and forced air heating is provided at low incremental cost compared to a cooling-only system. This inefficient but inexpensive forced-air base case presents a significant challenge to the radiant floor industry, whose full cost must be justified based on energy savings and comfort advantages. The three components to radiant system costs are:

- **Radiant Tube Array Cost:** Current installed costs for tubing and manifolds varies from about $1.00 per foot for repetitive systems with ½" tube, up to about $2.50 per foot for complex systems with 5/8" tube. Labor costs for tubing layout, placement and manifolds, plus overhead and profit, range from $25 to $70 per hour. Current tubing placement labor costs to the buyer therefore range from about $600 to $1500 for a 2000 ft^2 house with eight circuits and two manifolds.
- **Mechanical Equipment Cost:** The greatest cost portion of a typical radiant system is often associated with mechanical components including heat source, circulation pumps, heat exchanger, control valves, expansion tank, fluid mixing devices, air eliminators, and pressure balancing valves. These components are typically custom-assembled for each job, sometimes at the job site. <u>The design layout and installation process can be quite labor intensive.</u>
- **Forced Air Space Cooling Cost Combined with Radiant:** The addition of radiant heat to a dwelling that requires forced air cooling is seen as a luxury. Realizing the potential for radiant floor slabs to meet significant portions of the cooling load improves the picture. Evaporatively-cooled water circulated through the floor slab at night can cool the slab to contribute radiant cooling during the day and facilitate downsizing of the forced air and cooling components.

Construction Practices.

- **Tube Attachment to Reinforcing Steel:** The tubing is attached to concrete slab reinforcing steel with wire or plastic ties using a manual process that is slow, tedious, and awkward for the installer. Any RRDS improvement to the tube attachment process will yield significant benefit in terms of labor savings.

- **Interior Wall Floor Plates:** Steel nails driven by explosive charges are commonly used to attach interior wall floor plates to the slab. The steel fasteners present a hazard to radiant slab tubing if the tube is installed under the attachment point of the wall plate and the tubing is punctured, causing a leak in the HRF system.

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- **Contractor Communications:** HRF installation usually adds a specialty subcontractor rather than adding work for the plumber or HVAC subcontractor. Communications and timing are often poor between the radiant contractor and the traditional building team, resulting in unforeseen added costs or delays.

Lack of Awareness – Inertia

- **Fear of Leakage:** HRF leakage is rare, but the fear of leakage may prevent the homeowner from choosing radiant floor heating. Consumer education and pro-actively preventative HRF system design features are needed to remedy this barrier.

- **Lack of Competition:** There are relatively few qualified contractors available to compete for radiant heating work. Limited competition for these specialty contactors contributes to the high industry average cost of radiant systems.

4.2 RRDS Design Requirements and Options

After considering the market barriers described above, the team compiled final design requirements for the rapid radiant deployment system (RRDS), as tabulated in Table 4 which follows:

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Table 4: RRDS Product Requirements

Product Requirement	Engineering Requirements
Reduce design cost for HRF tubing layouts.	Reduce complexity of system, possibly using whole-house arrays rather than room-specific arrays.
	Standardize arrays with predetermined tube circuit lengths.
Reduce layout preparation cost for slab-on-grade HRF tubing.	Reduce or eliminate need to accurately locate interior wall locations prior to tubing installation.
Reduce installation labor cost by 50% for slab-on-grade HRF tube systems	Standardization of radiant tubing into pre-manufactured rectangular arrays with pre-shaped serpentine tube pattern.
	Easy attachment of tubing arrays to concrete steel reinforcement with quick-attach clips or efficient tying tool.
	Reduce the number of tubing attachment points necessary.
	Crosslinked PEX into serpentine shape.
Minimize radiant tube component costs.	Use commodity materials for assemblies.
	Include steel array substrate that serves double purpose as concrete reinforcement.
	Minimize shipping cost using compact, lightweight products for long distance distribution and local or on-site manufacture for heavy products.
Ease of installation	An installation crew of two must easily handle tubing arrays. Total Array weight should not exceed 100 lb.
Durablility	Tubing assemblies must withstand all stresses of shipping, installation, and concrete pour without functional failure.
Tubing arrays can be installed beneath interior walls.	Insure location of tube is at centerline of slab or lower with 2- inch minimum clearance from top of slab.
User friendly	Adequate product documentation.
	Standardized tubing connections.
	Easy to transport and install.
Provide for 3/8"; ½"; and 5/8" radiant tube sizes	Array options possible with tube spacing variations.
Radiant tube circuit lengths conform to industry standard lengths.	Use Radiant Panel Association (RPA) guidelines[8].
Insure structural steel reinforcement is kept at centerline in slab	Spacers, perhaps integral with substrate or tube clips to locate steel.
Code approved installation method and materials	Consider applicable plumbing and mechanical codes
	Use ASTM F876 rated PEX tubing or equivalent.

[8] See guidelines at www.radiantpanelassociation.org/i4a/pages/index.cfm?pageid=115

Design requirements tabulated above were reviewed by the Project Advisory Committee (PAC) to validate assumptions and gain added feedback, before proceeding with specific design work.

4.2.1 RRDS Specialty Materials and Tooling

We relied upon industry feedback, performed additional research and testing, and completed exploratory prototyping to compare various options for fabrication materials, array configurations and specialty tools. Following are discussions of major considerations and descriptions of the selected materials and tools.

Tube Attachment Means. We investigated available radiant industry products used for attaching tube to mesh and rebar. Tying tools used in other industries were also investigated. Current common methods and materials used in the radiant industry include plastic cable ties, wire ties applied with twisting devices, and a variety of molded plastic specialty clips.

To improve upon the current tube attachment technology, we looked for ways to accomplish the attachment of PEX to substrate more rapidly, with less labor cost, and at a reduced material cost per tie.

Two general approaches for tying process improvement became evident through our research:

- Processes that could facilitate efficient manual application of individual ties by a radiant installer.
- Processes that could automate the production of pre-assembled tube-and-substrate arrays.

Automatic Rebar Tying Tools. Our research into automatic rebar tying tools was more productive than that of manual process options, and revealed that there are light-weight hand tools suitable for use in the field or in a production setting. Though not marketed to the radiant heating industry, these tools seem well suited to the task of attaching PEX to mesh. We obtained three different rebar wire tying tools, tested them and found one vendor's product to be sufficiently fast and dependable to select it for use in our prototype fabrication process. The tool's mechanism is also a good candidate for integration into a more sophisticated automated process. The cost of the tool is approximately $2,000, with material use cost presently about 4 cents per tie, depending upon the tie diameter and tension adjustment.

A drawback of using the tool in its current form is the large amount of wire it consumes. Communications with the vendor’s manufacturing engineers indicated that it would be possible to adapt the tool to save at least 50% of the wire reducing cost per tie to $0.02.

We selected the MAX 213 rebar tying tool shown in Figure 3 for use in the fabrication of the RRDS prototype arrays[9]. It provided high quality one-handed wire ties for PEX on mesh at a rate of 1.3 seconds per tie in our testing of the tool.

