Energy Research and Development Division
FINAL PROJECT REPORT

Residential Water Heating Program

Facilitating the Market Transformation to Higher Efficiency Gas-Fired Water Heating

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PREFACE

The California Energy Commission Energy Research and Development Division 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 Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- Transportation

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ABSTRACT

Water heating is the single most significant residential end use for natural gas in California. Natural gas is used to heat water in nearly 90 percent of homes and represents 49 percent of the average 354 therms of annual household consumption per the 2009 Residential Appliance Saturation Survey. Nearly 90 percent of California's 12.3 million households use natural gas water heaters, with 2,111 million therms consumed yearly overall, according to the Energy Information Administration. An average California household could see its annual natural gas water heating consumption drop 35 percent using an advanced water heater combined with an improved distribution piping system.

This research program has helped facilitate the overall goal of reducing natural gas consumption for residential water heating in California with a broad-based set of closely linked project activities:

- Developing an integrated hot water generation and distribution system analysis tool, efficient water heating equipment and piping system best practices, and a design guide.
- Revisions for water heater standard testing and rating methods and updates to building and energy efficiency codes.
- Laboratory evaluations of water heating equipment and hot water distribution piping.
- Field performance monitoring of water heaters and surveys of consumer behavior and plumber distribution system installation practice.
- Advanced water heating system training for plumbing and other trades.

These findings could help facilitate a 3 to 4 percent reduction in statewide natural gas consumption for residential water heating approaching 86 million therms, along with significant emissions reductions and hot water requirements cumulatively through 2025, based on calculations by the Lawrence Berkeley National Laboratory. However, recent sustained lower natural gas prices, which were not anticipated at the outset of this program, will limit the cost-effectiveness of many of these efficiency improvements and will slow the market transformation process for achieving these consumption reductions.

Keywords: water heating, hot water distribution, models, field tests, lab evaluations, codes, standards, best practices.

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Introduction

Water heating is the single most significant end use for natural gas in the residential sector in California. Natural gas is used to heat water in nearly 90% of households statewide and represents 49% of the average 354 therms of annual household consumption, according to the 2009 Residential Appliance Saturation Survey (RASS). In the previous California Energy Commission (Energy Commission) sponsored Super Efficient Gas Water Heater Appliance Initiative (SEGWHAI), it was reported that “the replacement rate of close to a million units per year in California alone creates the potential to rapidly improve gas storage water heating efficiency … [and] reduce annual gas consumption by 17– 29 percent.” That scoping activity established the need for a broad-based program to follow through on the projects necessary for facilitating a market transformation to higher efficiency water heating and the resulting reduction in natural gas consumption.

Nearly 90 percent of California’s 12.3 million households use natural gas water heaters, with 2,111 million therms consumed yearly overall, according to the Energy Information Administration. An average California household could see its annual natural gas consumption for water heating drop 35 percent with an advanced water heater combined with an improved distribution piping system. The findings from this program could help facilitate a 3 to 4 percent reduction in statewide natural gas consumption for residential water heating approaching 86 million therms, along with significant reductions in emissions and hot water requirements on a cumulative basis through 2025, based on calculations by Lawrence Berkeley National Laboratory (LBNL). However, recent sustained lower natural gas prices, which were not anticipated at the outset of this program, will limit the cost-effectiveness of many of these efficiency improvements and will slow the market transformation process for achieving these consumption reductions.

Project Purpose

The Gas Technology Institute (GTI) proposed and executed this 36-month research program of closely linked projects to help facilitate the overall goal of reducing natural gas consumption for residential water heating in California. Using guidance from the Energy Commission’s Public Interest Energy Research (PIER) Program on appliance research topics, the program met the overall goal with a broad based set of one administrative and five project activities that included:

1. Administering the overall program, as well as meeting and reporting coordination.
2. Developing an integrated hot water generation and distribution system analysis tool, efficient water heating equipment and piping system best practices, and a design guide.
3. Revisions for water heater standard testing and rating methods, and updates to building and energy efficiency codes.
4. Laboratory evaluations of water heating equipment and hot water distribution piping.
5. Field performance monitoring of water heaters and surveys of consumer hot water use behaviors and plumber distribution system installation practices.

6. Advanced water heating system training for the plumbing and other trades.

These project activities were well connected to the marketplace through collaboration by expert researchers with participating manufacturers, utilities, and trades training organizations. This collaboration helped expedite the emerging next generation of higher efficiency gas water heating technologies into wider use in California and the larger U.S. marketplace. The Project Advisory Committee (PAC) formed for this program was indicative of that collaboration with all three major domestic manufacturers – A. O. Smith, Rheem, and Bradford-White – participating along with several foreign-based manufacturers active in the California marketplace. GTI served as the prime contractor for administering the program and the PAC, and oversaw a number of California-based subcontractors performing work on the five projects.

LBNL and Davis Energy Group (DEG) co-led the analytical tool and design guide project, with support from RASNET Solutions. The purpose of this project was to extend the individual model capabilities and integrate them into a first-of-its-kind, whole house water heating system analysis tool using existing water heater and hot water distribution models. DEG led the design guide generation and utilized this integrated system model to conduct an analysis for generating best practices for the design guide. Applied Energy Technology (AET) provided critical expert assistance to LBNL and DEG, leveraging their past involvement with similar water heating development efforts at the Electric Power Research Institute (EPRI).

LBNL and DEG also co-led the standards and codes project. The purpose of this project was to instigate needed revisions to national residential water heating testing and rating standards and provide necessary input for energy efficiency code updates in California. LBNL led the standards work that proposed revisions to test standard method s that would accommodate more representative 24-hour draw profiles, along with more real world indicative performance rating results. These standard efforts were initially channeled through the American Society of Heating, Air-Conditioning, and Refrigerating Engineers (ASHRAE) and its Standard 118.2 Method of Testing for Rating Residential Water Heaters, but ultimately impacted the revision of the Department of Energy (DOE) Energy Conservation Program for Consumer Products: Test Procedure for Water Heaters, commonly known as the Energy Factor (EF) test. DEG led the codes work and applied best practice analysis results into suggested updates for California Code of Regulations Title 24 Energy Efficiency Standards for Residential Buildings with assistance from AET.

GTI led the laboratory testing project, with Pacific Gas & Electric (PG&E) Applied Technology Services (ATS) and AET joining in the testing activities. The goal of this project was validating analysis tools, confirming outcomes of the new method of testing and rating procedures, and examining testing protocols for and results from field studies in this program.The laboratory tests were conducted on tankless and storage water heaters and hot water distribution piping in their respective in-house laboratories.

DEG led the field test and survey project, and teamed with Amaro Construction, Lutzenhiser Associates, and AET for its execution. Evaluations of water heater conversions in homes were completed, from the very limited range of conventional 40 to 50 gallon storage water heaters to a wide range of higher efficiency condensing storage, tankless, and hybrid water heaters that were emerging in the marketplace. The purpose of these field evaluations was to determine energy and hot water usage patterns before and after the higher efficiency upgrades. Surveys of larger groups of homeowners and builders were also completed to understand broader hot water usage behavior among consumers as well as current distribution plumbing practices. Working closely with Southern California Gas (SCG), San Diego Gas & Electric (SDG&E), and PG&E during the field site selection and these broader field survey processes yielded informative demographics on residential water heating markets. This demographic information will better match home hot water draw patterns and user behaviors to advanced water heater alternatives from among the much wider range of emerging versus conventional product offerings, allowing utilities to better tailor their energy efficiency programs to consumers.

Affiliated International Management (AIM) led the outreach project. Outreach was accomplished through utility hosted workshops that disseminated the findings from the preceding program projects, especially the design guide best practices. The workshops were provided by the International Association of Plumbing and Mechanical Officials (IAPMO) and GreenPlumbers® USA, an innovative, non-profit venture based in California that trains plumbers to promote the benefits of energy efficiency and water saving technologies. Working with the participating utilities in this program, AIM, IAPMO, and GreenPlumbers® USA completed a series of nine in-state workshops that targeted the plumbing trades, homebuilding professionals, and code officials.

Project Results

Under the direction of DEG, the following enhancements were successfully completed to their HWSIM software, which analyzes energy and water use and waste in residential hot water distribution systems:

- Radiant Heat Transfer − The 2008 HWSIM version utilized a convective "UA" pipe heat loss model. Integrating radiant heat transfer algorithms to increase accuracy is an important addition to the model.
- Pipe Heat Loss Validation – Extensive runs were conducted comparing simulated pipe heat loss to laboratory results from AET to confirm the validity of the model.
- Multi-Run Capability – The original objective was to develop a parametric solver for comparative runs, however significant developmental tasks associated with the water heater integration effort delayed the development of this capability. Batch-run capabilities were developed as a first step toward meeting this objective.
- Database Result Storage – A database was provided for storing and retrieving discrete results to accommodate the addition of high-fidelity output from the integrated water heater results.
- Usability – Several changes were made to the user interface to make available the parameters necessary to run the specified piping and integrated water heater models, as well as to simplify the operation.
- Updated Documentation – Software documentation was updated in conjunction with the upcoming release of the public domain software.

Several of the noted HWSIM enhancements were necessary preparations for the integration of water heater models into the simulation program. With these preparations in place, DEG and LBNL successfully integrated existing tank (storage) and tankless type water heater models with HWSIM. The integration achieved a first-of-its-kind, whole house water heating system analysis tool capable of simulating interactive hot water generation and distribution and the resulting energy and water use and waste. These new modeling capabilities allowed DEG to develop best practices for a design guide focused on the latest California-specific information for delivering high efficiency hot water systems for single family homes commonly served by individual water heaters.

The integration of HWSIM with existing tank (storage) and tankless type water heater models proved complex, given the different program code vintages and the need for the integrated model to iterate to closure, resulting in excessive simulation times when running the TANK model. Furthermore, existing tank (storage) water heater models only provided an adequate representation of non-condensing equipment. A major limitation of the simple tankless models is that the nuances of the control system (e.g., variable time delays, initial firing sequencing, bypass of the HX) are not explicitly handled. Although sufficient for establishing best practices for the design guide, it was clear that next generation models were needed to simulate the performance of condensing tank (storage) and tankless type water heaters, as well as emerging hybrid products combining a tankless water heater with a buffer storage tank to eliminate tankless only performance drawbacks. In addition, application of modern programming code in these next generation models is needed to overcome the complexities experienced with HWSIM integration of older, existing water heater models and the excessive simulation runtimes encountered in the resulting integration. Under this program, LBNL completed initial models in modern Modelica programming language to create a strong starting point for more advanced models of condensing tank (storage) and tankless type water heaters and hybrid water heaters. These initial models are the first step in another longer-term Energy Commission and DOE funded effort to create modern and easily integrated models of entire water heating systems in buildings.

Water heater standard and code revisions were ongoing over the course of this program and were addressed by many program team members, including LBNL, DEG, AET, and GTI. LBNL's analysis of the DEG field testing results from this program reinforced the long recognized issue that people clearly use hot water differently than assumed in the DOE EF test procedure and that test procedure results consistently do not indicate actual efficiency in the field. Although hot water use is driven primarily by occupant behavior and there is significant variation in hot water use and draw patterns between households, the draw pattern used in the DOE EF test differs significantly from those recorded during field use. The DOE EF test should include a number of shorter, smaller draws at lower flow rates clustered closer together at particular times of the daily profile to better match field performance. After the DOE issued a request for information regarding test procedures for residential water heaters on October 12, 2011, recommendations for a more distributed 24-hour draw profile (and possibly multiple draw profiles of different daily hot water volumes) received strong consideration for use in a revised EF test procedure based on emerging industry consensus.

DEG provided input to the California 2013 Title 24 Energy Efficiency Standards adopted in mid-2012 along with later recommendations for the 2016 revision over the course of this program. Key changes being implemented in 2013 for single family homes include:

- New mandatory requirements for gas (or propane) water heater installations regarding proper electrical outlet, vent category, and condensate drain features to facilitate using high efficiency water heating equipment.
- Pipe insulation is now required on all hot water distribution piping greater than or equal to ¾ inch diameter, as well as all piping from the water heater to the kitchen.
- The Point of Use Distribution multiplier now applies to systems with water heaters no more than 5 feet (of 3/4'″ piping) from any point of use (10′ of ½″, or 15′ of 3/8″ are acceptable alternatives). This measure requires third party Home Energy Rating System (HERS) field verification. Compact distribution system design has been added as a new compliance option credit. To use this approach the furthest use point must be field-verified to be within a prescribed distance from the water heater by a HERS rater.
- Additional optional HERS verification elements have been added to offer credits for verified pipe insulation installation on both recirculating and non-recirculating distribution systems.

Recommendations for further study for the 2016 Title 24 revision for single family homes include:

- Field studies in this program and elsewhere suggested that the 2008 Title 24 derating of 8 percent (0.92 multiplier) is reasonable for non-condensing tankless units, but appears to be too little degradation for condensing tankless units. This should be investigated in more detail to determine the need for derating condensing and non-condensing tankless units differently. This may be unnecessary, however, under the revised DOE EF test procedure that may result in lower EF ratings across the board for tankless water heaters.
- Combined hydronic systems present an attractive option for high efficiency homes because these systems utilize one heat source that provides both space heating and domestic hot water. These systems use the water heater to deliver space heating via a hydronic furnace fan coil, baseboards, radiant floors, or hydronic delivery to distributed fan coil units. It is important to improve how these systems are modeled in Title 24. Activities are underway at ASHRAE (Standard 124) for updating testing and rating methods for combination systems. Developing a standard for combined hydronic system ratings for both heat sources and delivery systems is needed to accurately characterize performance.
- The area of distribution systems is very important for future research. Distribution system performance is very complicated and depends on a wide range of factors. The field surveys of California plumbing layouts completed in this program and earlier suggest that installations are highly variable and to a degree, dependent upon the configuration of the house. The 2013 revisions attempted to move toward an improved design strategy, but resistance from the building industry eliminated one of the proposed components. Educating the building community and the plumbing industry is

vitally important to improving future design and installation practice related to distribution systems. The builder value of improved distribution systems can be significant in terms of reduced cost (less piping), reduced water use, and improved customer satisfaction due to reduced waiting times at remote fixtures. This effect will be magnified with tankless water heaters, where the additional startup time delay compounds any distribution system associated delays. Distribution research in support of Title 24 improvements should include: collecting distribution system performance field data in both new and existing homes; lab testing of alternative distribution system configurations (typical layouts and "improved" layouts) with realistic draw patterns at various use points to explore the impacts of different flow rates, hot water and environment temperatures, usage patterns and quantities, and behaviors; validating advanced distribution modeling tools; and completing a comprehensive modeling study to assess performance of alternative distribution system configurations on different plumbing layouts, with varying usage patterns.

Supporting laboratory tests were completed in this program to:

- Assist in developing a more accurate component models in the integrated hot water generation and distribution simulation program (HWSIM with tank and tankless water heaters) with empirical quantification of heat transfer parameters for selected water heaters.
- Explore performance details of selected water heaters under controlled conditions to help explain phenomena seen in the field evaluations and to help understand feedback from participating homeowners regarding their experiences with advanced storage and tankless water heaters.
- Provide insight into alternative testing procedures (alternative draw profiles, for example) and their impacts on current water heater ratings (Energy Factors – EF) for selected water heaters.

AET generated and analyzed laboratory datasets of hot water distribution piping thermal losses, while GTI and PG&E's ATS lab generated and analyzed laboratory datasets of various performance characteristics of high-efficiency water heaters, with GTI focusing on tankless products and PG&E ATS focusing on tank (storage) products. Key findings from the laboratory testing included:

- Updated heat loss values for both ¾ and ½ inch rigid copper proved more consistent with HWSIM piping thermal loss predictions.
- Bundled versus single ½ inch PEX (high density cross-linked polyethylene) piping heat losses are up to 1.67 times higher due to active hot water pipe heat losses to cooler surrounding pipes.
- Storage water heater EFs are relatively unaffected by more distributed 24-hour hot water draw profiles of comparable daily volumes, but decreased daily volumes will decrease EFs due to an increased share of input energy diverted to standby losses.
- The modest gas savings achieved from transitioning from an unpowered, minimum 0.62 EF to powered, Energy Star rated 0.67 EF storage water heaters when combined with

added parasitic electricity would result in only modest positive, or even negative, net operating cost savings for customers under current energy pricing in California.

- Tankless water heater EFs are lowered when tested under hot water draw profiles with increased numbers of shorter duration draws that are typical of real world operation and increase thermal cycling losses, further supporting the current tankless EF derating assumed in Title 24.
- Compared to tank (storage) water heaters, tankless water heaters exhibit additional time delays to deliver hot water, with cold start firing delays averaging 3 seconds, delays to exiting temperature at setpoint (95 percent of setpoint) up to 20 seconds cumulatively, and delays to stable exiting temperatures (+/- 5 percent of setpoint) averaging up to 36 seconds cumulatively, depending on the control strategy.

The field monitoring activities in this program provided detailed hot water usage data and water heater performance data, but the relatively small sample size (18 sites) and intentional expansive selection of advanced water heaters limited the ability to make broad performance conclusions and observations. Clearly more field data are needed to bolster the findings in this report. Key project findings included:

- Hot Water Demand and Efficiency Implications − The average number of hot water draws was found to be 10 per person per day, ranging from 5 to 18 draws. Hot water consumption averaged 56.4 gallons per day (gpd) over the full monitoring period, or 15.6 gpd per person. Household hot water consumption varied widely across the different sites (from 21 to 138 gpd), with significant day-to-day variations observed at all sites. Despite occupancy levels above the national census average household size, the annual hot water recovery load averaged 27,200 Btu/day, or about one-third less than assumed in the DOE EF test procedure. This was due to warmer cold water inlet temperatures, lower water heater outlet temperatures, and lower overall hot water consumption. The implications of these lower loads are significant for California, with a 0.06 EF reduction (~10% of nominal) in annual performance for a conventional gas storage water heater.
- Water Heater Performance and Economics − All of the advanced water heaters were found to save site energy, with the most dramatic savings occurring with tankless units, primarily due to the low observed recovery loads. Projected annual savings for the EnergyStar™ storage products are under 30 therms per year, non-condensing and condensing tankless product savings range from 45 to 85 therms per year, respectively, and condensing storage product savings range from 30 to 60 therms per year. Projected simple paybacks for new construction are between 9 and 15 years for tankless products and from 13 to 32 years for the storage products based on current, representative California energy prices and in the absence of tax credits and utility incentives. In retrofit scenarios where implementation costs were considerably higher (especially for tankless), none of the projected simple paybacks were found to be less than 25 years. These economic results were discouraging, especially for the retrofit market, and indicated the need for increased production volumes and alternative equipment designs to reduce installed costs. Low California natural gas rates for the foreseeable future and

high electric rates (a second order effect on savings) also contribute to a challenging environment for implementing gas water heater efficiency measures.

- Customer Reactions to Advanced Water Heaters – In general, the participating homeowners who received the advanced water heaters at no cost were satisfied with these units. The only negative concern expressed by some customers who received a storage water heater replacement was related to increased noise due to combustion air blowers. A few tankless customers had similar concerns related to noise, and also generally noted the well-documented issues related to increased hot water wait times, problems satisfying low-flow rate draws, and occasional cold water sandwich concerns. Positive tankless feedback was received from most respondents in terms of hot water capacity, stable delivery temperatures, compact physical size, and perceived energy savings. Tankless water heaters were found to influence hot water usage behavior to some degree. The sites retrofitted with tankless units indicated an increase in average hot water draw volume from 1.40 to 2.09 gallons per draw, which was largely offset by an average 23 percent reduction in the daily number of draws. The net impact was that there was essentially no change in the hot water recovery load between pre- and post-monitoring at four of the six tankless sites, while two of the sites appeared to show higher hot water recovery load after the conversion. Further study is needed to better document this finding.

Recommendations based on these findings included:

- Further study by California utilities is warranted to develop a more robust understanding of performance impacts under different climates and load profiles. This project tested only a sample of the emerging high efficiency products on the market.
- Evaluating customer satisfaction of these emerging technologies is an important step in directing future activities. Careful tracking of maintenance needs and the associated costs is needed to better define the overall economics of the different technologies.
- The Energy Commission and California utilities should stay abreast of emerging water heater technologies. The costs for many of these products should come down in the years ahead as production volumes increase.
- Evaluate combined hydronic systems as a strategy to improve high efficiency water heater cost effectiveness. These systems offer the advantage of utilizing one high efficiency heat source to provide both space and water heating. New product offerings from several manufacturers are expected in the near term.
- Direct future Title 24 field research towards better quantifying hot water loads, cold water inlet temperatures in various locations statewide, and also identifying water heater setpoints at several hundred sites. This data can inform how water heating is modeled within the Title 24 code. The data collected here provided a start on that process.

Amaro Construction surveyed hot water distribution piping installations by 20 different plumbing contractors in 97 new houses under construction, primarily in the greater Sacramento and inland Los Angeles areas dnder the direction of DEG, with these findings:

- PEX has effectively replaced copper piping as the material of choice since the previous 2006 survey, largely due to cost.
- Home run systems linking dedicated water lines to individual fixtures from a single central manifold adjacent to the water heater are much less common than in 2006. Distributed mini-manifold systems are now the predominant system types. This also appears to be driven by cost.
- Average entrained pipe volumes are fairly consistent with a 2006 survey. For a typical 2000 square foot house, the average entrained volume to any hot water use point is close to one gallon of water. There is large room for improvement in this regard.
- Installation issues lead to significant variability in the installed hot water distribution system. There are many instances when a much more direct path could be followed, but for whatever reason, the installer chose not to. The need for training is critical to optimize best practices, and residential plumbing designs should ultimately be required.
- Builders need to recognize that there is value in good design. Good design begins with locating the water heater as centrally as possible as the first step in minimizing hot water distribution energy and water waste.

Lutzenhiser Associates surveyed 146 PG&E employees and 443 SCG customers to develop a more detailed knowledge of residential consumer hot water use under the direction of DEG. The following key findings were derived from the households in both respondent groups:

- Nearly two-thirds let hot water run continuously while washing or rinsing dishes.
- Only around one-quarter of respondents waited for hot water to arrive at bathroom or kitchen sinks (SCG customers were somewhat more likely to wait for hot water in the bathroom than the PG&E group).
- At least one-third of all laundry loads used cold water exclusively, while ~20% of laundry loads used a hot water wash cycle (PG&E 17%, SCG 24%).
- Showering most frequently took between 5-10 minutes (SCG 34%group, PG&E 48%).
- Small percentages of showers lasted "more than 15 minutes." (SCG 14%, PG&E 5%).
- Respondents rarely adjusted or delayed using hot water to avoid running out (SCG 86%, PG&E 78%).
- In the future, households said they were most likely to replace their water heater upon failure (not before) – 85% in both groups.

AIM, assisted by IAPMO and GreenPlumbers® USA, structured and executed a series of nine utility hosted training workshops, three each with PG&E, SCG, and SDG&E, targeted at disseminating the program results to the plumbing trades, homebuilding professionals, and code officials. The full-day workshop relied primarily on a slide presentation intermixed with interactive exercises. Workshop sessions were conducted in two separate time frames, with one workshop each in San Francisco, Ontario, and San Diego in the spring of 2012, and one workshop each in San Ramon, Stockton, Ventura, Downey, San Diego, and Los Angeles in the fall of 2012. Total attendance at the nine workshops was 222, averaging just under 25 per class.

Project Benefits

This research program has helped facilitate the overall goal of reducing natural gas consumption for residential water heating in California. The findings in this report could help facilitate a 3 to 4 percent reduction in statewide natural gas consumption for residential water heating approaching 86 million therms, along with significant emissions reductions and hot water requirements cumulatively through 2025, although lower natural gas prices may limit the cost-effectiveness of many efficiency improvements and could slow the market transformation process for achieving these consumption reductions.

CHAPTER 1: INTRODUCTION

This final report organizes the documentation on the five (5) project activities under this program into the corresponding chapters:

- CHAPTER 2: TOOLS AND GUIDES covers the development of integrated hot water generation and distribution system analysis tool, efficient water heating equipment and piping system best practices, and design guide;
- CHAPTER 3: STANDARDS AND CODES covers revisions for water heater standard method of test and rating, and building and energy efficiency code updates;
- CHAPTER 4: SUPPORTING LABORATORY TESTS covers laboratory evaluations of water heating equipment and hot water distribution piping;
- CHAPTER 5: FIELD TESTS AND SURVEYS covers field performance monitoring of water heaters and consumer behavior surveys; and
- CHAPTER 6: OUTREACH advanced water heating system training for the plumbing trades and others.

These individual chapters are supported by an extensive set of referenced Appendices A through Q which provide additional detailed information.

CHAPTER 2: TOOLS AND GUIDES

Lawrence Berkeley National Laboratory (LBNL) and Davis Energy Group (DEG) co-led the analytical tool and design guide project, with support from RASNET Solutions. Working with their respective existing water heater and hot water distribution models, the purpose of this project was to extend their individual model capabilities and then integrate them into a first-of-its-kind, whole house water heating system analysis tool. DEG led the design guide generation and utilized this integrated system model to conduct analysis for generation of the best practices for that design guide. Applied Energy Technology (AET), involved with similar past water heating development efforts at the Electric Power Research Institute (EPRI), provided critical expert assistance to LBNL and DEG.

2.1 Storage Water Heater Models

These modeling efforts by LBNL are part of a larger effort intending to create a library of water heating models in a manner which can easily leverage the LBNL Buildings library to include water heating in whole building simulations [1]. The buildings library, which is available at http://simulationresearch.lbl.gov/modelica/FrontPage, contains models that can be used to model various aspects of buildings. The available models range from ones modeling specific types of heat transfer to major HVAC equipment that can easily formulate a whole building HVAC system. Combining this model with the building library both makes the modeling effort easier, by allowing use of the buildings library models, and makes it easy to include water heaters in a whole building simulation.

There is an existing multi-nodal atmospheric center flue, storage water heater model, designated TANK which was originally developed by Battelle Columbus Laboratories in 1993 for the Gas Research Institute. However, the integration of HWSIM with this existing tank (storage) water heater model proved complex, given the different programming vintages, and resulted in excessive simulation timeframes. There is also a model for a storage tank water heater available in TRaNsient Systems Simulation (TRNSYS), but it cannot be combined with a distribution system, nor can it easily be included into detailed whole building energy simulations [2]. Creating a new model in Modelica allows easy access to the LBNL buildings library and the hot water distribution system, as well as creating a strong starting point for more advanced models, such as condensing storage and hybrid water heaters in the future [3].

2.1.1 Existing TANK Storage Water Heater Model

A Visual Basic version of TANK was created for later integration with HWSIM, the hot water piping distribution model. This Visual Basic version was based on the earlier spreadsheet version of TANK and uses two input files. One specifies the water heater hardware (tank_hardware.tin) and other the operating conditions (tank_operation.tin). The output files are Tank_out00.txt through Tank_out08.txt. It also provides an echo of the input and a log file.

Because TANK and HWSIM have such different ways of describing hot water draws, it ultimately didn't make sense to follow through with the originally planned common format hot water draw profile file. Instead a file transfer format was developed for exchanging hot water draw profiles and hot water supply temperatures between TANK and HWSIM, and is described later in this chapter.

So in this Visual Basic version, the times, durations, flow rates, and inlet temperatures for draws are specified in tank_operation.tin. The temperature and flow rate of delivered water at time steps throughout the simulation are reported in Tank_out00.txt.This version of TANK can be run either from the command line or by double-clicking on the file in Windows. Both input files have to be in the same directory. It gives the same results (within roundoff errors) as the as the spreadsheet version of TANK. The complied executable files were delivered separately to CEC with this final report.

A very limited comparison between TANK simulation model results and GTI laboratory tests results was conducted to highlight remaining challenges for advanced storage water heater models regarding accurate representation of temperature stratification phenomena.

When water is drawn from a fully charged tank it becomes stratified, with a layer of hot water resting on top of the colder water drawn in from the mains.

During the draw, the water in the lowest regions of the tank is well-mixed. The water temperature drops uniformly with time in that region as cold water pushes into the tank. This can be seen in the temperature traces for minutes 1 and 2 in Figure 1.

When the water at the level of the thermostat cools off enough, the burner begins firing. This happens at minute 2. After this time, when water is being drawn while the burner is on, the rate of the temperature decline in the bottom regions of the tank slows.

When the draw stops, the burner keeps firing to reheat the tank. The time the draw stops, just before minute 4, is when the water in the bottom of the tank is the coolest.

The buoyancy of the water heated by the burner keeps the water below the stratification layer well-mixed. This can be seen from the relatively uniform, but increasing, temperatures below 27 inches from minute 5 until the burner cuts out.

The algorithms in the TANK model do not capture this behavior very well. As can be seen in Figure 2, the TANK model results for a similar draw do not show a sharp boundary at the bottom of the stratification layer or the uniform temperatures below the stratification layer.

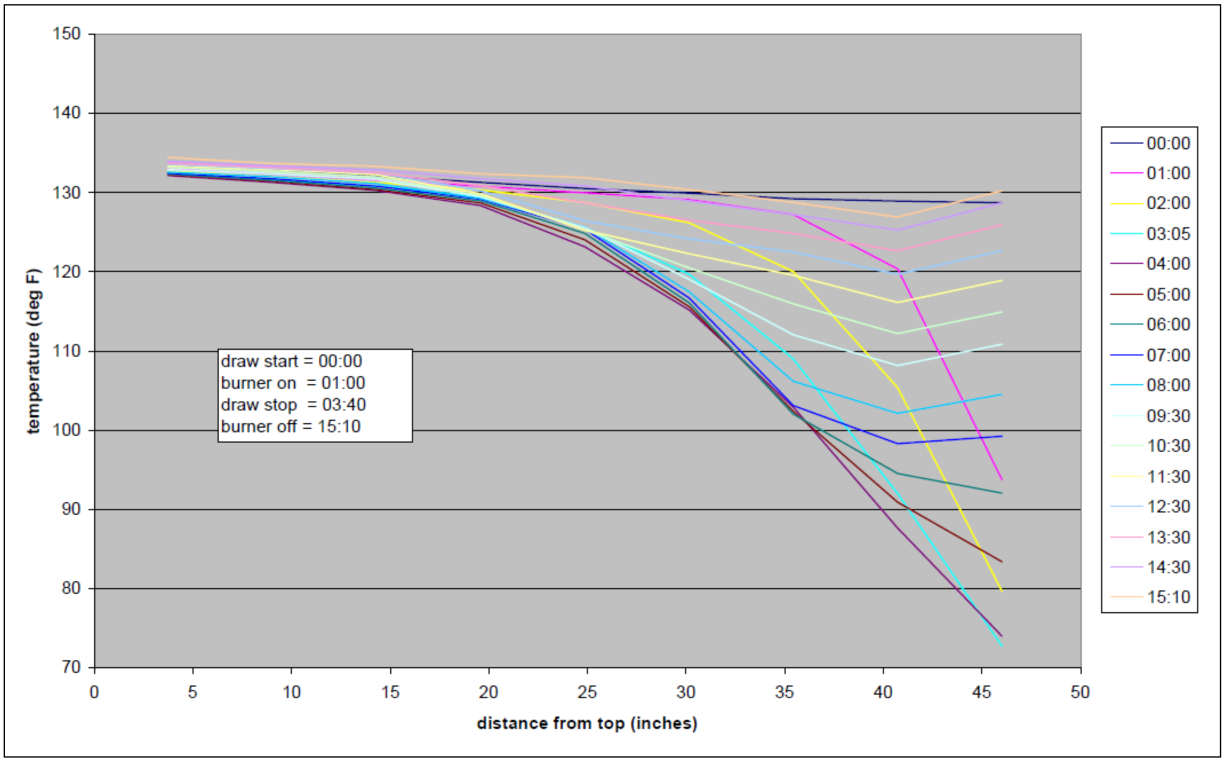

Figure 1: TANK Results
Water Temperature by Distance from Top

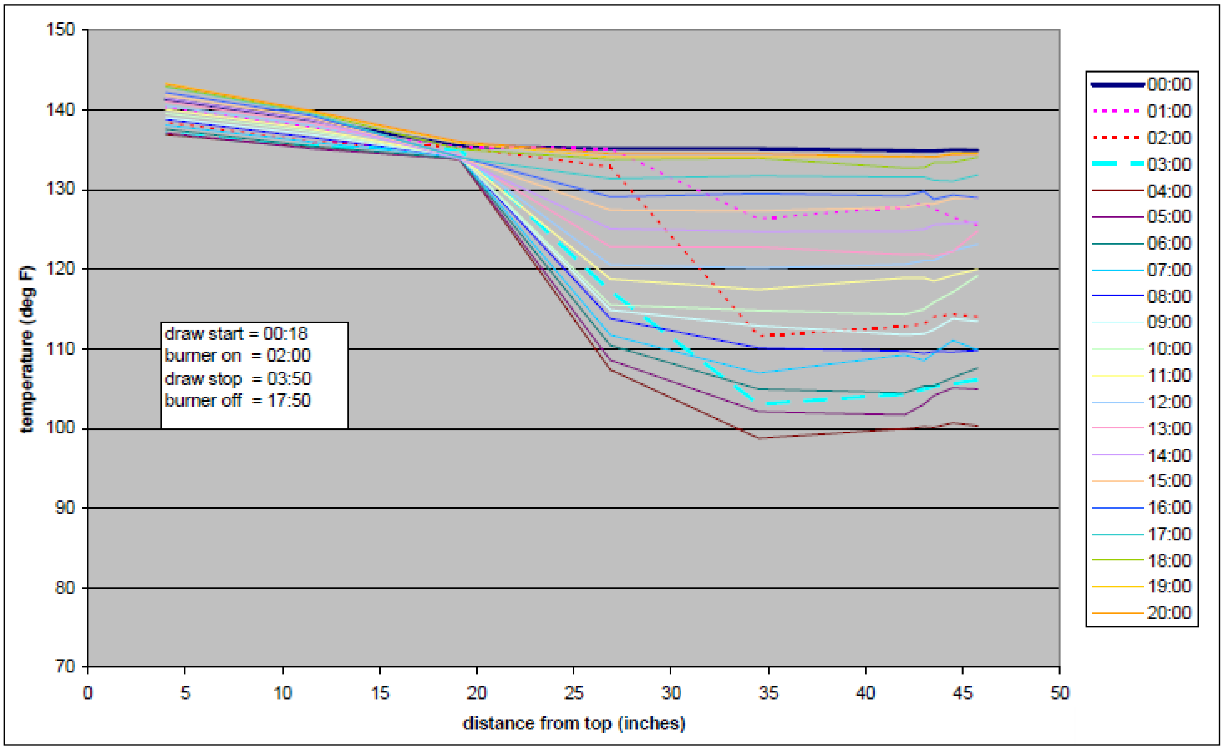

Figure 2: Test Results
Water Temperature by Distance from Top

2.1.2 Advanced Storage Water Heater Model

A series of equations were defined for developing advanced analytical simulation models for a variety of gas water heaters. In order to model the energy and mass flow in any system, global conservation laws must be implemented to derive the general equations. Conservation analysis begins with control volumes. The equations to be used in simple water heater simulation models for storage (tank) water heaters are described in this proceeding section, and in a later section for tankless water heaters.

2.1.2.1 Tank-Type

In the particular case of a tank-type water heater, mass conservation, also known as continuity, and energy conservation will be implemented to characterize the transient behavior of a water heater. The heated water directly adjacent to the flue will create a boundary layer of rising water due to buoyancy effects. For this system, annular control volumes will be used to balance the water recirculation movements along the central flue and the outer wall in addition to balancing the energy transfer through the flue, boundary layer, bulk water, and outer wall. The diagram below depicts one half of the annular control volume k.

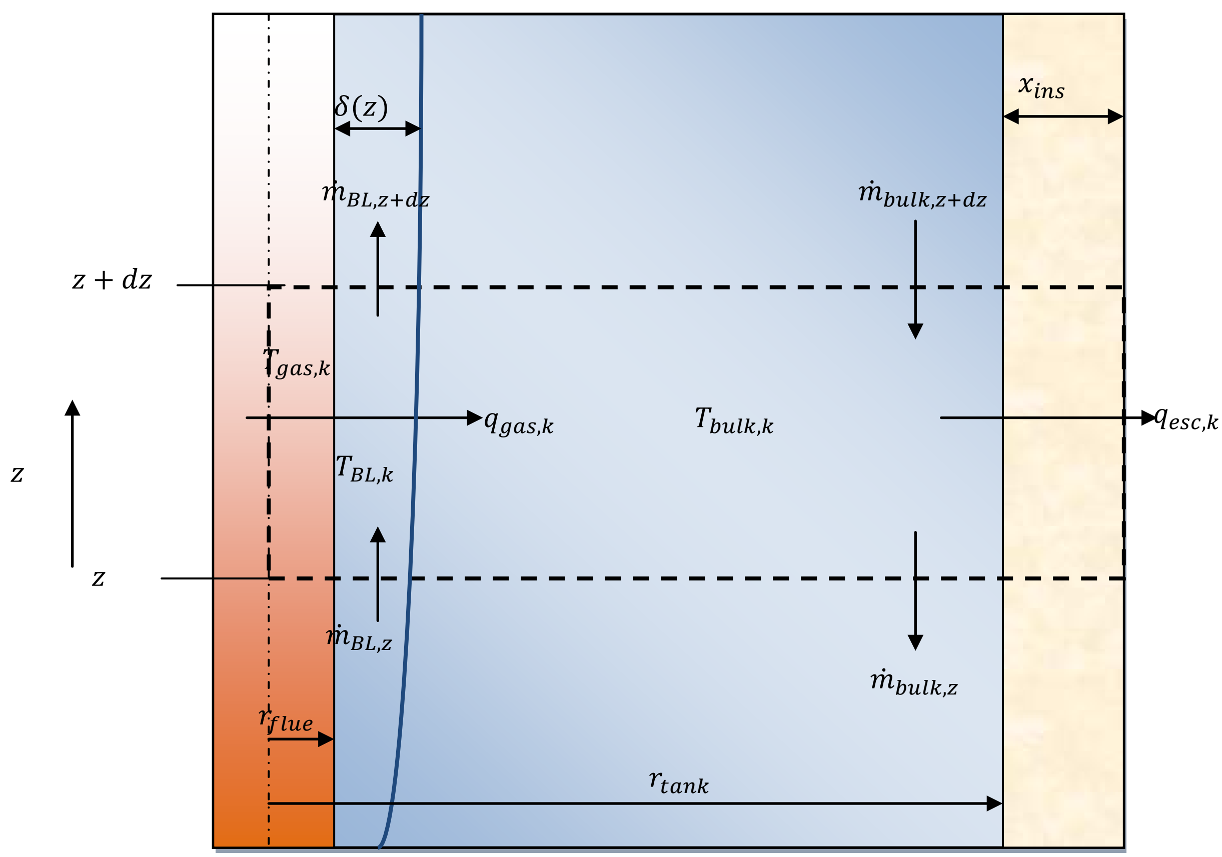

Figure 3: Half of a generic annulus control volume *k* within the tank-type water heater.

The following governing equations for control volume k were derived for the different elements in the water heater by using heat transfer definitions, implementing thermal resistance networks, and the mass and conservation laws. As a first step in the analysis, equilibrium, also known as steady-state, was assumed. With no transient effects, the general governing equations for a general annular control volume were developed and can be seen below.

Equation 1: Heat Leaving the Gas and Entering the Bulk Water

$$\boldsymbol{q_{gas,k} = U_{conv,k}A_{inner}\left(T_{gas,k} - T_{bulk,k}\right)}$$

where

$$\boldsymbol{U_{conv,k} = \frac{1}{R_{tot,conv,k}} = \frac{1}{\left(\frac{1}{h_{comb,k}} + \frac{1}{h_{BL,k}}\right)}}$$

$$\boldsymbol{A_{inner} = 2\pi r_{flue}L_{cv} = 2\pi r_{flue}(z + dz - z) = 2\pi r_{flue}dz}$$

$h_{BL} = \frac{k_\ell}{\delta}$, which is the convective coefficient of the boundary layer

h_{comb} , which is the convective coefficient of the combustion products

Equation 2: Heat Leaving the Bulk and Entering the Ambient

$$\boldsymbol{q_{esc,k} = U_{esc}A_{outer}\left(T_{bulk,k} - T_{amb}\right)}$$

where

$$\boldsymbol{U_{esc} = \frac{1}{R_{tot,esc}} = \frac{1}{\left(\frac{1}{h_{amb}} + \frac{x_{ins}}{k_{ins}}\right)} \approx \frac{1}{\left(0 + \frac{x_{ins}}{k_{ins}}\right)} = \frac{k_{ins}}{x_{ins}}}$$

$$\boldsymbol{A_{outer} = 2\pi r_{tank}L_{cv} = 2\pi r_{tank}(z + dz - z) = 2\pi r_{tank}dz}$$

Equation 3: Energy due to the Boundary Layer Entering the Control Volume

$$\boldsymbol{q_{conv}|_{BL,z} = A\rho v c_p \Delta T\big|_{BL,z} = \dot{m}_{BL,z}c_p\Delta T_{BL,z} = \dot{m}_{BL,z}c_p(T_{BL,k-1} - T_{BL,k})}$$

Equation 4: Energy due to the Boundary Layer Leaving the Control Volume

$$\boldsymbol{q_{conv}|_{BL,z+dz} = A\rho v c_p \Delta T\big|_{BL,z+dz} = \dot{m}_{BL,z+dz}c_p\Delta T_{BL,z+dz} = \dot{m}_{BL,z+dz}c_p(T_{BL,k} - T_{BL,k+1})}$$

Equation 5: Energy due to the Bulk Recirculation Entering the Control Volume

$$q_{conv}|_{bulk,z+dz} = A\rho v c_p \Delta T\big|_{bulk,z+dz} = \dot{m}_{bulk,z+dz} c_p \Delta T_{bulk,z+dz}$$
$$= \dot{m}_{bulk,z+dz} c_p (T_{bulk,k+1} - T_{bulk,k})$$

Equation 6: Energy due to the Bulk Recirculation Leaving the Control Volume

$$\boldsymbol{q_{conv}|_{bulk,z} = A\rho v c_p \Delta T\big|_{bulk,z} = \dot{m}_{bulk,z} c_p \Delta T_{bulk,z} = \dot{m}_{bulk,z} c_p (T_{bulk,k} - T_{bulk,k-1})}$$

Equation 7: Mass Conservation

$$In - Out = 0$$
$$\boldsymbol{(\dot{m}_{BL,z} - \dot{m}_{BL,z+dz}) + (\dot{m}_{bulk,z+dz} - \dot{m}_{bulk,z}) + \dot{m}_S = 0}$$

Equation 8: Energy Conservation

$$In - Out = 0$$
$$\boldsymbol{(q_{conv}|_{BL,z} + q_{conv}|_{bulk,z+dz} + q_{gas}) - (q_{conv}|_{BL,z+dz} + q_{conv}|_{bulk,z} + q_{esc}) = 0}$$

Due to the different conductivities, depths, lengths, and convective coefficients of each element in the water heaters, the magnitude of the thermal resistances for different components will be compared in order to determine which elements need the most accurate and detailed modeling. For instance as was done in for the U_{esc} term, the thick insulation in the wall of the tank-type water heater will probably have a larger order of magnitude than the thermal resistances of the neighboring components: the natural convection coefficient along the inside of the insulation wall, the metal and paint of the wall, and convective and radiation resistances outside of the water heater. There will also be a weak gradient on the outside of the water heater. As a result, the total heat transfer coefficient reduces to the conduction insulation component. This same order of magnitude analysis will be performed for the different components within the tankless water heaters.

In order to solve for all of the variables, a network of control volumes will have to be analyzed so that each unknown can be found. One of the most essential parts of this analysis is determining the boundary layer heat transfer coefficient. By finding h_{BL} as a function of distance, the temperature distribution and mass flow rates within the boundary layer can be obtained and will reduce the number of unknowns significantly, so that all of the other variables can be found using continuity and energy conservation.

Boundary layer theory will be used to analyze the convective coefficient on a wall of varying surface temperature. Since the tank-type water heater is a buoyancy driven system, the heat transfer coefficient will be from natural convection and this coefficient will be used to estimate the recirculation behavior. After finding the mass flow rising along the flue, it can be assumed that an equivalent mass flow is coming back down in the rest of the tank. Since the boundary layer flow is transferring mass to the top of the tank, there will be entrainment of fluid into the boundary layer from the down-flow. Once the mass flow rates for the circulation and entrainment are known, the mixture temperature can be calculated.

The integral method will be used to find the integral boundary layer equations. This method allows for a convenient, though approximate, determination of the desired transport quantities. By performing a mass, momentum, and energy balance on a differential control volume, the overall governing equations of the boundary layer can be found by integrating these equations. The velocity and temperature field distributions are subsequently chosen to satisfy the boundary conditions. If the thermal and velocity boundary layers are assumed to be equal (denoted by δ), the momentum and energy equations are taken as

Equation 9:

$$\frac{d}{dx}\left[\int_0^{\delta} u^2 dy\right] = -\nu \left.\frac{\partial u}{\partial y}\right|_{y=0} - g\beta\left[\int_0^{\delta} (T - T_\infty) dy\right]$$

Equation 10:

$$\frac{d}{dx}\left[\int_0^{\delta} u(T - T_\infty) dy\right] = -\alpha \left.\frac{\partial T}{\partial y}\right|_{y=0}$$

Equation 11: Velocity Profile

$$u = U\frac{y}{\delta}\left(1 - \frac{y}{\delta}\right)^2$$

Equation 12: Temperature Profile

$$T - T_\infty = (T_o - T_\infty)\left(1 - \frac{y}{\delta}\right)^2$$

where U and δ are functions of x and are obtained from the governing integral equations. By substituting the assumed temperature and velocity profiles into the integral equations, the following ordinary differential equations can be found for

Equation 13:

$$\frac{d}{dx}\left(\frac{U^2\delta}{105}\right) = \frac{g\beta(T_0 - T_\infty)\delta}{3} - \frac{\nu U}{\delta}$$

Equation 14:

$$\frac{d}{dx}\left(\frac{U\delta}{30}\right) = \frac{2\alpha}{\delta}$$

By assuming a polynomial variation in x for U and δ, the relevant constants can be determined by equating the indices and the coefficients in the ordinary differential equations.

Equation 15:

$$U = C_1 x^m + U_0$$

Equation 16:

$$\delta = C_2 x^n + \delta_0$$

When determining the boundary layer behavior, if the flow transforms from laminar to turbulent, the governing equations will be altered due to this change. After the first approximation of the boundary layer is completed, the stratification of the bulk water, which is when the hot water rises and the cold water is at the bottom, can be considered in addition to other forms of the velocity and temperature profiles.

2.1.2.2 Storage Tank Simulation Model

This model was created as part of a large effort to create models for the entire water heating system in a building. The models will include several kinds of water heaters, both common and advances, as well as models used to create a distribution system. The larger project is also intending to create the library of water heating models in a manner which can easily leverage the LBNL Buildings library to include water heating in whole building simulations [1]. The buildings library, which is available at http://simulationresearch.lbl.gov/modelica/FrontPage , contains models that can be used to model various aspects of buildings. The available models range from ones modeling specific types of heat transfer to major HVAC equipment that can easily formulate a whole building HVAC system. Combining this model with the building library both makes the modeling effort easier, by allowing use of the buildings library models, and makes it easy to include water heaters in a whole building simulation. While there is a model for a storage tank water heater available in TRaNsient Systems Simulation (TRNSYS) it cannot be combined with a distribution system, nor can it easily be included into detailed whole building energy simulations [2]. Creating a new model in Modelica allows easy access to the LBNL buildings library and the hot water distribution system, as well as creating a strong starting point for more advanced models, such as condensing storage and hybrid water heaters in the future [3].
The model was created based on the HEATER model developed by Arthur D. Little, Inc. (ADL) [4]. The ADL paper details calculations used to identify the temperature of hot gas in the combustion chamber, the flue, and how that translates into buoyant heat flow inside the tank. The calculations used by ADL are combined with calculation models in Modelica made available through the LBNL Buildings Library [1]. More information on how they are combined is provided later. The calibration process was performed using data provided by the Gas Technology Institute (GTI) for a previous experimental project they performed [12]. Their experiments were performed on a Rheem storage tank water heater (Model number: GG40T06AVG01). This heater is no longer being manufactured. Some of the specifications for the heater are provided in Table 1.

Table 1: GTI Tested Water Heater Specifications

Fuel Type	Natural Gas
Capacity	151.42 L (40 gal)
Tank Diameter	0.45 m (17.75 in)
Tank Height	1.49 m (58.5 in)
Gas Input Rate	10.55 kW (36 kBtu/hr)
First Hour Delivery	253.6 L/hr (67 gal/h)
Energy Factor	0.59

2.1.2.3 Model Documentation

Design

The storage tank model is created in a hierarchical manner. Top-level models are composed of sub-models. For example, the storage tank water heater model includes sub-models that calculate the heat transfer through the flue wall to the water, and through the jacket of the tank to the environment. The top level of the model includes models describing the gas burner, the storage tank, the thermostat, the ambient conditions and the draw pattern. The components introduced here are the storage tank and gas burner models. This report will describe those two models while leaving other documentation to describe the other models. Documentation for each model is available within the Dymola environment when the buildings library is downloaded [5]. Dymola is a commercially available interface for programming in Modelica.

Design - Burner

The gas burner model was constructed based on calculations first proposed in the HEATER model [4]. An image of the burner model is shown in Figure 4.

A few of the calculations proposed by ADL have been replaced with components from the LBL Buildings Library [1] or more precise theoretical calculations. Specifically, the radiation heat transfer between the flame and the floor is replaced with the standard radiation heat transfer equation and the heat transfer with the base of the tank is calculated using Buildings.HeatTransfer.Convection.Interior. New models were created to handle all of the calculations performed in HEATER, and are presented in the burner model as sub models. Sub models were created to calculate the following variables:

- Adiabatic flame temperature (T_AD_Flame).
- The convection coefficient between the hot gas and the base of the tank (h_CB).

- A radiation heat transfer coefficient between the adiabatic flame and the tank bottom (h_RB).
- An energy flow rate of the flue gas represented by the mass flow rate times the specific heat (cdot_G).
- The temperature of the hot gas entering the flue (T_F0).
- The temperature of the hot gas in the burner (hotGas).

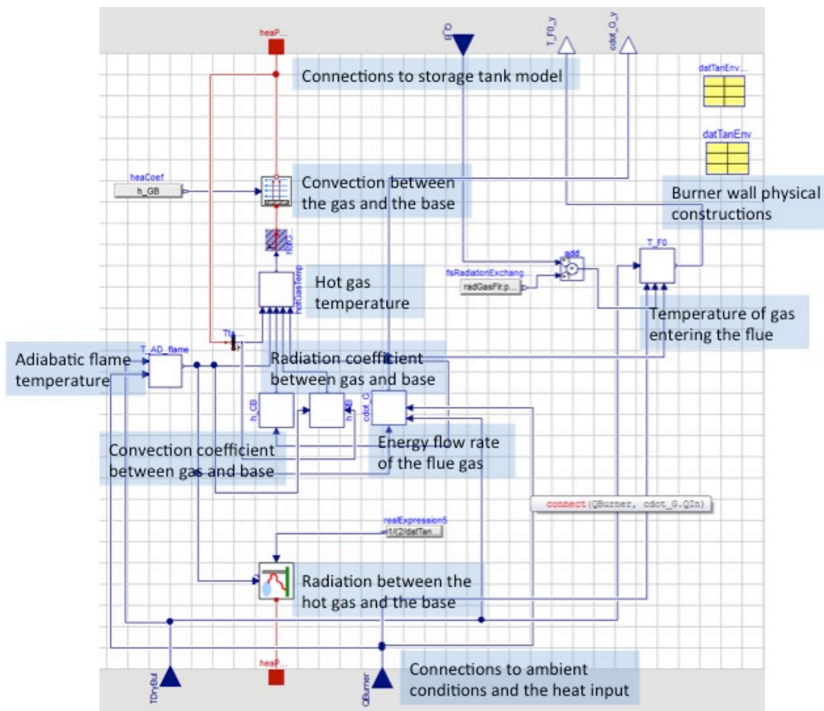

Figure 4: Gas Burner Model

Several inputs and outputs are used to connect the burner assembly to other models. Necessary inputs are handled in different manners as appropriate to each input. They are as follows:

- The ambient air temperature (TDryBul) is passed in as a Real variable.
- The heat input rate of the burner (QBurner) is passed in as a Real variable.
- The heat transfer rate from the hot gas to the base of the tank (Q_B). The convection calculation for this value is connected to a heat port. Heat ports are a kind of connection available in Modelica indicating that calculations should identify the temperatures of and heat transfer between two components. The heat port is used to interface with the storage tank model, representing the conditions at the base of the tank. Through this

connection the heat transfer rate is calculated. Finally, the heat transfer rate is passed into the burner assembly as a Real variable.

- Radiation losses to the floor. This is handled in a similar manner to the heat transfer between the hot gas and the base of the tank. The radiation model is connected to the floor with a heat port, enabling the heat transfer to be calculated.
- The temperature of the hot gas as it enters the flue (T_F0_y) is passed out as a Real variable.
- The energy flow rate of the flue gas (cdot_G_y) is passed out as a Real variable.

Design – Storage Tank

The storage tank model is a combination of calculations proposed by ADL, components from the Buildings library and calculations created for this model. The calculations for the tank documented by ADL primarily focused on the temperature of the hot gas passing through the flue [4]. Calculations determining the heat transfer from the flue gas to the water, or from the water out the jacket of the tank to the surrounding conditions were performed using components from the Buildings library. Calculations describing the heat transfer and mixing within the tank were created based on observations of experimental data.

Many of the calculations for the heat transfer into and out of the tank are performed using components previously created for inclusion in the LBL Buildings library. As a result, this section will focus on conceptual discussion of how the components are all assembled rather than the specific details of each individual component. An image of the storage tank model is shown in Figure 5.

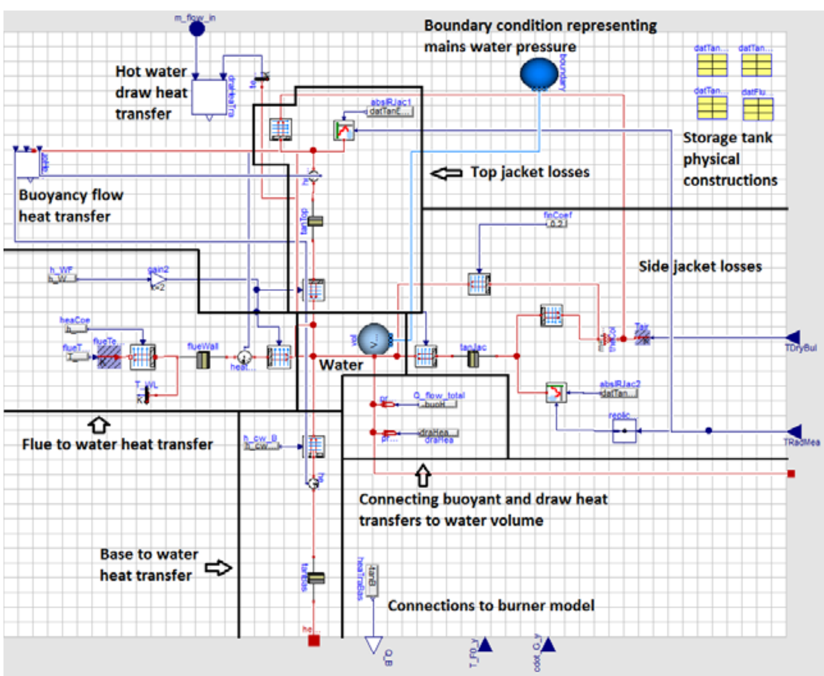

Figure 5: Storage Tank Model

Several input variables are passed into the tank model from other models. These include the following:

- The previously mentioned heat port connecting the base of the heater to the hot gas in the burner.
- T_F0_y passed in from the burner model as a Real input.
- cdot_G_y passed in from the burner model as a Real input.
- A heat port connecting the water in the tank to T_sensor. This allows the sensor used for thermostat control to identify the temperature of the water in the tank.
- The mean radiant temperature (TRadMean) is passed into the model as a Real input and used to identify the radiant losses from the jacket of the tank to the surrounding environment.
- The drybulb temperature (TDryBul) of the air surrounding the heater is passed into the model as a Real input and used to identify the convective losses from the jacket of the tank to the surrounding environment.
- The flow rate of a hot water draw (m_flow_in) is passed in as a Real input.

Conceptually, the calculations for the model start at T_F0_y representing the temperature of the hot gas entering at the bottom of the flue. The temperature of the hot gas at each level of the flue is then identified using the same methodology as in HEATER [4]. Components from the Buildings library, and convection coefficients specified by the user, are then used to identify the heat transfer rates between the hot gas and flue wall, across the flue wall, and between the flue wall and water in the tank. Heat and mass transfer within the tank are calculated using algorithms based on observations of experimental data. These algorithms are discussed in the following section. The volume of water is then connected to models representing the heat loss to ambient conditions. These calculations include heat lost through the top of the tank, through the side jacket and through the fittings (modeled as fins).

Calculations are also performed to identify the heat transfer through the base of the heater. Components from the Buildings library are used to connect the water to the base of the tank, which is then connected to the hot gas model in the burner model using the previously mentioned heat port.

The heat transfer impacts of a hot water draw are handled in a sub-model called draHeaTra. To perform these calculations the storage tank is modeled in two sections. One section represents water near the bottom of the tank. In this section it is assumed that the cold water entering the tank causes mixing with even volumes of cold water entering each segment. The user specifies the height of the mixing section. The second section represents water above the mixing zone, but below the stratification layer. In the top section, above the thermocline, draws are treated as plug flow. The associated heat transfer is calculated by assuming that all water leaving the top of a segment is replaced by colder water coming in from the segment below. The values of heat transfer caused by the hot water draw are then connected to the volume of water. The heat transfer caused by a draw was not mentioned in the HEATER documentation, and is new to this model. Details are provided in the Calculations section.

Heat and mass transfer impacts of buoyant heat flow are calculated in a sub-model called buoHeaTra. These calculations are performed using new algorithms developed specifically for this model. The assumptions behind the algorithms are based on previously collected experimental data [3, 4].

The calculations assume that there are two regions which develop when the burner fires. The bottom region, below the stratification layer, is well mixed and all heat is applied evenly to each segment. The top region, above the stratification layer, is not mixed and all heat transfer is handled by the Buildings library convection component external to the buoyancy calculations.

2.1.2.4 Calculations

Many of the calculations were performed using components of the Buildings library. The components have been validated previously, and a detailed discussion of those components will not be provided here. This section will handle a description of the calculations that are new for this model.

Calculations – Burner

The majority of the calculations in the burner model are used to identify the heat transfer rate between the hot gas in the burner and the base of the storage tank. These calculations include:

- Calculating the temperature of the adiabatic flame (T_AD_Flame).
- Calculating the convection coefficient for convective heat transfer between the gas in the burner and base of the storage tank (h_CB).
- Calculating a simplified radiation coefficient to describe the radiation heat transfer between the hot gas and the base of the tank (h_RB).
- Identifying the energy flow rate up the flue as a combined expression of the mass flow rate and specific heat of the gas (cdot_G).
- Using these four values to identify the temperature of the gas in the burner (hotGasTemp).

Equation 17 uses properties of the gas to identify the temperature rise caused by combustion. The temperature rise is then added to the dry bulb temperature to find the adiabatic flame temperature.

Equation 17: Temperature of the adiabatic Flame

$$T_{AD} = T_{DB} + \frac{{}^{\Delta H_C}/_{c_{p,g}}}{1 + AF_{ST} * (1 + EA)}$$

The convection coefficient for convective heat transfer between the hot gas and the base of the storage tank is calculated usingEquation 18 is an empirical correlation that has been shown to describe the heat transfer of a hot gas impinging on a surface [4].

Equation 18: Convection Coefficient for convective Heat Transfer

$$\boldsymbol{h_{C,B}} = \frac{\mathbf{0.51} * \boldsymbol{k_g}}{\boldsymbol{X_n}} * (\frac{\boldsymbol{(\rho V)_G} * \boldsymbol{X_n}}{\boldsymbol{\mu_G}})^{\mathbf{0.62}}$$

where

Equation 19: One half of the difference between the tank diameter and the flue diameter

$$X_n = 0.5 * (D_T - D_F)$$

Equation 20: Mass Velocity of Hot Gas

$$(\rho V)_G = \frac{\dot{m}_G}{\pi D_M b_B}$$

where

Equation 21: Average of the Tank and Flue Diameters

$$\boldsymbol{D_M} = \mathbf{0.5} * (\boldsymbol{D_F} + \boldsymbol{D_T})$$

Equation 22: width of the area of the base that is in contact with the hot gas

$$b_B = 2 * L_{BRN} * \tan(\frac{\alpha_F}{2})$$

The radiation coefficient is calculated using Equation 23. The radiation coefficient is used by ADL to linearize the radiation heat transfer. It combines the standard radiation constants (Stephan-Boltzmann, emissivity of the surfaces) with the cube of the temperature of the flame. This allows the radiation heat transfer to the base to be calculated using average temperatures for the hot gas and base of the tank [4].

Equation 23: Radiation Coefficient

$$\boldsymbol{h_{R,B}} = \boldsymbol{\sigma} * \left(\mathbf{0.5} * (\mathbf{1} + \boldsymbol{\varepsilon_B}) * \boldsymbol{\varepsilon_G} * \boldsymbol{T_{AD}}^3\right) * (\mathbf{1} + \frac{\boldsymbol{T_{WL,B}}}{\boldsymbol{T_{AD}}})$$

Equation 24: The mass flow rate of the hot gas

$$\dot{m}_G = \frac{\dot{Q}_{In}}{T_{AD} - T_{DB}}$$

The results from the preceding equations are then used to calculate the effective mean temperature of the hot gas for heat transfer to the base of the tank.

Equation 25: The effective mean temperature of the hot gas for heat transfer to the base of the tank

$$T_G = \frac{T_{AD} + N_{tu,B} * T_{WL,B}}{1 + N_{tu,B}}$$

Where

Equation 26: Intermediate value used to describe the effectiveness of heat transfer between the base and the hot gas

$$N_{tu,B} = \frac{(UA)_B}{\dot{c}_G}$$

where

Equation 27: Effective heat transfer coefficient between the hot gas and base of the storage tank. It represents the heat transfer coefficient for both convection and radiation.

$$(UA)_B = (h_{R,B} + h_{C,B})A_B$$

The mean temperature of the hot gas for heat transfer to the base of the tank is calculated using Equation 17 through Equation 27. It is then connected to a Buildings library model for calculating convective heat transfer using a user supplied convection coefficient. The convection coefficients used in model development are presented in the section First Comparison to Experimental Data. The convection model identifies the rate at which heat transfers from the hot gas to the base of the storage tank.

The temperature of the hot gas entering the base of the flue is calculated in the burner model. It is presented in Equation 28. The calculation is based on the energy increase caused by combustion, the heat removed from the gas through heat transfer with the base of the tank, and the heat capacity of the gas.

Equation 28: hot gas entering the base of the flue

$$T_{F,0} = T_{DB} + \frac{{}^{\Delta H_{C,L}}\!/_{\Delta H_C} * \dot{Q}_{In} - \dot{Q}_B - \dot{Q}_{R,FE}}{{}^{\dot{c}_G}\!/_{1.06}}$$

Calculations – Storage Tank

This section focuses on the calculations that are based on the work by ADL as well as new algorithms developed for this model. It will not discuss the calculations completed using components from the Buildings library in detail. The calculations that do not use the Buildings library components fall into three categories.

- The temperature of the hot gas in the flue as it progresses up the flue. This is handled using the equation developed by ADL [4].
- Heat and mass transfer caused by buoyant flows. These calculations are performed using newly developed algorithms.
- Heat transfer associated with hot water draws. The documentation for HEATER did not include information on how hot water draws were handled so these calculations were created specifically for this model.

Flue Gas Temperature

The flue gas temperature was calculated using a slightly modified version of the equation implemented in HEATER. A separate flue gas temperature, T_F, is calculated for each segment in flue gas. This is programmed using a "for loop." The index of the for loop is *i* and the equation is calculated *nSeg* times. The modified version is presented in Equation 29.

Equation 29: Flue Gas Temperature

$$T_F(i) = T_{WL}(i) + (T_{F,0} - T_{WL,Avg}(i))e^{-\left(h_{F*}C_F/\dot{C}_G\right)\left(L_{Flu}*(nSeg-i+1)/_{nSeg}\right)}$$

The original calculation for the flue gas temperature used in HEATER referenced the average temperature of the flue wall [4]. It is believed that this was done to simplify calculations. This equation was changed in two ways in the LBNL model.

- The first flue wall temperature term was changed to *T_*$_{WL}$ *(i)*, the temperature of the flue wall in the current segment. It is believed that this will result in a more accurate calculation of the flue gas temperature.
- The second flue wall temperature term was changed to *T_(*$_{WL,Avg}$*) (i)*. In HEATER the average temperature used was based on the average temperature of the entire flue wall. The LBNL model calculates the average temperature of the flue wall in all segments below the current segment. This results in a specific average flue wall temperature for each segment, and a more accurate calculation of the flue gas temperature along the length of the flue.

Manufacturers, when designing baffles, attempt to keep the rate of heat transfer through the flue constant along the length of the flue wall [6]. Including this logic in the model required either changing the convection coefficient along the length of the flue or using an effective constant temperature for the flue gas. A constant flue gas temperature was used because it was much simpler to implement. The effective flue gas temperature used to calculate heat transfer through the walls is shown in Equation 30.

Equation 30: Effective Flue Gas Temperature

$$T_{WL,Eff} = \frac{\sum_{i=1}^{nSeg} T_{WL}(i)}{nSeg}$$

Hot Water Draw Heat Transfer

To calculate the heat transfer impacts of a hot water draw, a sub-model titled draHeaTra (Draw Heat Transfer) was created. The inputs to the sub-model are the temperature of each segment in the storage tank, the mass flow rate of the hot water draw and the user specified segment representing the top of the mixing region. Within the model calculations are performed to identify the heat transfer rate caused by water flowing into the tank, and between segments. The following assumptions are used:

- The mass flow rate entering and exiting each node is identical, resulting in no mass balance equations.
- The water inlet temperature is a constant value that is specified by the user in the parameters window for the storage tank. This can be changed to a varying input with little effort.
- The flow of water entering the tank will cause some mixing. As a result, the segments at the bottom of the tank will be at the same temperature.

The heat transfer for each segment caused by the hot water draw is then calculated using one of two equations. If the segment is above the user defined mixing zone Equation 31 is used. Heat transfer for segments in the mixing zone is calculated using Equation 32.

Equation 31: Heat transfer if segment is above the user-defined mixing zone

$$\dot{Q}_{Draw}(i) = \dot{m}_{In} * c_p * (T_{Wat}(i + 1) - T_{Wat}(i))$$

Equation 32: Heat transfer for segments in the mixing zone

$$\dot{Q}_{Draw}(i) = \frac{1}{nSeg - H_{mix} - 1} * \dot{m}_{In} * c_p * (T_{Wat}(In) - T_{Wat}(i))$$

The segments are numbered by *i*, with the top of the storage tank corresponding to segment 1, and segment *nSeg* represents the bottom of the tank. In Equation 31, $T_{Wat}(i+1)$ represents the water temperature of the segment just below segment *i*. For the bottom segment of the tank, in the case where $i = nSeg$, $T_{Wat}(i+1)$ is replaced with $T_{Wat}(In)$.

Equation 31 assumes that plug flow between two segments. Equation 32 assumes that the water entering the storage tank is split between multiple segments. The total number of segments in the simulation and the height of the mixing zone specified by the user determine the number of segments. Currently the model uses a fixed height for the mixing zone. It is believed that the height of the mixing zone will vary with draw flow rate and dip tube geometry. A new algorithm, allowing the height of the mixing zone to vary with draw flow rate, will be included in future versions of the model.

The calculated heat transfer rate for each segment is then passed out of draHeaTra to the larger storage tank model. The values of draHeaTra are presented in a RealExpression model, and connected to the heat port for the volume of heated fluid.

Buoyancy Flow Heat Transfer

Calculations for heat transfer within the tank are performed using algorithms created specifically for this model. The assumptions behind the algorithms were taken from experimental data [7]. The calculations break the heater into two sections.

- One section below the stratification layer. Experimental data has shown that water below the stratification layer is well mixed [7].
- One section above the stratification layer. Experimental data shows the water in this section is not well mixed [12].

The stratification is tracked by comparing the temperature of each segment to the temperature of the segment below. When the two temperatures are equal it is assumed that both segments are below the stratification layer. Mixing amongst all segments below the stratification layer is simulated by dividing the heat transfer evenly between all segments. The location of each segment relative to the stratification layer is identified using Stratification Tracking Equations

Equation 33 through Equation 35.

Stratification Tracking Equations

Equation 33:

$$H_2(nSeg - i) = f(X(nSeg - i + 1) - \Delta T, \Delta T)$$

Equation 34

$$H_1(nSeg - i) = f(T_{Wat}(nSeg - i) - T_{Wat}(nSeg - i + 1) - \Delta T, \Delta T)$$

Equation 35

$$X(nSeg - i) = \min(1, H_1(nSeg - i) + H_2(nSeg - i))$$

In Stratification Tracking Equations

Equation 33 and Equation 34 the "f" represents the smoothHeaviside function from the Buildings library. It is used to replace if statements with a differentiable function that can be more easily handled by the ordinary differential equation (ODE) solver used. The smoothHeaviside function checks the first term in the equation. A one is returned when the first term is greater than zero. The result is a zero if the first term is less than zero. The ΔT represents the width of the smoothing function. The smoothHeaviside function will return a value between zero and one when the result of the first term is in the smoothing band. It is possible for this effect to introduce some error into the simulation. The potential for error will be examined in future versions of the model.

Stratification Tracking Equations

Equation 33 checks the status of the segment beneath the current segment. If the lower segment is beneath the stratification layer Stratification Tracking Equations

Equation 33 returns a zero. If the lower segment is above the stratification layer Stratification Tracking Equations

Equation 33 returns a one. The ΔT term is subtracted from the status of the lower segment to handle potential errors caused by the smoothing function. If the first term in the smoothHeaviside function equals zero, it will return a value of 0.5. This is because zero is in the center of the smoothing band. Subtracting the smoothing range from the first term shifts a zero value to the lower end of the smoothing band. The smoothHeaviside function then reports zero instead of 0.5.

Equation 34 compares the temperature of the current segment to the temperature of the segment beneath it. If the temperature of the current segment is higher than the segment below it, indicating that it is above the stratification layer, Equation 34 returns a one. In all other cases Equation 34 returns a zero.

Equation 35 combines the two results to determine the final state of the segment. If both Stratification Tracking Equations

Equation 33 and Equation 34 return zeros the segment is considered to be below the stratification layer. If either segment returns a one it is treated as being above the stratification layer.

Once the sections above and below the stratification layer have been identified calculations are performed to identify the heat transfer into each segment. Because the region below the stratification layer is assumed to be well mixed, the heat transfer in that section is applied evenly to all segments. The heat transfer for each section above the stratification layer is treated individually. Heat transfer for the segments below the stratification layer is handled using Equation 36 through

Equation 39.

Equation 36: the amount of heat entering the section below the stratification layer from the flue in a specific segment

$$\dot{Q}_{Str}(i) = \dot{Q}_{Flu}(i) * f(1 - X(i) - \Delta T, \Delta T)$$

Equation 37: The total amount of heat added to the stratification layer

$$\dot{Q}_{Str,Tot} = \sum_{i=1}^{nSeg} \dot{Q}_{Str}(i)$$

Equation 38: the heat added to each segment in that section

$$\dot{Q}_{Seg} = \dot{Q}_{Str,Tot} \Big/ \sum_{i=1}^{nSeg} X(i)$$

Equation 39

$$\dot{Q}_{In,Seg}(i) = \dot{Q}_{Seg} * f\big(0.01 - \big(T_{Wat}(i) - T_{Wat}(i+1)\big) - \Delta T, \Delta T\big) + \dot{Q}_{Flu}(i) * f(T_{Wat}(i) - T_{Wat}(i+1) - 0.01 - \Delta T, \Delta T)$$

In Equation 36 and

Equation 39, $\dot{Q}_{Flu}(i)$ is calculated using the buildings library component for convective heat transfer, and passed into the buoyancy heat flow calculations. Equation 36 is used to identify the amount of heat entering the section below the stratification layer from the flue in a specific segment. If the segment is below the stratification layer (indicated by $X(i) = 0$) then $\dot{Q}_{Str}(i) = \dot{Q}_{Flu}(i)$. When a segment is above the stratification layer (indicated by $X(i) = 1$) then $\dot{Q}_{Str}(i) = 0$. In the case where $i = nSeg$ an additional term is added performing the same calculation for $\dot{Q}_{Bas}$. Equation 37 sums $\dot{Q}_{Str}(i)$ for all segments to find the total amount of heat added to the stratification layer.

Equation 38 divides $\dot{Q}_{Str}(i)$ by the number of segments below the stratification layer to identify the heat added to each segment in that section. It is used to find the heat transfer entering each segment. The smoothHeaviside functions are used to determine whether the segment is above or below the stratification layer. New inequalities are used instead of reusing *X(i)* because, when *X(i)* is used, the smoothHeaviside equations output are always in the smoothing region. The result is both slow simulations and erroneous results. This phenomenon is not fully understood and will be investigated in future versions of the model.

The first smoothing function in

Equation 39 returns a one when the segment is below the stratification layer, and a zero when the segment is above the stratification layer. It ensures that $\dot{Q}_{Seg}$ is only added to the segment when it is below the stratification layer. The second smoothing function operates in reverse and ensures that $\dot{Q}_{Flu}(i)$ is only added to the segment when it is above the stratification layer.

2.1.2.5 First Comparison to Experimental Data

The validation for the model was performed by comparing simulation results to test data collected by the Gas Technology Institute (GTI) [5]. To create the experimental data GTI performed a 24 hour simulated use test. A small portion of the test data, which included one of the six draws of the Energy Factor (EF) test procedure and the time the burner was firing to recover from that draw, was used for the initial validation process. The data is shown in Figure 6.

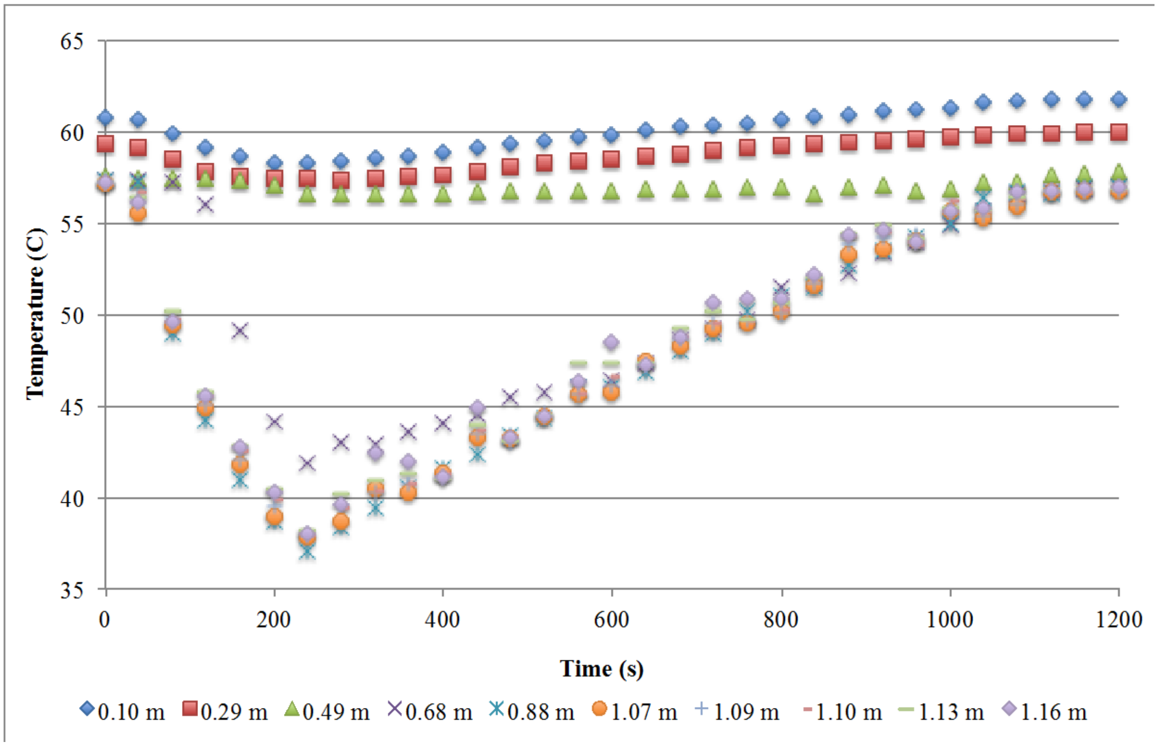

Figure 6: Validation Test Data

The parameters in the simulation model were changed to match the model tested by GTI. They were presented in Table 1 and are re-presented in Table 2.

Table 2: Tested Water Heater Specifications

Fuel Type	**Natural Gas**

Capacity	L (40 gal)
Tank Diameter	m (17.75 in)
Tank Height	m (58.5 in)
Gas Input Rate	10.55 kW (36 kBtu/hr)
First Hour Delivery	253. L/hr 6 (67 gal/h)
Energy Factor	0.59

The convection coefficients describing heat transfer between the hot gas and the water were needed to emulate the GTI experiment. A diagram showing the heat transfer represented by each convection coefficient is shown in Figure 7. The convection coefficient in the base of the tank was adjusted until the temperature at the bottom of the flue matched the experimental data. The coefficient describing heat transfer between gas in the flue and the flue wall was found by varying the convection coefficients until the temperature of the gas at the top of the flue predicted by the simulation matched the experimental measurements. The coefficient describing heat transfer from the wall of the tank to the water was adjusted until the water temperature rise rate matched the experimental data. The convection coefficients used are provided in Table 3.

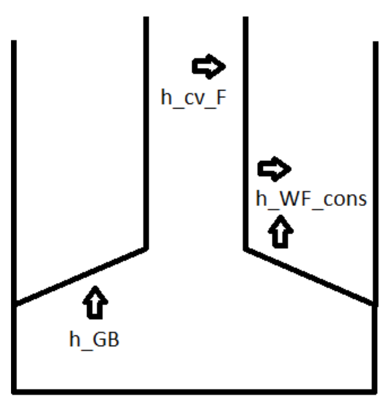

Figure 7: Convection Coefficients Used to in the Model

Table 3: Convection Coefficients Describing the Tested Heater

Coefficient Name	Coefficient Description	Value (W/m2-K)
h_WF_cons	Convective heat transfer between the flue wall and the water	12.66
h_cv_F	Convective heat transfer between the flue gas and flue wall	115
h_GB	Convection between the hot gas and the base of the tank	362.6

The following inputs in the model were used to emulate the conditions in the test data.

- The water flow rate in the experimental data was found to be 11.73 liters per minute. The hot water draw began 18s into the experiment, and stopped 230s into the experiment. This information was used as input data in the simulation.
- The start temperature of all segments in the simulation was 60 °C. This was an approximation based on experimental data. In the data the initial temperatures ranged from 58 °C to 62 °C. Because the simulation, at the time of this comparison, was only able to handle a single start temperature for all segments the simulation used the average start temperature of 60 °C for all segments.
- The burner began firing 120s into the experiment when the temperature 0.88 m from the top of the tank fell to 42 °C. The burner stopped firing when the temperature at the same height reached 58 °C. To emulate this, the simulation was performed using a setpoint of 50 °C and a deadband of ±8 °C. The thermostat read the temperature in segment 15, which corresponded most closely with the 0.88 m measurement. Twenty segments were used in the simulation.
- The room temperature recorded during the experiment was consistently approximately 21 °C. This value was used for both the ambient and mean radiant temperature in the simulation.
- The inlet temperature recorded during the experiment was consistently approximately 15.6 °C. This value was used for the inlet water temperature in the simulation.

The results of the first comparison to experimental data are shown in Figure 8.

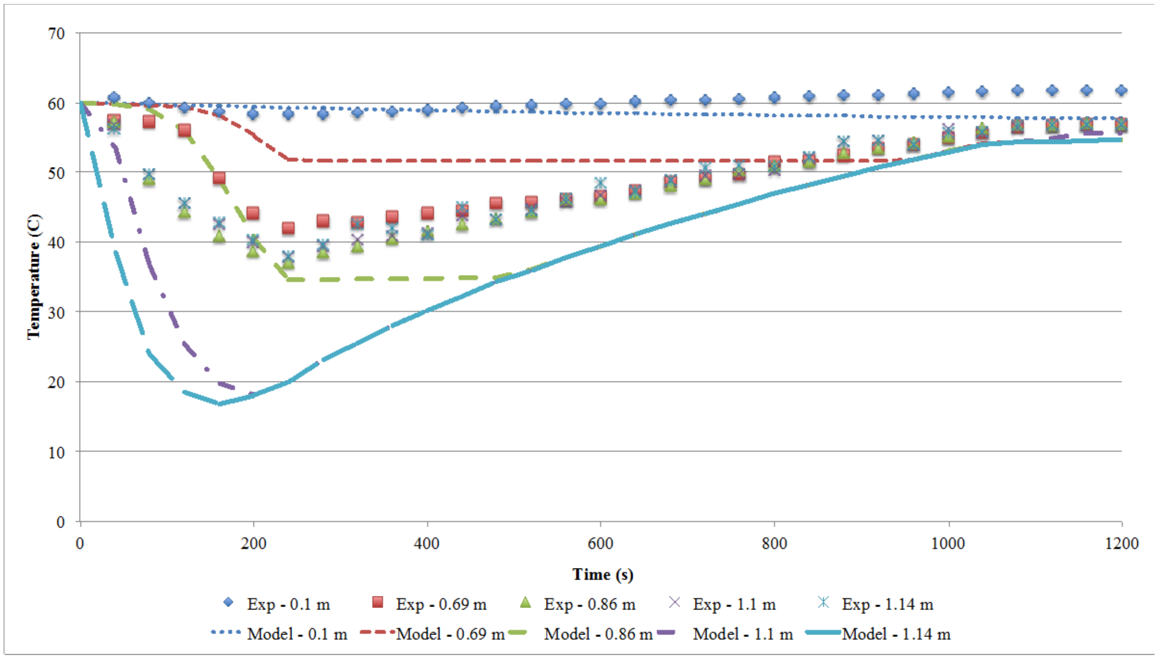

Figure 8: Results from the First Comparison with Experimental Data

Figure 8 shows data comparing the simulation results to experimental data at various depths in the tank. The goal is to correctly characterize the temperatures in the tank. The numbers in the series names refer to the depth in the tank the measurement was taken in meters. The term "Exp" applies to experimental data while the term "Model" indicates that a data set is simulation results. The data series at a given depth in the tank are the same color.

The simulation could not be set up to have measurements at the exact same depth as the experimental data. The depth of measurements in the simulation is at the center of a segment, so the depth of each measurement depended on the number of segments. As a result, some of the measurements are slightly higher or lower than the corresponding experimental data. While the difference in depth is minimal, some error will result from the different heights of measurements. A comparison of the heights of various measurements is shown in Table 4.

Table 4: Comparison of Measurement Depths

Exp Depth (m)	Model Depth (m)	Model Segment
0.1016	0.0895	2
0.6826	0.6864	12
0.8763	0.8655	15

1.1049	1.1043	19
1.1621	1.1640	20

The first comparison to experimental data was performed before the algorithm modeling mixing caused by a draw was added to the model. Several conclusions can be drawn from the data in Figure 8.

- The logic simulating the stratification layer is working well. The temperatures in the tank, as predicted by the model, varied significantly before the burner engaged. After the burner began firing, at 190s, the heat in the bottom segment began to rise. Once the temperature of the 1.14m measurement reached the temperature of the 1.1m measurement those two segments increased in temperature at the same rate emulating a well mixed section of the tank. The same behavior can be observed when the stratification layer meets the 0.86m prediction (500s) and the 0.69m prediction (950s). The same behavior is demonstrated in the experimental data. At the start of the burn the 0.69m measurement is higher than the 0.86 – 1.14m measurements. At approximately 550s the temperature of the lower segments reaches the temperature of the 0.69m measurement. For the rest of the experiment they are observed to be approximately the same temperature.
- The simulation model's prediction of stratification in the tank during a draw is not adequate. At the start of the draw the simulation prediction shows the temperature in the bottom segments decreasing far below the experimental data. At the same time, the simulation predicted higher temperatures than experimental data for locations higher in the tank. This was caused by the assumption of how the water flow behaved. The simulation model was based on the assumption of plug flow. Heat transfer in each segment was modeled as a constant flow rate of water between each segment. Hot water from a segment was replaced with slightly colder water from the segment below resulting in stratification. The experimental data shows that the temperatures in the 0.86 – 1.14m measurements actually decreased at nearly identical rates during the draw. This implies that there was a region of perfectly mixed water in the bottom of the tank.
- The heat transfer in the top segment of the tank is incorrect. The model assumes that there is no recirculation between segments above the stratification layer. The top segment, losing heat out of the top of the tank in addition to the side jacket, decreases in temperature faster than the other segments. In a real storage tank buoyant flows would cause mixing, but this effect is not captured in the model. As a result, the top segment loses heat to the surroundings faster than heat is added through the flue. The simulation model predicted the top segment losing heat during a burn while experimental data clearly shows otherwise.