Figure 1. MAX Rebar Tier

[9] See RB213 rebar tying tool information at http://wis.max-ltd.co.jp/int/na/pshow.php3?productcode=RB92130

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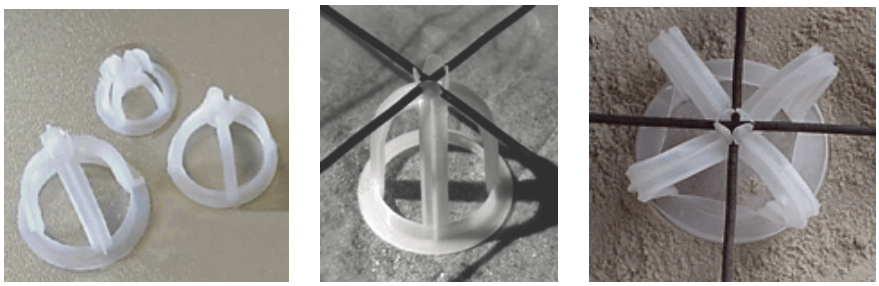
Tube and Mesh Spacers. For optimal thermal performance and protection from shallow penetrations, RRDS tubing arrays should be installed just below the mid-point of the slab's thickness. The installation method should include a support product that suspends the reinforcing steel grid system above the bottom of the slab cavity during the pouring and finishing of the slab. The spacer product must address the need for proper location and support of the mesh when undisturbed, but also have sufficient rebound or spring capacity to return the mesh to its proper place if walked on by installers or cement finishers.

We located a source for flexible plastic products having the desired characteristics. The "Mesh-Up"™ product (Figure 2 below) was specified to support the RRDS prototype arrays during installation and pouring of the prototype slab.

Figure 2. Mesh-ups



Manifold Systems. Simple well-designed systems are needed to bring radiant heating and cooling into the volume builder market. Not all necessary components for reaching this market are available yet but they will be in the near future. Better floor manifold boxes are one of the needs. While some systems use “wall manifolds,” arguments for specifying floor manifolds with slab construction include better protection for tubing and manifolds, shorter tubing runs, and better leak protection.

Figure 3 shows the manifold chosen for use in the RRDS design. The manifold is a modular plastic product lower in cost than comparable brass manifolds distribution systems. The "MINIBLOC"

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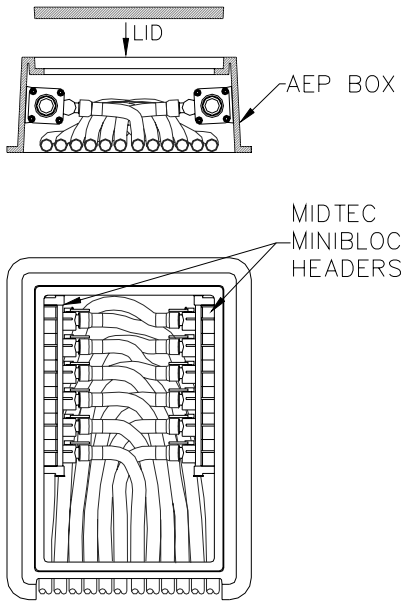
Figure 3.

MidTech MINIBLOCbc headers mounted



headers[10] provide shutoff valves at each header connection to facilitate isolation of individual loops as needed. Materials used in the manufacture of these manifolds are approved by model building codes for use in hot and cold water distribution systems.

Design Conclusions. Conclusions of the Rapid Radiant Deployment System design study are summarized below.

- The number of tubing connections should be minimized by making the circuits as long as possible, within Radiant Panel Association recommendations. For the ½" diameter PEX most commonly used for residential radiant heating, 300' is the maximum recommended circuit length.

- On 7' wide flat mesh panels with a basic serpentine array configuration (see Figure 4), the maximum circuit length defines a maximum panel length of 40'.

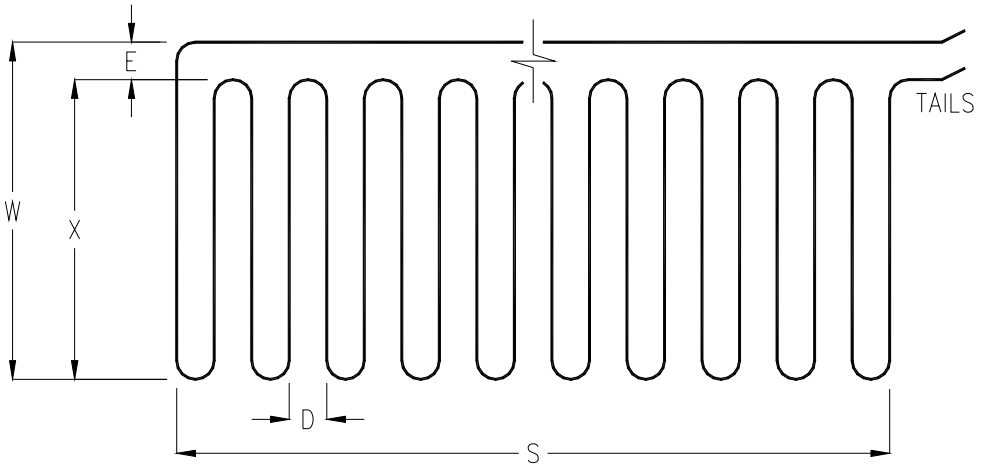
- Both supply and return "tails" should exit the panel at the same end (refer to Figure 4). Tail length is determined on a case-by-case basis depending on distance from the enclosure.

- The 7' by 40' panels should be built such that they can be hinged in the middle for transport. The tubing should be folded inside the mesh to protect it during shipment. These folded arrays are also a reasonable size for the manual movement and placement during installation by two workers.

- Pre-formed "figure 8" IPEX tubing should be used to simplify the layout process.

[10] See ??? – couldn't find anything relating to 'minibloc' on Vanguard's website, though there was lots of manabloc info listed.

Figure 4. Basic Serpentine Array Configuration



Flexible mesh supports are advisable to keep the mesh near the midpoint of the slab during the concrete pour. An improved product would be desirable that is more stable than the "Mesh-ups"™ used in the prototype project. A broader base was added to some of the prototype mesh ups to test an improved version

- Modular plastic manifold assemblies located in boxes that finish flush with the slab surface level should be used where possible. High quality, hinged and weather-stripped wall boxes may also be used but are more expensive and intrusive during post slab construction.

- Collapsible jigs should be used to construct the panels offsite or onsite depending on conditions. Panels built offsite can then be transported to the jobsite just before the pour and stacked in order of placement.

4.3 Prototype Installation

4.3.1 Site selection. To identify potential sites for installation of the prototype RRDS system, Davis Energy Group contacted Mark Rutheiser, Pyramid Construction manager and a member of the RRDS PAC. Pyramid Construction builds custom homes in the Davis area. Mark suggested a site in Davis as a good candidate; a 5,024 ft^2 new home to be constructed during 2003. The Davis house fit the requirements for the prototype site, and the client was interested in the prototype technology and opportunity. The first floor of the house was approximately 3,321 ft^2 with slab on grade construction. The Davis location was also quite convenient for coordination. Consequently, the house was selected as the RRDS prototype site.

4.3.2 Site-specific design for Davis house. The design of the tubing arrays for the Davis house was influenced by several factors in addition to the layout of the house. Though hydronic radiant floor (HRF) systems typically are zoned room-by-rooms, the RRDS design is optimized for construction and transportation. Figure 5 shows the resulting design of the 15 tubing arrays in the Davis house. See Section 3.2.2 for a description of the panel construction process.