2.1.2.6 Second Comparison to Experimental Data

Having determined that the model's assumption of plug flow during a draw was inaccurate, the model was changed to include mixing. The plug flow calculations were removed and replaced with the algorithm described in section Hot Water Draw Heat Transfer. With the new algorithm the simulation model was again compared to the experimental data. For this simulation H_{mix} was set to 15 indicating that all segments below 14 would be well mixed during the draw. Results are presented in Figure 6.

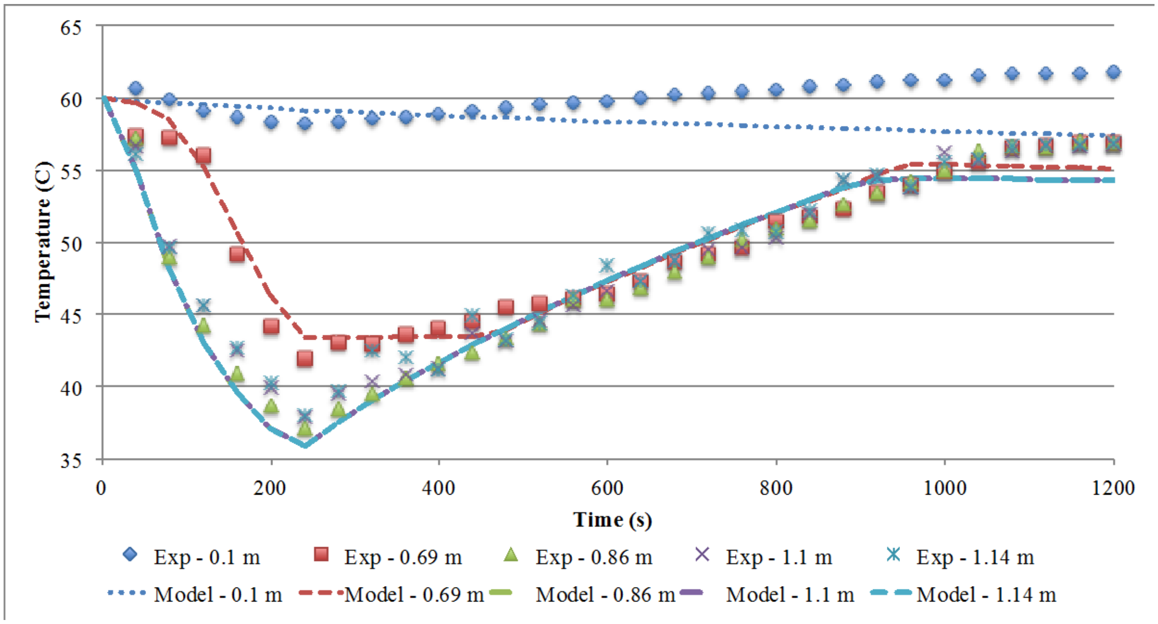

Figure 9: Results from the Second Comparison to Experimental Data

The data in Figure 9 is shown in the same manner as the data in Figure 8. The chart has only been changed to reference new simulation results. Some conclusions can be drawn from the results in Figure 9.

- The new algorithm adding mixing to the draw heat transfer equation is working well. During the draw, from 18s to 230s, the simulation predictions match experimental data well. Both simulation and experiment show the readings from 0.86-1.14m to be well mixed. Additionally, the temperatures predicted by the simulation model closely match the experimental data. The model prediction at 0.69m also closely matches the experimental data at 0.69m.
- There is an error in the heat transfer calculations causing some of the segments to gain heat when the burner stops firing. This can be seen at approximately 900s. The burner stops firing and the model predictions at 0.86-1.14m stop gaining heat. The prediction at 0.69m, however, rapidly increases in temperature by 2 °C. This issue will be addressed in future versions of the model.

- The temperature in the top segment of the tank is still incorrect. No changes were made to address this discrepancy between the first and second comparisons to experimental data. Changes were made to the model to improve this behavior before, again, comparing to experimental data.

2.1.2.7 Third Comparison to Experimental Data

The results in the second comparison to experimental data indicated that improvement was needed to improve the results of segments above the stratification layer. In response to a conversation with William Hoover the use of hot gas temperature was changed [6]. Baffles in water heaters are designed to change the flow of flue gas along the length of the flue, thus changing the convection coefficient and heat transfer to the flue wall [6]. The model was using a constant convection coefficient and changing flue gas temperature, resulting in changing heat transfer along the flue. To account for the baffle design the model was changed to use a constant hot gas temperature.

Additionally, the model was modified to allow a different initial temperature for each segment. This change makes it possible to more accurately imitate experimental data at the start of a simulation, and allows a more effective validation.

Simulation results comparing to experimental data with the above-mentioned changes are presented in Figure 10.

The data in Figure 10 is shown in the same way as in Figure 8and Figure 9. The plot has been updated to show improved simulation results. No other changes were made. Some conclusions can be made from the data in Figure 10.

- Adding the ability to input a specific initial temperature for each segment makes the validation of the simulation more effective. Having the correct starting temperatures for each segment causes the simulation results to more closely match the experimental data.

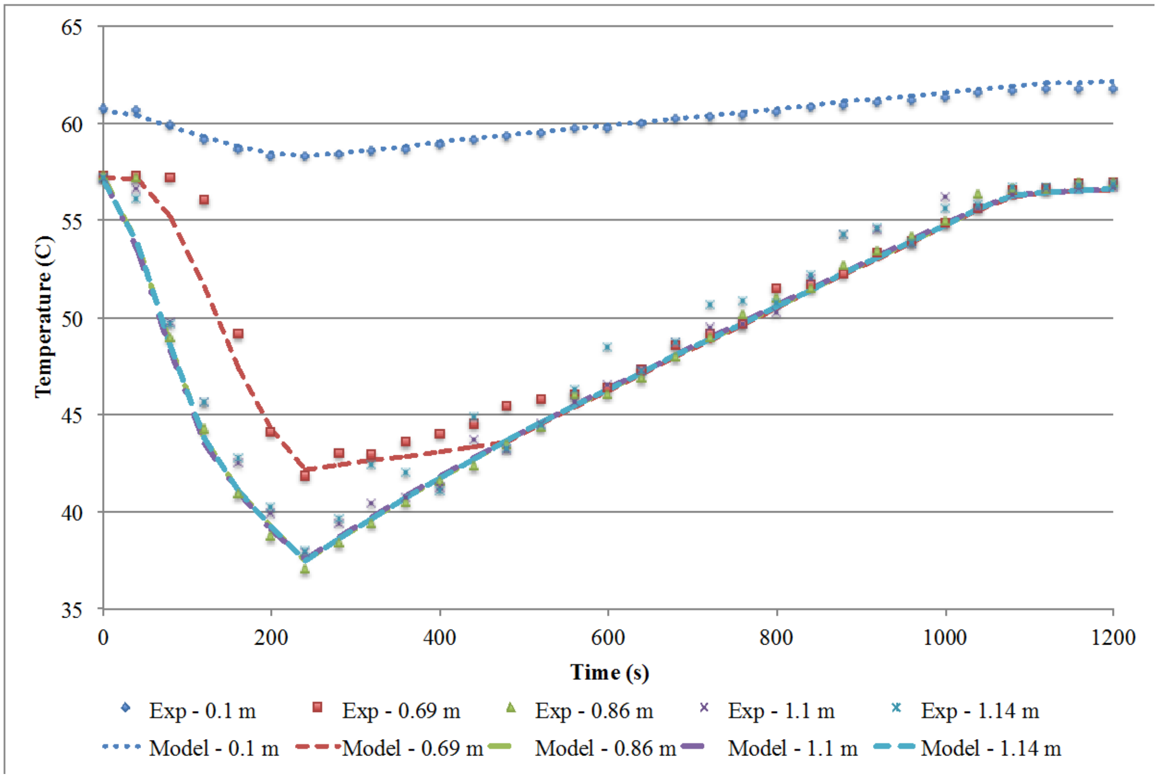

Figure 10: Results from the Third Comparison to Experimental Data

- The changes to the flue gas temperature calculation (using an average temperature to calculate a constant heat transfer to the flue wall) made a big improvement in the sections above the stratification layer. The experimental data and simulation results at 0.1 m agree very strongly. The 0.69 m data imply that there are still some improvements that can be made. The experimental data show that the temperature at that height in the simulation results should begin to decrease later and the temperature rise after the draw is still slower than in experimental data.
- In this data simulation the results did not show an increase in temperature after the burner stopped firing. No change was made to the model that was expected to solve this problem, so it is still considered an issue.

2.1.2.8 Future Work

There are several known issues with the storage tank water heater model that need to be resolved in future work. They are as follows:

- The current calibration was performed using a single convection coefficient between the hot gas and the flue wall for both when the burner is firing and when it is not. This assumption both makes no sense physically (when the burner is firing there will be a higher flow rate, and higher convection coefficient) but also creates an inaccurate temperature profile for the hot gas in the flue. Creating a second convection coefficient for when the burner is off would allow for a better calibration and a more accurate model.

- Due to the nature of simulation in Modelica smoothing functions were used in some situations instead of if statements. Smoothing functions were a necessary improvement as they cause the simulation to operate much faster; however, they introduce some error. In situations where the temperature difference checked in the smoothing function is smaller than the delta of the smoothing function a value between 0 and 1 will be returned. This can cause some mass and energy to be lost in the calculations resulting in error. As future work code should be added to address these induced errors.
- The algorithm modeling mixing in the bottom of the tank caused by a water draw event is currently coded such that there is a region that mixes in all draws. We believe that the height of the mixing region will vary depending on the flow rate of the draw and the dip tube end geometry. Future versions of the model will have a more complex algorithm that can change the height of the mixing zone depending on the draw flow rate.
- In some situations segments of the tank gain a noticeable amount of heat right after the burner stops firing. Future versions of the model will improve the model to avoid this behavior.
- The stratification layer is identified using two different algorithms in two different calculations. The calculations were previously performed using the same algorithm. Attempts to do the calculations with the same algorithm resulted in calculations within the smoothing region of the smooth Heaviside function. The simulations were very slow, and the results were poor. There is some error with the current algorithm, situations where heat will not be accounted for. Future work includes finding a way to use the same algorithm for both calculations of the stratification layer without introducing the smoothing error.

The Storage Model Use Tutorial is available in **Error! Reference source not found.**.

2.2 Tankless Water Heater Models

An existing single-nodal tankless model, designated Type 940 and originally developed for the TRaNsient SYstems Simulation (TRNSYS) was utilized for the HWSIM integration to achieve a first-of-its-kind, whole house water heating system analysis tool capable of simulating interactive hot water generation and distribution and its resulting energy and water use and waste. This tankless TRNSYS model also served as the basis for the development of a more advanced Modelica tankless model.

2.2.1 Existing Tankless Water Heater Model

The existing tankless water heater model was presented by J. Burch, J. Thornton, M. Hoeschele, D. Springer, and A. Rudd, in a paper entitled “Preliminary Modeling, Testing and Analysis of a Gas Tankless Water Heater” [75].

Tankless Water Heater Modeling

The operation of the tankless water heater is broken into four modes:

1. Steady state is the period with outlet temperature of the tankless water heater is steady, within controller ability.
2. Ramp-up is the period of time of draw up until steady state is reached.
3. Environmental delay is the mass temperature decay after firing; outlet temperature of the tankless water heater approaches temperature of the environment.
4. Draw decay is the mass temperature decay after firing, but with the draw continuing; outlet temperature of the tankless water heater approaches the inlet water of the tankless water heater

A one-node model with heat exchanger mass is presented to allow accurate efficiency estimates under any operation or assumed draw pattern, as is shown in Figure 11. Key model parameters, including burner efficiency (η), thermal capacitance (C), and loss coefficient to the environment (UA), were determined from test data.

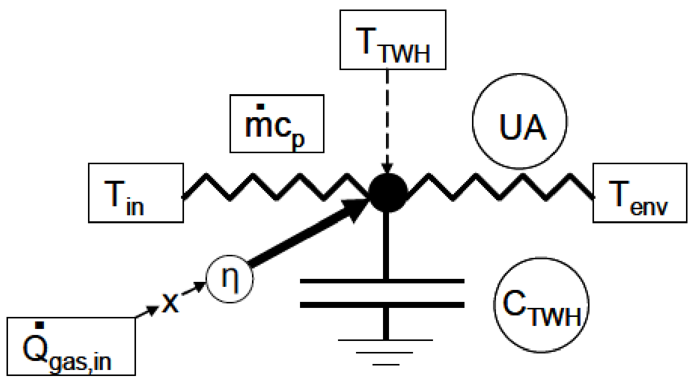

Figure 11: Tankless thermal circuit model.
Variables in boxes are measure; parameters in circles are to be determined.

Tankless Water Heater Testing

Although standard test results are available to compare tankless heaters with storage tank heaters, actual savings depend on the draw details because energy to heat up the internal mass depends on the time since the last draw. Two data sets were analyzed, the first is the published energy factor, which uses large-volume draws only (10.6 gallon or 40 L/draw), and the second data set is a realistic draw pattern of frequent of small-volume draws.

Tankless Water Heater Analysis

Burner efficiency showed inconsistency between the two data sets analyzed. Model calculations show that efficiency with a realistic draw pattern is ~8% lower than that resulting from using the large 10.6 gallon draws, as specified in standard water-heater tests.

The model is also used to indicate that adding a small tank controlled by the tankless heater ameliorates unacceptable oscillations that tankless with feedback control can experience with pre-heated water too hot for the minimum burner setting. The added tank also eliminates problematic low-flow cut-out and hot-water delay, but it will slightly decrease efficiency.

2.2.2 Advanced Tankless Water Heater Model

As noted previously, a series of equations were defined for developing advanced analytical simulation models for a variety of gas water heaters. In order to model the energy and mass flow in any system, global conservation laws must be implemented to derive the general equations. Conservation analysis begins with control volumes. The equations to be used in simple water heater simulation models for tankless water heaters are described in this proceeding section, and for storage (tank) water heaters in a previous section.

The heat exchanger in the tankless water heaters will be modeled using the effectiveness-NTU method.

Equation 40: Maximum Possible Heat Transfer

$$\boldsymbol{q_{max} = C_{min}(T_{h,i} - T_{c,i})}$$

Where

$T_{h,i}$ is the temperature of the hot fluid at the inlet and

$T_{c,i}$ is the temperature of the cold fluid at the inlet.

C_{min} is equal to C_c or C_h , whichever is smaller.

C_c and C_h are defined as

$$\boldsymbol{C_c \equiv c_{p,c}\dot{m}_c}$$

$$\boldsymbol{C_h \equiv c_{p,h}\dot{m}_h}$$

Equation 41 The number of transfer units (NTU) is a dimensionless parameter

$$\boldsymbol{NTU \equiv \frac{UA}{C_{min}}}$$

U is the overall heat transfer coefficient. U is calculated from the thermal resistances in the system.

Equation 42: Effectiveness

$$\boldsymbol{\varepsilon = \frac{q}{q_{max}}}$$

The effectiveness, ε, is the ratio of actual heat transfer to the maximum possible heat transfer rate for a heat exchanger. For a variety of flow arrangements in heat exchangers, the effectiveness can be expressed as a function of NTU andC_{min}, and vice versa. By measuring the inlet temperatures and the mass flow rates of both the hot and cold fluids, in addition to the heat input from the hot gases, a relation can be derived for the performance of the heat exchanger. This will provide an empirical model for the given water heater. However if the heat exchanger has a specified flow arrangement, various correlations for the effectiveness-NTU can be employed.

Tankless Water Heater Simulation Model

The tankless water heater model was developed based on the TRNSYS Type 940 tankless water heater model. Documentation describing previous work converting the original single node Type 940 to a multi-node model was used as the basis for the model [9].The previous work detailed algorithms used for calculations, assumptions used in the creation of the model, a recommended test protocol to identify parameters calibrating a given heater and a validation test protocol.

Experimental data from the previous work was used to validate the Modelica version of the model. As part of the thesis, experiments were performed on a Rinnai R75Lsi tankless water heater at the National Renewable Energy Laboratory. The specifications of the heater are given in Table 5 [8].

Table 5: Rinnai R75Lsi Specifications

Rated Inlet Heat Rate (kW / Btu/hr)	52.75 / 180,000
Minimum Inlet Heat Rate (kW / Btu/hr)	4.40 / 15,000
Energy Factor	0.84
Minimum Water Flow Rate (kg/s / gal/min)	0.043 / 0.7

2.2.2.1 Model Documentation

Design

The model is created in a hierarchical manner. The top layer consists of six components; one component keeping track of the time in the simulation, four components reading data input files, and one component for the tankless water heater. An image of the top layer of the model is presented in Figure 12**.** The tankless water heater model itself is broken into two components; one component describes the heat transfer within the burner and heat exchanger while the other component emulates the logic contained within the controller. The model of the tankless water heater itself is shown in Figure 13.

The four data input files are used to read time varying data. A user can edit these files to vary the conditions and model any given situation. The input models read user specified text files.. The four input files contain data describing the ambient temperature, temperature of fluid entering the heater, draw pattern and power signal. The power signal is a simple binary operator used to say whether or not the heater is turned on.

The heat exchanger and burner is a simplified model which uses a number of assumptions to make the model more usable. Creating a simplified model allowed for the ability to describe any heater using parameters easily identified from experimental data. The parameters used in TRNSYS Type 940 include the capacity of the heat exchanger, the heat loss coefficient (UA value) of the unit, and the steady state efficiency of the heater [9]. These three parameters are also used in the LBNL model. Currently the burner and heat exchanger are modeled using written code instead of using the more visually accessible schematic diagram editor that makes Modelica user friendly.

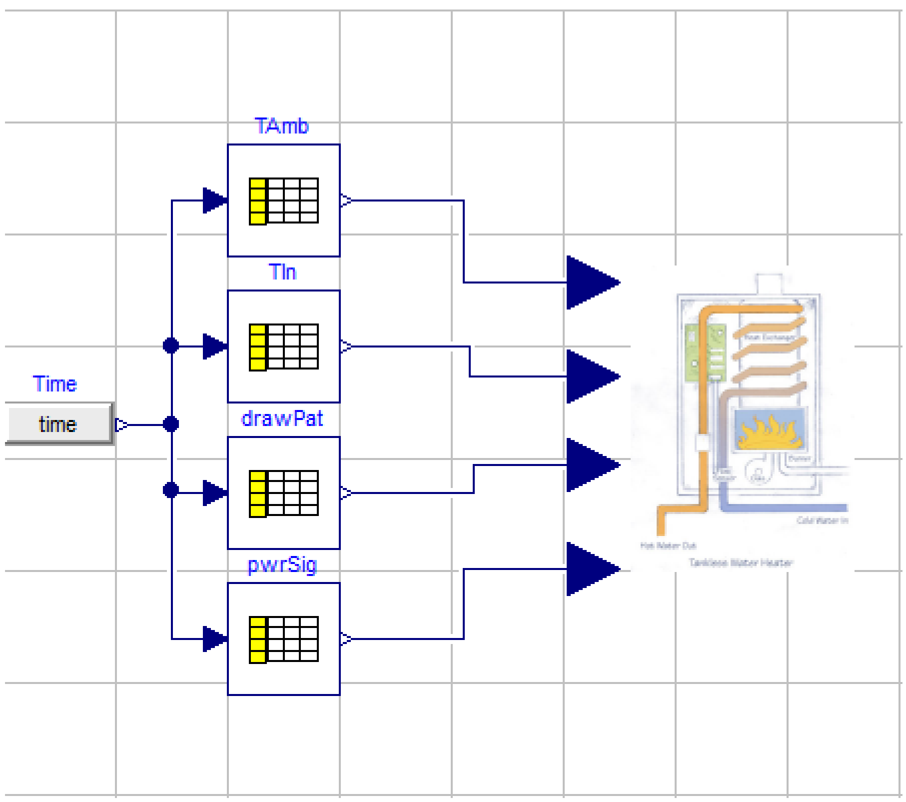

Figure 12: Top Level of the Tankless Water Heater Model

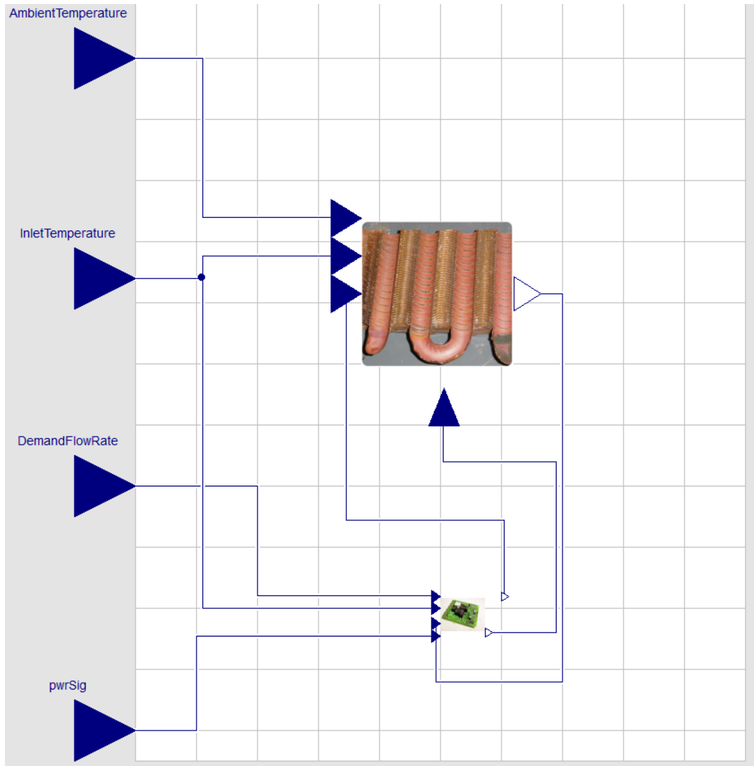

Figure 13: Image of the Tankless Heater Model

The controller module was designed to imitate the control logic of the Rinnai R75Lsi. It includes logic checks for the minimum flow rate, minimum heat rate, maximum heat rate, Proportional-Integral-Derivative (PID) control and a power setting. The power setting can be used to simulate situations where the heater is turned off. Currently the controller is implemented as one single unit that contains all of this logic. The minimum flow rate, minimum heat rate, maximum heat rate and power signal logic were taken from TRNSYS Type 940 while the PID control is new to the LBNL model.

Similar to models in TRNSYS information is passed between components through lines connecting the models. To gather input information four data files are used to describe the hot water draw pattern, inlet water temperature, ambient temperature and power status of the heater. This information is passed into the heater model. Within the water heater model the inlet temperature, demand flow rate and power signal are passed to the controller. The controller then determines how the heater will behave based on the logic presented in Figure 14.

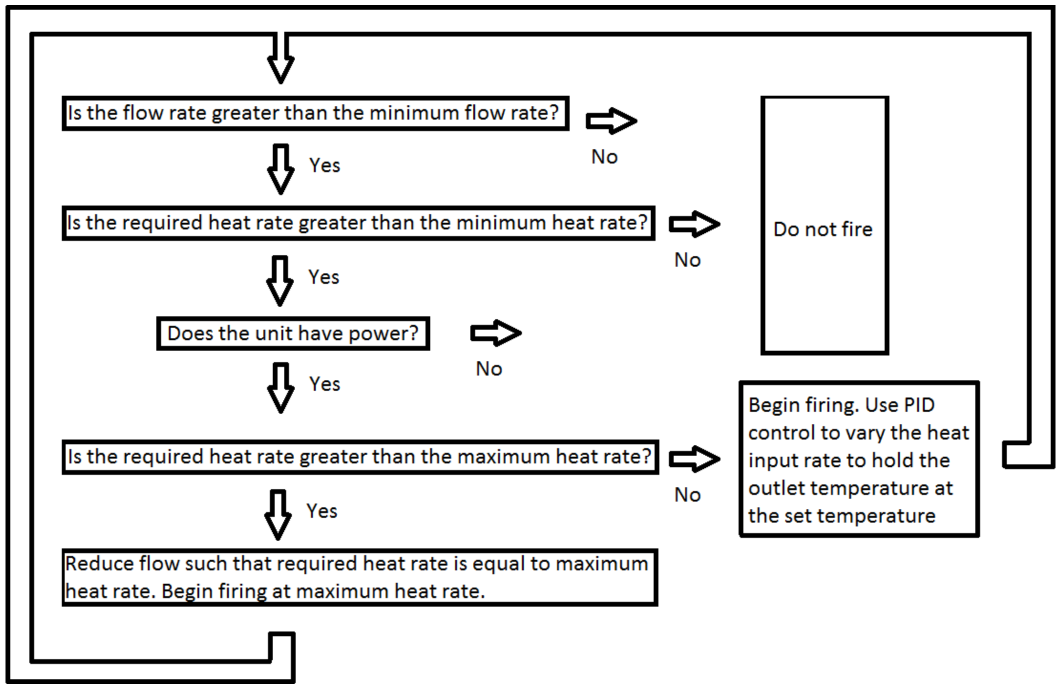

Figure 14: Tankless Heater Control Logic

Once the control checks are completed the controller sends a control signal and a water flow rate value to the burner and heat exchanger module. The control signal represents a fraction of the maximum heat rate the burner should use when firing. In cases where the heater should not fire the control signal is zero. In cases where the heater operates at maximum capacity the control signal is one. In any other case the control signal is determined by the control logic. The water flow rate signal from the controller will almost always be the flow rate entered by the user. In some situations however the inputs will result in a situation where the heater cannot meet the set temperature. When this situation arises the controller will reduce the water flow rate until it can maintain the set temperature. In those situations the water flow rate sent to the burner and heat exchanger will represent the reduced flow rate.

The component representing the burner and heat exchanger uses the inlet temperature, ambient temperature, controlled water flow rate and control signal as inputs. Calculations in this component are performed using the algorithms in TRNSYS Type 940 [9]. It then calculates the temperature of the heat exchanger in a user specified number of nodes, the energy delivered to the water, the energy lost to the environment, the energy stored in the heat exchanger (relative to 0°C), the input energy and the outlet temperature. Several other intermediate variables are also available as outputs. The outlet temperature is then passed to the controller for use in the feedback control logic used to calculate the control signal.

Outputs from the model, which are available for connection to other components, are the outlet water temperature and the controlled water flow rate.

Calculations

Calculations for the Modelica tankless water heater model are performed in the same manner as TRNSYS Type 940 [9].

Equation 43: Burner and Heat Exchanger component are based around the governing differential equation for a multiple node heat exchanger model.

$$\frac{C}{N}\frac{dT_i}{dt} = \frac{\eta_{SS}\gamma\dot{Q}_{Rated}}{N} + \frac{\eta_P\dot{Q}_P}{N} - \dot{m}c_p(T_i - T_{i-1}) - \frac{UA(T_i - T_{Amb})}{N}$$

In the case where the first node is being simulated T_{i-1} is replaced with T_{Inlet}.

In order to make Equation 43 easier to program it was broken into three separate pieces. The system of equations is then solved together. The equations are presented in Equation 44 through Equation 46.

Equation 44: Part One of Equation 43

$$\frac{dT_i}{dt} = aT_i + b$$

Equation 45: Part Two of Equation 43

$$a = \frac{-1}{C}\left(\dot{m}C_pN + UA\right)$$

Equation 46: Part Three of Equation 43

$$b = \frac{1}{C}(\eta_{SS}\gamma\dot{Q}_{Rated} + \eta_P\dot{Q}_P + \dot{m}c_pNT_{i-1} + UAT_{Amb})$$

In Equation 46 the T_{i-1} term is replaced with T_{Inlet} when calculations are being performed for the first node. Equation 44 through Equation 46 are the only equations necessary to determine the temperature of each node in the tankless heater during the simulation. Other equations are used to identify the delivered energy, energy lost to the environment, consumed energy and energy stored in the heat exchanger. They are displayed in Equation 47 through Equation 50.

Equation 47: Delivered Energy

$$\dot{Q}_{Delivered} = \dot{m}c_p(T_{Out} - T_{Inlet})$$

Equation 48: Energy Lost to the Environment

$$\dot{Q}_{Environment} = \sum_{i=1}^{N}\frac{UA}{N}(T_i - T_{Amb})$$

Equation 49: Consumed Energy

$$\dot{Q}_{Consumed} = \gamma \dot{Q}_{Rated} + \dot{Q}_p$$

Equation 50: Energy Stored in the Heat Exchanger

$$Q_{Stored} = \sum_{i=1}^{N} \frac{C}{N} * (T_i)$$

Most of the calculations performed in the controller for the tankless water heater are very simple. There are four logic checks used to determine the control signal and one used to determine the controlled water flow rate. The four logic checks used to identify the control signal are as follows:

1. Comparing the minimum flow rate to the draw flow rate
2. Comparing the required heat rate to the minimum heat rate
3. Checking the power signal to ensure the unit is turned on
4. Calculating the appropriate control signal based on PID control

All four checks report a control signal value. Logic checks one through three are binary, and return a control signal of either zero or one. A zero signal indicates that the condition is not met and the burner should not fire while a one signal indicates that conditions are met and the burner should fire. For an example see Table 6.

Table 6: Logic Check Example

	Case	
	1	2
Minimum flow rate (kg/s / gal/min)	0.043 / 0.7	0.043 / 0.7
Draw flow rate (kg/s / gal/min)	0.0312 / 0.5	0.056 / 0.9
Check one control signal	0	1

In case one the draw flow rate is below the heater's minimum flow rate and the burner should not fire. This is indicated by the returned control signal of zero. In case two the draw flow rate exceeds the minimum flow rate and the burner should fire. This is indicated by the returned control signal of one.

The first three control logic checks operate in the same manner as the minimum flow rate check. The fourth logic statement used to identify the control signal uses a standard PID controller to identify what the control signal should be when the unit is firing. The P, I and D values are inputs in the model. When all five logic checks are performed the control signals are identified to find the final control signal. The algorithm used is presented in

Equation 51.

Equation 51: Final Control Algorithm for Logic Check

$$\gamma = \gamma_{\dot{m}} * \gamma_{\dot{Q}} * \gamma_P * \gamma_{PID}$$

Equation 51 multiplies the four control checks with each other. The three terms for flow rate, heat rate, and power signal are all binary. The PID term returns a value between zero and one representing the fraction of rated heat the heater should burn. In a case where all three binary logic checks are met the equation will return the PID value. In a case where one of the binary logic checks is not met the equation will return a zero indicating that the heater should not fire.

The logic checks are performed continuously. The heater begins firing when all of the logical conditions are met, and stops firing when one or more of the conditions are no longer met.

Two equations are used to control the flow rate through the tankless water heater. They are presented in Equation 52 and Equation 53.

Equation 52: Amount of Heat Required to Bring Fluid to Set Temperature

$$\dot{Q}_{Required} = \dot{m} c_p (T_{Set} - T_{Inlet})$$

Equation 53: Available Flow Rate

$$\dot{m} = \frac{\eta_{SS} \dot{Q}_{Rated}}{c_p (T_{Set} - T_{Inlet})}$$

Equation 52 is used to identify the amount of heat required to bring the heated fluid to the set temperature. Once it is identified $\dot{Q}_{Required}$ is compared to the available heat rate, which is equal to $\eta_{SS} \dot{Q}_{Rated}$. If the required heat rate exceeds the available heat rate the heater limits the water flow rate such that it can meet set temperature with a control signal of one. That flow rate is identified using Equation 53.

Characterization and Validation

The model was validated using a two step process. First experimental data was used to calibrate the model. This step identified the parameters used to describe a specific heater. Experimental data collected at NREL by Grant was used for this process [9]. The test model Rinnai R75Lsi was previously described in Table 2. After the characterization process was complete the results of the model were compared against experimental results for a different draw profile.

Characterization Procedure

A special data set was prepared specifically for calibrating the model. It was designed to contain sections of the test that could be used to identify the three parameters (η_{SS}, C, UA) necessary to describe a certain heater. A plot detailing the characterization test protocol is shown in Figure 15.

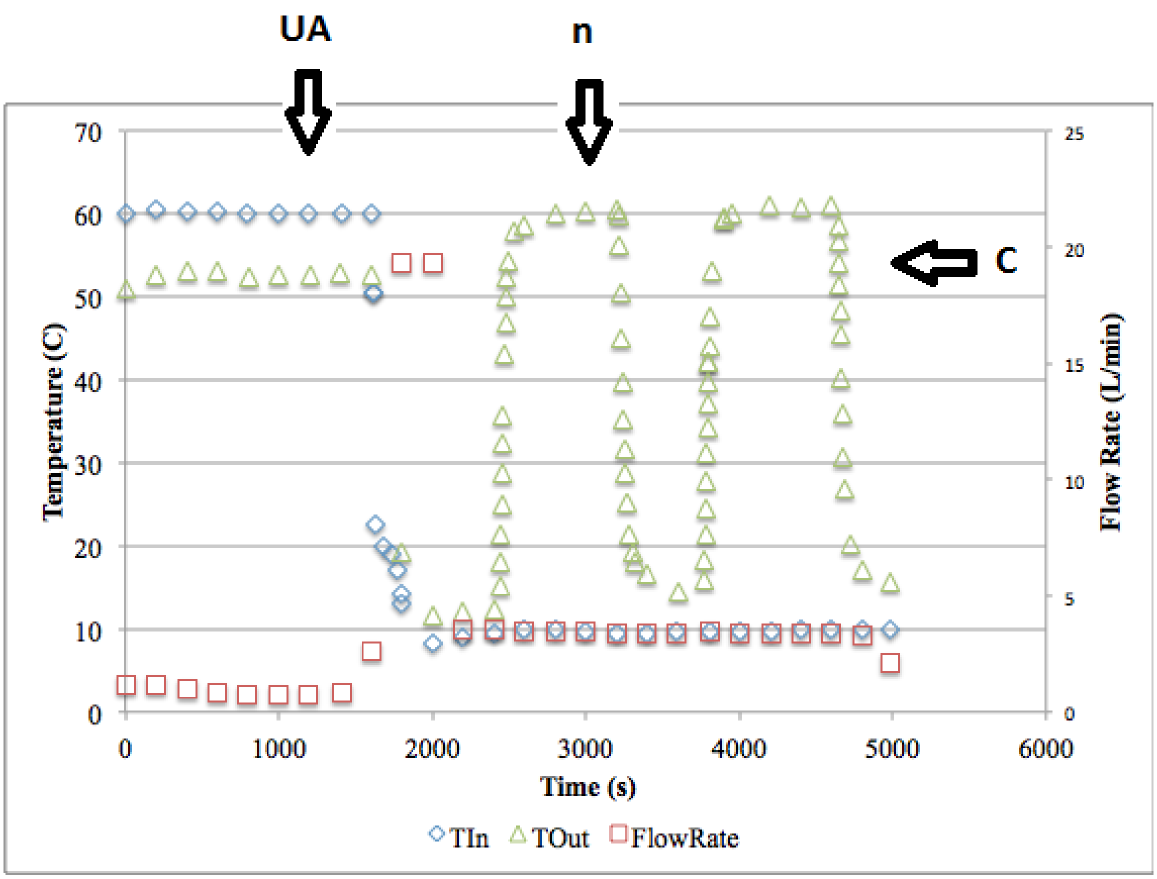

Figure 15: Characterization Protocol Data

The characterization test consists of four phases.

- The first phase is used to identify the heater's UA value. During the first phase the inlet water was preheated and introduced to the tankless heater at a low flow rate. During this phase the heat lost to the environment was equal to the heat lost from the water. Because the heat lost from the water was identifiable the only unknown in the equations was the *UA* value. An example of this phase can be seen between approximately minutes 0 and 25 in Figure 15.

- The second phase was used to purge the system of all heated water. Mains water was introduced to the tankless heater at a high flow rate. Doing so purged all room temperature water from the mains line, and removed heat from the heat exchanger (reducing the temperature of the heat exchanger to the mains water temperature). An example of this phase can be seen between approximately minutes 25 and 30 in Figure 15.
- The third phase of the test was a steady state burn, and is intended to be used to identify the steady state efficiency of the heater. For this phase of the test the inlet water was not preheated, and was held at a flow rate of 3.5 L/min. The heater was turned on allowing it to heat the water to the set temperature. Burns were allowed to run for 10-20 minutes leaving enough time for clear steady state operation. The steady state efficiency could be identified by comparing the inlet heat rate in the simulation to the inlet heat rate in the experimental data. An example of the third phase of the test can be seen between approximately minutes 40 and 55 in Figure 15.
- The fourth phase takes place right at the end of the third phase. In the fourth phase the tankless water heater was turned off, and the water flow rate was allowed to continue. During this period the temperature of the heat exchanger and the temperature of water leaving the heat exchanger rapidly decayed. This temperature decay was caused by both heat being transferred to the water and environmental losses; however, the heat transferred to the water was several orders of magnitude higher than heat lost to the environment. The rate at which the temperature of the exiting water decayed allowed identification of the capacitance of the heat exchanger. An example of this phase can be seen in approximately minute 85 in Figure 15.

The characterization process was completed using the characterization protocols contained within Dynamic Modeling Laboratory (Dymola) [10]. The Dymola characterization protocols were only able to run a single characterization test, varying a single parameter at a time. In order to overcome this weakness a script was created which told Dymola to perform several characterization simulations in a row.

For this characterization the parameters identified by Grant when working on TRNSYS Type 940 were used as starting points [9]. The beginning capacitance used was 8360 J/C, the original UA value was 3.6 W/C and the steady state efficiency was set to 0.83. The steady state efficiency was left at 0.83 as this allowed the script to be used to identify PID constants for the controller as well.

Characterization Results

The final values identified by the characterization process are shown in Table 7.

Table 7: Characteriztion Results

Capacitance (J/°C)	13140
UA (W/°C)	13.65
Steady State Efficiency	0.83
PID - P	0.4059
PID - I	47600
PID - D	35.35

Plots displaying how simulation results compare to experimental data are shown in Figure 16 and Figure 17.

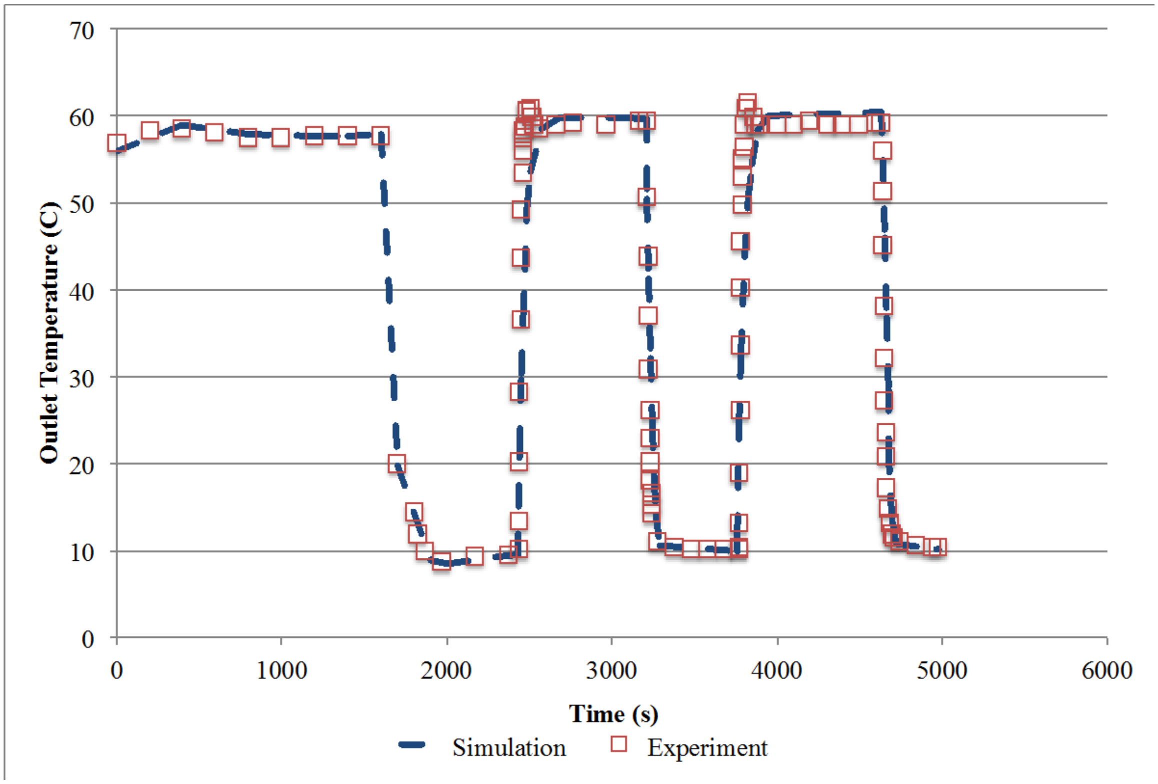

Figure 16: Comparing Water Temperature During the Characterization Test

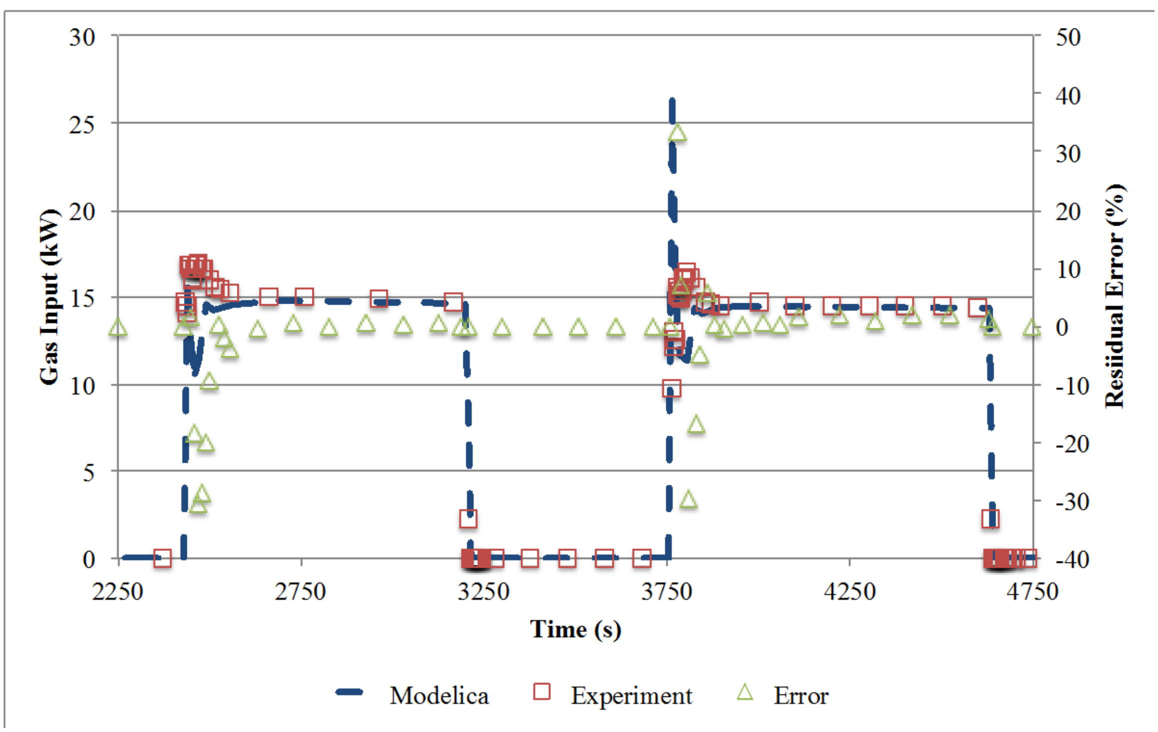

Figure 17: Comparing Natural Gas Flow Rate During the Characterization Test

As can be seen in Figure 16 and Figure 17, the simulation results closely match the experimental data. Figure 16 allows for comparison of the outlet temperature while Figure 17 allows for comparison of the heat consumption rate. There are a few notable differences between the simulation and experiment.

- At the start of the test the simulation results show fluctuation in the outlet temperature while the experimental results do not. This is likely caused by the fact that the simulated heat exchanger had more nodes than experimental data measurements. Because of this difference several temperatures used to describe the initial conditions of the heat exchanger were assumptions and will cause some error.
- The PID controller is not precisely matching the controller in the Rinnai R75Lsi heater. This can be determined by examining the error data in Figure 17. The error in natural gas consumption is typically nearly zero, but can rise to ±30% at the start of a draw. This error at the start of a draw is likely caused by integrator windup in the PID controller [11]. Future versions of the LBNL model will improve these results.

Validation Protocol

After the characterization process was completed a second test was performed to validate the model. The model may have matched the experimental data during the characterization protocol specifically because the characterization process forced it to and the validation protocol was intended to ensure that the model could match a different draw profile. The validation protocol was used to check the behavioral control logic of the model as well as its ability to predict outlet temperatures and heat rates. The inlet conditions used in the validation protocol can be found in Figure 18. The validation draw profile consisted of seven phases. Vertical lines are drawn at important points to help differentiate phases.

The 18 L/min flow rate at the very beginning of the test was used to purge the lines of room temperature water. After the purge the flow rate was reduced to 4 L/min and the inlet flow was switched to preheated water. The combination of 4 L/min flow and 44 °C inlet temperature (with a set temperature of 49 °C) created a situation where the heater should not fire because the required heat was less than the minimum the heater could provide. The third phase reduced the flow rate to 2 L/min and returned the inlet water to mains. This phase tested the response of the heater and simulation tool to a water flow rate below the minimum flow rate. The fourth phase increased the flow rate to 6 L/min creating a normal burn situation. The fifth phase increased the demand flow rate to 22.5 L/min and surpassing the heaters ability to meet demand. This phase was used to check the simulation tools ability to predict water flow rate controlled by the heater. The sixth phase reduced the flow rate back to 6 L/min continuing the burn phase. After the burn the flow was stopped causing gradual heat decay in the heat exchanger on heat transfer to the environment for 30 minutes (seventh phase). After the 30 minute delay the flow rate was increased to 2 L/min to push the hot water out of the heat exchanger and identify the stored heat.

Validation Results

LBNL model results are compared to NREL's experimental data in Figure 19 through Figure 21.

Figure 19 shows outlet temperatures as predicted by the LBNL model and as collected experimentally. Throughout most of the test, the model results agree closely with the experimental data. The following conclusions can be drawn regarding model behavior:

1. The LBNL model correctly identified when the required heat rate was less than a heater's minimum heat rate for firing.
2. The LBNL model correctly determined when the water flow rate was less than the heater's minimum flow rate and the heater did not fire.
3. During periods when the heater did fire, the simulation model correctly maintained the set temperature.

The model results and experimental data show some discrepancy in temperatures during the long decay from 4,500s to 6,500s. The discrepancy occurs because the two results represent slightly different measurements. The data from the LBNL model represent the water temperature precisely at the outlet of the heat exchanger. The experimental data represent the temperature of water in a pipe just outside the jacket of the tankless water heater. This

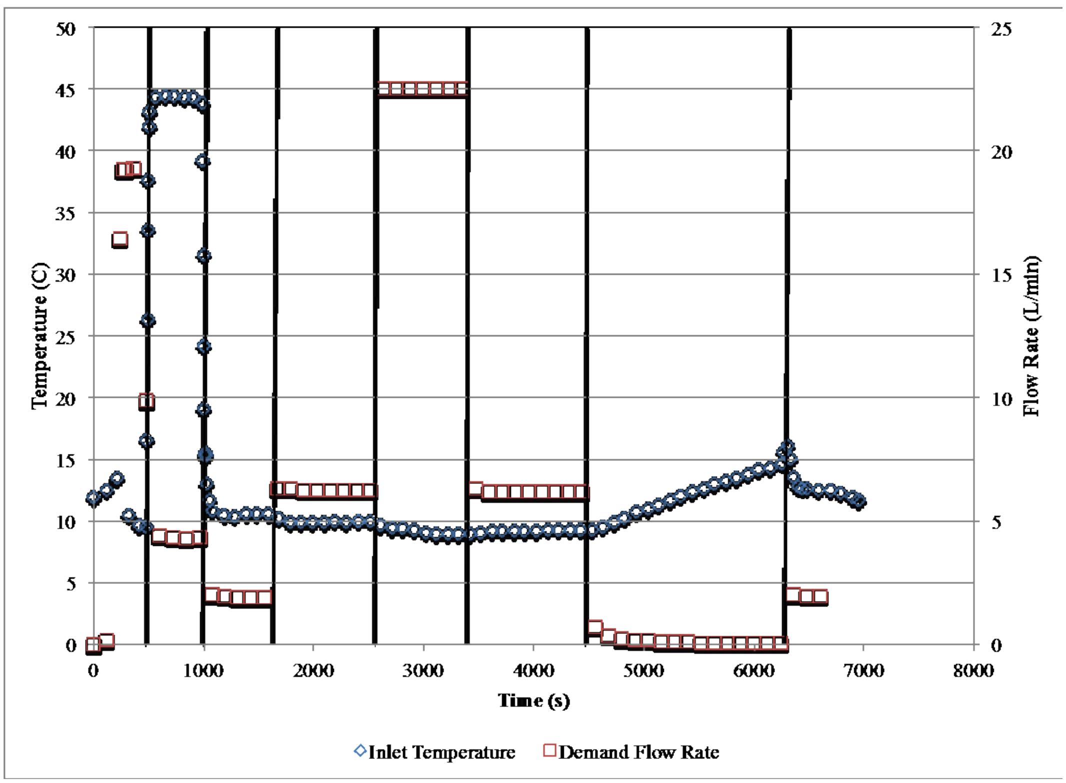

Figure 18: Conditions Describing the Validation Protocol

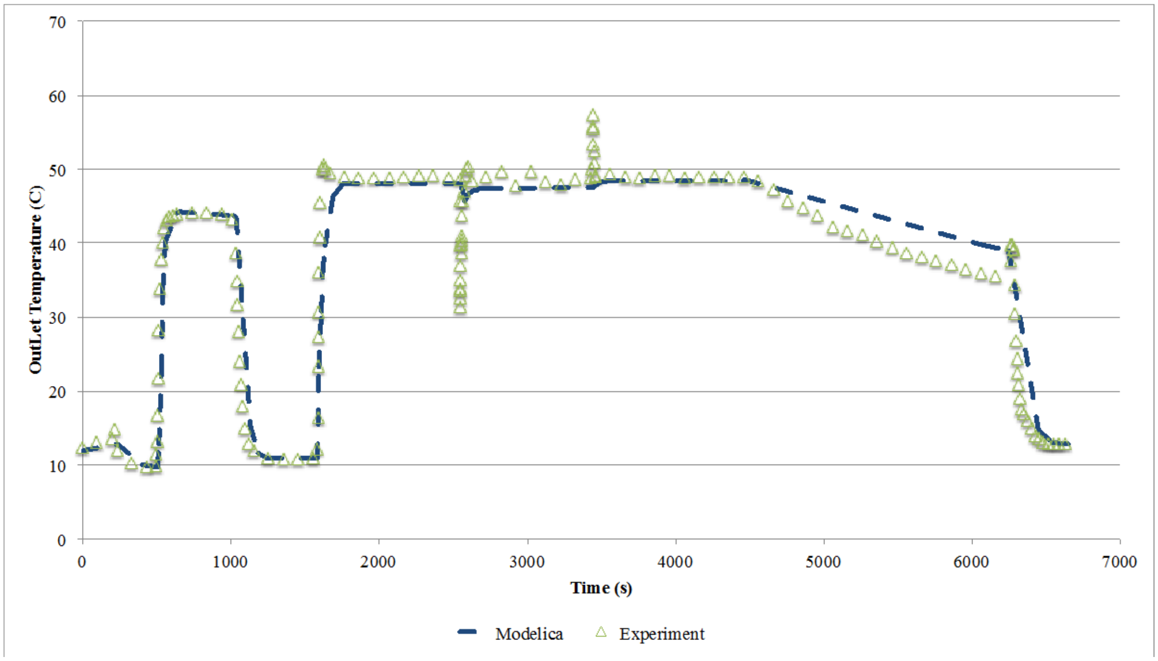

Figure 19: Outlet Temperatures During Validation Simulation

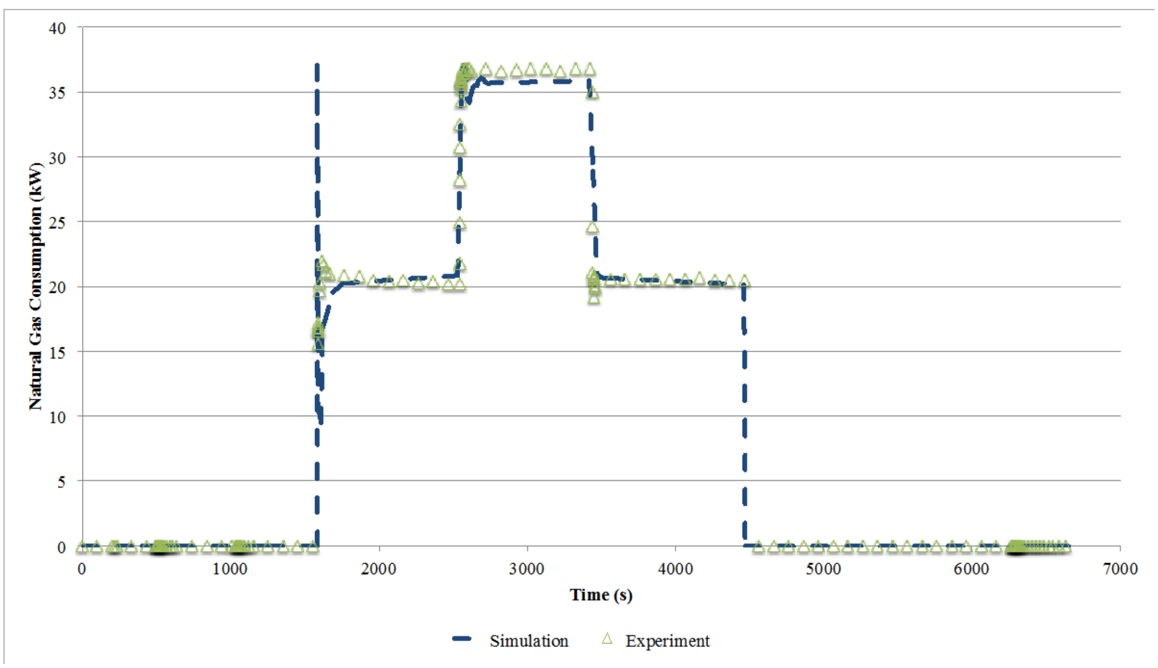

Figure 20: Gas Consumption Rates During Validation Simulation

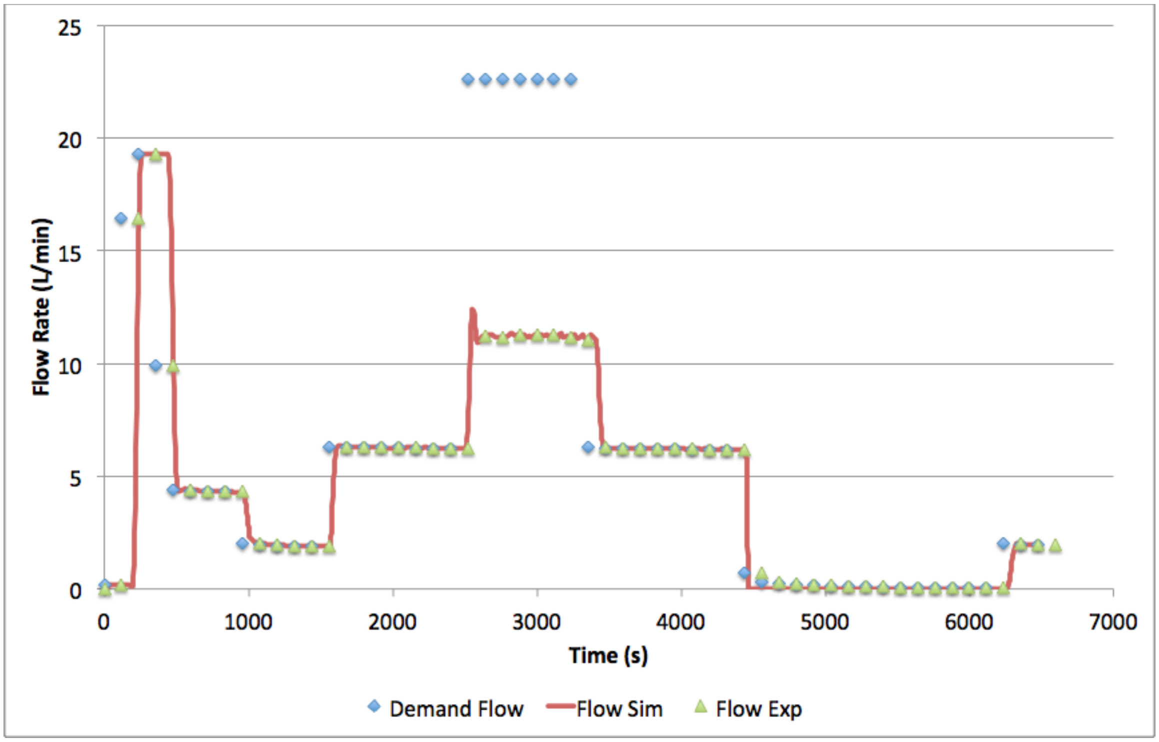

Figure 21: Water Flow Rates During Validation Simulation

discrepancy may be caused because water in the pipe outside the heater cools off faster than does the heat exchanger itself. This theory is supported by the data at 6,500s. When a slow water flow rate is initiated at 6,500s, the experimentally recorded water temperature instantly increases by 5 °C, indicating that the water in the heat exchanger was hotter than the water in the pipe. The temperature of the experimentally measured water also increases to that predicted by the simulation, indicating that the simulation accurately predicts the heat lost in the heat exchanger between draws.

Figure 20 compares data on the rate of natural gas consumption as predicted by the LBNL model to experimental data. The data in Figure 20 support the following conclusions, which were noted previously.

1. The LBNL model correctly identified when the required heat rate was less than the heater's minimum rate, so that the heater did not fire.
2. The LBNL model correctly determined that when the water flow rate was less than the heater's minimum rate, the heater did not fire.
3. The LBNL model correctly predicted the amount of natural gas needed to bring the water to the setpoint during steady-state periods of the draw.
4. Characterization of the PID controller remains inadequate. The LBNL model does not yet capture the transient behavior of the heater.

5. The LBNL model may predict gas use poorly for the start of a draw (see 1,750s in Figure 20). We believe this result is caused by windup in the PID controller, an effect that will be accounted for in future versions of the model.

Figure 21 shows water flow rates as predicted by the LBNL model and as collected experimentally. The period of interest in Figure 21 is the draw between 2,500s and 3,500s. The demand flow rate during this period was 23 L/min requiring more heat than the heater could provide. The controls of the tested heater reduced the water flow rate, as measured experimentally, to 11 L/min. The simulation model also reduced the flow rate to 11 L/min indicating that the flow reduction logic is working correctly.

2.2.2.2 Conclusions

The LBNL Modelica model was created using code taken directly from TRNSYS Type 940. During the creation of the Type 940 model, statistical evaluations were used to demonstrate that the model predictions were within the uncertainty of the data used in the validation process [9]. Because the LBNL model both uses Type 940 code and agrees closely with both Type 940 results and experimental data, we believe that validation of the LBNL model, as described here, is adequate.

2.2.2.3 Future Work

There are several ways the model of the tankless water heater can be improved. They are:

- The PID constants do not accurately mimic the behavior of the controls in the Rinnai R75Lsi. This is likely a characterization issue; the experimental data used to develop TRNSYS Type 940 was not intended for use identifying PID constants making it hard to use that data to do so. Plans for future work include creating a different characterization draw profile that will be better suited to identifying PID constants. The characterization will then be repeated to identify the more accurate PID constants. Additionally, experimental data has shown that non-condensing tankless water heaters sometimes have a default initial burn rate [12]. Future versions of the LBNL model will be able to simulate this control strategy.
- Currently the portion of the model describing the heat exchanger and burner is programmed in Modelica language code instead of using a schematic diagram. This makes it more difficult for future users to use, and will be improved at a later date.
- The controller model contains logic for several different logic checks and calculations. Currently it is presented as one single controller with several logical checks. Not all tankless water heater controllers will have the same logic. Plans for future work include changing the assembly of the controller so that it contains one component designed to model each logical check. This process will include creating single components to perform each logical check. Doing so will make it easier for future users to create their own controllers to match the heater they are using.

The complete Tankless Model Use Tutorial is available in **Error! Reference source not found.**.

2.3 Hot Water Distribution Model Enhancement and Water Heater Models Integration

Several HWSIM enhancements were necessary preparations for the integration of water heater models into the simulation program. With these preparations in place, DEG, in coordination with LBNL, successfully integrated existing tank (storage) and tankless type water heater models with HWSIM.

2.3.1 HWSIM Enhancement Overview

HWSIM is a simulation software suite that analyzes the energy and water use and waste in residential hot water distribution systems. The original version of the Windows-based, public domain tool was released in 2008. The 2008 tool used simplistic models of gas and electric storage water heaters and gas tankless water heaters, as the primary function of the model was to exclusively evaluate the distribution system. The simplistic water heater models accounted for water heater efficiency variations with load, but assume a fixed hot water outlet temperature to the distribution system. A major element of the GTI PIER hot water project was to enhance the model by integrating detail atmospheric gas storage water heater and gas tankless models with the distribution model. The enhanced model also has user interface improvements, ability to perform batch simulations, and database reporting of both summary and high fidelity results.

Developmental challenges prevented resources from being available to develop and validate buried pipe systems, continuous recirculation systems with the enhanced Tank and Tankless models, and water waste due to mixed flow regimes. As it stands, HWSIM is a tool that provides better clarity and insight into energy and water use in hot water distribution systems, and can help evaluate design alternatives for maximizing water heating system energy efficiency.

2.3.2 Objectives

In developing a higher fidelity hot water distribution simulation software, a few key objectives were defined early in the process:

- **Integrate Tank and Tankless Models** - First, a high resolution multi-nodal atmospheric center flue water heater model (TANK) was targeted for integration into HWSIM. TANK is a detailed variable time step simulation model developed by Battelle in 1993 for the Gas Research Institute. In addition, the Type 940 gas tankless model (first developed for TRNSYS, a time-based transient performance model simulation suite), was also chosen for integration. Both models were originally time-derivative models and used different approaches to integration to the discrete volume based simulation.
- **Add Radiant Heat Transfer** - The 2008 HWSIM utilized a convective “UA” pipe heat loss model. Integrating radiant heat transfer algorithms is an important addition to the model in terms of accuracy.
- **Multi-Run Capability** – The original objective was to develop a parametric solver for comparative runs, however significant developmental tasks associated with the water

heater integration effort delayed the development of this capability. Batch-run capabilities were developed as a first-step towards meeting this objective.

- **Database Result Storage** - With the addition of high-fidelity output from the integrated water heater results, an SQL database was provided for storing and retrieving discrete results. Results from the models were also used to validate the annual results compiled for the reports.
- **Usability** – Several changes were made to the user interface to make available parameters necessary to run the specified models, as well as to simplify the operation.
- **Pipe heat loss validation** – Extensive runs were done to compare simulated pipe heat loss to lab results from Applied Energy Technology.
- **Update documentation** – Software documentation is being updated in conjunction with the release of the public domain software.

2.3.3 Project Approach

Tank Model Integration and Validation

The approach to integrating TANK with HWSIM was governed by the different simulation method used (TANK using time step versus HWSIM using discrete volume), the amount of runtime required, and a lack of detailed programming documentation available for TANK. The TANK source model used a variable time step based on the level of activity (short time step for draw events and burner firing events, incrementally longer time steps during standby periods), and iteratively solved for the outlet temperature until the solution converged, which could involve several iteration steps. To begin transferring to HWSIM, the processing model was normalized to a single 24 hour simulation run and called as a separate process by HWSIM at the end of each simulation day. The convergence algorithm was removed and a fixed number of iterative steps were provided as an input parameter to the simulation.

The original implementation of TANK uses MS Excel and Visual Basic for Applications (VBA), which was used as the baseline for comparing results. LBNL provided a port of this model as a Visual Basic .NET executable, which was the starting point for the integration project.

TANK integration with HWSIM was implemented by isolating the calling code from the LBNL executable and recompiling the core simulation code into a .NET DLL (Dynamic Link Library) callable from HWSIM through an I/O layer (input/output). The IO layer was developed based on the existing TANK input file structure and a subset of available output by creating .NET classes that could be readily managed programmatically by HWSIM. The major challenge to this was translating the HWSIM Draw Schedule, the primary variable input, into draw format required by TANK. Much of this translation was done through experimentation due to a total lack of programming documentation for TANK and the many discrepancies exposed throughout the project.

TANK was modified to read and write the HWSIM-TANK data structures, in addition to the standard TANK input and output files. In fact, many of the simulation parameters are still contained in the two TANK input files for Hardware and Operation, and read normally.

Changes are then made to selected variables, including the draw schedules, ambient and water temperature, water heater setpoint, plus a number of custom status tracking and value variables. Output is normalized to the HWSIM structure for insertion into the database.

It was determined that in order to obtain more accurate results from the Tank model, it is necessary for multiple simulation iterations to TANK's solver to converge on the final temperature. This is accomplished by iteratively running the simulations for HWSIM and then TANK, each time using the updated temperature profile from the TANK runs. The amount of time required for a TANK simulation of 24 hours to complete can easily exceed 15 minutes for a typical run. The original 2008 HWSIM simulation year was comprised of a seven day draw pattern capability for 12 months per year[1]. The integrated HWSIM-TANK tool with 84 days (7 x 12) to simulate, and multiple iterations, could take 7 hours or more to complete a full simulation. To expedite simulation time, a single representative day per season was defined. The weighting values assigned to each season can be modified through the user interface as shown in Figure 22.

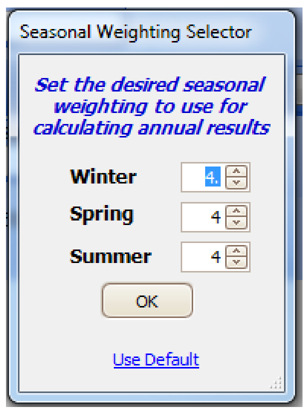

Figure 22: Seasonal Weighting

Final results were compared against the Visual Basic (Excel model) to ensure with multiple runs, multiple iterations, the tank is reporting correctly and it's results, including burner usage, are parsed properly to HWSIM results.

Tankless Model Integration and Validation

[1] The seven day, twelve month approach allowed for day-to-day variations in hot water draw patterns, and month-by-month variations in cold water inlet temperatures and varying temperatures of the pipe heat loss environments.

A different approach was taken to integrate the Tankless model, as the original source model was a discrete time-based model, and could be easily modified to solve on a discrete volume at varied flow-rates. The source model was a Type 940 model developed for TRNSYS, a time-derivative modeling platform. The model was essentially one core function, with inputs and outputs defined while model parameters were contained in a file look-up. To integrate into HWSIM the original FORTRAN function was converted to C, as a stand-alone solver, and then to Visual Basic for ease of integration into HWSIM. The solution time-step was converted to a discrete volume (for HWSIM consistency), and to solve for the effects of the heat exchanger, the tankless model was constructed as a series of multiple identical tankless elements, each equal to the solver's discrete volume. Each heat exchanger element could be individually controlled, in terms of firing status. At startup, all elements are likely firing, but as the outlet temperature reaches setpoint, later elements stop firing or fire at a reduced rate. The tankless parameters were initially separate input files, but were later integrated into the simulation input file, for ease of transport and lookup. Figure 23 shows the model inputs, outputs, and model parameters.

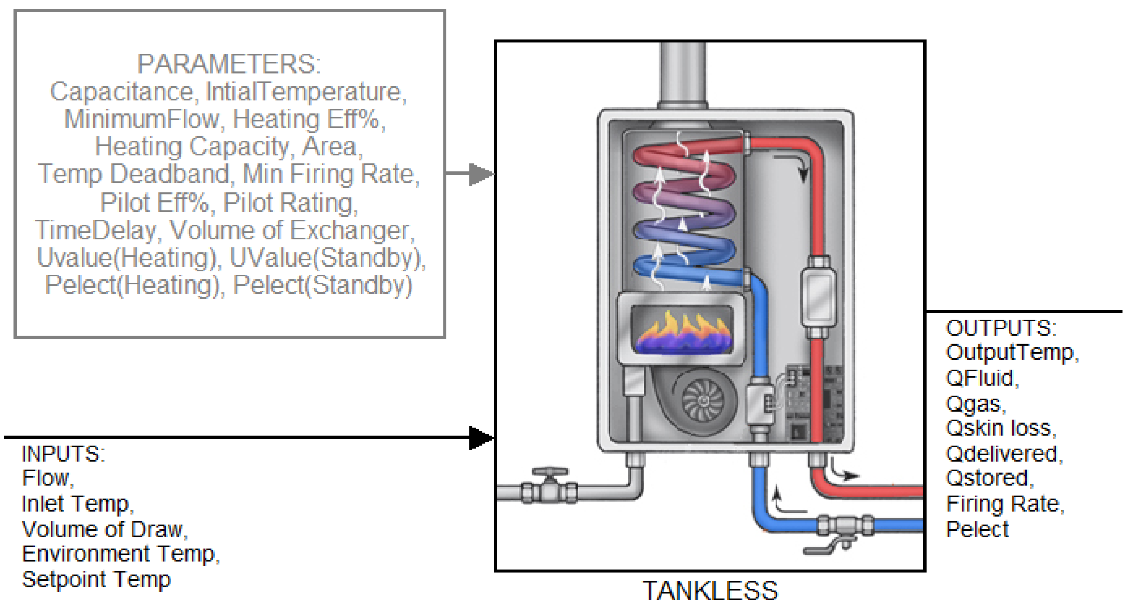

Figure 23: Tankless Model

The original call-back structure for TANK was to simulate TANK first, then use a lookup function to grab the correct temperature at time-of-day to simulate moving through the pipe. HWSIM's existing simplistic water heater model assumed the outlet temperature was always at the user-specified set point, ignoring any variations that are common to both storage and tankless units during the course of a draw event. In order to simulate HWSIM with Tankless, the tankless routine needed to be called in every instance HWSIM does a lookup, and it needs to store its state variables for the next call-back, so that capacity and heat exchanger temperatures could be maintained between discrete volume elements and between draws. To save simulation time, the tankless model was represented as a single lumped mass element in between draw times, and relaxed thermally along with the distribution system, until the next draw event in the schedule occurs. The validation effort spanned the entire development process, with each integration step followed up with a set of runs to compare tankless output back to the original TRNSYS model.

Multi-Run Capability

The objective was to achieve a platform for parametric runs for analysis. The first step was to provide the ability to run a batch of input files and assemble results. The integration effort for TANK and Tankless was exhaustive, including ensuring state information for multiple iterations of tank for multiple simulations did not cross-pollinate, left little time to develop this capability further. As it stands, it is fairly easy to modify inputs manually and save them as separate input files to be run in batch mode.

Figure 24 shows the batch run setup, with the software auto-recognizing input files from the user's directory and polling them for selection. Batch runs are selected by water heater, so that a series of distribution systems could be analyzed with the same specified water heater.

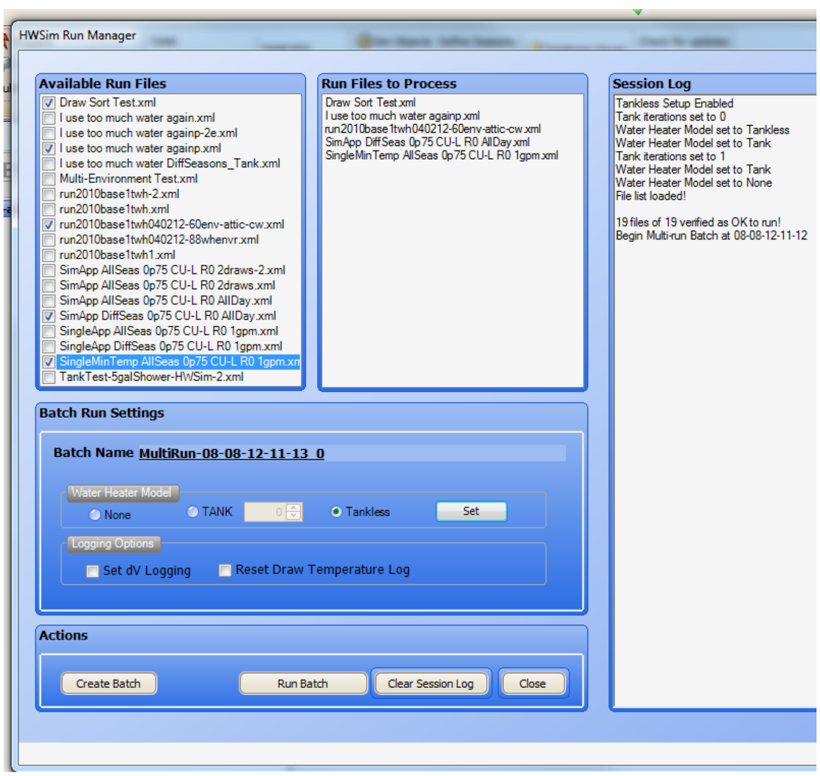

Figure 24: HWSIM Run Manager

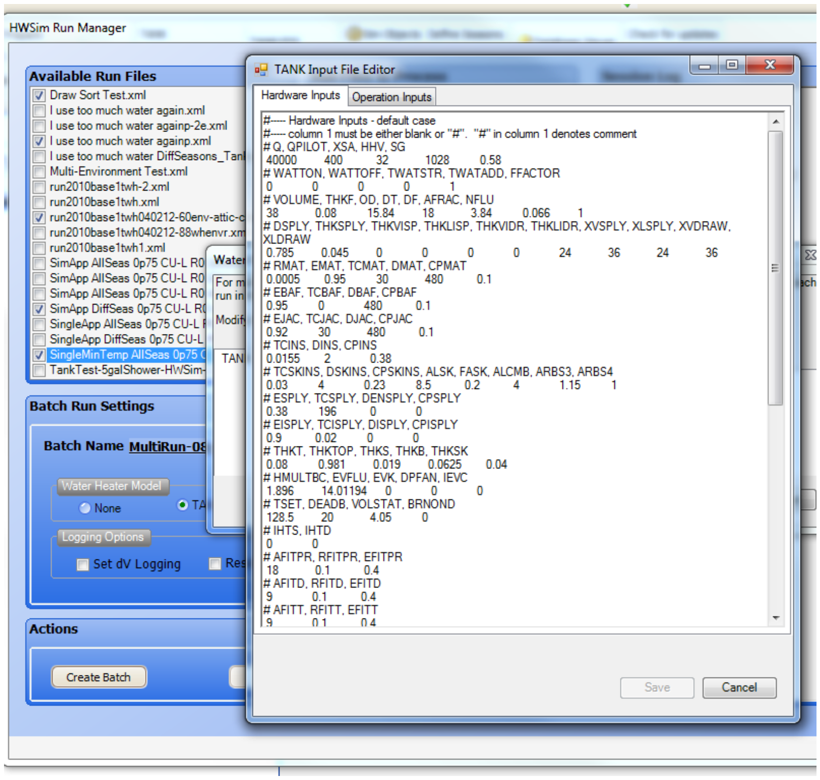

Figure 25: HWSIM Run Manager - Edit TANK Inputs

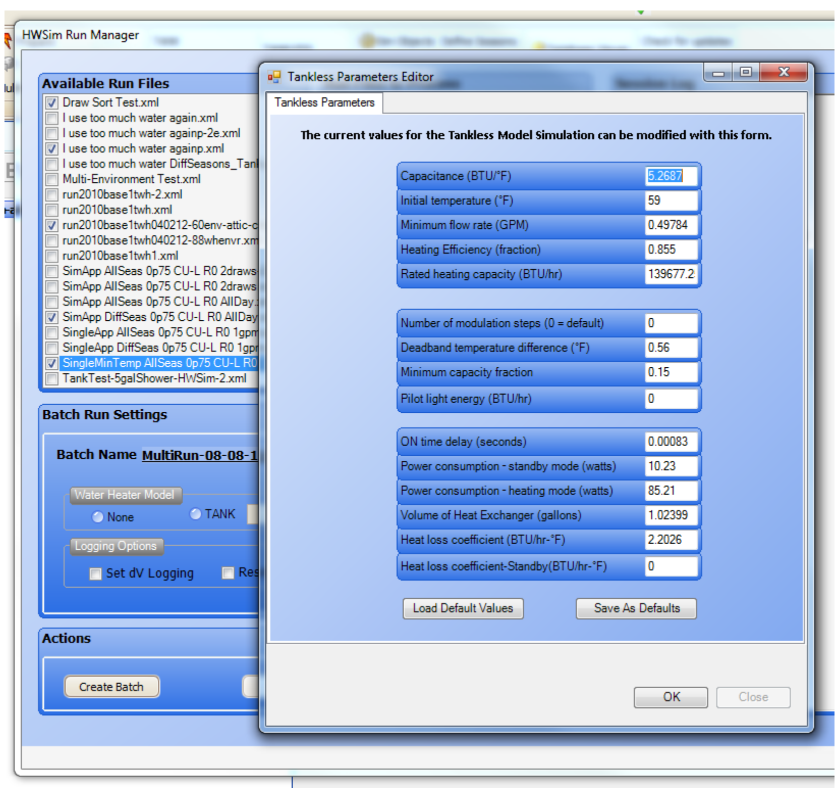

Figure 26: HWSIM Run Manager - Edit Tankless Parameters

When selecting either TANK or Tankless, the parameters show up as an editable file or menu (Figure 25 and Figure 26), just as they do when you run a single case. After editing parameters, you save and then run the batch file. A status window is provided on the right to monitor progress.

Database Result Storage

A compact SQL database (Figure 27 and Figure 28) has been added that stores the results for each run. The results shown are a single run for each day (the source data for the annual reports), and can be exported from the application to Excel. The detailed TANK and Tankless results are provided as well, whereas TANK results are shown for a full day of each iteration, Tankless results are only shown during the draw or recirculation periods. The initial states at each draw or recirculation event are reflective of the relaxation period between these events. The database can also be accessed independently from HWSIM by using any number of database tools to query the data. (One such free tool is CEQuery and can be downloaded at http://cequery.codeplex.com/.)

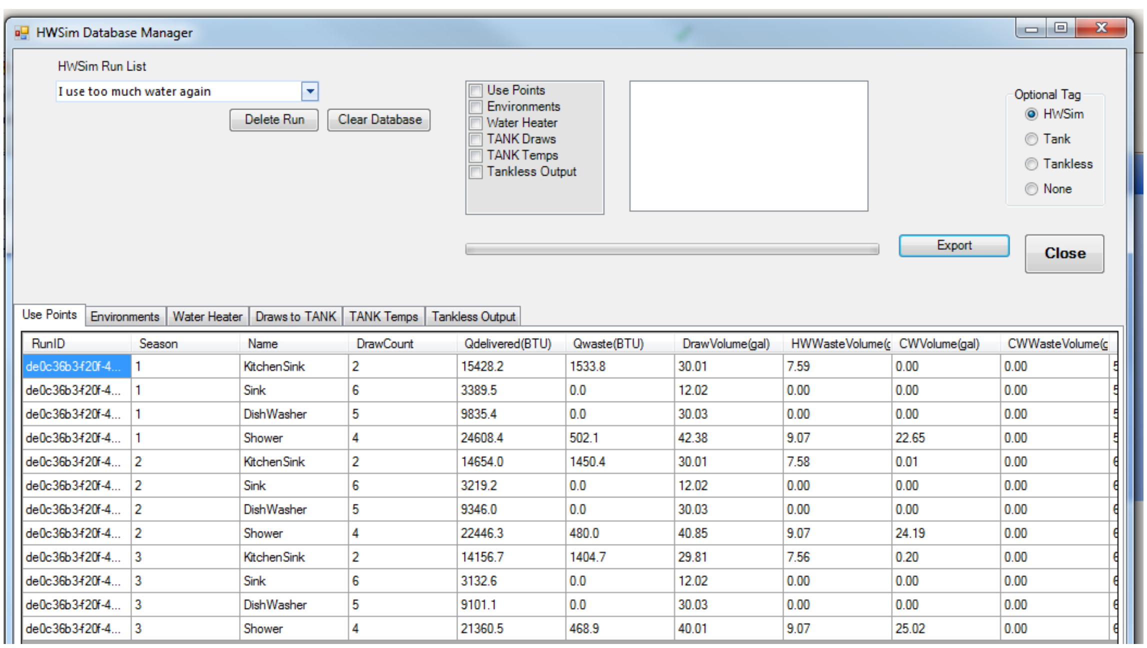

Figure 27 - HWSIM Database Manager

Interface Usability

A number of new input and process control forms were added to HWSIM as part of the water heater models integration, database and multi-run additions. The main application form was improved with a ribbon-style tool bar (Figure 29) to accommodate the new features. In addition to the multi-run manager and database viewer, software updates can be easily integrated with a built in utility that self-installs the latest code updates.

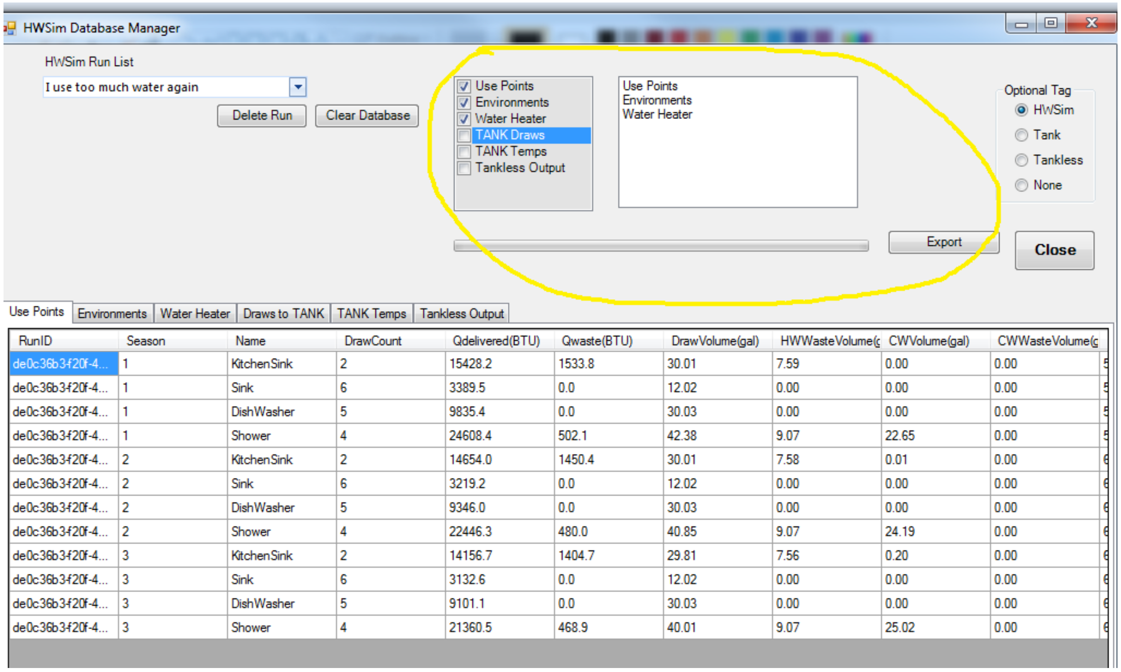

Figure 28: HWSIM Database Manager - Export to Excel

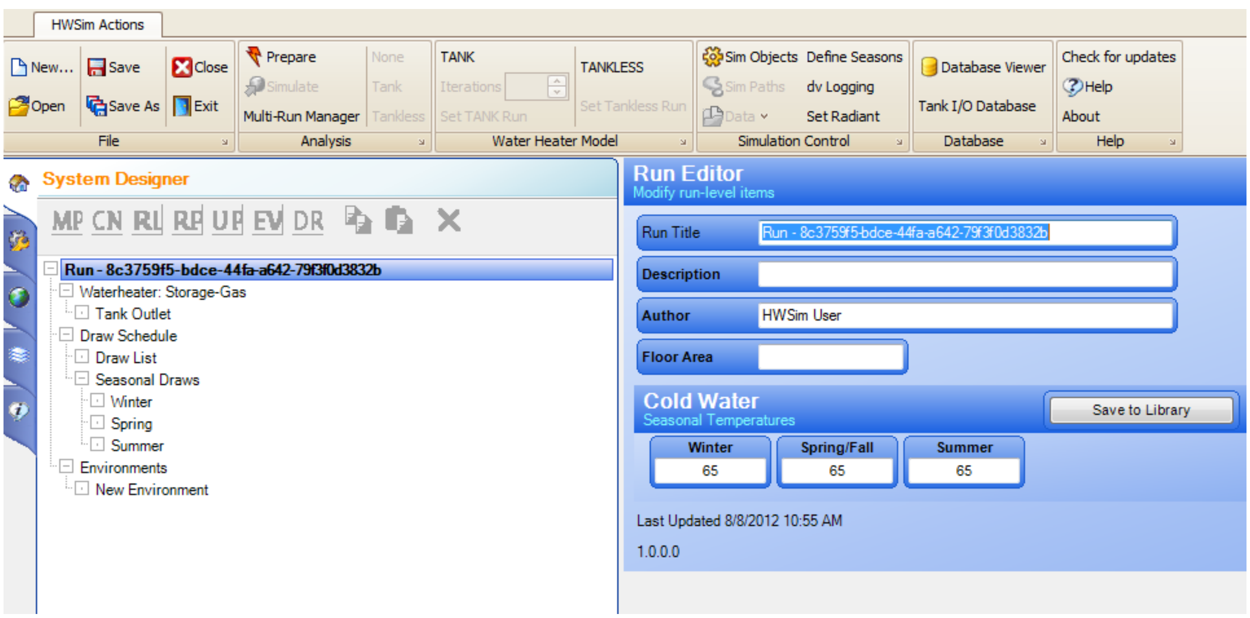

Figure 29: HWSIM System Layout

Pipe Heat Loss

The development of the combined convective/radiant pipe heat transfer relied on calculating a combined surface heat transfer coefficient based on the input parameters shown in Table 8. The calculation methodology, outlined in

Table 9, is based on standard heat transfer calculations for free convection and radiation. The calculation process involves first determining an exterior surface coefficient based on an initial estimate of surface temperature. The initial coefficient was calculated using standard pipe heat transfer modeling for horizontal cylinders at moderate surface temperatures. The interior coefficient is then calculated based on the pipe fluid velocity. The methodology utilizes Newton's method to iterate in determining a final surface temperature estimate that is used for determining the combined convective and radiant heat transfer. This technique is then used for each discrete volume node of the piping network where water is flowing, accommodating changes in fluid temperature, environment air and mean radiant temperature, and fluid velocity (as pipe diameters change). Nestled inside the HWSIM simulation log, at the end of each draw, the starting and ending draw outlet temperature is reported with the draw summaries. To validate the pipe heat loss algorithm, this log was modified to additionally supply temperatures before and after relaxation times. Laboratory testing results from Applied Energy Technology (AET) provided discrete results on testing a series of pipes, tested at two steady-state flow rates and stagnant relaxation. Simulated versus lab heat loss comparisons were completed for 100 foot pipe lengths for the parameter combinations shown in

Table 10.