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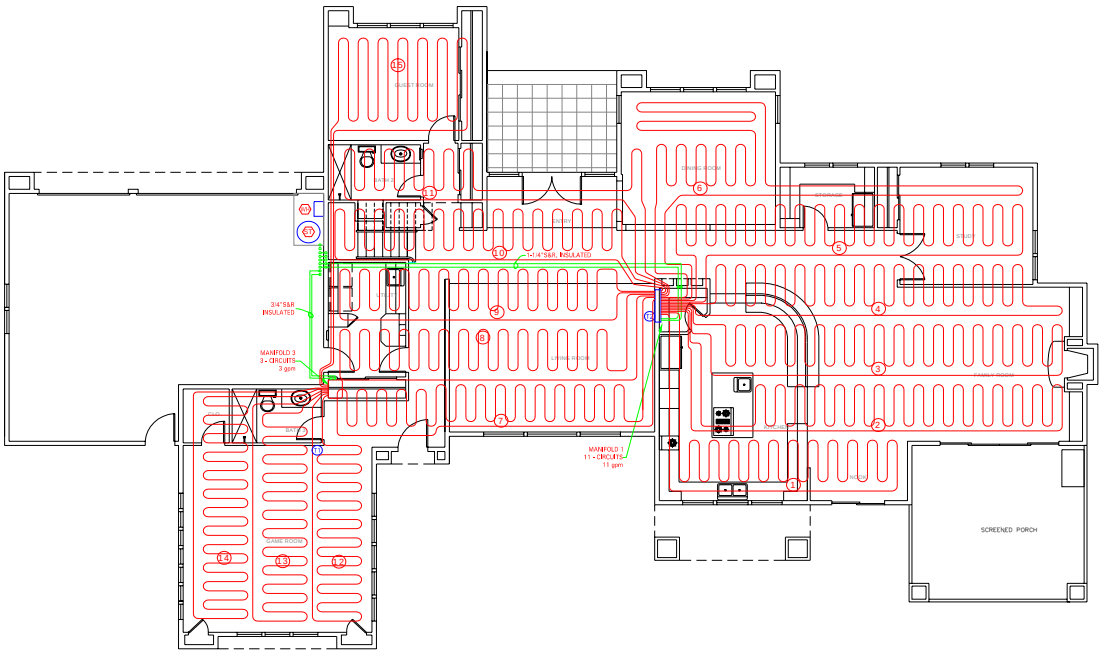
Figure 5. RRDS hydronic tubing layout for Davis house.



4.3.3 Fabrication of Panels for Davis House

The following drawing shows the panels as they were built in the warehouse and transported to the job site. With the exception of panels #6 and #15, all panels were built by hinging two 20' flat sections together, then folding them in half for transportation. Panel #6 was build by adding a third panel, which was also hinged, but along the long side of the original panels (see Figure 6, panel #6). Panel #15 was built on site due to a misunderstanding with the owners as to which rooms were to be radiantly heated.

Figure 6 - RRDS panels designed for Davis house.

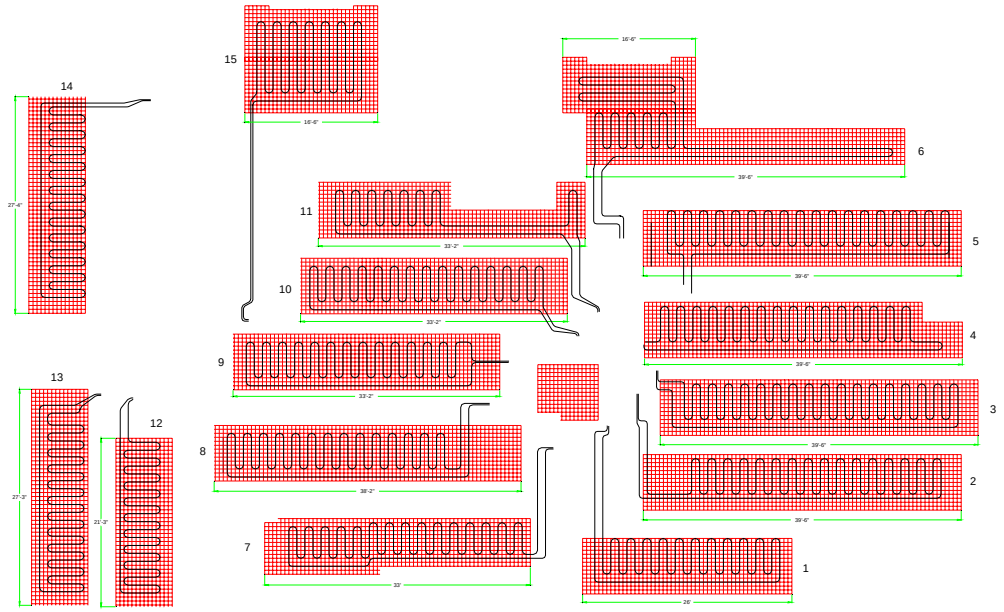


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Figure 7 – Panel Assembly Jigs

Figure 8 – Tubing Tied to Mesh

The construction process was completed as described in the Prototype Design Report, using the wooden assembly jigs (see Figures 7 and 8 above) in conjunction with the MAX Rebar Tier. We hinged the 7' by 20' welded wire mesh sheets to form continuous panels up to 40' long. The panels were folded and labeled for transportation to the jobsite. For a standard panel, it took about 15 minutes for two workers to secure the tubing to the mesh, saving 50% of normal tie labor, even before "learning curve" advances.

4.3.4 Installation

Installation was completed in four steps: panel placement, tubing connections at the manifold boxes, "Mesh-up" placement, and the pouring of the slab. Installation steps are discussed in the following sections:

Panel placement. The panels were pre-stacked in the order that they were to be placed, simplifying the placement process. Each panel was taken from the stack and moved to its position on the slab bed. The panels were first held vertically, then unfolded and laid flat in position with tubing down (Figure 9). Each panel overlapped the adjacent panels by one grid row (6"). An installer then went along this overlap, cutting the wire from the bottom panel and wrapping it around the upper every two feet or so to interlock the panels (Figure 10). The mesh was trimmed to accommodate plumbing and other vertical penetrations that wouldn't fit through the 6" by 6" mesh openings.

Figure 9 – Panel Extended for Placement

Figure 10 – Interlocking Installed Panels

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Manifold connections. The "tails" of each circuit run to one of two manifold boxes (Figure 11 & 12). The tails were routed, trimmed and connected at the manifolds by the plumbing contractor. The system was then pressurized to check for leaks. The pressure was maintained throughout the pour and for two days thereafter to make sure there were no slow leaks.

Figure 11 - Wall Mount Manifold Box

Figure 12 – Floor Mount Bo

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Mesh-ups. The mesh supports were placed the morning of the pour. They were used both with and without solid plastic bases designed to improve stability. A video tape of the installation documents the placement of these mesh supports and their effectiveness with and without the base during the pour. Figure 13 below shows the supports with and without the bases. The supports with bases are in the background, those without are in the foreground. The supports without the flat bases sink into the sand.

Figure 13 – "Mesh-Up" mesh supports with (background) and without (foreground) bases.

Pour. The final phase of the installation process was the slab pour. After the mesh supports were installed and the inspector gave his approval, the pour began. The concrete crew started in the southwest corner that had the stabilized "Mesh Up" mesh supports and it was immediately apparent that the base was successful in keeping them from falling over. However, their ability to "spring" the mesh back up to the right height is related to the density of their placement. Because the concrete crew may have as many as six people finishing the concrete, the mesh can be pressed down and have difficulty rising back up, especially if the mesh supports don't have bases and are pressed down into the sand.