Table 8: Pipe Heat Loss Calculations - Inputs

Input Variable Description	**Equation (or value)**
T_w, water temperature (°F)	
T_e, environment temperature (°F)	
T_{si}, initial surface temperature estimate (°F)	$(T_w+T_e)/2$
T_r, Mean radiant temperature (°F)	
F, flow rate (gpm)	
k_p, pipe conductivity (Btu/hr-ft-°F)	
k_i, insulation conductivity (Btu/hr-ft-°F)	
L_i, insulation thickness (inches)	
σ, Stephan-Boltzmann constant (Btu/hr-ft^2-degR^4)	1.714×10^{-9}
ε, surface emissivity (non-dimensional)	
R_i, inside pipe radius (ft)	

R_o, outside pipe radius (ft)	
R_s, outer surface radius (ft)	$R_o+L_i/12$

Table 9: Combined Convective and Radiant Heat Transfer Modeling Algorithm

Calculated Variable Description	Equation
h_{oi}, initial surface air film estimate (Btu/hr-ft^2-°F)	$.27*\left[\frac{\mid T_{si}-T_e \mid}{2*R_s}\right]^{.25}$
V, fluid velocity (ft/sec)	$\frac{\frac{.1337*F}{60}}{\pi R_i^{\ 2}}$
h_i, inside film coefficient estimate (Btu/hr-ft^2-°F)	*If V < .02* $\frac{1.828*.3641}{R_i}$ *Else* $150*\frac{(1+.011*T_w)^{.8}}{(R_i*2*12)^{.2}}$
U_i, inside total U-value (Btu/hr-ft^2-°F)	$\frac{1}{\frac{\frac{1}{R_i*h_i}+\frac{\ln\frac{R_o}{R_i}}{k_p}+\frac{\ln\frac{R_s}{R_o}}{k_i}}{R_s}}$
f, T_s written as a function	$\sigma\varepsilon(T_{si}+460)^4+(h_o+U_i)*T_{si}$ $-\left(U_i*T_w+h_{oi}*T_e+\sigma\varepsilon*(T_r+460)^4\right)$
f', derivative of f	$4\sigma\varepsilon(Tsi+460)^3+hoi+Ui$
T_{sf}, final surface temperature (°F)	$T_{sf}-\frac{f}{f'}$
h_o, final surface airfilm (Btu/hr-ft^2-°F)	$.27*\left[\frac{\lvert T_{sf}-T_e\rvert}{2*R_s}\right]^{.25}$
Q/l, heat flow to environment (Btu/hr-ft)	$2\pi R_s*(\sigma\varepsilon((T_{sf}+460)^4-(T_r+460)^4+(T_{sf}-T_e)*h_o)$

UA, overall pipe UA (Btu/ft-°F)	$\frac{Q}{(T_w - T_e)}$

Table 10: Pipes Validation Cases

Parameter 1 Pipe Type	Parameter 2 Nominal size	Parameter 3 Insulation	Parameter 4 Flow Rates
Copper Type L	3/8 ″	None	1 gpm
Rolled Copper	½″	½″	2 gpm
PEX	¾″	1″	stagnant
CPVC			

Update Software Documentation

An update to the user documentation will be submitted with the next public release version of the HWSIM software package. This will include instructions for simulation, interpretation of results, and user tips.

2.3.3.1 Results of TANK Model Validation

The initial validation of the conversion of TANK to Visual Basic was completed by LBNL. Once integrated into HWSIM, a number of simulations were performed to evaluate the iterations necessary for a stable solution. In Figure 30 below, a sample single day simulation shows close convergence within 3 iterations.

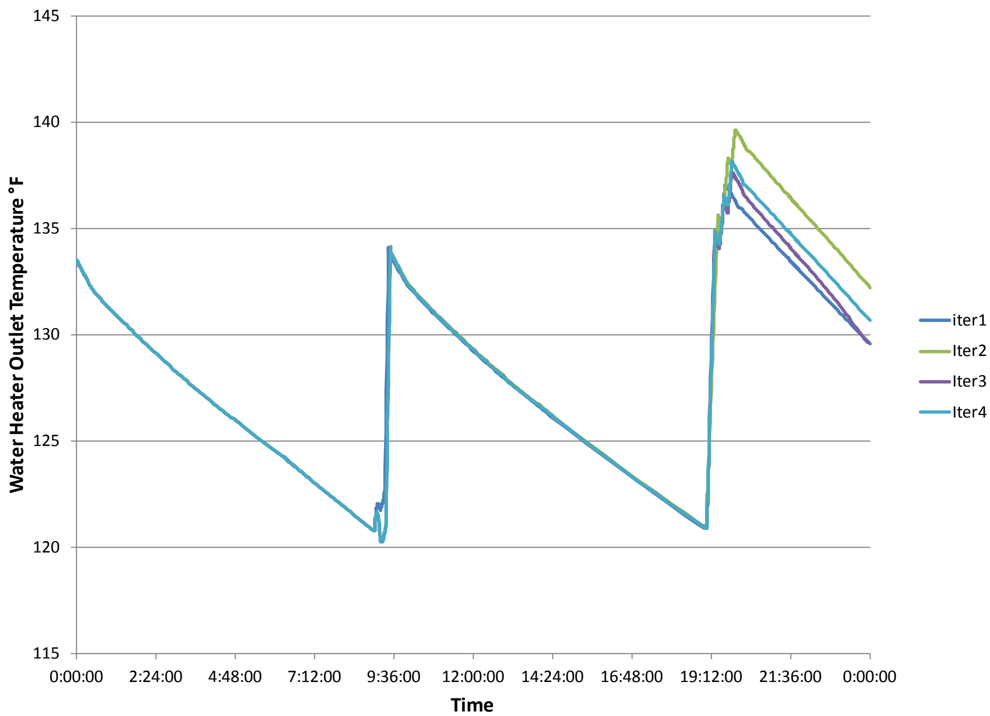

Figure 30: Iterative Results for TANK outlet Temperature

GTI provided a set of TANK input files that were generated based on experimental runs performed with the original TANK code by GTI. The single difference between these two models is the solution solver, where the Excel VB model has an auto-convergence algorithm, HWSIM has a discrete convergence technique (in this case, four iterations for convergence). Both models were simulated utilizing the Energy Factor test specifications. Table 11 compares results from the two models.

Table 11: Pipes Validation Cases

Rated EF Tank Model	Draw Schedule	TANK Vb Model			HWSIM+Tank		
		Q_{load} (Btu)	Q_{gas} use (Btu)	EF (unadjusted)	Q_{load} (Btu)	Q_{gas} use (Btu)	EF
0.54	EF_{Test}	42,915	76,536	**0.5607**	43,283	76,395	**0.5666**
0.59	EF_{Test}	40,562	67,159	**0.6040**	43,777	72,284	**0.6056**
0.614	EF_{Test}	40,811	65,128	**0.6266**	44,004	69,975	**0.6289**
0.67	EF_{Test}	40,660	59,804	**0.6799**	43,866	64,642	**0.6786**

Tankless Model Validation

At each integration step, a set of draws was simulated to verify the integrity of the model as its language was modified, as it was broken out to a series of tankless elements and changed to the discrete volume solver. The final comparison, shown in Figure 31 below, shows a representative appliance draw and min-temp draw[2] simulated with TRNSYS and with HWSIM-Tankless. HWSIM-Tankless shows some minor settling error, due to the simulation assuming the tankless is divided into a series of self-controlled units, where downstream heat exchanger elements throttle back the burner quicker than others based on the current hot water demand and heating rate. “Stored Energy” represents the capacitance effect and skin loss represents the thermal losses from the heat exchanger to the ambient environment.

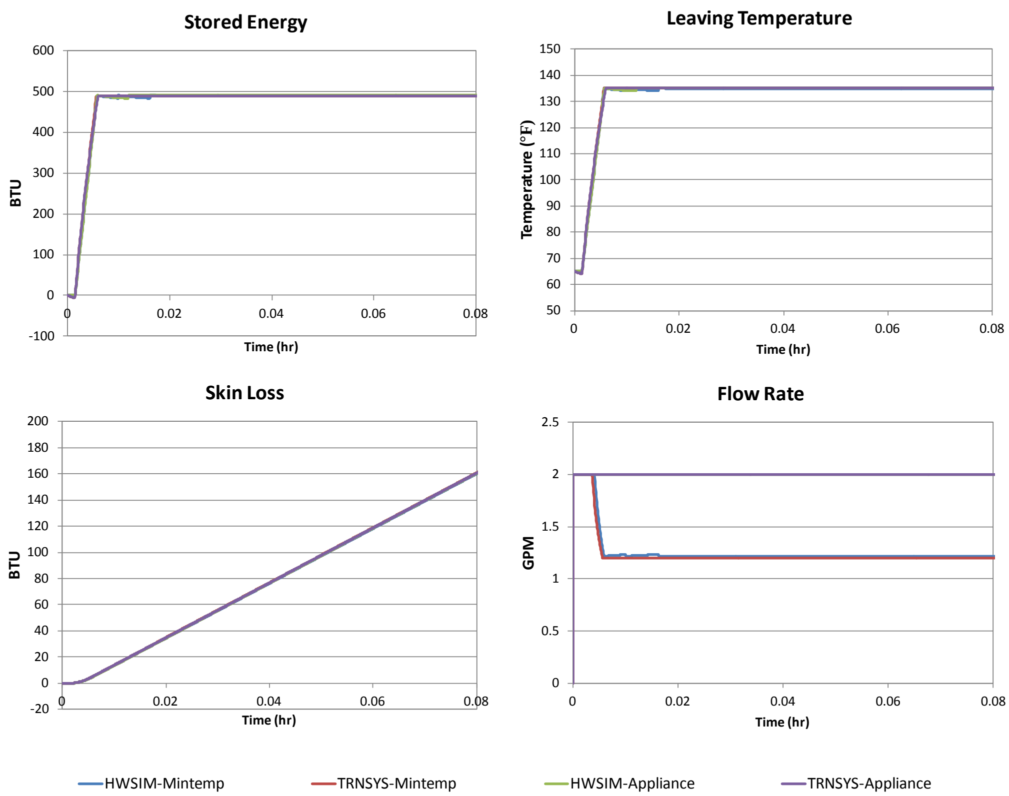

Figure 31: Comparison of Results from TRNSYS and HWSIM+Tankless

Figure 32 show … use point is assumed to be … h point flow is throttled back to maintain 105°F for the remainder of the draw. The same draw was simulated in a warmer (summer) condition, to show the environmental effects on the draw (less hot water

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[2] Appliance draws are so named because they reflect a discrete volume of hot water, regardless of the condition of the water delivered at the usepoint. “Min-temp” draws, are characteristic of showers, whereby the usepoint temperature must exceed a value (nominally 105°F), before the use starts.

flow due to mixing with warmer cold water, and lower distribution losses). Figure 33 shows a representation of the relaxation function broken out of the original tankless time-based model to expedite the solution time as HWSIM must divide and simulate multiple tankless elements. The decay is shown as a straight line connecting the end of the previous draw's data and the start of the next draw. The 5 second tankless delay to trigger the burner[3] in the Tankless model is also apparent in this chart, in that at the start of the second draw (at ~ 6:43 AM), there is a rapid cooling of the exchanger as a cold plug of water passes through it before the burner fires.

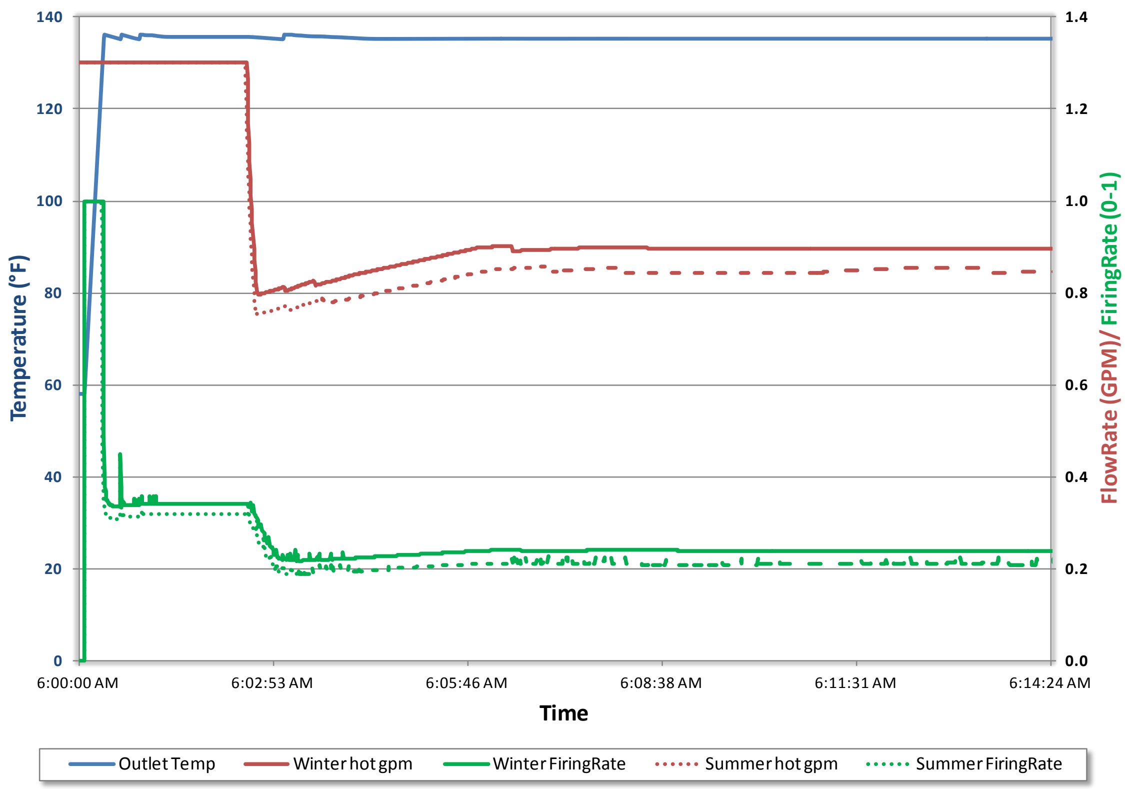

Figure 32: Single Min-Temp Tankless Draw (Winter and Summer Environments)

[3] This is a default input that can be adjusted by the user.

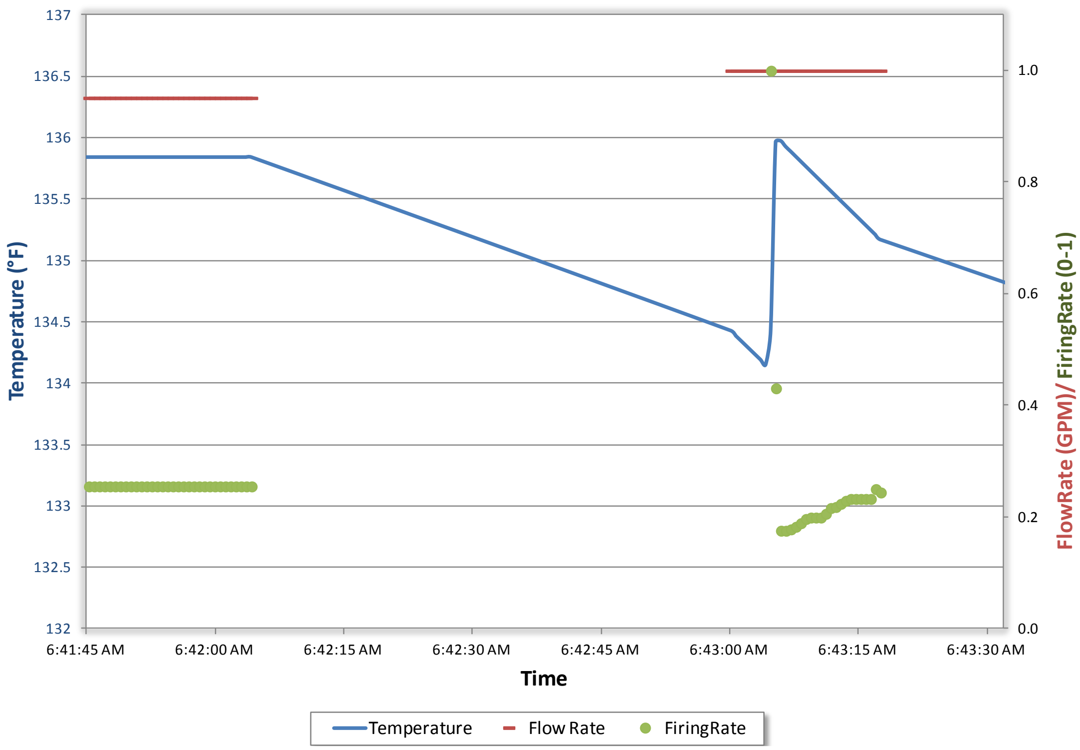

Figure 33: Tankless Heat Loss (Between and During Draws)

Pipe Heat Loss Validation

AET lab testing results were provided for a number of samples of 100 feet of pipe, to evaluate the pipe heat loss at different flow rates and as a stationary plug (relaxation). The reports provided for pipe loss listed the UA value, the flow rate tested, and the water supply and environmental air temperatures.

Equation 54: UA Value

$$UA = \frac{\frac{(T_{hwsupply} - T_{hwout}) * rhoCP * Q_{flowrate}}{(T_{hwsupply} - T_{air})}}{PipeLength}$$

The instrument accuracy for air and water temperatures was reported as 0.01°F, while the flow meter accuracy was 0.01 gpm.

Equation 55:

$$\mu_{UA} = \sqrt{\left(\mu_{Thws} * \frac{\delta UA}{\delta Thws}\right) + \left(\mu_{Tair} * \frac{\delta UA}{\delta Tair}\right) + \left(\mu_{Thwout} * \frac{\delta UA}{\delta Thwout}\right) + \left(\mu_{flow} * \frac{\delta UA}{\delta flow}\right)}$$

The sensitivity coefficients of the measured variables were calculated and the compiled uncertainty in the heat loss calculations was evaluated to be 9.25%. Figure 34 and Figure 35 show the results of the simulation overlaid with the lab findings and the associated uncertainties. The copper pipes were difficult to test in the lab as the results were different between runs, possibly due to observed variances in flow regimes or in the uncertainty in specifying copper pipe surface emissivity based on its oxidation level. PEX and CPVC results were relatively more stable.

The insulation conductivity was optimized due to the observed large variances in lab results. Figure 36 shows the calculated insulation conductivity based on the lab reported heat loss. The uncertainty in lab results was also over-laid to determine the density of results around the possible insulation conductivities, and an optimal insulation conductivity value of 0.032 Btu/hr-ft-°F was determined.

The thermal decay of stagnant pipes (relaxation) was also evaluated with lab data. In each case, the pipe was heated to a uniform water temperature, and then allowed to relax to environment until it reached 105°F. Figure 37 shows the comparison of decay times for both the lab and HWSIM. HWSIM evaluates the pipe heat capacity a little less than was experienced in the lab for Copper, yet for CPVC and PEX, the lab observed slightly higher capacities for both. It should be noted that the lab decay times were actually calculated from the pipe heat loss experienced, and not all cases provided were actually measured.

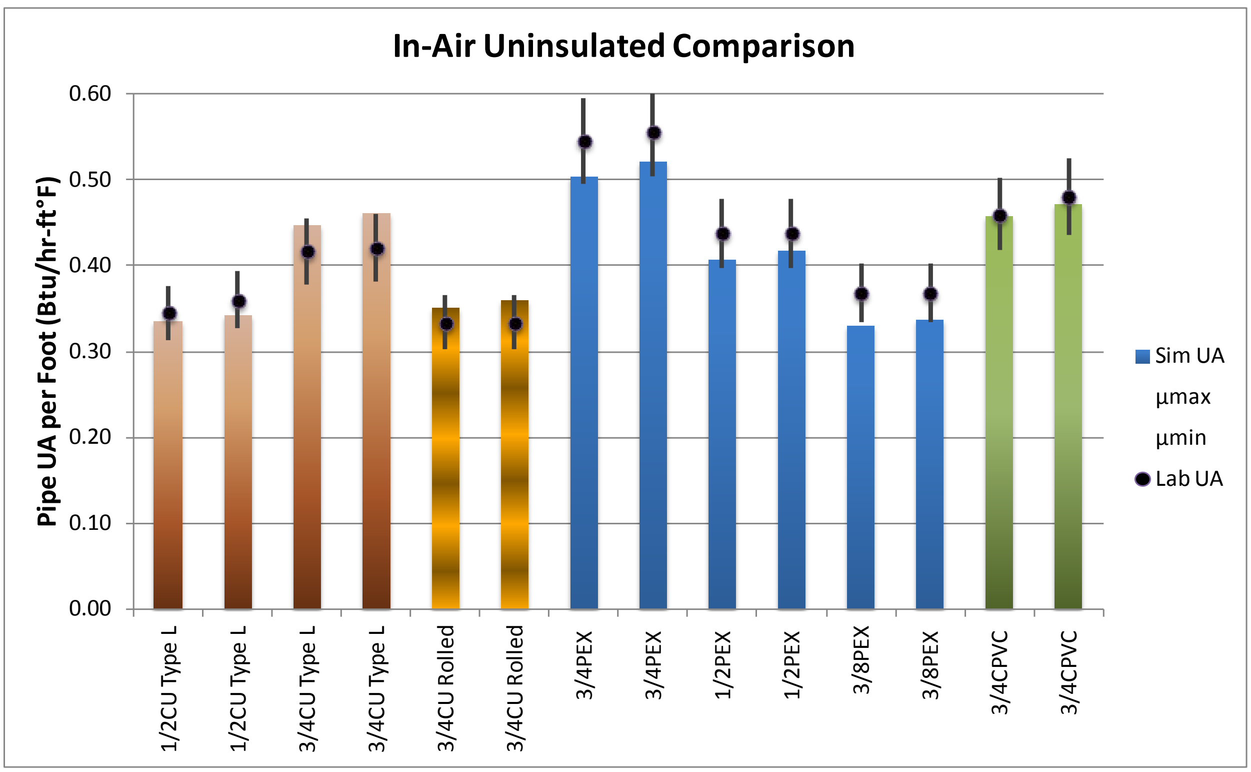

Figure 34: Heat Loss in Uninsulated Pipes

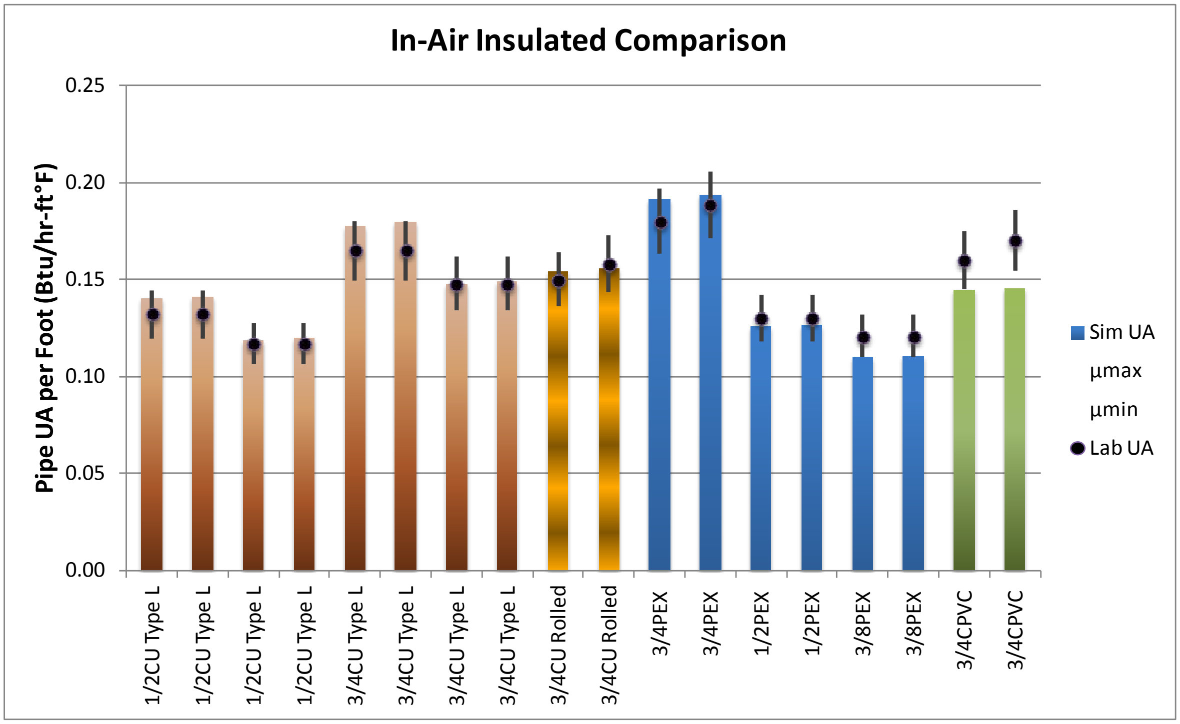

Figure 35: Heat Loss in Insulated Pipes

Insl Conductivity (Btu/hr-ft-°F)	3/4" PEX 3/4" Insl	1/2" PEX 3/4" Insl	3/8" PEX 3/4" Insl	3/4" CPVC 3/4" Insl	1/2" CU 1/2" Insl	1/2 Cu 3/4" Insl	3/4" CU 1/2" Insl	3/4" CU 3/4" Insl
0.02	**0.108**	**0.093**	**0.081**	**0.107**	**0.105**	**0.091**	**0.133**	**0.112**
0.021								
0.022								
0.023								
0.024								
0.025					**0.132**			
0.026						**0.117**	**0.165**	
0.027								
0.028								**0.148**
0.029								
0.03								
0.031								
0.032			***0.121***					
0.033		***0.130***		***0.160***				
0.034								
0.035								
0.036								
0.037								
0.038								
0.039								
0.04	***0.188***							
0.041								
0.042	**0.191**	**0.165**	**0.149**	**0.189**	**0.185**	**0.165**	**0.231**	**0.202**

Figure 36: Calculation of Insulation Conductivities in Lab Testing

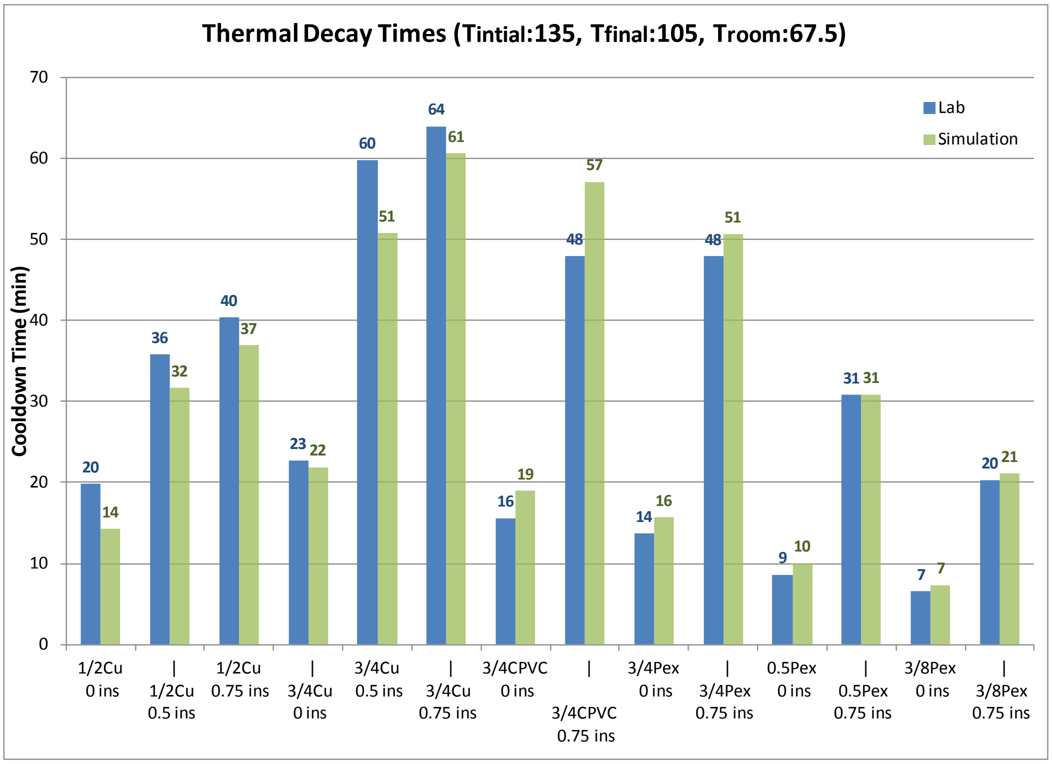

Figure 37: Comparison of Relaxation Times

2.3.4 Conclusions

Integrate Tank and Tankless Models – The TANK and Tankless models were integrated and validated with their stand-alone counterparts. TANK runtimes are exceedingly long, which drove fundamental changes to how HWSIM calculates annual usage data. Some analysis on the computational loops formed around this process could provide insight into alleviating the computational load. As it stands, TANK+HWSIM is best run in a 64-bit environment with more access to system RAM. Future enhancements would be to optimize TANK computations and re-instate the weekly draw pattern schedule.

Multi-Run Capability – The ability to run batch files was a successful first step. A future enhancement would be to generate a parametric solver, or at minimum, a utility that generates multiple input files based on differing parameters, that could then be batch simulated. The ability to have a concise report for the batch results would aid in analysis.

Database Result Storage- The database has proven invaluable for evaluating the discrete performance of HWSIM, TANK and Tankless. It was initially developed to assist troubleshooting during code development, but will remain in the public deliverable.

Pipe heat loss validation –Extensive review on pipe heat loss results between HWSIM and laboratory findings gave insight onto the suggested emissivity and thermal conductivity values for common simulated pipes and insulation. Results for insulated pipe were in nearly perfect agreement with lab results, while un-insulated copper pipe results were within the margin of uncertainty.

Other Future Enhancements

Common Draw Schedules - In HWSIM, the pipe layout and draw schedules are inextricably linked. A future enhancement would be to provide a draw schedule as a separate input file for evaluating different system configurations under similar draw patterns.

Continuous Recirculation – Demand Recirculation was updated after the integration of TANK and Tankless to poll the correct schedules. Due to the difficult nature of iterating TANK and the number of discrete elements simulated with Tankless, the continuous recirculation function was disabled in both the TANK and HWSIM-Tankless versions. A future enhancement would be to optimize TANK runs to allow for continuous draws without sacrificing simulation speed. Simulations with Tankless need only to determine the rates when the system approaches steady state operation, and calculate the usage based on the rates.

Buried pipes – HWSIM is only capable of simulating pipes in air, though laboratory data exists for pipes buried differing soil types. Buried pipes, whether in soil or in blown attic insulation, represent a difficult modeling situation due to a range of issues including soil conductivity, soil moisture effects, and attic insulation burial depth and variability.

Water Waste – Laboratory research showed observed hot water waste was inconsistent with calculations based on plug flow. Differing flow regimes were observed and estimated to be the source of the difference. HWSIM does not assume equal mixing, rather it assumes minimal mixing. This means that it under predicts water waste and its associated energy waste on the order of 25-50% under cold start conditions. Addressing this issue is important in improving the accuracy of water waste calculations.

2.4 Best Practice Design Guide

2.4.1 Introduction

For most people, the concept of a residential water heating “system”, begins and ends with the water heater itself. The appliance, which in California homes often sits in the corner of a garage, is neglected until the unit fails. Owner interaction during normal operation may go no further than occasional water heater setpoint adjustments to insure that sufficient hot water is available. The most critical hot water use in most households is by far the shower, where users demand a reliable, consistent stream of hot water. In reality, the overall performance of the water heating system depends on the following primary factors:

1. Building design (as it impacts water heater and use point locations);
2. Use points and usage characteristics;
3. Distribution system (type, pipe materials, pipe length and diameter, pipe location, insulation);

4. Water heater (type, capacity, efficiency);

5. Climate (affecting hot water loads, cold water temperatures, and pipe loss); and

6. The occupants.

From this point forward, we will refer to the "system" as the combined sum of these six components. Although it is important to evaluate and understand each of these elements, system performance involves the interactions between all these components.

Realizing that typical household hot water consumption is on the order of 15-20 gallons per person per day [13], an average family of three would only draw hot water from the water heater for 30-45 minutes a day[4]. Understanding the complexities of hot water system performance involves characterizing the interactions between the building design, the plumbing layout, the climate (both in terms of cold water temperature and pipe heat loss environments), hot water flow quantities and patterns, and water heater type and efficiency.

According to the U.S. Energy Information Administration's 2005 Residential Energy Consumption Survey (RECS), annual residential water heating totals 2.11 quads of energy annually, or 20% of the energy delivered to residential buildings[5]. Over the past seventy years, gas and electric storage water heaters have been the predominant water heater type in the United States[6]. Recently, gas tankless water heaters have made inroads in market share with current industry projected gas tankless sales estimated at 400,000+ annually, and an expected higher growth rate than storage water heaters in the years ahead [14]. Additionally, heat pump water heaters (HPWHs) are starting to gain a presence as they offer potential savings of 50% or more relative to electric resistance storage water heaters. Figure 38 presents a national perspective on natural gas water heating by region of the country.

For many areas, the lack of natural gas and the availability of inexpensive electricity has resulted in electric water heaters being the predominant water heating system type. In California, with widespread availability of natural gas to the major population centers, roughly 90% of households are served by a natural gas water heater. Two other factors also contribute to this trend:

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[4] At an assumed average hot water flow rate of 1.3-1.4 gpm.

[5] Ranging from 17% of household consumption in the Northeast to 27% in the Western states.

[6] 2005 RECS national data estimates average electric water heater consumption is 2,814 kWh/year, and gas water heater use is 230 therms/year.

1. The Title 24 Energy Code strongly promotes natural gas as a water heating fuel (vs. electric resistance water heating); and
2. Electric rates are generally high (~1/3 higher than the national average) while natural gas is fairly economically priced.

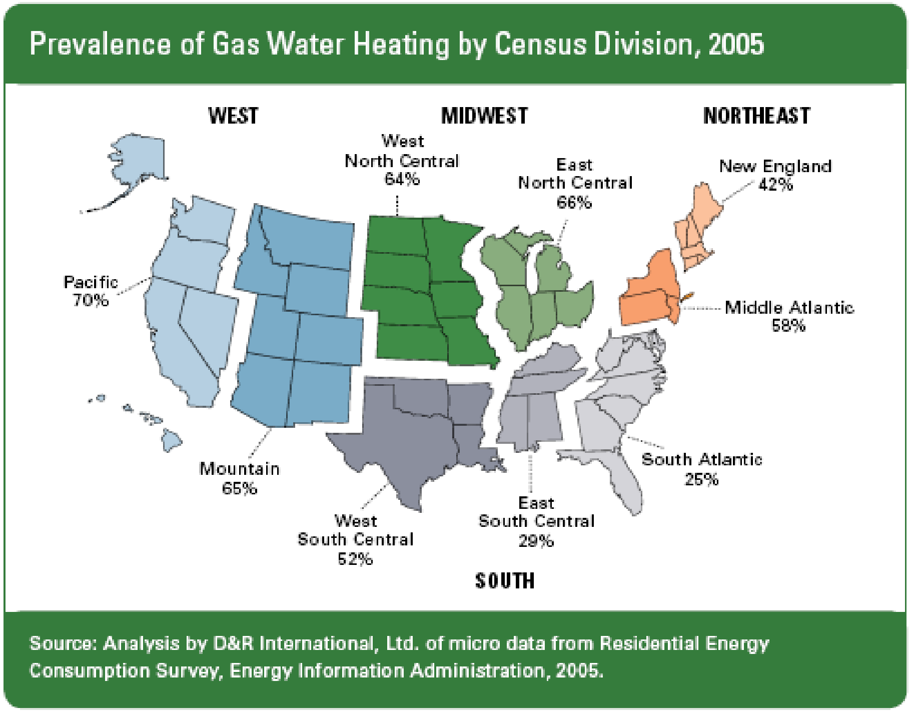

Figure 38: National Distribution of Residential Gas Water Heaters
Source: DRI International, 2009. Water Heater Market Profile

The primary goal of this design guide is to educate key stakeholders and practitioners on the latest California-specific information focused on delivering high efficiency hot water systems to consumers. The design guide focus is directed primarily towards single dwelling units commonly served by individual water heaters, consistent with the research direction of the California Energy Commission's sponsorship of the Gas Technology Institute (GTI) Water Heating research project, which funded the development of this design guide.

The findings in this design guide draw heavily from the PIER research project and other California-based studies. The authors realize that the development of this design guide is part of an evolutionary process in integrating new research findings into a document to translate best practice information to the design and construction community. Advancements in modeling tools, lab and field performance evaluations of equipment and distribution systems, and the fundamental knowledge of how hot water is used will all factor into future enhancements of this design guide.

2.4.1.1 Water Heating Energy Use and Behavior

Water heating is a very behaviorally driven energy end use. Two identical houses with similar household size, occupant ages, and lifestyle patterns could very well see radically different annual water heating energy usage. Showering, tub, and clothes washer use typically represent the vast majority of hot water use in a home, but other household characteristics can have a strong influence on overall consumption. For example, kitchen sink use is highly correlated to the level of in-home cooking, and tub use is also much more common with very young or elderly household members. To help foster a better understanding of use behaviors on a larger scale, the GTI Advanced Gas Water Heating project commissioned a survey of how people use hot water. Approximately 500 people (400+ in the greater Los Angeles area, with the remainder in the San Francisco Bay Area) completed this survey. Although self-reported findings using this type of online survey process are subject to some level of uncertainty, the findings do provide insights on behavior, which should be beneficial in designing future more quantitative studies. A sampling of some the interesting survey findings include:

Bathroom and Kitchen Sinks

- ~30% never use hot water at the kitchen sink; of the remainder, nearly 2/3 let hot water run continuously while washing or rinsing dishes.
- Only around one-quarter of respondents waited for hot water to arrive at bathroom or kitchen.
- 8% typically wait over 1 minute for hot water at kitchen sink; 3% wait over 2 minutes.
- Single lever behaviors: ~ 50% of respondents set bathroom faucets to full hot.
- Slightly more respondents (26%) said they "rarely wait" for hot water to arrive for kitchen use than "usually waited" (22%). This contrasts to bathroom behavior where 20% of respondents "rarely" and 33% "usually" waited for the hot water to arrive.

Showers and Tubs

- 23% of households had one or more whirlpool or jetted tub, although they were used in only 10% of the households.
- On average "per person" shower use was found to be 4.9 showers per week, with an average 8.8 minute duration. Shower length was highly variable. The most common shower length was 8 minutes, with a 20% response; the next most common was 3.5 minute shower at 10% response; and 8% indicated they took a 13 minute shower.
- Overall, 13% of households used both tubs and showers, while 87% took showers exclusively.

Other Comments

- 62% of respondents report that they never run out of hot water with their existing water heater.
- Respondents rarely adjusted or delayed using hot water to avoid fully depleting the tank.
- In estimating their annual hot water expenditures, ~70% of respondents had no idea of their costs. For the remainder, the average annual estimated cost was ~$340 (or nearly double typical California household costs). More significantly, the standard deviation was an astonishing $685.

- 1/3 of respondents report having a front-loading clothes washer (this is slightly higher than the 25% saturation indicated in the 2009 Residential Appliance Saturation Survey).
- At least one-third of all laundry loads were reported to exclusively use cold water.

Figure 39 shows a summary of hot water usage data from the 18 homes in the PIER field monitoring study (average household size of 3.6 occupants). The hot water usage data, monitored over a year long period, was disaggregated into bins categorizing daily hot water use (e.g. 30-45 gallons per day) to represent how hot water consumption can be expected to vary. The red bars show that slightly under 20% of all monitored days (from all 18 sites) were represented by usage in both the "15-30 gal/day" and the "30-45 gal/day" ranges. The general trend is that as hot water loads increase, the percentage of days represented by that ibin also decreases (the exception to this is the "> 120" bin.) Average daily household usage among all sites over the year long period was ~ 57 gal/day. The three colored lines on the graph represent individual households: the blue line (lowest use household), green (average user), and orange (highest use). The average user shows a very symmetrical usage pattern with about ½ the days being represented by hot water loads ranging from 45-75 gal/day. The low use household has a much smaller variation in usage with about ½ the days represented by 15-30 gal/day, and no days >75. The high use household (family of six) averaged nearly 140 gal/day and was found to have 60% of days with usage exceeding 120 gal/day. Clearly household variation in hot water use is significant and has implications on overall system performance and the ability of the water heater to satisfy peak events.

Developing monitoring-based California-specific representative hot water usage profiles is a key goal of ongoing research efforts. Jim Lutz of LBNL is leading an effort to collect detailed usage data from monitoring projects across the U.S. To date, not enough California-specific data has been collected to adequately characterize use patterns.

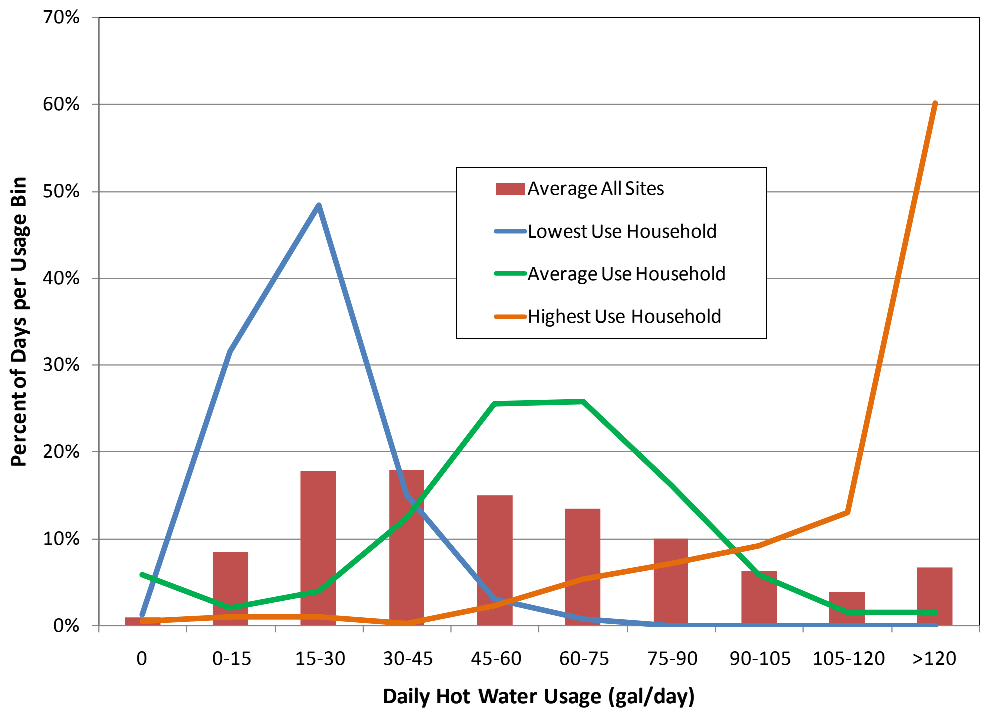

Figure 39: Monitored Household Hot Water Usage Variations

2.4.1.2 Components of Hot Water Systems

An optimally designed and performing hot water system will quickly and consistently deliver hot water under varying load and climate conditions, while minimizing energy use and water waste. From the homeowner's perspective, prompt delivery of hot water is the top attribute of a high performance hot water system. It is important to keep in mind that any water heating system can be overwhelmed by the confluence of events that contribute to peak (short duration) hot water demands. Unlike sizing of an air conditioning system for a given outdoor design temperature (which may be exceeded by 5-10°F in any given year), a water heating peak event is much more spiky and random, as evidenced by the nearly 40% of people in the hot water behavioral study who indicated that they have, at some point in time, experience sub-standard hot water delivery.

Non-optimal performing water heating systems exhibit some level of performance degradation in the design, installation, and operational efficiency of the key system components. The following sections of the guide focus on the key components: building architecture, hot water loads and use point characteristics, distribution systems, water heaters, and load reduction strategies. To the extent possible, the design guide focuses on California-specific results as identified from the GTI PIER study research findings.

Building Architecture

The basic building block for a hot water system begins with the design of the house and the relative location of the water heater(s) and hot water use points. The most geometrically simple house design (a circle or square) with the water heater centered in the structure represents the best configuration for a compact plumbing layout with minimized potential for water and energy waste. Deviations from this idealized optimal situation are, of course, to be expected when one builds real houses. However efforts should be taken in the schematic design phase to:

1. Minimize sprawling house designs where use points are distributed throughout the building
2. Logically group bathrooms and hot water use points (both horizontally and vertically) to minimize distance to the water heater
3. Locate the water heater(s) as centrally as practical[7] relative to the use points

These first steps are absolutely critical in providing a favorable starting point leading to the installation of a compact hot water system that can efficiently deliver energy and hot water throughout the house. Figure 40 below shows a reasonably typical two-story floor plan with the water heater located in the far corner of the garage, the kitchen located at the opposite corner, and the master bath on the second floor at another corner. This configuration, not ununsual for typical California new home construction, immediately poses a challenge in the delivery of hot water to the two primary use points: the master bathroom and the kitchen.

Another floor plan, shown in Figure 41, depicts a very different house design. Here the water heater is located on the wall adjacent to the kitchen. Second floor baths and laundry are located immediately above the water heater. This house is off to a much better start in delivering a compact hot water design that should realize significant reductions in energy and water waste relative to the design in Figure 40.

One strategy in achieving a compact design involves use of an indoor mechanical closet. The advantage of this strategy is that both the water heater and the air handler for space conditioning can be centrally located within the structure, minimizing both piping runs and duct runs, and facilitating the installation of ducts within conditioned space. This first cost savings (and operational cost savings) would partially offset the expense of lost indoor floor area. Historically, the California building industry has not embraced this concept due to sacrificing valuable indoor space, but increasing pressures to achieve zero net energy residential designs may cause this to be reevaluated in the near future.

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[7] Center of building water heater locations imply potential venting complications which should be evaluated for both feasibility and cost.

Figure 40: "Common" Production Home House Layout

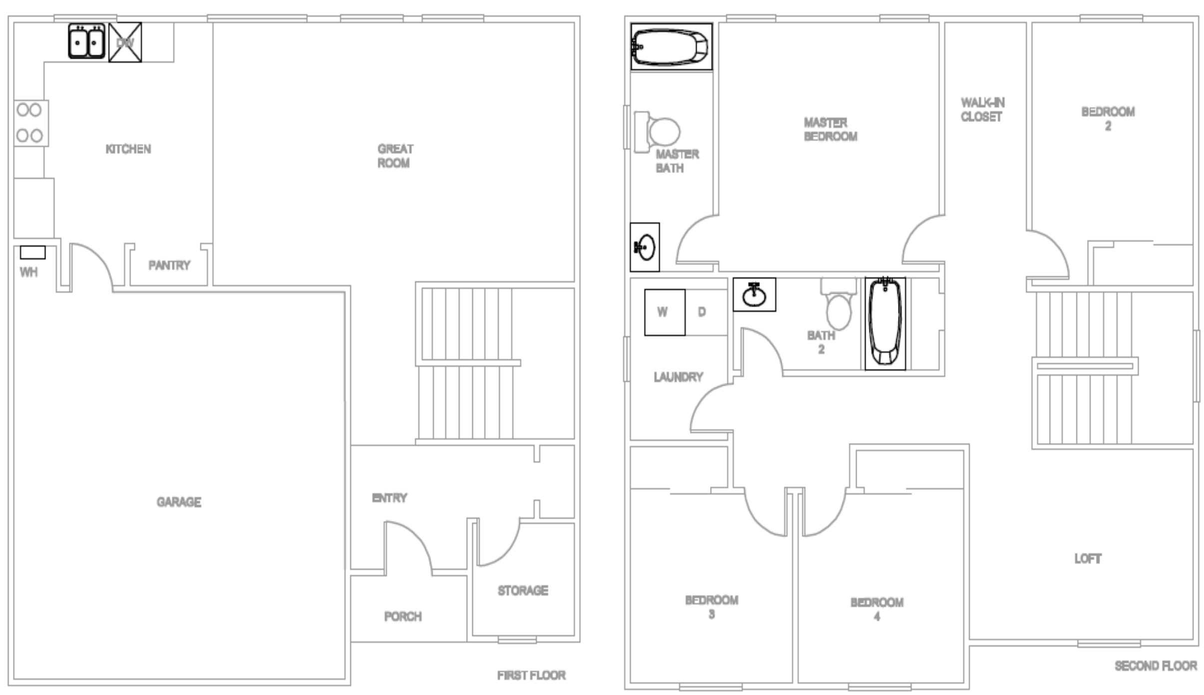

Figure 41: Good House Layout

In terms of home design, we make the following recommendations:

Key Takeaway #1: House design plays a critical first step in determining whether the plumber will be handicapped in delivering a “good” hot water system. Prompt and consistent hot water delivery is highly desired by homeowners, with substandard delivery performance a common source of builder complaints.

Key Takeaway #2: Consider an indoor mechanical closet as an approach to centralize the water heater location. A mechanical closet would also contribute to improved space conditioning performance by shortening duct runs and facilitating installing ducts in conditioned space. An alternative is adding a second water heater. This choice must balance first cost and operating cost impacts, as well as the comfort benefit of improved hot water delivery characteristics

Hot Water Loads and Use Point Characteristics

A hot water system has some similarities to a forced air HVAC installation in that a central plant generates the thermal energy which is delivered to use points throughout the house via a distribution (i.e. duct or pipe) system. There are, however, some clear distinctions to be made in this analogy. For space conditioning, typically all registers (“use points”) deliver the conditioned air, while in a DHW system, where and how hot water is used is driven by the house layout, number of occupants, their usage patterns, and the characteristics of the devices they are operating. What is most critical in a hot water system is efficiently satisfying the peak load events which occur when multiple uses occur simultaneously or within a short time period. To the extent one can mitigate the magnitude of the peak load events potentially contributes to lower energy use and greater homeowner system satisfaction.

Showerheads

The largest hot water use in most homes can be attributed to showering. This is a regular hot water use event which occurs for most occupants on nearly a daily basis (4.9 showers per person per week, as per the project’s behavioral study survey findings). The U.S. Environmental Protection Agency (EPA) estimates that average daily household shower water use (hot + cold) is about 30 gallons per day, and that more efficient showerheads can reduce shower usage by over 20% [15]. EPA WaterSense® listed showerheads are required to have maximum flow rates of 2 gpm or less (at an operating pressure of 80 psig). Further energy and water savings are available with showerheads with maximum flow rates of 1.5 gpm or less. A 2008 showerhead study found the mean flow rate of existing showerheads in 71 Pacific Northwest homes (139 showerheads) was 2.53 gpm at 73 psi [16]. These homes were retrofitted with 2.0 gpm rated showerheads with a resulting maximum flow of 1.82 gpm (28% reduction).

Multi-head “rain” showers have achieved some market share in recent years, primarily in upscale remodels[8]. This is a trend to watch, since the energy and water use implications can be significant. In addition, increasing the flow requirements within a bathroom would likely increase distribution pipe sizings, with associated distribution loss impacts.

Clothes Washers

Clothes washers are another key hot and cold water end use. EnergyStar rated clothes washers use about 35% less energy and water than competing conventional products [17].The Consortium for Energy Efficiency publishes a list of products that meet the CEE criteria at either the Tier 1 (EnergyStar performance level), the Tier 2 level, or Tier 3 [18]. The current California saturation of efficient horizontal axis washers is ~25% [19]. In addition, cold water clothes washing is starting to gain some traction as evidenced by the findings from the project’s behavioral survey, as well as recent national reporting on residential clothes washing trends [20]. With an estimated ¾ of laundry load energy use associated with the heating of water, continued movement towards both efficient horizontal axis washers and cold water washing will contribute to reduced overall water heating loads.

California Hot Water Loads

In a geographically diverse state such as California, cold water inlet temperature varies considerably both seasonally and with location. Climate (and associated cold water inlet temperatures) vary from year round cool North Coast conditions, to cold winter/moderate summer mountain area, to seasonally varying Central Valley, and finally to moderate/hot southern California. The field monitoring effort captured some pieces of this variation by monitoring water heater cold water inlet temperatures at eighteen sites (six each in PG&E, SCG, and SDG&E service territories). Figure 42 summarizes the average monthly cold water temperatures recorded only at times when flow was occurring into the water heater. The PG&E sites (located in Northern California from San Francisco to Stockton to Sacramento) demonstrate 5-10°F lower average inlet temperatures than the southern California sites where inlet temperatures exceed 80°F in mid-summer. Warmer inlet water temperature reduces the load on the water heater in two ways:

1. Less heat needs to be added to bring the cold water up to temperature
2. Warmer cold water means less hot water is needed to mix to a final shower temperature

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[8] Chapter 5.3 Single Family Construction Plumbing Layout Practices Survey found one home in the sample that featured a multi-head shower.

Another potential "hot climate" effect that is not currently well understood is the reduced summer desire for hot water for showering and handwashing, both in terms of volume and desired temperature.

Since water heater recovery load is primary influencing water heater efficiency, it is important to understand how loads may vary in California due to variations in cold water inlet temperatures.

Table 12 presents a simplified approximation of annual average cold water inlet temperatures for different regions of California. The values are derived from the field monitoring dataset in the PIER project, prior monitoring, and extrapolations from existing data used under Title 24. Local variations will occur due to factors such as whether the supply water is from wells or surface water.

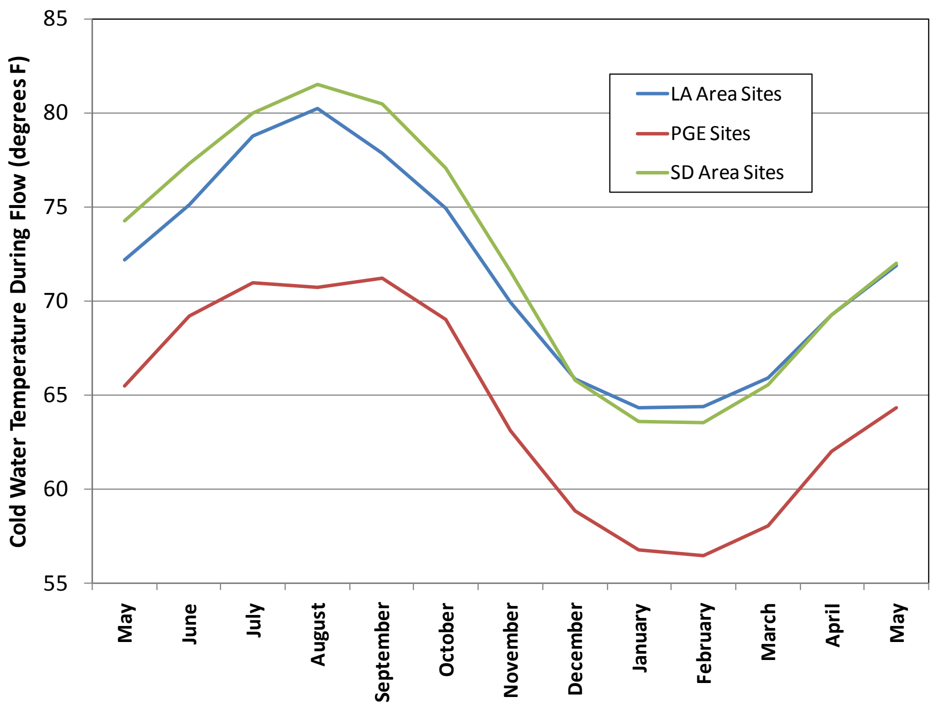

Figure 42: Monitored Water Heater Cold Water Inlet Temperatures

Given the

Table 12 data, California county population estimates, and an estimation of what fraction of the county population fits within each temperature range, we project that roughly 75% of California's population resides in areas with average annual cold water inlet temperatures in the 70-75°F range. As shown in Figure 43, this means that typical water heater recovery loads (at a 60 gal/day hot water use level) are about 1/3 less than the Energy Factor test assumption. The only case where projected loads are expected to exceed the Energy Factor recovery load level, is the "50 140" mountain region case, where "50" represents the average inlet water temperature and "140" the average tank outlet water temperature. A review of California county population data suggests that less than 0.5% of California's population resides in areas with inlet water temperatures that cold.

Table 12: Assumed Cold Water Inlet Temperature by California Climate Type

Climate Characterization	Assumed Annual Average Cold Water Temperature
Mountain Region	50°F
Northern Coastal areas, higher elevation foothills	60°F
Central and Southern coast areas, LA and San Francisco transitional areas, lower foothills, moderate Central Valley areas	70°F
Inland LA area	75°F
Hot desert regions	80°F

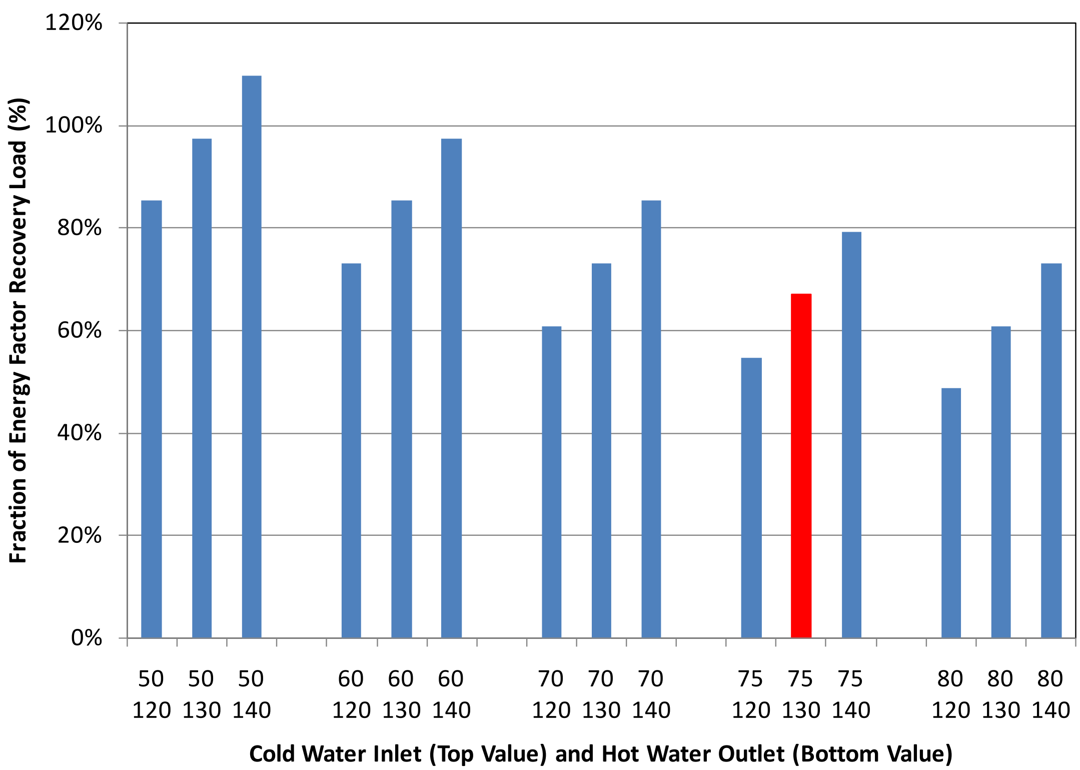

Figure 43: Estimation of Recovery Load as a Function of Inlet and Outlet Water Temperatures

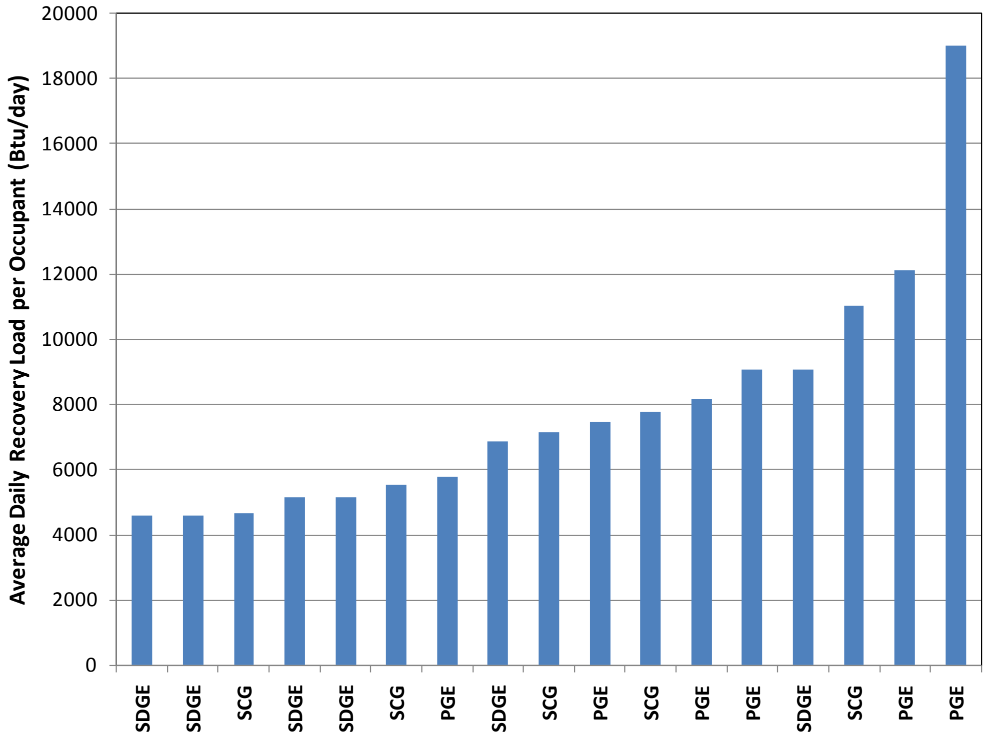

Figure 44: Average Monitored Recovery Load (per capita) at California Field Test Sites

Figure 44 plots monitored average per capita recovery load from the California field monitoring study, which averaged 7,700 Btu/person-day. All but three sites have daily per capita recovery load < 10,000 Btu/day. Northern California PG&E sites averaged 25% higher than the statewide average and the southern California sites (SCG and SDGE) averaged 13% less.

In terms of minimizing hot water loads in homes, we make the following recommendation:

Key Takeaway: Opportunities exist to reduce hot water demands both in new construction and retrofit. Selecting efficient appliances, showerheads, and faucets is often the most cost-effective hot water system improvement option available.

Historically, hot water load has been characterized in terms of gallons per day. The thermal load on the water heater (recovery load), is likely a better indicator of water heater performance, especially for the predominant storage water heaters on the market. Typical monitored California household hot water recovery loads are ~40% lower than assumed in the Energy Factor test that rates most residential water heaters. Improved low-flow showerheads and faucets, as well as efficient appliances can contribute to further load reductions.

Distribution Systems

Hot water distribution systems in California have evolved over the past ten to fifteen years as plastic pipe has made significant inroads relative to copper piping which had been the norm for more than forty years. The primary plastic piping material seen in California in recent years is cross-linked polyethylene piping (PEX), although CPVC pipe also was found to have a small market presence in recent field plumbing surveys. California's statewide acceptance of PEX in the California Plumbing Code in 2009 [21], the rising cost of copper over the past ten years, and ongoing concerns over liability due to solder joint failures and pipe pitting have been the primary factors leading to the widespread use of PEX. Plastic pipes have other apparent non-cost advantages over copper, with a primary benefit being that for a given nominal pipe size, the plastic pipes have considerably less entrained volume per 100 feet of pipe length. Figure 45 plots the entrained volume in "gallons per 100 feet" for copper (type L and M), PEX (SDR[9] 9), and CPVC (SDR 11). An additional relationship to look at is the relative volume of smaller to larger diameter piping. Relative to ½" PEX, ¾" PEX contains nearly twice the volume per foot, and 1" PEX contains 3.25 times as much. The entrained volume of water that remains in a pipe after a hot water draws is a strong indicator of energy and water waste associated with the distribution system. As a general rule, the larger the entrained volume to a use point, the greater the energy waste, water waste, and hot water wait time.

Table 13 summarizes key PEX advantages and disadvantages. Field survey of plumbing piping installations in 2006 and 2011 has indicated that one of PEX's main positive attributes (flexible pipe promotes ease of installation) has also resulted in abuses in terms of inefficient plumbing layouts.

Unlike copper distribution systems which require a moderate level of installer skill to properly solder fittings and Tees, plastic pipe is simpler to install. There are two common techniques for making PEX connections: crimp connections and the use of expansion fittings. The PEX Design Guide for Residential Supply Plumbing Systems provides more information on these techniques (shown in Figure 46 and Figure 47) [22]. CPVC piping utilizes slip fitting connections that require solvent cement[10].

[9] Standard Dimension Ratio

[10] http://www.nibco.com/assets/CPVCMAN2.pdf

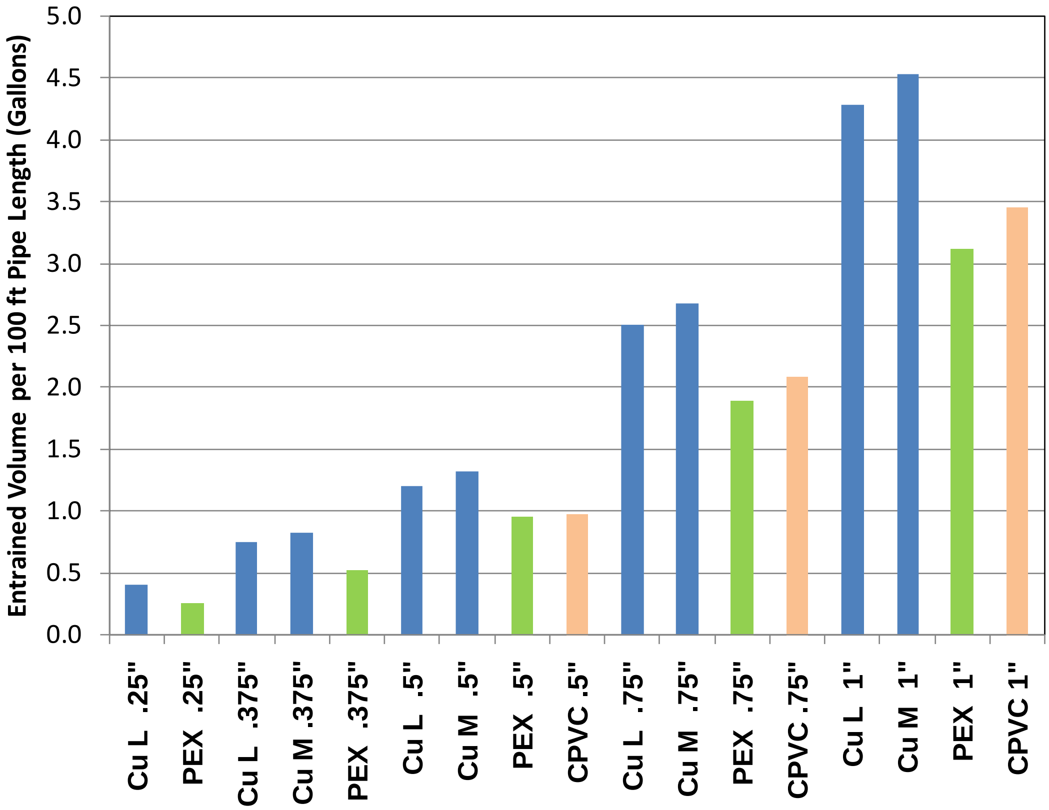

Figure 45: Entrained Pipe Volume Comparison - Copper vs. Plastic Pipe

Table 13: Comparison of PEX Pros and Cons

Pros	**Cons**
Pipe flexibility and ease of handling	Higher heat loss than copper if uninsulated or unburied in insulation (radiant effects)
Potential for direct routing of piping	Little data on long term fitting reliability
Less entrained volume per foot than copper pipe (hot water faster to the fixture for a given flow rate)	Low material cost and ease of handling may encourage ease of installation over optimal installation practice
Elimination of solder joints reduces leak potential	Degradation from sunlight (generally not an issue)
Lower installed cost than copper	
Less likely to suffer freeze failure	

Figure 46: PEX Piping Connection Options

http://plasticpipe.org/pdf/pex_designguide_residential_water_supply.pdf

Figure 47: PEX Crimp Ring Connection

http://www.pexinfo.com/images/1pexinfocopper3b-6x4.jpg

Pipe Heat Loss

The heat loss from distribution system piping has several direct impacts on overall system performance:

1. The heat loss from distribution piping diminishes the temperature of supplied hot water relative to the temperature leaving the water heater.

2. The volume of water between the water heater and the use point defines a minimum[11] wasted hot water volume before "useful" hot water arrives at the use point. For the unsatisfactory "quality" water that is dumped, the full energy content of that volume has been lost.

3. The volume of water wasted from a cold start will be further increased if a tankless water heater is installed, as the majority of these units require 15-30 seconds to approach the setpoint delivery temperature.

4. A final human component of the distribution system delivery inefficiency, is how the occupant responds to the time delay between start of water draw and availability of hot water at the use point. Slow hot water delivery times may support wasteful behaviors leading to more waste, as the user is trained to become less mindful of when hot water actually arrives.

All of these factors come into play in real world situations. Understanding and quantifying these effects requires a detailed understanding of the distribution system layout, climate, usage patterns, and behaviors. These effects can then be input to a model to extrapolate to full season effects. One part of the puzzle that is now fairly well understood, is the quantification of pipe heat loss and energy/water waste associated with different piping materials. Table 14 reports detailed laboratory measured steady state pipe heat loss results completed by Applied Energy Technology over the past five years and reported in numerous ASHRAE papers [23, 24, 25, 26, 27]. Pipe heat loss was calculated by measuring the hot water temperature drop over a long length of pipe (~100 feet) at fixed inlet water and environmental temperature conditions. Results shown are presented for both uninsulated pipe "in air", and "in air" pipe insulated with nominal one inch pipe insulation[12]. The most interesting, and perhaps non-intuitive finding, is that low thermal conductivity plastic piping materials (PEX and CPVC) have 10-30% higher heat loss per foot than copper pipe. This is primarily due to the fact that the emissivity of

[11] The actual water waste for a cold start situation is higher than the entrained pipe volume and is dependent upon temperatures and flow rate, as discussed in the Hiller/AET reports.

[12] Additional lab test results look at pipe buried in sand, in attic insulation, and in contact with drywall.

plastics (~ 0.91) are higher than that of new copper pipes[13]. Insulated piping was found to have roughly comparable heat loss among the different piping materials, as one would expect since the pipe insulation represents the dominant thermal resistance to pipe heat loss.

Table 14: Laboratory Measured Pipe Heat Loss (Btu/hr-ft-°F) at 1.0 gpm Flow Rate

Pipe	Nominal Pipe Diameter		
Material Type	3/8″	1/2″	3/4″
Uninsulated			
Copper Type L	--	0.345	0.417
PEX	0.368	0.438	0.545
CPVC	--	--	0.460
Insulated (1″)			
Copper Type L	--	0.117	0.148
PEX	0.121	0.130	0.180
CPVC	--	--	0.160

(Data from AET test summaries)

Distribution System Types

Davis Energy Group has completed two field assessments evaluating how hot water distribution systems (HWDS) are being installed in new California production homes. The first study, completed in 2006, surveyed sixty homes throughout California in the pre-drywall stage. The second assessment, completed as part of the current PIER project, surveyed another 100 homes throughout California. At each site, measurements were made to accurately define:

- Pipe material (length and diameter),
- Pipe location (garage, attic "in air", attic "buried in insulation", between floors, exterior wall, interior cavity), and
- Presence of pipe insulation.

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[13] Reported copper emissivities ranging 0.02 (highly polished), to 0.15 (slightly polished), to 0.78 (black oxidized) Siegel and Howell, Thermal Radiation Heat Transfer 2nd Edition. Appendix D.

Table 15 summarizes the locations of the sites surveyed for each of the studies. In the 2006 study, during California construction boom years, we planned on limiting the number of surveyed homes to a maximum of three to four per plumbing company, in an effort to get as broad a representation as possible. This was much more challenging in the 2011 study due to consolidation amongst the industry. The net result was that in both field survey efforts, the work of about 20 plumbing contractors were represented in the statewide survey findings.

Figure 48 shows a central home run manifold system, with the manifold being fed with hot (red) and cold (blue) from the top, and distributing to each use point with ½″ PEX from the manifold ports. Tube bundling, as shown in Figure 49, provides for more coherent pipe runs, but this approach has negative thermal implications due to heat transfer to adjacent hot/cold pipes and also a tendency to keep bundles together longer, resulting in backtracking to some of the use points. The central home run manifold is generally installed in close proximity to the water heater, although the ¾″ or 1″ line feeding the manifold from the water heater may take a circuitous path. The 2006 survey found the average length between the water heater and manifold was 20.2 feet, and contained and average of 0.55 gallons of volume, <u>or nearly 60% of the average entrained volume between the water heater and the hot water use points</u>. (This finding led to a 2008 Title 24 requirement limiting the water heater to manifold to length to 15 feet. A pending proposal for 2013 Title 24 Standards will provide a small credit for installations with a maximum five foot water heater to manifold pipe run length.)

Table 15: Location of Plumbing Survey Sites by Field Survey Phase

Title 24 Climate Zone	Number Of Sites	Site Locations
2005-2006 Field Survey		
6	6	San Juan Capistrano, Costa Mesa
8	3	Tustin
10	1	Menifee
11	6	Lincoln, Redding
12	29	Woodland, El Dorado Hills, Elk Grove, Rancho Cordova, San Ramon, Tracy, Mountain House
15	15	Indio, Palm Springs, Desert Hot Springs
2009-2011 Field Survey		
7	2	Carlsbad, Chula Vista
8	3	Yorba Linda
10	29	Menifee, Temecula, Moreno Valley, Beaumont, Murietta, Poway
11	6	Roseville, Rocklin

12	35	Folsom, El Dorado Hills, Rancho Cordova, Davis, Manteca, Livingston
13	19	Bakersfield, Fresno
15	1	Palm Desert

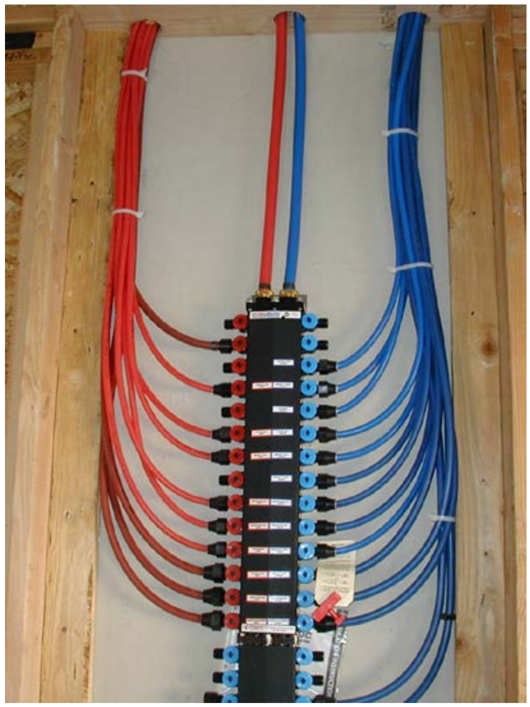

Figure 48: Home Run Manifold

Figure 49: Common Pipe Bundling for Home Run Systems

The central home run manifold systems were found to be fairly common in the 2006 survey (found in ~40% of surveyed sites), but have only been observed in a few of the sites surveyed in this project. Feedback from the field suggests that home run manifolds are too costly in the current hyper price sensitive construction market. In its place, we found that distributed mini-manifolds were the predominant system (~60% of installations). An example mini-manifold installation is shown in Figure 50. Generally the manifolds are plastic and uninsulated, although more expensive brass or copper manifolds are also occasionally observed. The manifolds are commonly fed with ¾″ inlet lines which then feed multiple ½″ lines that typically serve 4-5 use points. They are often installed in a series configuration (as shown in Figure 50) where the main ¾″ feeder line continues horizontally on to the next manifold. Performance-wise the mini-manifolds can mimic the performance of a home run system if they are all located within 15 feet of the water heater. In reality, where they are located in homes was found to be highly variable, and often based more on installer preference rather than on a systematic approach to reduce entrained pipe volume and minimize water and energy waste.

Figure 50: Plastic Mini-Manifold

Recirculation System Types

Recirculation systems are generally designed for larger homes, especially custom homes where cost concerns are less pronounced. A recirculation design essentially brings the hot water supply outlet closer to the fixtures by employing a pumped loop that circulates hot water close to end use points. A hot water demand draws hot water off the loop, resulting in much faster delivery of hot water, and reduced water waste. The water and time savings is countered by the added cost of piping[14], pipe insulation, controls, and pump; and increased energy use due to pumping and thermal losses from the loop. Single family recirculation control strategies include continuous pump operation, timer control, temperature control, and demand control. The strategies are listed in terms of least efficient to most efficient, since the general trend is a decrease in loop operating hours.

Continuous

By recirculating hot water continuously, the occupant of the house with a well laid out loop is able to have rapid access to hot water at any time. The disadvantage of this approach is that pump is operating 8760 hours per year, and the pipe thermal losses are therefore continuous. Shoddy pipe insulation installation contributes to even greater thermal losses. Typical recirculation loop flow rates are on the order of 1 gpm.

Timer Control

Timers can be used to activate the recirculation pump on a schedule dictated by occupant schedules. This offers flexibility, but also results in situations where the owner may increase pump operating hours beyond what is generally needed to insure that all expected hot water use schedules are covered. It is important to remember with any intermittent pumping strategy that initiation from a cold startup condition requires the entire loop to be primed[15].

Temperature Control

A temperature controlled recirculation system involves installation of a surface mount temperature sensor installed on the recirculation return line (under the pipe insulation) either at the use point branch furthest from the water heater or where the return line returns to the water heater. The temperature sensor provides input to a controller which energizes the pump to maintain a minimum sensed return water temperature. Ideally this control should provide a reduction in the pump run time by 50% or more, but our experiences indicate that the low recirculation flow rate and higher than anticipated pipe heat loss result in much greater pump operation that anticipated.

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[14] Piping costs are higher since the loop supply line must be sized to meet the full flow requirements of simultaneous draws. Often this results in much of the recirculation loop being 1” or ¾” piping.

[15] Similarly pump shutdown and loop decay results in the heat of the full entrained pipe volume being lost.

Time/Temperature Control

A time/temperature control combines the two functions and theoretically provides the benefits of both timer operation and temperature control.

Demand Control

A demand control strategy utilizes a user-activated control to initiate pump operation when the recirculation line is below a useable temperature. Push buttons or occupancy sensors installed at the primary use points[16] allows the pump to be energized "on demand". Since this approach will operate the pump much less frequently than other system types, the energy lost in the recirculation loop and the pump energy are both reduced significantly relative to conventional recirculation strategies. Due to the infrequent operation, a larger pump is needed to more quickly deliver the hot water. A temperature sensor, typically installed at end of the supply loop, shuts the pump off once it notices a rise in temperature at the sensor. Push buttons are the preferred control strategy, since activation represents clear intent from the occupant. This control strategy does require the user to interact with the system, which will be an issue for some people. Occupancy sensors, which resolve the need for direct interaction, will result in unintentional pump cycles as people will enter the bathroom or kitchen with no intention to use hot water. Strategic placement of the sensor can help reduce the number of false signals, although there is no definitive monitoring data to document the added energy use associated with unintended occupancy sensor pump initiations. Despite concerns about the occupancy sensor, the demand recirculation strategy clearly represents the best recirculation approach, if a recirculation system is indeed needed.

Pipe Insulation

Properly installed pipe insulation serves the vital role of reducing heat loss during hot water flows and extending pipe cool down times at the end of draws, potentially resulting in available hot water for the next draw. The "during draw" benefits result in an approximate 2/3 reduction in pipe heat loss as determined by the lab testing completed by AET (Table 14 data). The energy savings benefit of pipe insulation is most pronounced in distribution systems that contain or circulate hot water for most of the day. As loads decrease and approach zero, the benefit of pipe insulation from a cost-effectiveness viewpoint (energy saved per dollar invested) is reduced. Most households with non-recirculating distribution systems will see hot water flow occurring

[16] Pump activation may or may not be necessary for laundry rooms and powder rooms.

anywhere from 30-100 minutes per day[17]. The "during draw" benefit of pipe insulation is reduced relative to a recirculation case, but pipe insulation also offers benefits in delaying pipe thermal decay time, which means subsequent draws will benefit from insulation if the water remains above a minimum desired use temperature, resulting in avoided waste.

The cool down benefit is difficult to quantify since it is highly dependent on load patterns within a house (how clustered hot water draws are), the plumbing layout (pipe location and which pipes see flow at what time during the day), and climate and seasonal effects (heat loss to environment). The 18 home field survey data indicated that on average, ~45% of hot water flows occur within ten minutes of a prior draw, and 30% occur at an interval greater than 60 minutes. Some fraction of the draws in the "< 10 minute interval" would see a benefit if flows are occurring at different legs of the distribution system, however none of ">60 minute" interval draws would see a benefit. An educated guess might suggest that half of the draws in a typical household would be favorably affected by pipe insulation.

In the development of the 2013 Title 24 Standards, simulation runs were completed to assess the cost effectiveness of pipe insulation of six different house floor plans under "typical" hot water use profiles. Findings of the evaluation indicate that insulating ¾" or larger piping is cost effective on a life cycle basis at a (conservative) insulation installed cost of $3.87 per foot[18] [28]. Insulating half inch piping was not found to be cost effective under typical usage assumptions, largely due to the reduced flow and less entrained pipe volume for the smaller pipe. This is not to say that ½" piping should not be insulated, since benefits will accrue, only that under the Title 24 consensus cost assumptions, insulating ½" pipe was not found to be cost-effective.

Current State of New Home Distribution Systems

The field survey efforts completed in this project, as well as the prior effort in 2006, provides useful data on the preferred plumbing layouts and how those systems are installed. We have represented the data in the form of average entrained pipe volume from water heater to use points, as a key metric for comparing the different types. This is not a perfect approach but it does provide a method to get a sense of how much volume exists in the installed hot water

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17 A rough rule of thumb to apply to hot water flow is to assign a reasonable average hot water flow rate of 1 gpm to the estimated daily usage. A 30 gallon per day load would therefore have 30 minutes of hot water flowing per day, while a 60 gallon load would be 60 minutes. Typical per person use ranges from 15-20 gallons per day.