The pour took less than two hours, and was not impeded in any way by the presence of the radiant flooring tubing. The only additional floor penetrations made necessary were the risers for the main (wall) manifold and the floor box for the remote manifolding near the garage. Both of these additions were standard HRF features for the concrete contractor.

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Figure 14 – Concrete pour over stabilized mesh supports.

4.3.5 Commissioning

The plumber monitored the pressure on the circuits to check for leaks. Full commissioning of the radiant heating system was completed after the water heater and controls were installed.

4.3.6 Critique and Revisions

Interviews. We conducted interviews with key members of the construction team to capture their assessment of the RRDS design and installation experience in this case. Interview results were very positive, as outlined below.

We first interviewed Dave Leal, the job foreman from the concrete contractor, JML Concrete Specialties. Dave supervised both the mesh placement and the slab pour. His observations:

- The installation went far faster than any other radiant installation he has completed. It only added an hour to the mesh placement, and reduced the floor tubing installation by days.
- This is a good product.
- A possible improvement could be to construct the panels on-site so that adjustments could be made immediately.
- Having a numerical key (or building them on site) aids greatly in array placement.
- Adding bases to the mesh supports was a great improvement, especially with 6 people walking on the mesh during the pour.
- Using more supports, with bases, might eliminate pulling up the mesh with a hook during the poor.
- The “Mesh-Up” mesh supports could be taller.
- The tails worked well. The lengths were appropriate and the manifold attachments were very easy.

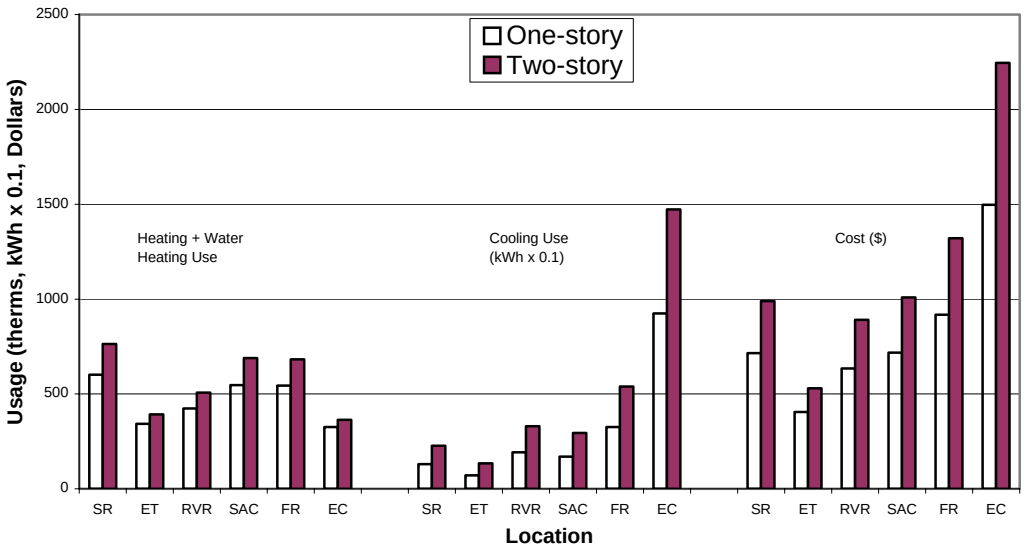
The second interview was with Mark Rutheiser of Pyramid Construction. His observations:

- Adds very little time to the construction schedule compared to the 2 or 3 days a conventional radiant installation would add.
- The benefits of zoning with radiant systems are questionable due to slow response time. The RRDS system, which isn't zoned room-by-room, is not at a disadvantage.
- Both the concrete and the plumbing contractors liked the system and would be happy to work on future projects. Neither had any problems or issues. The concrete subcontractor mentioned that it was very similar to the installation of a non-radiant foundation.
- The installation process after the array installation is comparable to a standard HRF installation.
- He would not use RRDS if it were more expensive than standard HRF.
- No suggestions for improvements.
- The wall manifold was impressive, but he wouldn't expect a homeowner to pay more for it if given the choice between it and the less expensive floor manifold.

4.4 Projected Performance and Energy Savings

Figure 15 summarizes MICROPAS-projected annual base case space and water heating energy use. Combined heating and water heating consumption is fairly constant for the six climates. Cooling ranges more significantly, and approaches 15,000 kWh per year for the El Centro two-story case. Projected operating costs range from about $400 per year to $2200 in El Centro.

Figure 15 - Projected Annual Base Case Space Conditioning and DHW Use

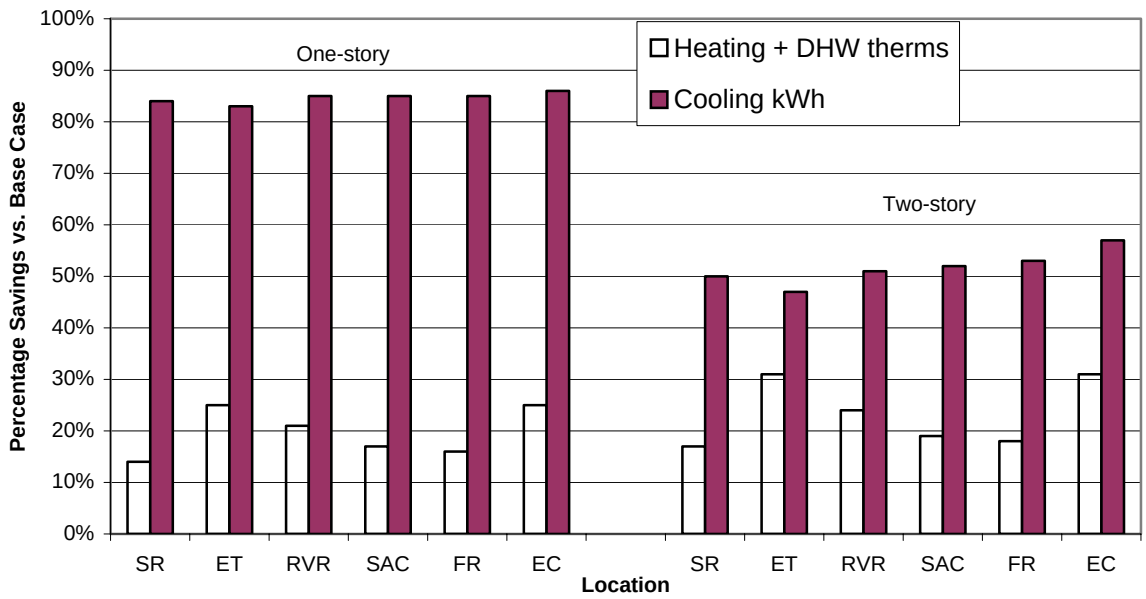


Results indicate significant energy savings potential for the full-year RRDS design. In cooling mode the integrated system will satisfy cooling loads with an average EER that exceeds 40. For heating loads, the tankless gas water heater operates at higher efficiency than conventional equipment, and eliminates standby losses associated with storage gas water heaters.