18 Title 24 Standards cost effectiveness calculations require the use of conservative (i.e. high) cost assumptions.

distribution systems and can therefore be used to develop "typical" input conditions for modeling tools. Table 16 compares the 2006 and 2011 datasets by normalizing the average volume by house floor area (per 1,000 ft^2). Key conclusions include:

- Home run manifold systems, popular in 2006, have largely been supplanted by the mini-manifold design approach.

- Excluding home run and recirculation systems, the average volume per 1000 ft^2 is ~ 0.5 gallons (a 2,000 ft^2 "typical" house would have, on average, ~ 1 gallon of water sitting in the pipe between the water heater and any use point). The 2006 and 2011 findings are virtually identical in terms of gallons/1,000 ft^2.

- Both central home run manifold systems and recirculation system entrained volumes were significantly lower in the 2011 survey. Since both the home run and the recirculation samples are not statistically significant (three and seven sites, respectively), further study is warranted.

Another significant finding in the 2011 survey relates to the use of larger diameter 1" piping in non-recirculating residential applications. In some cases this may be dictated by pipe sizing requirements in the Uniform Plumbing Code. A review of Figure 51, which plots the length of 1" piping as function of house floor area (each data point represents one house), indicates that there is no clear relationship between the amount of 1" piping and the size of the house. One would expect such a relationship to exist, since larger homes will as a rule have more bathrooms and use points, which will affect pipe sizing as the number of fixture units increase. Our assessment of this situation is that the use of 1" piping is based on what the plumber is comfortable installing, suggesting that more industry education and training is needed.

Table 16: Average Entrained Volume to Use Point per 1000 ft^2 of Floor Area

System Configuration	2006 Survey		2011 Survey	
	gallons/ 1000 ft^2	number of sample sites	gallons/ 1000 ft^2	number of sample sites
Conventional Trunk and Branch	0.49	12	0.48	27
Central Home Run Manifold	0.39	23	0.29	3
Hybrid Systems (includes mini-manifold)	0.43	13	0.45	60
Recirculation Systems	0.82	12	0.45	7

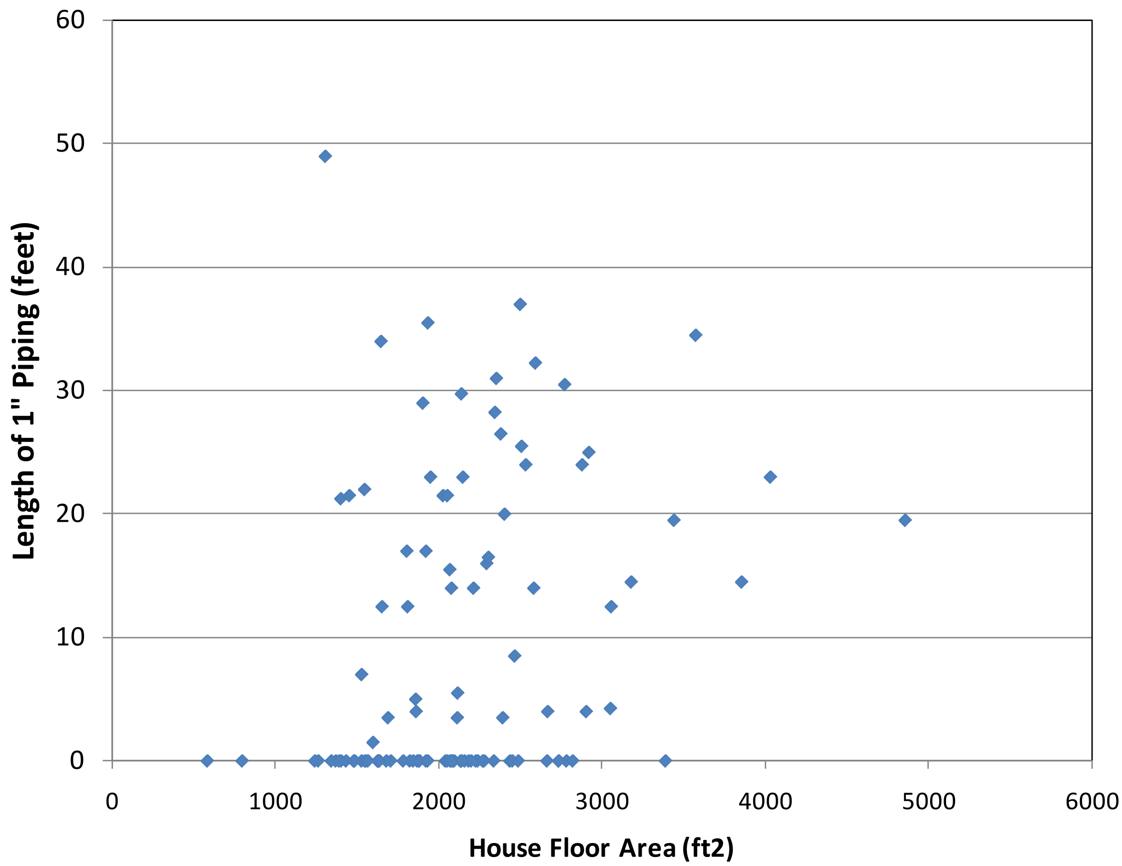

Figure 51: Length of 1" Pipe vs. House Floor Area

Modeling of New Home Distribution Systems

A key component of the GTI water heating research project involved advancing the state of current water heating system modeling tools. This included integrating improved water heater models into the HWSIM hot water distribution system simulation model, as well as enhancing some of pipe heat loss modeling capabilities. The model was used to provide some example projections of distribution system performance for this design guide. It is important to recognize that modeling in this area is highly complex as it brings together a wide range of factors that combine to define the performance of a water heating system. These factors include the configuration of the house, the layout of the plumbing system, the location of the pipes, the climate, the type of hot water using fixtures and appliance in the house, the occupancy of the house, and most importantly, the occupants themselves. The HWSIM tool is capable of accommodating these inputs, but our current level of understanding in some of these areas is limited and evolving as more research in the field is performed.

An example of the variability that exist is shown in Figure 52 where the monitored distribution of hot water draw events from the 18 field monitoring sites is plotted against the elapsed time between hot water draws. The graph shows that on average (red line) nearly 45% of hot water draw events at these sites occurred within 10 minutes of a prior draw, and 55% within 20 minutes. However, the variation among the individual sites (shown as gray lines) is very large. The implications of this site-by-site variation are significant in many respects, since the time between hot water draws is a key determinant of whether energy within the piping may be "useful" for subsequent hot water draws, and also whether pipe insulation has more or less value in a given application. In non-recirculating hot water distribution systems, pipe insulation is least effective in the extreme conditions of draws that are highly clustered, or draws that well spaced out in time. Pipe insulation is most effective when the draw pattern falls between the two extremes, whereby insulation can slow the pipe heat loss sufficiently to provide benefit for the next draw. As a general rule, pipe insulation can extend the usefulness of entrained hot water from ~15 minutes (uninsulated) to ~40 minutes (if insulated).

To explore typical performance impacts of different hot water distribution systems and hot water usage quantities, a series of HWSIM runs were completed on a 2,496 ft^2 floor plan. The first and second floor layout, shown in Figure 53 and Figure 54, is representative of many homes of that size. To evaluate performance, runs were completed with three hot water usage levels (26, 49, and 78 gallons per day) and several different distribution types. The modeled distribution system types included:

- Conventional practice (PEX with mini-manifolds, "typical" piping layout)
- Improved practice (better water heater location; shorter, more direct piping runs)
- Demand recirculation[19] (with "typical" recirculation loop system layout)
- Improved demand recirculation (with improved recirc system layout & water heater location)

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[19] Assumes manual pushbutton control of the demand recirculation system. Occupancy sensor control would have higher energy use.

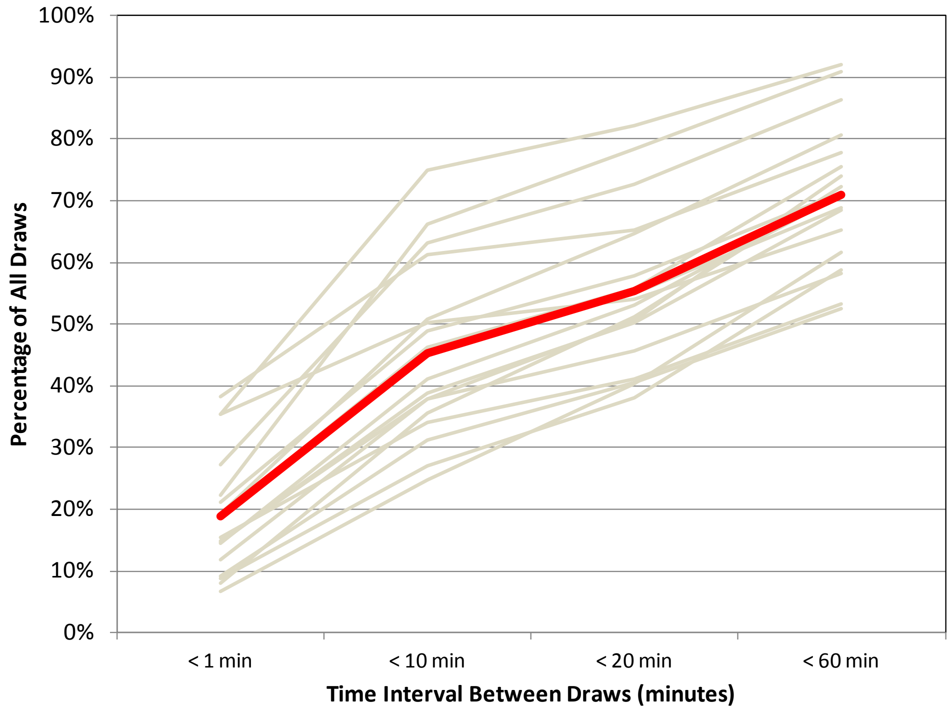

Figure 52: Monitored Time Between Hot Water Draws From 18 Home Field Survey Monitoring

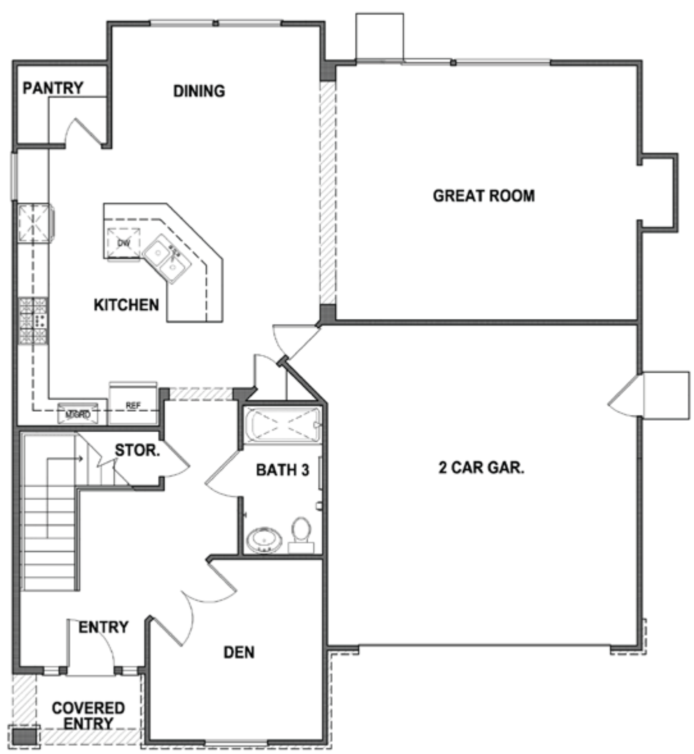

Figure 53: First Floor Layout (2,496 ft² Production Home)

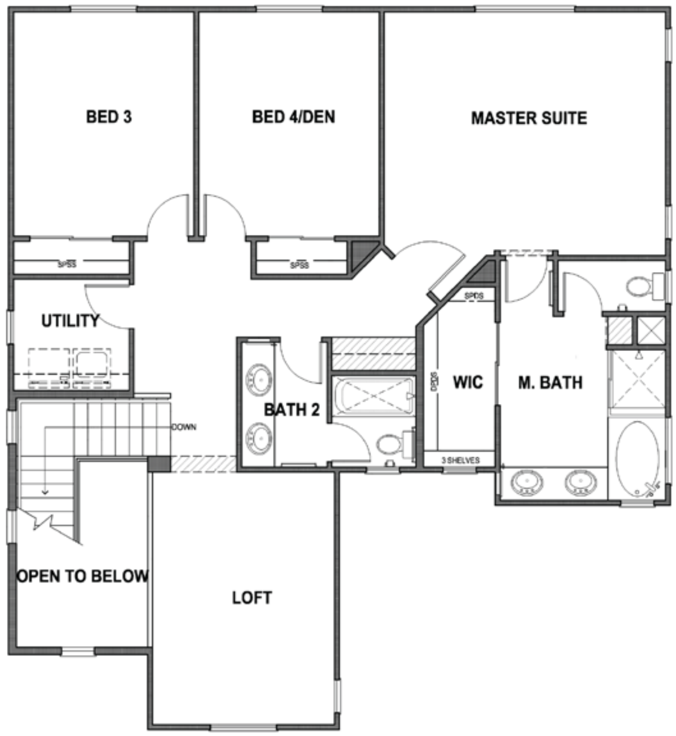

Figure 54: Second Floor Layout (2,496 ft² Production Home)

Results from the simulations are included in Table 17 for estimated annual water heater gas consumption (for a 0.59 EF atmospheric water heater) and wasted hot water volume for each of the distribution system cases evaluated. Base annual gas usage ("conventional practice") varies from 122 to 246 thermsyear. Improved conventional practice results in a projected 10-12% reduction in gas consumption (15-31/year therm savings). The demand recirculation case (with "typical" piping layout) is estimated to result in slightly higher annual gas use (ranging from 1 therm saved to 8 therm increase), while the improved demand recirculation case shows usage only slightly higher than the improved conventional case.

In terms of hot water waste, base case ("conventional practice") shows daily water waste ranging from about 6-15 gallons per day (2,125 to 5,318 gallons per year). Improved conventional practice shows a 6-7% reduction in hot water waste. Recirculation systems show a 40-60% reduction in waste for the "conventional" recirculation system, increasing to over 80% for the improved recirculation system.

It is important to note that these performance projections are based on reasonable input assumptions, but variations in behavior and use pattern will have a significant influence on savings. As better data becomes available and modeling tools improve, these projections can be refined.

Table 17: HWSIM Results Summary

System Configuration	26 gal/day average hot water use	49 gal/day average hot water use	78 gal/day average hot water use
<u>Estimated Annual Gas Use (therms)</u>			
Conventional Practice	122	180	246
Improved Conventional Practice	107	162	215
Conventional Demand Recirc	121	183	254
Improved Demand Recirc	109	164	218
<u>Estimated Annual Water Waste(gals)</u>			
Conventional Practice	2,125	2,758	5,318
Improved Conventional Practice	1,998	2,593	4,946
Conventional Demand Recirc	1,158	1,226	3,021
Improved Demand Recirc	451	543	892

Distribution Systems Key Takeaways: Good Plumbing Design- Centrally locate the water heater to the extent possible. Provide input to the architectural design to avoid sprawling hot water layouts. A bad plumbing design and layout institutionalizes waste over the life of the house.

Central Manifold Home Run Systems- Minimize the length of piping between the water heater and the manifold. More than half of the entrained volume between the water heater and use points can be found here, therefore minimizing this length is more critical than minimizing the pipe length between the manifold and the use point.

Bathroom Sinks- Use a single ½" line to feed adjacent bathroom sinks as opposed to individual dedicated lines.

Distributed Mini-Manifold Designs- Bring manifolds close to the water heater as this will reduce the overall entrained volume of water, reducing heat loss, water waste, and hot water wait times.

Whirlpool Tubs- The high flow rate requirements of tubs creates pipe sizing problems that often contribute to added waste throughout the distribution system, since the piping is sized to accommodate simultaneous flows.

Recirculation Systems- Carefully consider the need for a recirculation system. Recirculation systems may be needed due to the following factors: 1) a very large house, 2) poor architectural design (use point locations spread out), 3) poor plumbing layout, 4) clients who demand rapid hot water delivery. Recirculation systems will consistently save water and reduce hot water waiting times, but only a demand recirculation system <u>can potentially</u> save energy. Care should be taken to minimize the length and entrained pipe volume of the recirculation loop. If the house layout suggests two loops, install a second recirculation system rather than one oversized loop serving the entire house. As an alternative to recirculation, consider the costs and benefits of adding a second water heater, recognizing that there may be cost savings by eliminating some pipe runs.

Pipe Insulation- Pipe insulation offers benefits in reducing heat loss, delivering hotter water to fixtures, and reducing hot water waste associated with cool downs between draws. All piping ¾" or larger should be insulated. Attic piping should be buried in blown insulation (4" coverage) were possible. Insulating all piping certainly represents a Best Practice approach, but is likely not cost-effective for most ½" and smaller piping.

Pipe location- For piping installed in attics, make every effort to keep piping in the blown insulation (4" minimum coverage desired). If mini-manifolds are buried by insulation, provide a flag that denotes where the manifold is located (for future service).

Water Heaters

Most water heaters used in single family applications are covered under and rated according to the U.S. DOE's Code of Federal Regulations (10CFR430, Subpart B)[20]. According to the standard, residential water heaters are rated according to the following three parameters:

- "**First Hour Rating** means an estimate of the maximum volume of hot water that a storage-typewater heater can supply within an hour that begins with the water heater fully heated (i.e. with all thermostats satisfied). It is a function of both the storage volume and the recovery rate."

- "**Recovery Efficiency** means the ratio of energy delivered to the water to the energy content of the fuel consumed by the water heater." Standby losses are a minor component of this factor, and it is roughly equivalent to the Thermal Efficiency rating for large water heaters.

[20] Covers gas storage water heaters with input ratings of <= 75 kBtu/hour and volume between 20 and 100 gallons, gas tankless units with input ratings between 50 and 200 kBtu/hour and a volume of <2 gallons.

- "**Energy Factor** means a measure of water heater overall efficiency." It is a combination of energy recovery efficiency following a series of water draws and 24-hours of standby loss.

The 24 hour test draws a total of 64.3 gallons of hot water in six equal draws of 10.7 gallons. Each draw is separated by one hour, and the remainder of the 24 hour test is designed to capture system standby energy use.

Table 18 summarizes current and proposed 2015 water heater Energy Factor (EF) requirements based on fuel type and water heater type. In 2015, the key distinction is that gas water heaters with greater than 55 gallon storage will be required to be condensing, and the larger electric water heaters will be required to be HPWHs.

Table 19 presents the current EnergyStar criteria for eligible water heater products. Eligible gas storage products must exceed 0.67 EF, gas tankless > 0.82 EF, and HPWHs must exceed 2.0 EF.

Table 18: Federal Water Heater Current and April 16, 2015 Standards

Product Type	**Current Requirement**	
Gas Storage	EF = 0.67 – (0.0019 x Volume)	
Electric Storage	EF = 0.970 – (0.00132 x Volume)	
Gas Tankless	EF = 0.67 – (0.0019 x Volume)	
	Effective April 16, 2015	
Product Type	**Volume <= 55 gallons**	**Volume > 55 gallons**
Gas Storage	EF = 0.675 – (0.0015 x Volume)	EF = 0.8012 – (0.00078 x Volume)
Electric Storage	EF = 0.960 – (0.0003 x Volume)	EF = 2.057 – (0.0013 x Volume)
Gas Tankless	EF = 0.82 – (0.0019 x Volume)	

Table 19: EnergyStar Water Heater Minimum Critieria

Product Type	Efficiency	First Hour Rating	Minimum Warranty	Safety
Gas Storage	0.67 EF	> 67 gal/hour	6 years on sealed system	Compliance with ANSI Z21.10.1/CSA 4.1
Gas	0.82 EF	> 2.5 gpm	10 years on heat	Compliance with ANSI

Tankless		@ 77°F	exchanger; 5 years on parts	Z21.10.1/CSA 4.1 or Z21.10.3/CSA 4.3, depending on burner size
Gas Condensing	0.80 EF	> 67 gal/hour	8 years on sealed system	Compliance with ANSI Z21.10.1/CSA 4.1
Heat Pump	2.0 EF	> 50 gal/hour	6 years on sealed system	Compliance with UL 174 and UL 1995
Solar	0.50 Solar Fraction	n/a	10 years on collector, 6 years on storage tank, 1 year on piping and parts, 2 years on controls	OG-300 certification from SRCC

The following sections provide a brief overview of the various water heating technologies on the market.

Storage Gas Water Heaters

Atmospheric storage gas water heaters (Figure 55) represent the vast majority of water heaters installed in California. These units have a gas burner located at the bottom storage tank, with typical tank volumes between 30 and 50 gallons. Typical water heater setpoints range from 120°F to 140°F, although outlet temperatures can vary considerably due to the wide hysteresis band in the thermostatic control. Heat from the burner is transferred to the water through both the concave tank bottom and the walls of the center flue that extends upward through the tank. Typical recovery efficiencies are in the range of 76-78%. A standing pilot ignites the burner when the tank thermostat indicates the tank has fallen below the temperature setting. The gas input rating typically ranges from 34,000 to 40,000 Btu/hour, with higher capacity models (up to 75,000 Btu per hour) available. The vast majority of storage gas water heaters are atmospherically vented, although some are direct vented and some employ fans to assist venting.

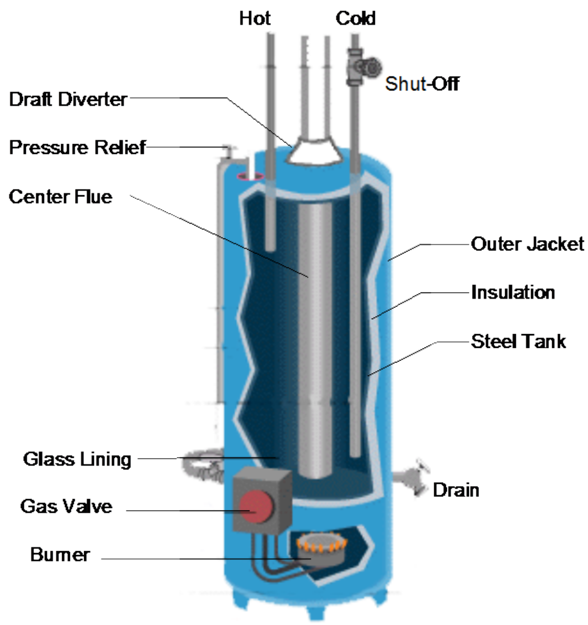

Figure 55: Storage Water Heater Schematic

The continuously burning pilot consumes about 400-500 Btu/hour, which in many situations provides enough heat to offset typical tank standby losses. Actual burner firing time in response to hot water loads is on the order of 1 hour per day[21], meaning that for the vast majority of the time the water heater is in standby mode. This low utilization rate (~5%) highlights one of the inherent inefficiencies of storage water heaters. In fact, extrapolating the typical 40 therms a year of pilot energy to the 88% of California single family households with natural gas water heaters [19] amounts to a total of 27.5 billion cubic feet of natural gas consumption, or almost 6% of the California Energy Commission estimated 2009 statewide residential gas consumption [29]. In applications where a home requires a second water heater, think carefully of the implications of raising the annual standby energy from 40 to 80 therms.

Higher efficiency gas storage water heaters have historically been a small part of the total number of the nearly 8 million residential water heaters shipped nationally [30]. In the past few years an increasing number of higher efficiency storage models have entered the market. As of September 2010, Energy Star has a program in place for high efficiency gas and electric water heaters [31]. To meet the EnergyStar 0.67 Energy Factor efficiency level, the manufacturers have

[21] 35,000 Btu/hour input capacity translates to about 50 gallons of hot water per day at a 65°F temperature rise.

included measures such as automatic flue dampers, electronic ignition, and power vent technology. Most of the available condensing storage products are primarily intended for the combined hydronic or small commercial market (larger in input capacity and storage volume) and are therefore not rated under the Energy Factor test procedure. The thermal efficiency ratings of these units reflect their steady-state combustion efficiencies, not a seasonal value as intended by the EF rating. All of these EnergyStar or higher efficiency water heaters require an electrical connection for controls, combustion fans, and in some cases pumps. The need for an electrical connection may increase installation costs, adds parasitic usage (roughly on the order of 100 kWh/year), and adds vulnerability during power outages.

Gas Tankless Water Heaters

Tankless gas water heaters integrate a high capacity burner, a heat exchanger (typical volume of less than one gallon), and controls, to provide hot water only when there is demand. Water is heated in a single pass through the heat exchanger. Supply water temperatures are maintained by either modulating the firing rate in proportion to the water flow rate, mixing cold and heated water to maintain a stable outlet temperature, or some combination of the two approaches. Both condensing and non-condensing tankless units are on the market. Despite the fact that non-condensing tankless units have combustion efficiencies roughly equal to that of conventional atmospheric gas storage water heaters, tankless units have been found to demonstrate consistent gas savings versus atmospheric gas storage units based largely on the elimination of standby losses [32, 33]. Tankless water heaters operate most efficiently with larger volumetric loads, whereby the energy required to bring the heat exchanger up to temperature is a smaller fraction of the total energy consuming during firing. Conversely small loads result in more inefficient operation, as the initial energy required to bring the heat exchanger to temperature is a large fraction of the energy consumed.

All newer models include electronic spark ignition and combustion air blowers to achieve higher output and efficiency, and to allow horizontal "direct" venting. Higher capacity models are capturing a larger market share[22] because of their increased ability to satisfy multiple simultaneous hot water loads. Input capacities range from roughly 140,000 to 240,000 Btu/hour, or roughly 5-8 times greater than a gas storage water heater. The higher capacity is needed since water must be instantaneously heated. Larger gas lines, increased venting costs, and the need for a 120 V electrical connection contribute to higher installation costs, particularly in retrofit applications. In recent years, condensing tankless water heaters appear to be capturing a larger

[22] 2011 Navigant study for Oak Ridge National Laboratory estimates that the gas tankless share of the national gas water heater market was about 10%.

fraction of the tankless market. Although the water heater itself is roughly 15-20% more expensive than a non-condensing tankless unit, use of plastic vent piping may reduce installed costs relative to the more costly, proprietary vent systems for the non-condensing units.

Since hot water generation for tankless units is very different from a conventional storage water heater, we have highlighted a few of key performance differences:

Time delay from cold start: Tankless units undergo an initial pre-firing sequence (which takes a few seconds), and then must come to temperature before useful heat is delivered from the unit. This results in added delay in hot water delivery, resulting in increased water waste and potential homeowner inconvenience.

Minimum hot water flow rate: A minimum flow rate is required to initiate the firing sequence. This is typically in the 0.4 to 0.75 gpm range. Although most household hot water uses are at higher flow rates, some tankless customers have expressed dissatisfaction that certain low flow rate draws cannot be satisfied. Conversely, it has been observed in field monitoring studies that many of these short, low flow rate draws simply disappear resulting in a small energy savings benefit.

Outlet temperature stability: Once tankless units come up to temperature, they generally maintain very stable outlet temperatures under steady flow conditions (and if the load is less than output capacity). Moderate change in flow rates from steady state flow may contribute to outlet temperature fluctuations. Different control logic used by different manufacturers results in varying performance.

Cold water sandwich: A potential comfort issue can occur whereby a hot water draw occurs, followed by a short interval of no flow, and then flow resumes. In this case, a slug of cooler water can be delivered by the unit, before the tankless unit refires.

These issues have been identified over the past years and manufacturers are continually looking at how to improve the delivery performance of their products.

Figure 56 shows a typical garage installation of a tankless unit, and highlights several key installation benefits of tankless units: the units are small, typically wall mounted, and can be sidewall vented. Units can also be located in exterior water heater closets, interior closets (with proper ventilation), and mechanical rooms. Unlike storage water heaters which require seismic strapping, tankless water heaters do not. The schematic shows key components including the heat exchanger, multiple gas solenoids for controlling the combustion process, combustion air fan, and temperature and flow sensors.

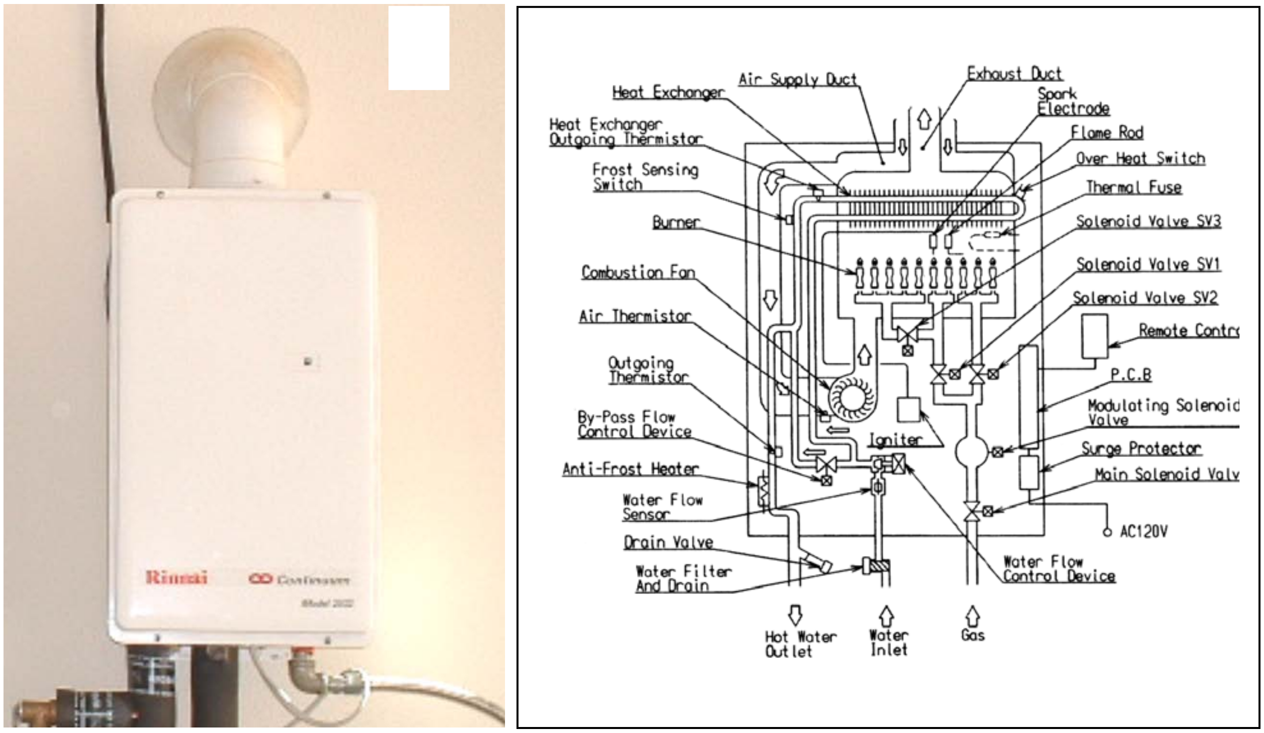

Figure 56: Typical Tankless Installation and Unit Schematic

The need for ongoing maintenance of tankless water heaters is an issue that is currently not well understood [34]. Tankless units, with small diameter heat exchanger flow pathways, are more susceptible to experiencing significant flow and performance degradation in situations with hard water. Preferred maintenance in areas with hard water include inlet water treatment or water softening, and/or flushing of the heat exchanger with mild acid solution to remove scale deposits. Little data is currently available on how well installed units have been maintained, the costs associated with that maintenance, and the number of tankless units which have experience heat exchanger failures due to lack of maintenance.

Hybrid Storage/Tankless Products

A new emerging product class has come to the market which combines a tankless unit with a downsized storage tank (~25 gallons). This product was designed to combine the benefits of tankless and (downsized) storage technologies, deliver condensing levels of performance, while maintaining a retrofit option were gas line upsizing is not needed. The AO Smith NEXT is the current existing hybrid product on the market [35]. This product class offers interesting potential since the incorporation of storage should alleviate any of the identified tankless performance issues, while operating at a lower standby loss than a full sized storage unit. Limited monitoring has been completed to date. The potential of applying intelligent controls may be a key future enhancement to achieve optimal storage performance.

Electric Storage Water Heaters

Storage electric water heaters are common to much of the U.S., particularly in the Southeast where they represent over half of the installed water heaters. Storage electric units typically have two 4500 Watt electric elements, one located at the bottom of the tank, and one at the top. The controls are interlocked, so only one element is energized at a time. Typically the lower element fires as the lower thermostat is tripped, typically when cold water enters the dip tube during hot water draws. If heavy hot water demand triggers the upper thermostat, the upper element is energized and the lower element is de-energized. The heating capacity of an electric storage water heater is roughly 40-50% that of a typical gas water heater, so electric units are more prone to running out of hot water, requiring homeowners to be more mindful of hot water usage patterns.

From the "source[23]" energy perspective employed under California's Title 24 energy code, electric resistance storage water heaters are not highly regarded, despite the fact that from a strict Btu viewpoint, electric storage standby losses are considerably lower than for a center flue atmospheric gas water heater[24]. However coupling renewable technologies, such as solar thermal, with electric storage may well be a viable option. Solar water heating is the logical renewable technology, but there are other potential renewable strategies that can complement electric storage units as well. One strategy is to utilize off-peak (excess) wind generation to charge electric resistance tanks to high temperatures, and coast through next day utility peak periods [36]. Electric water heating technologies coupled with renewable generation also simplify the pathway to achieving true net zero energy homes.

Instantaneous Electric Water Heaters

Instantaneous electric water heaters offer an alternative to electric storage water heaters. Similar to the comparison between gas storage and gas tankless, instantaneous electric offers the advantage of small physical size and elimination of standby losses, however the efficiency benefit due to eliminating tank standby losses is smaller than for gas tankless vs. atmospheric gas storage. The real performance advantage of instantaneous water heaters lies in point of use applications where hot water distribution losses can be eliminated. Instantaneous electric water heaters come in sizes ranging from 120 V units that serve individual bath faucets, to the more

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[23] Source energy reflects the energy consumed at the power plant (as well as transmission and distribution system losses) to deliver 1 kWh to the end user. Historically the California Energy Commission has assumed 1 kWh delivered requires 3 kWh of "source" energy. In recent years the source energy calculation has become more sophisticated to reflect time-of-use and societal effects.

[24] The center flue design of a standard gas storage water heater results in significantly higher standby losses. The 78% recovery efficiency of a center flue water heater is reduced 23% to approximately 60% (0.60 EF) with standby losses. Conversely an electric storage water heater is reduced only about 10%, from 99% recovery efficiency to 0.90 EF.

typical 240 V units with capacities ranging from 9 to 32 kW. The 240 V units require significant electrical capacity (with resulting peak electrical demand implications), which may prove challenging to implement, especially in retrofit applications. The larger capacity units cost more than standard electric water heaters, but may result in a first cost advantage if significant distribution piping costs can be eliminated.

Ideal applications for instantaneous electric water heaters would be locations with low electric rates, houses with widely spread out use points, and applications where a fairly constant source of year round supplemental heat could be used to deliver pre-heated water allowing downsizing of the required heater and also minimize the use of inefficient electric heat. This supplemental heat could be in the form of solar water heating, or some sort of waste heat recovery.

Heat Pump Water Heaters

Heat pump water heaters (HPWHs) offer the potential for significant energy savings relative to electric resistance water heaters. A HPWH system is comprised of a storage tank, a refrigeration system (compressor, fan, and heat exchangers for extracting heat from the air, and for delivering heat to the storage tank), controls, and in some cases a pump to circulate water. The unit can either be "integrated" with the storage tank (as shown in the schematic in Figure 57) or be an add-on module that is mounted on or adjacent to a conventional electric water heater. Pumps, activated when the compressor operates to circulate water to the condenser, are used with some models, depending upon the configuration. All models currently on the market provide the user control over the extent to which the unit utilizes electric resistance heating to supplement heat pump operation. This feature is desirable in some situations, since the heat pump recovery capacity is lower than for standard gas and electric water heaters, as shown in

Table 20.

In the heat pump mode of water heating operation, refrigerant is vaporized at the evaporator coil (extracting heat from the surrounding environment), compressed to a high temperature gas via mechanical work (compressor input), and then condensed, delivering heat to the storage volume. With current conventional refrigerants, the thermodynamics dictate that the energy added to the water is roughly 2-3 times greater than the electrical energy consumed by the compressor and fans. Efficiency degradation in the heat pump cycle occurs as tank water temperatures become hotter and the air entering the evaporator becomes cooler.

HPWH controls allow the user to select both the tank setpoint and an operating mode, which determines whether system operation is biased towards "heat pump only" operation, or electric resistance heating. "Heat pump only" mode offers the highest efficiency, but also the lowest recovery capacity since it relies only on heat pump heating. "Resistance only" operation provides performance comparable to a standard electric storage water heater, hence no energy savings. The hybrid mode, which may turn out to be how most users utilize these systems, offers a balance between the two extremes. Each manufacturer utilizes a different hybrid control strategy to balance heat pump and resistance heat operation. Data from the field is informing the manufacturers on hot controls should be modified to improve performance without compromising hot water delivery.

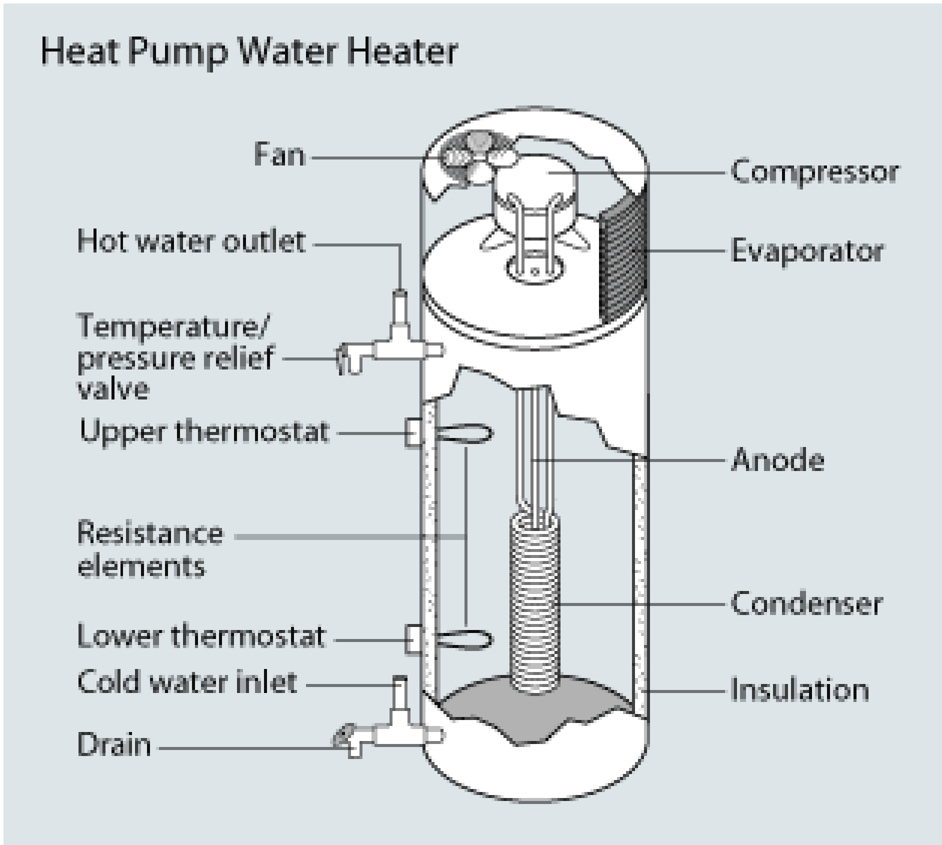

Figure 57: HPWH Schematic of Integrated Unit with Immersed Heat Exchanger

http://www.eere.energy.gov/basics/buildings/water_heaters_heat_pump.html?print

Table 20: Heating Rate Comparison by System Type

System	Typical capacity	Heating Rate (Btu/hr)
HPWH (compressor capacity)	0.5 to 1.0 ton	7,800 to 15,600[25]

[25] For the HPWH, the heating rate is the cooling capacity plus the energy input to the compressor, i.e. the heat rejection. This is typically about 130% of the cooling capacity.

HPWH backup electric heat capacity	2.0 to 4.5 kW	8,880 to 19,955[25]
Typical electric storage capacity	4.5 kW	15,350
Typical gas storage WH gas input rate	33,000 – 40,000 Btu/hr	33,000 to 40,000

Relative to gas and electric storage water heaters, HPWHs require a significant volume of air (typically 700-1000 ft^3) to insure that operation will not overcool the space, resulting in low evaporator inlet air temperatures, leading to a low temperature cut-out situation (typically at around 45°F). All of the listed HPWHs require 240V electrical service which is not an issue in new construction (or in retrofit applications if an existing electric water heater is being replaced), however it would represent an added cost a gas water heater were being replaced. In many California applications, these units will be installed in garages. Since HPWH heating capacity and efficiency are proportional to the evaporator inlet air wet bulb temperature, colder climates and colder operating environments will reduce system performance. Indoor HPWH installations offer the potential for improved performance in cooling-dominated climates where additional cooling is beneficial.

Lab Findings on Advanced Water Heater Performance

One element of the PIER project was to utilize both laboratory and field testing results to better characterize the performance characteristics of high-efficiency gas-fired water heaters. Lab testing is generally more useful for precisely identifying performance characteristics and control nuances under very controlled conditions, while field testing allows for real world effects to be observed and quantified. In support of this effort, the Gas Technology Institute and Pacific Gas & Electric (PG&E) evaluated high-efficiency water heaters in their test labs, focusing on two classes of products:

- **High-Efficiency Storage Water Heaters** (PG&E effort) – Driven by both the change in EnergyStar® requirements and the 2015 change in the federal minimum efficiency standards, manufacturers have filled out their gas-fired storage water heater (SWH) product families to meet these efficiency requirements. In addition to new condensing, power/direct vent, and hybrid gas-fired SWH offerings, many new products are compatible with Category I venting, including features such as small combustion air blowers & inducers and powered vent damper. Unlike the common minimum efficiency products, these > 0.67 EF products are powered, resulting in parasitic energy consumption and susceptibility to power outages.
- **Tankless Water Heaters** (GTI effort) – Gaining popularity over the past decade, tankless water heaters (TWH) have enjoyed increasing market share due to their high-efficiency relative to standard gas-fired SWHs, marketing of "endless hot water", and incentive programs. Deficiencies in the field versus EF rated efficiency of tankless water heaters are a known issue [32, 33] due to the minimum draw rate requirements and startup sequence delays. The GTI lab effort focused on characterizing physical parameters, start up

sequences, standby capability, and ability to maintain temperature stability under varying hot water loads.