Figure 16 summarizes projected full-year RRDS energy savings percentages. For the one-story prototype, projected gas savings range from 14-25% of base case consumption and electricity savings exceed 80% in all cases. Projected gas savings are slightly higher (17-31%) for the two-story prototype, especially in the mild El Toro and El Centro winters where second floor heating loads are small.

Projected RRDS two-story cooling energy savings percentages are smaller than for the one-story because second floor cooling loads are met by a vapor compression system. Projected annual cooling energy savings range from 47 to 57%.

Figure 16 - Projected Full-Year RRDS Savings



The full-year RRDS system extends the cooling and comfort range of the IDEC by delivering a significant fraction of the annual cooling load through the floor slab. However, high cooling loads in El Centro present a comfort challenge for the IDEC. Even with the floor cooling benefit, the IDEC was projected to fall short of maintaining daytime cooling setpoints for 133 hours of the year. Multiple IDEC units could be used to enhance comfort through improved zoning and control.

4.4.1 Overall System Economics

Table 5 summarizes incremental costs. In the current cost scenario, we project incremental homebuyer costs ranging from $1,195 to $3,340. The two-story RRDS incremental cost is higher since an additional 2nd floor forced air system is required. Climate zone 15 (El Centro) requires dual HVAC systems in the base case configuration to satisfy cooling loads for the 2,600 ft^2 two-story house[11]. The El Centro RRDS incremental cost is lower than for the other climates since the base case requires multiple HVAC units to satisfy peak cooling loads. Under mature market assumptions, we project negative incremental installed costs for the RRDS systems chiefly due to elimination of forced air components and consolidation of heating and water heating systems. In this scenario, the RRDS manufacturing capability and installation infrastructure are fully developed and compete effectively with current HVAC practice.

[11] with typical Climate Zone 15 sizings of 350-400 ft2 per ton, about 6 to 7 tons would typically be needed.

Table 5: Projected Full-year RRDS Incremental Cost

Scenario	Current Incremental Cost	Mature Market Incremental Cost
One-story	$1,195	($697)
Two-story		
All zones (excluding El Centro)	$3,340	($125)
El Centro	$1,624	($1,841)

Table 6 summarizes annual operating cost savings based on the $0.13 per kWh average electric cost and the $.91 per therm average natural gas cost. Savings increase primarily with the severity of the cooling season, with the highest savings projected for El Centro.

Table 6: Projected Annual Energy Cost Savings

Location	One-story	Two-story
Santa Rosa	$216	$261
El Toro	$155	$193
Riverside	$291	$328
Sacramento	$270	$316
Fresno	$437	$480
El Centro*	$1108	$1192

"*"cooling setpoint exceeded

Table 7 summarizes annual homeowner cash flow based on the projected operating cost savings and the current incremental system cost amortized over 30 years. One-story cases are projected to have favorable economics in all six climates. The two-story cases show less favorable economics due to the higher cost associated with the assumed second floor vapor-compression cooling system. Experience may show that the vapor compression system is not needed in many climates, but a second floor ducted fan coil or "underfloor" radiant system will still be needed for heating. With mature market full-year RRDS costs projected to be lower than conventional practice, projected net annual savings are considerably higher than in the current scenario.

Table 7: Projected Annual Savings

	Current		Mature Market	
Location	One-story	Two-story	One-story	Two-story
Santa Rosa	$130	$21	$266	$270
El Toro	$69	($47)	$205	$202
Riverside	$205	$88	$341	$337
Sacramento	$184	$76	$320	$325
Fresno	$351	$240	$487	$489
El Centro	$1,022*	$952*	$1,158*	$1,324*

"*"cooling setpoint may be exceeded

4.4.2 Conclusions

The full-year RRDS concept integrates a low-cost radiant heating configuration with an efficient indirect-direct evaporative cooler (IDEC), and uses the slab mass for summer cooling as well as winter heating. This strategy effectively increases the capacity of the IDEC unit and maximizes returns on the floor tubing investment. In most one-story applications, the full-year RRDS can eliminate attic ductwork and its associated costs and energy losses.

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4.5 Occupant Satisfaction Results

Key results of the hydronic versus forced air heating comfort and reliability surveys are summarized below. Occupant satisfaction survey details are provided in the subtask Summary Report (Appendix A).

Auxiliary heat incidence. Roughly one third of all respondents indicated the presence of some auxiliary heat source in addition to their primary radiant or forced air systems. With only one or two possible exceptions, they indicated they "seldom" or "rarely" used wood burning fireplaces or stoves.

Longevity. Years of service were totaled for each system population in the left hand columns, and then divided by the number of respondents in each population to derive the average years of service, 9.0 and 12.4 for radiant and forced air respectively, shown in the right-hand columns.

Overall satisfaction. 92% of radiant system respondents said they were "very satisfied" (highest rating) with their heating systems. 86% of forced air responses were equally divided between "very satisfied" and "somewhat satisfied", with 8% saying "somewhat dissatisfied".

Satisfaction factors. "Superior comfort" (97%); "Environmentally friendly", "Clean and quiet" (69%); and "Low operating cost" (50%), were specific satisfaction factors cited by radiant system respondents. "Other (doing what was expected)" was the single satisfaction factor cited by a majority of forced air respondents.

Direct comparison. 97% of radiant respondents said radiant systems are "More comfortable" than forced air, in a head-to-head comparison. Forced air responses were mixed with the largest plurality (19%) conceding forced air by comparison is "Less comfortable" than radiant.

Cost sensitivity. The majority of respondents in both radiant (44%) and forced air (58%) populations said their heating energy bills are "About as expected".

Recommendation worthy. All radiant respondents (100%) said they would recommend their heating system to a friend, relative or co-worker. 78% of forced air respondents were willing to offer an equivalent endorsement for forced air heating.

Service and repairs. 56% of both populations said repairs and service to their systems were easily obtained and effectively performed.

Demographics

The large majority of respondents in both groups (over 70%) were between 35 and 64 years of age.

About 80% of respondents in both groups said 1 to 4 persons lived in the household.

Over 50% of respondents in both groups reported 2001 gross income over $50,000. The largest group overall reported over $100,000.

Most respondents were male, 50% and 61% respectively, in the radiant and force air populations.

Responses from thirty-six participants occupying dwellings equipped with hydronic radiant heating systems evidence a strong preference for, and high degree of satisfaction with, the comfort and

performance of such systems. Such strong preference and high satisfaction levels are not evident from responses of an equal number of participants with forced air furnace systems.

4.6 Optimal Implementation Plan

In developing a preferred RRDS market implementation strategy, we considered manufacturing, subassembly, and subcontractor/trade issues.

4.6.1. Manufacturing. The most expensive manufacturing operation, and major manufacturing opportunity, anticipated for the RRDS product is the coiling of the "figure-8" tubing. IPEX evaluated these costs in their "Production Readiness Plan" (see Attachment 3). The single extrusion line proposed by IPEX would have an annual production capacity of approximately 16,000,000 feet of PEX tubing in a range including 3/8", 1/2", 5/8", 3/4" and 1" pipe sizes. The product mix and annual production volumes were weighted toward the predominant pipe size of 1/2". The RRDS can lend itself not only to single and multi family heating applications but to larger commercial heating jobs as well; hence the inclusion of larger pipe sizes in the capital costing.

IPEX performed a preliminary analysis on the RRDS figure eight coiler design, concluding that the figure eight coiler can be commercialized and automated. IPEX estimated the total capital cost for a RRDS production line to be approximately USD equivalent $1,276,000). This cost includes design, procurement of equipment, installation, commissioning, and product certification. The capital cost is for items necessary for producing the finished product only, and assumes the RRDS production line would be installed in an existing facility. Incremental costs for new building space must be added to the capital cost shown in this plan if existing space is not available for use.

Our review of sub-assembly and installation alternatives indicated that the figure-8 arrays are most valuable in reducing the labor requirements for tubing installed on the floor rather than on vertical subassembly jigs. For the latter, conventional coiled tubing will also be workable when placed in long spiral patterns on the 7' x 20' mesh sheets. This observation is important because there is no need to have figure-8 manufacturing capability in place before pursuing next steps for the RRDS system. Therefore, given the high figure-8 capital outlay, our optimal implementation scenario delays the commitment to manufacture figure-8 tubing until other RRDS features have proven their marketability. For the RRDS manifolds, regional or local subassembly in a shop is preferred. National distribution from a single point of manufacture would substantially increase shipping costs, while offering relatively little value-added.

4.6.2 Sub-Assembly. We considered national, regional, local, and on-site sub-assembly of the mesh/tubing arrays. The regional option would maintain four to six assembly points around the U.S., while the local option means assembly at the nearest metropolitan area where steel mesh would be readily available. After an initial review, we dropped the national and regional options, because they would prevent rapid response to orders, and would incur higher shipping costs than the local (renamed "off-site") and on-site options. We developed a mobile trailer-based assembly concept and evaluated its pros and cons relative to off-site assembly. We concluded that the cost of the trailer system, in conjunction with its set-up and disassembly time steps, space requirement, and greater vulnerability to weather, made on-site subassembly the wrong choice. Manifolds will best be sub-assembled at the same point as the mesh/tubing, to ensure proper coordination between the manifolds and tubing arrays.

4.6.3 Subcontractor/Trade Issues. We considered several issues related to project management and subcontractor jurisdictions that could prove crucial to RRDS implementation. The first and major issue is who should install the various RRDS components, and the second is how to minimize the danger that framing contractors will puncture tubes placed by the tubing/mesh installers. Regarding who should install, we relied on our discussions with the prototype site custom builder, and also conferred with John

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Suppes of Clarum Homes, a relatively small Bay Area production builder. In both cases, the builders would prefer not to add a specialty "radiant floor" subcontractor unless their current subcontractors could not successfully and reliably perform the installation tasks. Our experience with the prototype project strongly suggests that the conventional subcontractors can install the RRDS components. Table 8 below shows how the conventional subcontractors might share responsibilities for the RRDS full-year system. The only unusual assignment is for the concrete crew to connect and pressure test the tubing and manifolds; this approach eliminates the need for the plumbers to make another trip to the site. The task is relatively easy, and helps remind the concrete crew that they are responsible for monitoring pressure during the pour to verify that the tubing has not been punctured.

Since the system involves very little sheet metal work, it might actually be possible for the plumbing subcontractor to install the OASys unit and up-ducts as well as the radiant floor components. However, the HVAC subcontractor often supplies and installs other sheet metal components, so many builders may prefer to continue using an HVAC subcontractor to install the "forced air" components. Union issues might affect the choices in some locations, but in general, production homes in California are built by non-union crews.

Table 8: Preferred RRDS Installation Contractors

Component/task	Subcontractor	Schedule/Coordination
Manifold box	Plumber	with foundation plumbing, before mesh
Mesh/tubing arrays	Concrete	day before pour
Connect & pressure-up	Concrete	day before pour, trained by plumbers
Tankless heater & module	Plumber	plumbing rough-in
OASys cooler, up-ducts	Plumber or HVAC	plumbing rough-in
Startup, commission	Plumber or HVAC	finish stage

One management headache faced by builders is the damage by one subcontractor to completed work by another. Modern radiant floor systems with polymeric tubing have an excellent durability record, but the slab tubing is vulnerable to damage when fasteners for wall framing or carpet strips are driven into the floor from above. Conventional HRF practice runs tubing into rooms under doorways to prevent damage from wall plate fasteners, and assumes that the tubing is deep enough at doorways to limit damage from carpet strip nails. However, this may not always be the case, because conventional rolled reinforcing mesh, to which the tubing is secured, has its "ups and downs" due to difficulties in unrolling. With the tubing secured on top of the mesh, and with water and tube both lighter than concrete, the tubing can sometimes "float" at or near the surface as the concrete pour proceeds. Two other factors contribute to this "tubing too high" possibility. First, the typical 3' spacing between tube-to-mesh tie-downs leaves the tubing able to rise between the ties. Second, during the pour the concrete crew tries to lift the mesh to the middle of the slab using "j-hooks." If they pull it too high, or hook a tube, the tubing is vulnerable.

The RRDS strategy provides better tubing protection by placing it on the underside of flat mesh sheets that are placed on stand-offs, eliminating the j-hook task and risks. While it does place the mesh/tubing sheets under interior wall framing in many cases, the array will always be below the 1-1/2" penetration of standard framing anchors. The 6" x 6" mesh grid pattern prevents the tubing from rising higher although the tubing still is secured at 3' spacing. Future tests are recommended that cut up a demonstration RRDS slab to verify that the tubing is not threatened by framing or carpet installation practices.

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5.0 RRDS Project Conclusions

Conclusions relating to each objective are as follows:

- **Market barriers.** Cost is the major market barrier to hydronic radiant floors (HRF), followed by construction practice impediments and market inertia. Major cost constraints include hardware, installation labor, and the need for ducted forced air cooling systems. Construction impediments include added installation time, the danger of tubing puncture, and management of an additional subcontractor. Market inertia includes the construction market's general reluctance to adopt new technologies, and fear of leakage. The barriers study directed design efforts toward time and labor-saving improvements, as well as strategies that can:

    1) better protect the tubing during construction
    2) allow installation by contractors already on site, and
    3) facilitate combination with energy-efficient ductless cooling technologies.

- **Optimized RRDS design and fabrication approaches.** The system developed in the project that assembles a narrow serpentine tubing pattern to flat sheets of steel mesh reinforcement should provide significant advantages over current HRF practice. The standardized arrays will minimize design time, and the vertical assembly jig facilitates rapid fastening of tubing to mesh using a power tie tool. The pre-fabrication strategy should facilitate faster mesh placement than in conventional non-HRF slab construction. Also, the flat mesh and support stand-offs should result in stronger slabs with reduced danger of tubing puncture from above. The modular in-floor manifolds will reduce costs and eliminate interference associated with current wall manifolds.

- **Prototype Project.** The prototype project confirmed the technical viability of the RRDS concept. Although the installation was completed on a custom home rather than a production home, the process verified the speed and quality benefits of the system. The economies and efficiencies of the prototype installation were praised by the experienced construction management and trades participants.

- **Occupant preferences.** Project research on occupant satisfaction confirmed anecdotal claims that occupants prefer radiant floors over forced air heating. 92% of radiant system respondents said they were "very satisfied" with their heating systems, while 86% of forced air responses were equally divided between "very satisfied" and "somewhat satisfied." 100% of radiant respondents would recommend their heating system to a friend, relative or co-worker, compared to 78% for forced air.

- **RRDS cooling savings potential and overall economics.** Computer modeling and cost studies predict "full-year" RRDS cooling savings ranging from 47% to 86%, RRDS combined space and water heating savings from 14% to 31%, and lower "mature market" installed costs compared to conventional systems. Added value should derive from utility incentives where RRDS causes cooling demand reduction. In mild cooling climates, installed costs may be lower, improving economics where the ductless two-stage evaporative cooler is not coupled to the radiant floor.

- **Implementation Plan.** The USD equivalent ~ $1,276,000) investment needed for manufacturing the preferred figure-8 tubing forces the conclusion that rolled tubing should be used in the RRDS system until the market is proven. This adjustment allows near-term RRDS marketing for conventional HRF applications. Other key implementation conclusions include the following:

    1) the tubing/mesh sheets and manifold sets should be assembled off-site to minimize costs and interference at the construction site
    2) plumbers and concrete crews already on site can easily complete the RRDS installations
    3) the RRDS arrays should not be vulnerable to damage from fasteners driven into the floor.

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6.0 RRDS Project Recommendations

The positive technical results and economic projections from this project underscore the potential benefits of commercializing the full-year RRDS system. The next logical steps on the market path include presentation of the radiant floor components to custom home HRF installers, verifying that tubing will not be punctured by fasteners, further technical development on hardware components that facilitate rapid installation on "balance of-system" elements, initial field projects combining HRF and ductless indirect-direct evaporative cooling, and a subsequent larger field test/demonstration project in cooperation with a production builder. The latter should be designed to produce statistically valid performance, reliability, and customer satisfaction data.

We recommend the following specific activities and timeline for continuing the effort to bring RRDS technology into the residential marketplace. The fourth activity must await the completion of prior tasks.

1) **Verify Tubing Depth:** (1 month) Working with concrete and framing subcontractors, form and pour a 7' by 20' slab with an RRDS array installed on stand-offs. Secure "dummy" floor plates across the 7' dimension at 1' intervals using explosive-charged fasteners. Monitor the tubing for leaks, and subsequently saw the slab at regular intervals to measure tubing depth. Create a video suitable for presentation to builders and to the Radiant Panel Association[12] that verifies tubing safety from fasteners.

2) **Present to the HRF Industry:** (3 months) Present the RRDS system to the existing HRF industry, which can immediately benefit from the reduced costs and increased construction speed of these new floor components. The RRDS videos and contractor interviews will be valuable in this effort.

3) **Develop Hardware Center:** (12 months + certification time) Work with component suppliers to develop a pre-packaged hardware center that includes a tankless water heater, a floor circulation pump, a heat exchanger, automatic valving, and controls to select between heating and cooling mode. This package would minimize on-site plumbing time and facilitate meeting "mature market"cost targets used in the economic analyses.

4) **Implement Prototype Projects:** (24 mos, begin immediately) Find three to five "close-to-home" projects where the RRDS/IDEC ductless combination can be implemented in the near future. Install and monitor the systems and gather occupant input. Available candidates include:
   - Four existing Habitat for Humanity homes in Davis with existing combined-hydronic radiant floor systems. These units currently have no ductwork or cooling systems, and could be readily retrofitted with IDEC units; they would be ideal for verifying simulation results.
   - A 1300 ft^2 City of Davis building now being designed as a swimming club building behind City Hall. The City is receptive to equipping this building with both radiant floor heating and IDEC for cooling.
   - (Less close-to-home) a four-unit demonstration project to be built by Clarum Homes in Borrego Springs, CA. The builder has stated an interest in applying RRDS and floor-coupled IDEC on at least three of these test homes.

5) **Develop a Production Builder Demonstration Project:** (24 months) Work with a selected production builder to implement the RRDS/IDEC combination on 30-40 one-story homes in an appropriate climate. Monitor selected units and comparable control homes; provide technical

[12] RPA; see www.radiantpanelassociation.org)

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support as needed to all RRDS/IDEC homes. Monitor for a minimum of one year. This project would be large enough to resolve outstanding implementation issues, including:

- pricing schedules, promotions, and sales plans
- need for additional safety, quality, and codes certifications
- optimal RRDS packaging/assembly format
- building trades process flow and options

If successful, this larger-scale demonstration project should be fully publicized to enhance market prospects for this high efficiency residential HVAC alternative.

Support from other governmental agencies and electric utilities might be available to further advance the RRDS system and, where cooling systems are commonly installed, the RRDS/IDEC combination. Completion of these four recommended activities should provide further evaluation and ample exposure for judging the potential of the RRDS/IDEC combination to substantially reduce energy consumption and peak demand in new California homes.

7.0 References

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3. IPEX, ***RRDS Production Readiness Plan***, California Energy Commission, July 7, 2003 – Attachment 3

4. Davis Energy Group, ***Radiant Versus Forced Air Heating Analysis***, California Energy Commission, January 5, 2004

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6. Davis Energy Group, ***Rapid Radiant Deployment System Concepts Summary Report,*** March 30, 2004

7. Davis Energy Group, ***Development of an Improved Two-Stage Evaporative Cooling System,*** California Energy Commission, March, 2004, publication # 500-04-016, downloadable at www.energy.ca.gov/pier/building/reports.html

8. Dick Bourne and Ira Krepchin, ***Natural Cooling Systems Make Big Cuts in Energy Use and Demand, Platts/E-Source report ER-02-15, September 2002.***

Appendix A

Radiant Vs Forced Air Heating
Occupants Satisfaction Analysis
Summary Report

Radiant Versus Forced Air Heating
Occupants Satisfaction Analysis

Summary Report

Background. This report summarizes work we completed in 2003 to assess satisfaction levels among occupants of dwellings equipped with hydronic radiant versus forced air (FA) heating systems.

This work was a subtask within the Synergistic Water Heating and Distribution Technologies (SWHDT) Project partially funded by the California Energy Commission under the Public Interest Energy Research (PIER) Program. The results were intended to supplement and support work on Task 3.2 of the Project, Rapid Radiant Deployment System development and demonstration.

Subtask goals included acquiring satisfaction feedback from thirty or more members of both the target populations, radiant and FA system occupants.

Sample. In early to mid-2002, we prepared and sent questionnaires designed to assess relative customer satisfaction among the two target populations. We initially sent copies to persons positioned to assist in generating responses from the target populations. These included manufacturing, contracting and heating industry association representatives. Due to very low response rates, materials were sent to these persons on three different occasions over several months with unsatisfactory results, particularly within the radiant populations.

Gradually through the summer, resorting to various devices including offering a small bounty ($5) per completed questionnaire, DEG staff networking efforts, neighborhood canvassing, and installing a display at the Davis City Energy Office, we managed to fill our quota for the FA population. We were still less than half way to our radiant goal entering the last quarter of the year.

Fortunately, "WARM FLOORS", a hydronic heating system manufacturer headquartered in Napa, represented by Mike Luttrell and John Chiarella, agreed to join our cause in early fall. After modifying the questionnaire to a form they felt was more customer-friendly, they succeeded in generating enough responses to put us over our radiant population goal (36 total) by mid-November.

Sample questionnaires are provided in Attachment A.

Instrument. We adapted the original questionnaire forms from a format developed in cooperation with a research group for a satisfaction survey of advanced cooling equipment (AC2) in 1998. The WARM FLOORS version was adapted from our original radiant population questionnaire form, for their customers in late 2003.

Analysis. Responses for each population were entered in a spreadsheet to facilitate computing totals by question, and the corresponding value of each response total as a percentage of the respective population totals (36 each). Percentage values were not computed for system longevity which is shown in total years and average years of system service, 9.0 and 12.4 for radiant and forced air, respectively.

Results. Detailed spreadsheet tabulations for all respondents in both populations are provided in Attachment B. Response totals and corresponding percentages for both radiant and FA populations are shown in Table 1.

Table 1: Questionnaire Response Summary

No.	Question	Radiant Total	Radiant %	Forced Air Total	Forced Air %
1.	Is your radiant/FA heating system your only heating system?				
	Yes	24	67%	23	64%
	No	12	33%	13	36%
	Other				
2.	How long have you lived with this heating system?				
	Years (round to nearest whole)/Average system life	323	9.0	435	12.4
	Other				
3.	Overall, how satisfied are you with your heating system?				
	Very satisfied	33	92%	15	42%
	Somewhat satisfied	3	8%	16	44%
	Very dissatisfied	0	0%	0	0%
	Somewhat dissatisfied	0	0%	3	8%
	Other	0	0%	0	0%
4.	If satisfied, please explain further why?				
	Low operating cost	18	50%	8	22%
	Superior comfort	35	97%	8	22%
	Environmentally friendly	25	69%	3	8%
	Clean and quiet	25	69%	1	3%
	Other (Doing what was expected)	19	53%	24	67%
5.	If dissatisfied, please explain further why?				
	High operating cost	2	6%	4	11%
	Lack of comfort	1	3%	3	8%
	Not reliable	1	3%	2	6%
	noisy and intrusive	0	0%	2	6%
	Other	1	3%	1	3%
6.	Assuming you have experience with FA and radiant systems, do you believe yours is generally:				
	More comfortable	35	97%	5	14%
	About the same	0	0%	6	17%
	Less comfortable	0	0%	7	19%
	Other	0	0%	0	0%
7.	As a rule, do you feel your energy bills for heating are:				
	Smaller than expected	10	28%	7	19%
	About as expected	16	44%	21	58%
	Larger than expected	0	0%	7	19%
	Other	0	0%	0	0%
8.	Would you recommend your heating system to a friend, relative or coworker?				
	Yes	36	100%	28	78%
	No	0	0%	5	14%
	Other	0	0%	1	3%

Table 1: Questionnaire Response Summary – Cont.

9. Any other comments to share regarding your heating system?				
Good product	12	33%	17	47%
Has potential	3	8%	4	11%
Other	9	25%	2	6%
10. Have you experienced any of the following problems with your heating system? How many times?				
Boiler, heater failure? Fan failure?	5	14%	4	11%
Circulation pipe leaks? Clogged filters	0	0%	4	11%
Pump(s) failure? Duct blast, register noise?	10	28%	5	14%
Control defects, adjustments?	6	17%	7	19%
Temperature variations within zones?	3	8%	11	31%
Excess fuel costs?	0	0%	1	3%
Other?	14	39%	7	19%
Incidence subtotals	38		39	
11. If you needed repairs to your system have services been easily obtained and effective?				
Yes	20	56%	20	56%
No	1	3%	1	3%
Other	9	25%	0	0%
12. What is your age bracket?				
18-24	0	0%	0	0%
25-34	2	6%	3	8%
35-54	12	33%	20	56%
55-64	13	36%	7	19%
65+	6	17%	2	6%
13. How many persons reside in your home				
1-2	22	61%	12	33%
3-4	6	17%	18	50%
5-6	2	6%	2	6%
6+	3	8%	0	0%
14. What was your total income from all sources before taxes in 2001?	0	0%	0	0%
< $20,000	0	0%	0	0%
$20,000 - $35,000	3	8%	1	3%
$35,000 - $50,000	0	0%	3	8%
$50,000 - $75,000	4	11%	3	8%
$75,000 - $100,000	3	8%	4	11%
$100,000+	19	53%	15	42%
15. Gender				
Male	18	50%	22	61%
Female	15	42%	10	28%

Discussion. Observations below are numbered consistently with the questions they address.

Question #	Discussion
1.	Roughly one third of all respondents indicated the presence of some auxiliary heat source in addition to their primary radiant or forced air systems. With only one or two possible exceptions, they indicated they "seldom" or "rarely" used wood burning fireplaces or stoves.
2.	Years of service were totaled for each system population in the left hand columns, and then divided by the number of respondents in each population to derive the average years of service, 9.0 and 12.4 for radiant and forced air respectively, shown in the right-hand columns.
3.	92% of radiant system respondents said they were "very satisfied" (highest rating) with their heating systems. 86% of forced air responses were equally divided between "very satisifed" and "somewhat satisfied", with 8% saying "somewhat dissatisifed".
4.	"Superior comfort" (97%); "Environmentally friendly", "Clean and quiet" (69%); and "Low operating cost" (50%), were specific satisfaction factors cited by radiant system respondents. "Other (doing what was expected)" was the single satisfaction factor cited by a majority of forced air respondents.
5.	The handful of "dissatisfied" responses registered by radiant respondents to this question is difficult to reconcile with nearly unanimous indications of high satisfaction elsewhere throughout the form. The anomaly may reflect misunderstanding or confusion on the part of several radiant respondents. The larger number of negative responses from the forced air population are more consistent with results overall.
6.	97% of radiant respondents said radiant systems are "More comfortable" than forced air, in a head-to-head comparison. Forced air responses were mixed with the largest plurality (19%) conceding forced air by comparison is "Less comfortable" than radiant.
7.	The majority of respondents in both radiant (44%)[1] and forced air (58%) populations said their heating energy bills are "About as expected".
8.	All radiant respondents (100%) said they would recommend their heating system to a friend, relative or co-worker. 78% of forced air respondents were willing to offer an equivalent endorsement for forced air heating.
9.	Less than 70% of both populations responded to this question, and the responses that were registered appear largely inconsistent with results overall. For example, 47% of forced air respondents selected the multiple choice "good product" response describing their systems, while in question #3, 52% of FA respondents said they were only "somewhat satisfied" or "somewhat dissatisfied" with their heating systems. 33% of radiant respondents said "good product" and another 25% registered "other" open-ended responses citing "clean", "quiet" or "superior comfort" radiant characteristics. By comparison in question #3, 100% of radiant respondents indicated satisfaction, 92% saying they were "very satisfied".

[1] Only 72% of the total radiant system population responded to this question.

10. This question solicited somewhat specific information about the nature and incidence of operating "problems" experienced by both populations. The number of incidence reported by both groups, 38 and 39 for radiant and forced air respectively, suggests that reliability is generally high for both systems.

11. 56% of both populations said repairs and service to their systems were easily obtained and effectively performed.

Demographics

12. The large majority of respondents in both groups (over 70%) were between 35 and 64 years of age.

13. About 80% of respondents in both groups said 1 to 4 persons lived in the household.

14. Over 50% of respondents in both groups reported 2001 gross income over $50,000. The largest group overall reported over $100,000.

15. Most respondents were male, 50% and 61% respectively, in the radiant and force air populations.

Conclusion

Responses from thirty-six participants occupying dwellings equipped with hydronic radiant heating systems evidence a strong preference for, and high degree of satisfaction with, the comfort and performance of such systems. Such strong preference and high satisfaction levels are not evident from responses of an equal number of participants with forced air furnace systems.

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