PG&E testing was completed on a group of water heaters listed in Table 21[26]. Tests were completed according to the Energy Factor procedure to replicate results and also determine the first hour rating. Two more realistic draw profiles developed by GTI were also used: the "mid" case had loads equal to the 64 gal/day EF test, but distributed in a more realistic use pattern, while the "low" use case featured a 30 gal/day load, also with a more realistic profile. The key points to highlight in Table 21 are:

- The general agreement of manufacturer and tested EF ratings at the "DOE Std Draw" condition.
- The minimal impact the EF six draws vs. GTI Mid "real" draw pattern has on the EF.
- The impact of the "Low" draw pattern on overall efficiency and the implications for climates with lower recovery loads, such as California.

As water heater recovery loads go down, not only is the efficiency of the water heater reduced, but the absolute savings are reduced, affecting cost-effectiveness. Since all the >.67 EF water heaters require electrical input, there is also the question of electrical energy use. With typical standby consumption of 5 Watts for controls, plus more during operation (combustion fans), the electrical energy use can start to erode the value of the gas savings.

The four tankless water heaters tested by GTI are shown in Table 22. One non-condensing and three condensing units were tested. The variation in water side volume has implications for hot water delivery characteristics. The fourth unit, with the 2 liter buffer tank, has the ability to heat the buffer tank on a schedule (from 0 to 24 hours per day), providing improvement in hot water delivery characteristics at the expense of added energy use.

Table 23 reports the test results under the DOE EF test conditions as well as the GTI mid and low use tests. The degradation in efficiency from the rated EF is apparent, although less so for Condensing #1 & 2. The continuous (24 hour) heating of the buffer tank has a sizable impact on the EF reducing it from 0.85 to 0.67.

Table 24 summarizes average and maximum time delays for draws included in the GTI mid draw profile. For most of the units, the average time delay to fire is about 5 seconds, with

[26] Note that the "15 year old" water heater was one of the existing units removed as part of the field test.

typical delays in delivering water at 95% of setpoint between 15 to 30 seconds. Longer delays were experienced in the buffer tank unheated case. These time delays are of course compounded by the time delays related to getting the heated water from the water heater to the use point.

Table 21: EF Results for Storage Water Heaters

Description	DOE First Hour Rating		DOE Std Draw		GTI Mid Draw	GTI Low Draw
	Mnfr.	Test	Mnfr.	Test	Test	Test
"15 Year Old" Water Heater	63	80	0.64	0.59	0.60	0.44
0.62 EF Atmospheric	71	70	0.62	0.60	0.60	0.48
0.67 EF Atmospheric/Vent Damper	67	70	0.67	0.66	0.66	0.57
0.67 EF Power Vent	70	89	0.67	0.64	0.64	0.53
0.67 EF Direct Vent	73	76	0.67	0.64	0.64	0.53
0.70 EF Atmospheric/Fan Boost	70	77	0.70	0.66	0.66	0.54
Hybrid	189	130	90% TE	0.68	0.68	0.56
Condensing Storage	123	148	90% TE	0.74	0.73	0.62

Table 22: Tankless Water Heater Description and Physical Characteristics

Description	Firing Rate (Btu/hr)		Certified Performance			Unit Weight (lbs)	Water side volume (L, measured)
	Min	Max	EF	Max GPM	at ΔT (°F)		
Non-condensing	11,000	199,900	0.82	4.3	77	54	0.875
Condensing #1	9,500	199,000	0.93	4.4	77	70.5	1.7
Condensing #2	19,900	199,000	0.91	6.7	55	74	0.92
Condensing with small 2 liter buffer tank	17,000	199,000	0.95	5.1	77	86	3.7

Table 23: Summary of 24 Simulated Use Test Data

	EF	Estimated EF		Average Delivered T (°F)		
	DOE	Mid	Low	DOE	Mid	Low
Non-condensing	0.77	0.75	0.73	129.6	125.3	129.9
Condensing	0.92	0.90	0.87	127.5	123.7	123.8
Condensing (Buffer tank heated)		0.67			126.4	
Condensing (Buffer tank unheated)		0.85			119.8	

Table 24: Summary of Delays from GTI-Mid Draw Schedule Testing

	Average Time Delay (seconds)		Maximum Time Delay (seconds)	
	To fire	**To reach 95% of final temperature**	**To fire**	**To reach 95% of final temperature**
Non-condensing	4.5	15.1	6.0	28.0
Condensing #1	5.4	27.1	6.0	32.0
Condensing (Buffer tank heated)	6.5	13.1	7.0	31.0
Condensing (Buffer tank unheated)	11.3	13.4	18.0	54.0

These laboratory findings should be taken as a snapshot view of a sample of currently available products, and not necessarily representative of the product class as whole. The key goal of presenting this information was to inform the reader of observed performance characteristics in a laboratory setting.

Field Findings on Advanced Water Heater Performance

The PIER field monitoring efforts collected data at the eighteen California field sites (six in Northern California and twelve in the Los Angeles and San Diego areas) over a period of 14 months from spring 2010 to summer 2011. Detailed base case monitoring spanned seven to nine months, at which time advanced gas water heaters were retrofitted at the sites. Post retrofit monitoring continued for four to five months. Detailed data were collected on hot water flows, temperatures in and out of the water heater, and energy consumed by the water heater. Figure 58 presents an "input-output" plot from one site, showing daily pre- and post-retrofit thermal energy input (gas use) as a function of thermal energy delivered from the water heater. In the example shown, the existing atmospheric gas water heater was replaced with a condensing tankless water heater (CTWH). The blue symbols, representing the base case water heater, indicate higher consumption per unit of energy output than the CTWH unit. Of special note is the Y-axis intercept which identifies the energy required at zero load (standby energy).

The input-output data from each site was averaged among similar units in its product class, defined as:

- Entry level EnergyStar (0.67 – 0.70 EF),
- Non-condensing tankless
- Condensing tankless, and
- Condensing storage.

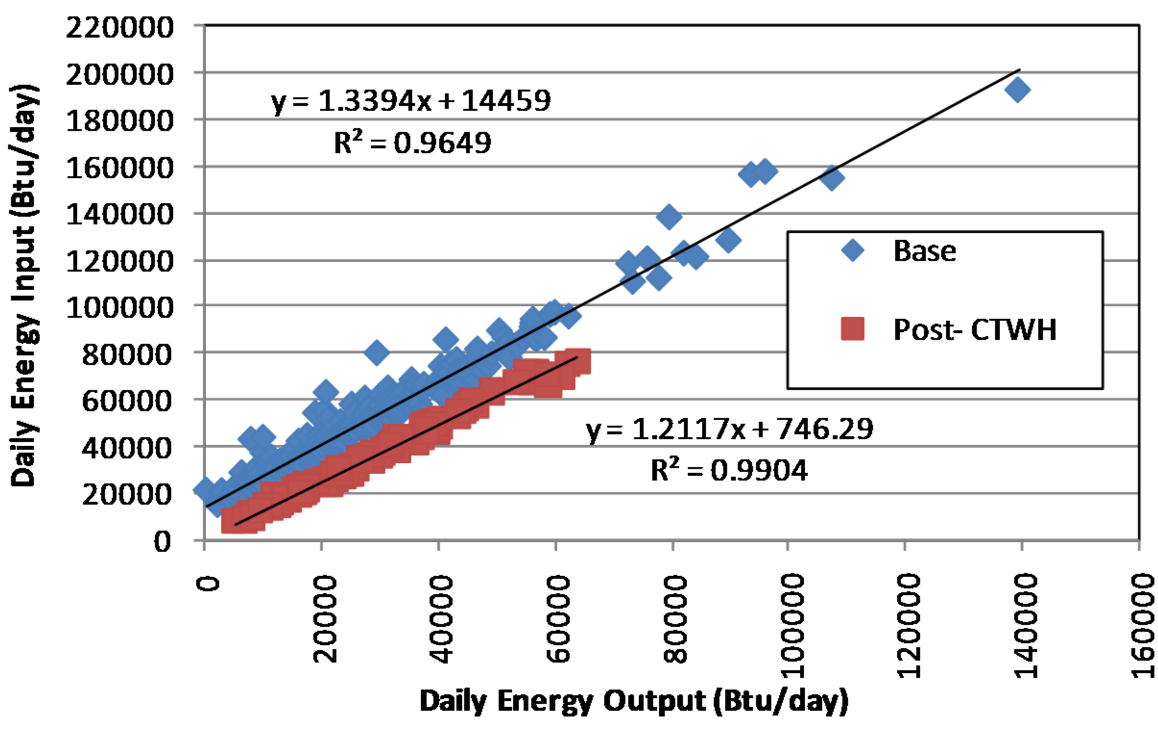

Figure 58: Sample Daily Input-Output Curve

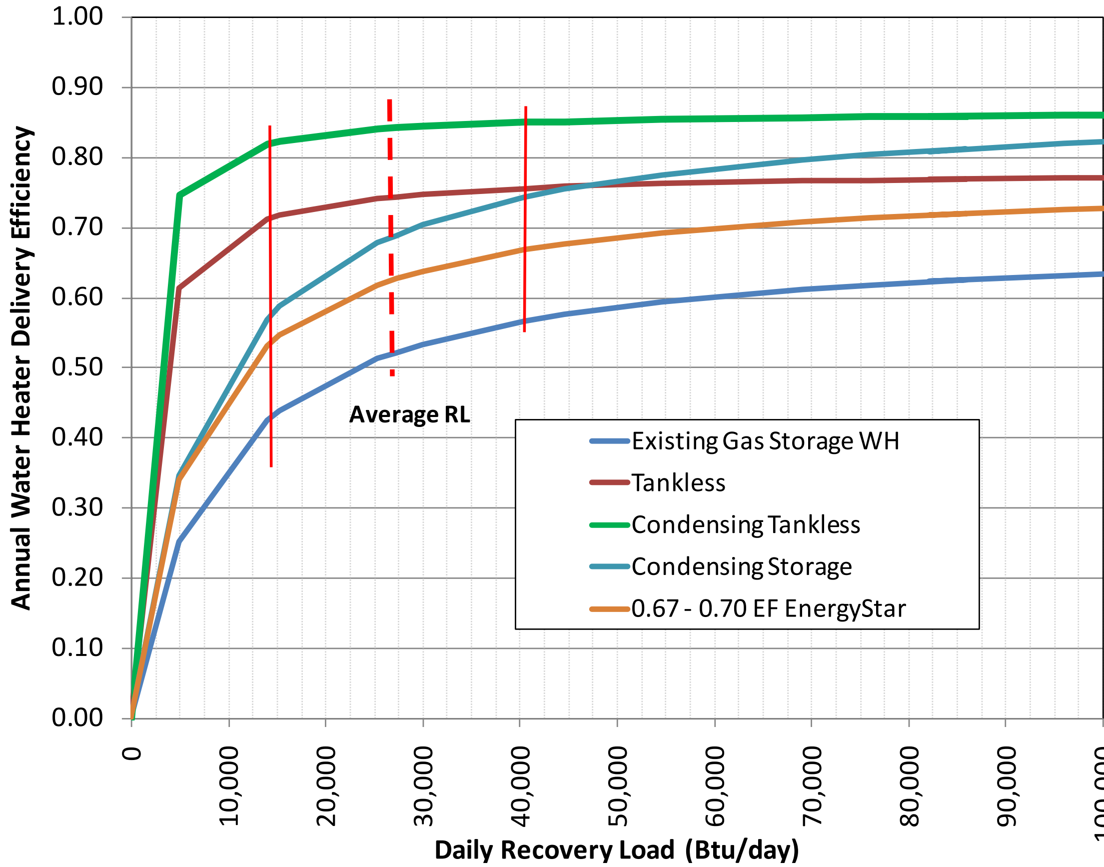

Figure 59: Comparative Performance of Gas Water Heater Types as a Function of Recovery Load

Figure 59 depicts the overall field-monitored efficiency of a particular product class by averaging the individual site input-output relationships. The field monitored efficiency varies strongly with recovery load, especially for the storage products. The vertical "Average RL" line depicts the observed average recovery load at the 18 sites, which is over 1/3 lower than the 41,050 Btu Energy Factor recovery load level. (One standard deviation above and below the mean are also shown on the plot.) The key takeaway from this plot is how different water heater product types respond to changes in hot water loads. The existing atmospheric storage gas water heaters show the most degradation from rated efficiency at small loads and tankless units show the least. EnergyStar and condensing storage water heaters show little advantage at very low load levels, with increasing benefits as the loads increase. As loads exceed the Energy Factor level (41,050 Btu/day), condensing storage projected efficiencies surpass those of the tankless water heater.

Error! Reference source not found. contains a detailed step-by-step procedure for completing a cost-effectiveness calculation for advanced water heater options for different climates, hot water loads, and utility rates. This tool[27] was developed for DOE's Building America program and is based on the PIER project performance results and HPWH field data provided by the CARB Building America Team.

The following key takeaway inform in the selection of water heating equipment:

1. Water Heater Ratings- Clear evidence from laboratory and field testing indicate that EF ratings do not accurately reflect the performance of water heaters in California. Tankless water heaters are overrated by 8-10%, since hot water draws (and therefore cycling impacts) are underestimated in the test procedure. Gas storage water heater in-situ performance is (on average) overestimated by at least that much, since typical California water heating loads are 35-40% lower than assumed in the test procedure, increasing the impact of standby losses on overall annual performance.

2. Entry level EnergyStar water heaters (0.67-0.70 EF) are the least cost-effective of the advanced gas water heaters for most California customers. Relatively cheap natural gas and expensive electricity result in gas savings being significantly depreciated due to the 80-100 kWh electrical consumption of these water heaters.

3. Gas tankless water heaters offer reasonable economics, especially in new construction, but the need for maintenance (in hard water areas) may offset savings.

4. Gas tankless water heaters do offer a different hot water delivery experience relative to storage water heaters. Increased hot water wait time, no hot water at very low flow rates, and "cold water sandwich" effects will occur. For most customers this may not be a significant issue. For others, it may be an inconvenience.

5. Trends in water and energy conservation are pushing hot water loads lower and lower. This has implications on performance (storage unit performance is further degraded; tankless unit minimum flow rate issues and hot water waiting times become more significant), as well as economics.

6. HPWHs offer significant potential as an energy efficient alternative to electric storage water heaters. In California, electric water heating is not that common, representing

[27] http://www.nrel.gov/docs/fy12osti/55074.pdf

~10% of residential customers. High electric rates in much of the state, also contribute to poor economics relative to natural gas water heating. The best applications may be zero net energy projects where HPWHs can be an effective component of an all-electric home.

Load Reduction Strategies

The movement towards more efficient water heating systems in the years ahead will ultimately lead the industry to develop and implement strategies that reduce the load on the gas or electrically driven water heaters. Examples of such load reduction strategies include solar thermal systems, drain heat recovery devices, desuperheaters, and possibly grey water heat pump pre-heaters.

Solar thermal is an attractive renewable technology to combine with conventional water heating strategies to reduce fossil fuel water heating energy use. Ideally an effective solar thermal system would provide year round consistent contributions to the daily hot water load, allowing for conventional system downsizing (e.g. reduced capacity tankless unit) or improved performance (e.g. lower load on a HPWH would likely reduce resistance heat operation). In reality, for many U.S. climates, the solar contribution can be large during the summer, but contribute little in the winter months when water heating loads are highest. Solar integration and optimization are important areas to explore in the pursuit of a high performance domestic water heating system. This study will not address these issues in any detail, but refers readers to the Building America Best Practices Series on Solar as a starting point [37, 38, 39].

Other potential water heating load reduction strategies that should be explored include drain water heat recovery systems which reclaim heat from water used in showers. As shown in Figure 60, the system (a copper heat exchanger that pre-heats cold inlet shower water with warm/hot shower drain water) will reduce the required hot water flow rate at the shower since the cold water is warmer. The system requires a second story shower, or first story if there is a basement, but the beauty of the design is that it will reliably reduce the load on the water heater year round. The benefit of the device is proportional to the flow of water through it and the temperature difference between drain water and entering cold water. Conceptually drain heat recovery systems have positive benefits for a variety of water heating system types. HPWHs would benefit from lower loads by experiencing fewer second stage heating events, and lower capacity gas tankless water heaters could potentially be developed that wouldn't require a gas line upsizing for retrofit applications[28]. Further research is needed to assess these impacts.

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[28] A potential concern exists in matching drain heat recovery with gas tankless units in warm or hot climates, since hot water flows may fall below the unit's minimum flow rate.

It is important to realize that any load reduction technology will reduce the load on the primary water heater, which has implications on the operating efficiency, as characterized in Figure 59.

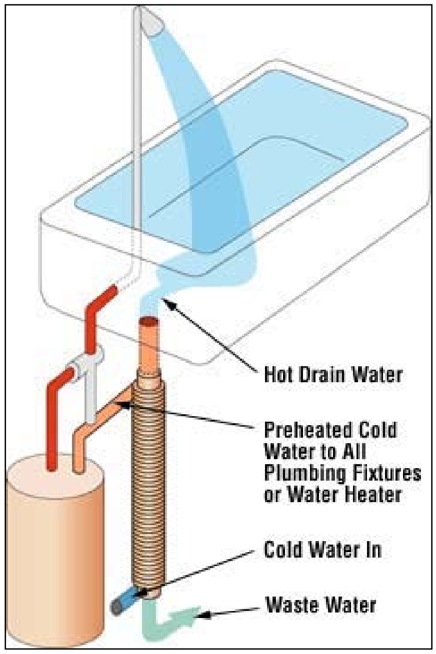

Figure 60: Drain Heat Recovery Schematic

Source: http://www.toolbase.org/Technology-Inventory/Plumbing/drainwater-heat-recovery

2.4.1.3 Design Recommendations

Architects, builders, and contractors all have an opportunity to positively influence the performance and efficiency of domestic hot water systems in new and existing buildings. Existing buildings are clearly a much bigger challenge since retrofit costs and site difficulties complicate more aggressive efforts to improve overall system performance. The goal should always be to reduce the load on the water heater, despite the fact that this may contribute to lower water heater efficiency.

The load on the water heater can be reduced in several ways:

1. By developing a house design for new construction that increases the efficiency of the distribution system (lower losses, reduced distance and entrained pipe volume between the water heater and the use points),

2. By selecting more efficient fixtures and appliances which reduce the need for hot water,

3. By offsetting a portion of the load through waste heat recovery or renewable sources, and

4. By educating homeowners on behaviors that contribute to lower hot water consumption.

By reducing the water heater recovery load, matching an appropriate water heater to the load, and educating the consumer on how to achieve optimal performance, one can achieve energy savings and improved system performance in terms of reduced water waste and waiting summary. A summary of the key elements follows:

Building Design From a Plumbing Perspective ("short and central")

The process begins, in the case of new homes, with the architectural design and the location of the water heater and hot water end use points in the home. One water heater centrally located relative to the use points (or two separated water heaters, each centrally located) represent an ideal configuration, in that the entrained volume between the water heater and the use points can be significantly reduced, if the plumbing layout is efficient and properly sized. A centrally located water heater improves hot water waiting time, and reduces water waste and energy losses from the piping. A smaller plumbing design also often eliminates the need for a recirculation system, since the driving factor in selecting a recirculation system is often unsatisfactory hot water waiting times. In some large homes, a second water heater may be a logical solution to add water heating capacity (and some level of supply redundancy), improve hot water delivery efficiency, and reduced distribution related waste. (Care should be taken in the selection of the second water heater, since excessive standby loss increases could negate reductions in piping heat loss.)

In cases where centrally locating the water heater is problematic (e.g. exhaust venting is complicated or costly), every effort should be made to at least locate the water heater in a location that balances "central-ness" vs. added installation cost. Remember that the first cost savings associated with installing a gas tankless unit on an exterior garage wall (easy install), may be more than offset by the added operating costs associated with a lengthier distribution system layout which will affect the consumer every day.

The architect must also take a hard look at the building design in terms of grouping hot water end points so that synergies can be achieved. The example shown in Figure 41 highlights how putting the master bath and kitchen "back-to-back" increases the likelihood of draws benefitting from existing hot water in the lines providing hot water for subsequent kitchen draws, and vice versa. Small distribution systems, with clustered use points, should be the goal of all designs.

Fixture and Appliance Selection

Showerheads represent the primary hot water end use in most households, conservatively representing ~ 20% of total indoor (hot and cold) water use in the U.S[29] [40]. EPA supported the development of a WaterSense showerhead standard at a level of 2.0 gpm, 20% lower than the Federal standard of 2.5 gpm [41]. In addition, significant testing was completed to characterize "performance" of WaterSense qualified showerheads with regards to temperature, shower force, coverage, rinsing action, and noise [40]. So as well as requiring less hot water, these units have been shown to provide high levels of consumer satisfaction. Directing designers, builders, and plumbers towards WaterSense showerheads will result in shower hot water use savings.

In addition to showerheads, WaterSense also provides a list of qualified bathroom sink faucets that can reduce sink water use by 30% [42]. Sink hot water use is a highly behaviorally driven usage, as different people have different methods of interacting with the fixture. Arguments can be made that single lever faucets may draw more hot water inadvertently as many users may naturally operate the faucet in the vertical position (half hot, half cold), regardless of whether they will actually wait for the hot water to arrive.

Finally appliance selection can further reduce hot water loads. Efficient clothes washers and dishwashers can reduce appliance water use [43]. These efficient units are often also eligible for water utility rebates. Providing these appliances as part of a standard builder package would demonstrate a strong commitment to water and energy efficiency.

It is important that these issues also become part of the retrofit discussion. Many existing showerheads, faucets, and appliances are inefficient in terms of flow rate or water use. Homeowners and plumbers need to become familiar with various low-flow options so that they can make informed decisions on what works best for their needs.

Distribution System Design and Installation

The architectural design represents the critical first step in defining the hot water system performance, but a poorly designed and implemented plumbing layout can still ruin a fundamentally "good" architectural design. More attention needs to be paid by the plumbing designer in making sure that the intended plumbing design is properly implemented in the field. PEX is an attractive piping material, but it does facilitate the potential for a fast and sloppy installation where the piping is run where it is easiest to run, rather than in a manner conducive to efficient hot water delivery.

[29] an estimated 3.8 million gallons per day.

General rules to follow:

1. Avoid using 1" hot water piping unless detailed pipe sizing calculations warrant its use. In virtually all residential applications, there is no need for 1" hot water piping.

2. Minimize the use of ¾" and larger piping. For "trunk and branch" or hybrid configurations, avoid the long trunk line snaking through the attic, if a more direct route from the water heater can be achieved more directly.

3. Home run manifold systems can offer an efficient alternative, even more so if 3/8" piping is allowed by the local building jurisdiction. It is absolutely critical to keep the water heater to manifold distance at an absolute minimum to achieve good home run system performance.

4. Hybrid systems with distributed mini-manifolds should strive to keep the manifolds close to the water heater.

5. Recirculation systems are certainly appropriate for some applications or for satisfying discriminating client who demand immediate hot water delivery. Prior to selecting a recirculation system, a careful review of the plumbing design should be completed. Is a second water heater a better solution? If so, a small powder room could possibly be served by a 1 gallon electric instantaneous unit on a timer. Or a tankless water heater or HPWH may be the right solution. Consider the standby energy impacts of having two storage water heaters given the expected load that will be served. If a recirculating system is to be selected, the demand recirculation system with push button control represents the best option. Careful recirculation loop sizing (to avoid pipe oversizing) and balancing of the loop layout vs. the loop proximity to the end use points is critical. If a recirculation system is still needed, use demand recirculation for best performance.

6. Installation practice should focus on avoiding excess pipe length and high quality pipe insulation installation. (A good pipe insulation job is especially critical in recirculating

systems.) Attic piping should be buried in blown ceiling insulation[30], especially PEX and CPVC due to their high radiant heat loss when uninsulated.

7. It is important to think of distribution losses and water waste in a manner similar to atmospheric water heater pilot energy (estimated to be equal to 6% of California residential gas consumption). Although impacts due to improvements are often not large, the cumulative statewide impact is significant.

Water Heater Selection

Numerous efficient water heater options are now available in the marketplace. Many of these new options come with a significant price premium, primarily due to current low production volumes which result in higher unit costs. High installation costs for efficient technologies are especially common in the retrofit market where transaction costs are high and some technologies (e.g. gas tankless) often require very costly infrastructure upgrades. The tool in **Error! Reference source not found.** allows one to evaluate the cost effectiveness of various high efficiency options.

For much of California, it appears that typical existing household water heating loads are roughly 30-40% lower than assumed in the Energy Factor test procedure. As loads continue to diminish in the future through improved fixtures and appliances (and potentially solar or heat recovery), economics will tend to drive the water heater selection from high standby storage units, to gas tankless or lower standby storage units. Lower water heating loads will also most likely tend to make the economics of condensing technologies less favorable, as the energy saved per $ of incremental cost is reduced. An important consideration for tankless units in retrofit applications is to understand the existing distribution system performance. A house with long hot water waiting times to the master bath will have that problem magnified by a tankless unit due to the cold start-up time delay.

The selection of advanced water heating systems should also focus on overall reliability and the need for ongoing maintenance. Many of the newer technologies need to log more field operating time before they are widely recognized as reliable water heating systems. Tankless

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[30] In cases of attic piping and batt insulation, care should be taken to make sure that the piping installed below the batts does not lift the insulation off the ceiling drywall. In that case, the benefit of keeping the pipe out of the more extreme attic environment is more than offset by the house thermal envelope degradation caused by separating the house thermal and pressure boundaries.

water heaters in areas with poor quality will absolutely require some level maintenance (or water softening) to preserve the performance of the heat exchanger. Maintenance costs may exceed the value of the energy savings, resulting in poor economics, despite the fact that energy savings are realized.

Water heater selection should also look for synergies to increase the energy savings or overall cost effectiveness. An example includes indoor HPWHs in warm climates[31], where the unit serves the dual purpose of water heating and supplemental space cooling and dehumidification. Another important option to consider is combined hydronic systems whereby a single high efficiency heat source (water heater) replaces the conventional furnace and water heater. By replacing the furnace with a lower cost air handler, more favorable economics can often be achieved.

The Efficient Water Heating System Scorecard

In conclusion, the following scorecard represents a simple summary of the key items discussed in this guide, as it relates to delivering a high performance water heating system. The goal is for each installed hot water system to achieve five checks.

Table 25: Efficient Water Heating System Scorecard

Attribute	**Achieved**	**Not Achieved**
Basic building design and hot water use points/ water heater intelligently located?	✓	
Hot water load reduction strategies and water efficient appliances in place?	✓	
Efficient distribution system installed and verified for compactness and low entrained volume; insulation and/or recirculation controls (if installed) properly verified/commissioned?	✓	

[31] If natural gas is unavailable, or electric rates are low enough to make HPWH's attractive.

Efficient water heater properly installed according to manufacturer's instructions (and local code) and commissioned (take into account actual or expected loads, homeowner expectations, available fuels and rates, installed costs, climate, and incentives)?	✓
Occupant education completed (how to maximize system efficiency)?	✓
TOTAL SCORE	✓ 5

CHAPTER 3: STANDARDS AND CODES

LBNL and DEG co-led the standards and codes project. The purpose of this project was to instigate needed revisions to national residential water heating testing and rating standards, and provide necessary input for energy efficiency code updates in California. LBNL led the standards work that proposed revisions to method of test standards that will accommodate more representative 24 hour draw profiles, along with more real world indicative performance rating results. These standard efforts were initially channeled through the American Society of Heating, Air-Conditioning, and Refrigerating Engineers (ASHRAE) and its Standard 118.2 Method of Testing for Rating Residential Water Heaters, but ultimately are impacting the present revision of the Department of Energy (DOE) Energy Conservation Program for Consumer Products: Test Procedure for Water Heaters, commonly known as the Energy Factor (EF) test. DEG led the codes work and has applied best practice analysis results, with assistance from AET, into suggested updates for California Code of Regulations Title 24 Energy Efficiency Standards for Residential and Nonresidential Buildings.

3.1 Method of Test Standard for Residential Water Heaters

Over the course of this Energy Commission program, water heater standard and code revisions were ongoing and addressed by many program team members, including LBNL, DEG, AET, and GTI. On the national level, the ASHRAE Standards Project Committee (SPC) 118.2, Method of Testing for Rating Residential Water Heaters, is currently drafting improvements to the test procedure used for measuring the energy efficiency of residential gas (and electric) water heaters. ASHRAE wants to develop this improved test procedure in part to support the DOE's latest rulemaking process to amend the Energy Conservation Program for Consumer Products: Test Procedure for Water Heaters, commonly known as the Energy Factor (EF) test, underlying the minimum energy efficiency standards for water heaters. DOE's test procedures are often based on or reference ASHRAE standards. LBNL's analysis of the DEG field testing results from this program reinforce the long recognized issue that people clearly use hot water differently than it is used in the DOE EF test procedure and that test procedure results consistently do not indicate actual efficiency in the field. Although, hot water use is driven primarily by occupant behavior and there is significant variation in hot water use and draw patterns between households, the draw pattern used in the DOE EF test differs significantly from those recorded during field use. To better match field performance, the DOE EF test should include a number of shorter, smaller draws at lower flow rates clustered closer together at particular times of the daily profile. Based on emerging industry consensus, after the DOE issued request for information regarding test procedures for residential water heaters on October 12, 2011, such recommendations for a more distributed 24 hour draw profile (and possibly multiple draw profiles of different daily hot water volumes) are now receiving strong consideration for use in a revised EF test procedure.

3.1.1 International Testing Standards for Water Heaters

The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) Standards Project Committee (SPC) 118.2, Method of Testing for Rating Residential Water Heaters, is seeking to improve the test procedure used for measuring the energy efficiency of residential gas and electric water heaters. ASHRAE is seeking to develop an improved test procedure in part to support the U.S. Department of Energy's (DOE's) desire to update and amend the water heater test procedure underlying the minimum energy efficiency standards for water heaters. DOE's test procedures are often based on or reference ASHRAE standards.

DOE's most recent minimum energy performance standards (MEPS) for residential water heaters were promulgated in 2010 [13]. The associated test procedures are stipulated in the Code of Federal Regulations (CFR) [46]. Although DOE currently is conducting a rulemaking to review and possibly amend the test procedures for residential water heaters, that rulemaking pertains to accounting for energy consumed during standby and off modes. In its notice of proposed rulemaking published in the *Federal Register* on August 30, 2010, DOE tentatively concluded that the test procedure for water heaters already fully accounts for and incorporates the energy consumed during standby and off modes [47].

3.1.1.1 Current Test Procedure

Under ASHRAE's current test procedure, two separate performance metrics are calculated: (1) recovery efficiency and (2) standby loss. Further calculations produce an efficiency descriptor (energy factor, or EF) that represents the overall efficiency of the water heater in providing a representative daily amount of hot water. Annual energy consumption and cost are estimated by extending the daily EF to a year (365 days). The test procedure describes methods for evaluating gas and electric storage water heaters, heat-pump water heaters, and instantaneous (tankless) water heaters [50].

SPC 118.2 is not alone in encountering difficulties in devising an improved test procedure—difficulties that to date have proved frustrating. To aid in the development of the test procedure, the status and content of water heater test procedures for other countries were investigated. Current water heater test procedures for other countries and organizations (Australia, the European Union (EU), and the International Organization for Standardization [ISO]) are described below in conjunction with their efforts to revise those test procedures.

3.1.1.2 Issues Surrounding the Test Procedure

A primary goal of any test procedure is that it be applicable to the full range of types and sizes of water heaters. A test procedure should be capable of evaluating all technologies fairly, including the newer ones, such as small gas-fired storage water heaters with a large burner. The current ASHRAE test procedure evaluates product efficiency for delivering 64.3 gallons[32] of hot water in 24 hours based on six relatively large draws. The same hot water load is applied regardless of the storage volume of the water heater or, in the case of tankless water heaters, whether the burner consumes 50,000 or 200,000 British thermal units per hour. The current test procedure with six major hot water draws tends to rate tankless water heaters higher than if the test consisted of more draws. Because of the cyclic losses associated with each draw, tankless water heaters tend to be less efficient at providing a larger number of smaller draws.

In addition to a need to broaden the applicability of the test procedures, another fundamental issue is the need to specify a draw (or tapping) pattern that describes the realistic field usage of a water heater. The current test procedure is based on a pattern of six draws in 24 hours. The flow rate for all draws is 3 gallons per minute for about 10 gallons. The draws are taken one hour apart, for a total of 64.3 gallons. After the sixth draw, the water heater is left in standby mode for the rest of the 24 hours. There is general agreement among the standard project committee members that the current draw pattern is not reflective of the way hot water is used. There currently is, however, no agreement on a better draw pattern. Internationally, different countries have different types of water heaters and use them differently. The test procedures for water heating appliances are not well harmonized throughout the world. The Collaborative Labeling and Appliance Standards Program (CLASP) is funding a study to assess international opportunities for harmonizing energy efficiency for all types of appliances. These initial assessments of the possibilities for harmonizing test procedures for water heaters conclude that the prospects are not bright.

- The current situation for water heating appliances is fairly bleak. There are many different product types and most are complex in their design and operation. Water heater energy consumption is heavily affected by hot water demand, which is highly variable at a regional level, and by many climatic factors, which are also very variable.

- There is very little international harmonization in test procedures and efficiency metrics for water heaters and even for simple appliances, such as electric storage water heaters, the comparison of settings is very complex due to testing and efficiency metric differences. … In the near term, however, harmonization prospects are not good for this group of products [49].

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[32] The 64.3 gallon draw is the DOE standard volume. The ASHRAE standard does not specify a volume quantity, other than referencing what the DOE standard uses in an annex.

3.1.1.3 Approaches to a New Test Procedure

The goal of any revised test procedure of course is to measure the energy efficiency of all types and sizes of water heaters fairly and consistently. There are two primary philosophical approaches for estimating the field energy consumption of water heaters based on laboratory tests.

One is to perform a simulated use test using a 24-hour draw pattern that is considered a realistic representation of how the water heaters are used in the field. Operating conditions (water and air temperatures) and draw patterns (timing, flow, and duration of draws) in the laboratory test are intended to represent typical use and conditions in the field. The energy consumption of the water heater in the test, would therefore represent the performance of the water heater in the field.

The other method is to run separate tests to determine key parameters of the water heater (such as recovery efficiency, standby loss, and cyclic losses). The parameters are then combined algorithmically to calculate energy use for any specified operating condition and draw pattern. The calculations could be performed using simple algorithms such as the one used to evaluate the annual energy use of commercial water heaters or the input/output (I/O) protocol [50, 51] Alternatively, more complicated methods such as transient system simulation models (TRNSYS) can be applied [52]. No consensus has been reached on whether it is better to apply a 24-hour simulated use test or measure parameters and apply an algorithm.

Table 26: Comparison of the Two General Approaches to Water Heater Testing

24-Hour Simulated Use Test		Parametric Tests and Algorithm	
Rating	**Aspect**	**Rating**	**Aspect**
+	Method easy to understand	-	Method more difficult to understand
+	Covers all water heater technologies	-	Different water heater technologies may require different types of tests
-	It is not obvious what draw pattern to use	-	It is not obvious what draw pattern to use
-	Results apply only to operating conditions and draw pattern used in test	+	Parameters can be applied to a range of operating conditions and draw patterns
-	Changing the draw pattern would require retesting	+	Changing the draw pattern would require only recalculation, not retesting

24-Hour Simulated Use Test		Parametric Tests and Algorithm	
Rating	Aspect	Rating	Aspect
-	Water heaters having different capacities would be tested with different draw patterns	+	Water heaters having different capacities would be tested the same way; only the energy use calculations would differ
-	Inappropriate draw pattern and operating conditions may bias the results by technology type	-	Inappropriate parametric tests may bias the results by technology type
-	May need to measure the water temperature inside the tank to correct for changes of stored energy during the test	+	May not need to measure the water temperature inside the tank to correct for changes of stored energy during the test
		-	Unclear what is the best method is to calculate energy use
		-	Need to validate or confirm that the selected energy calculation method

3.1.1.4 Sizing

Currently in the United States, water heaters governed by National Appliance Energy Conservation Act, regardless of size, are tested based on DOE's draw pattern that totals 64.3 gallons per day. Yet water heaters are designed and built to have a range of capacities. It seems reasonable that a water heater having a small capacity would be installed in applications where little hot water is needed. One potentially useful approach is to test a given water heater using a draw pattern that better matches its intended use.

The maximum amount of hot water a water heater can deliver in 15 minutes may provide a good rating of delivery capacity. Household usage varies, of course, with days of different hot water demand, but this rated delivery capacity coincidentally seems to equal an appropriate daily average amount of hot water use for testing a water heater of a given capacity. This approach is based on both current manufacturer sizing recommendations and a study that examined how people use hot water and the product capacity needed to avoid frequent run outs of hot water [53].

3.1.1.5 Current Status

Along with the United States, the European Union (EU), Australia, and the International Organization for Standardization (ISO) are all in the process of revising their test procedures for water heaters. Japan recently finished revising its test procedure for gas water heaters, but the results have yet to be translated into English [54].

ASHRAE

The current ASHRAE Standard is 118.2-2006, *Method of Testing for Rating Residential Water Heaters*.[4] That test procedure is a revision of ANSI/ASHRAE Standard 118.2-1993 by the same name. Among changes made to the 1993 standards were to require one pre-draw, require a 24-hour soak-in period before the test, and account for recovery periods that span multiple draws. The tolerances allowed in some measurements were reduced, and references to other standards were updated. Because of widespread dissatisfaction with the repeatability and appropriateness of the test, a revision committee was founded soon after the changes were adopted.

Australia

To date Australia's approach has been to do parameter testing. There have been Minimum Energy Performance Standard (MEPS) for electric storage water heaters since 1999 [55]. The current test procedure for rating electric storage water heaters is standing heat loss test [56]. Because the heat can go nowhere except into the water, the resistance elements are assumed to be 100% efficient.

Australia currently has no standards or labels for gas water heater efficiency. Starting in 2005, the Australian government began an effort to bring gas water heaters into a consistent regulatory framework, similar to the one governing electric water heaters. Legal deficiencies in the regulatory guidance caused some delays. The test method is being revised to ensure that it provides a solid basis for MEPS and/or a labeling program.

The current Australian test procedure uses bench tests to measure key performance parameters under defined conditions. Those measurements then are used to estimate the energy consumption for delivering a particular amount of hot water per day [57]. Key stakeholders, however, have raised questions concerning the accuracy and reproducibility of the test. In late 2005 and early 2006, the Australian Greenhouse Office sponsored a round-robin comparative test program that used accredited test laboratories to assess the repeatability and reproducibility of the test method for gas water heaters. The labs came up with different results, in most cases varying more than expected given the specified measurement accuracy. The variations among key parameters, including burner efficiency for storage systems, maintenance rate (standby losses), and startup energy, indicated much greater uncertainty than expected [57].

A consultant was hired to recommend improvements to the test procedure for gas water heaters. One of the important recommendations was to operate the product as it likely would be used in the field; that is, with cold water drawn into the inlet, hot water drawn through the outlet, and the unit allowed to recover under its own controls [58]. Harrington also recommended measuring the recovery efficiency of storage water heaters by conducting full-tank draw-offs down to the minimum usable delivery temperature. The draw-offs would be repeated until a consistent efficiency is observed (typically after three full-tank draw-offs), then the process repeated for an additional four or five draw-offs. This series of full draw-off cycles also establishes a consistent pre-conditioning prior to the standby testing. Although direct measurement of internal water temperatures is desirable, for many tank designs it is physically impossible to accomplish without compromising the integrity of the insulation. If performed consistently, full-tank draw-offs provide an indirect way of measuring the stored energy (heat) in the tank.

The recommended new test method would determine standby loss at the end of the series of full draw-off cycles to provide a standardized pre-condition. Energy correction for temperature decrease or increase in the tank at the end of the maintenance period would be included in the calculation based on one temperature probe.

Thermal interactions in storage systems are complex. Many factors vary during normal operation, and it may be impossible to provide a representative set of conditions that will provide test data from which in-use energy consumption can be calculated accurately.

For tankless water heaters, Harrington's recommendation was to determine the slope of energy output versus water delivery for the linear, steady-state part of a draw. The nonlinear part at the beginning would be characterized as an offset in terms of wasted water and startup energy. The startup energy until the time when hot water is first delivered would be added for each draw based on steady slope.

Harrington recommended that data from the above tests be input to a modified version of TRNSYS to calculate energy use. TRNSYS would enable the simulation of a wide range of delivery tasks under various conditions. The simulation model would be checked to confirm that it can replicate the range of laboratory task tests.

Harrington's proposed approach to testing newer hybrid units (which typically have a small storage volume and a large burner that can deliver hot water at a designated flow rate) was to test them separately as a tankless water heater and determine the maintenance rate as described above for storage water heaters.

Following up on Harrington's recommendations, Working Group 11 of the Australian Standards Association drafted a new trial test procedure that was evaluated in four laboratories. Another consulting company evaluated the results, with an eye to simplifying the procedure. One of the recommendation is perhaps to use a simple 24-hour simulated use test for storage water heaters. A proposed test procedure has not been released for public review yet. The situation in Australia clearly is uncertain and in flux.

European Union

The EU's attempt to develop a test procedure for water heaters, meanwhile, represents one of their efforts to harmonize Europe-wide Ecodesign standards for all appliances based on life-cycle performance. Council Directive 92/75/EEC of 22 September 1992 established, for all member countries, a uniform labeling program that required household appliances to display their consumption of energy and other resources [59]. Although the European Commission has issued directives regarding the performance labeling of many appliances (such as washing machines, dryers, refrigerators, electric ovens, air-conditioners, and dishwashers), they have not done so for water heaters, in part because they have not finalized the necessary test procedure.

In 2005, the European Parliament and the Council of the European Union issued a directive that established a framework for setting so-called ecodesign requirements for energy-using products (EuP) in Europe [60]. Ecodesign integrates environmental aspects into product design with the aim of improving the environmental performance of the EuP throughout its life cycle. Measures adopted to implement the directive stipulated ecodesign requirements for EuPs. In 2009 the directive was expanded and recast to cover energy-related products [61].

In 2007 VHK performed a preparatory study on the ecodesign of water heaters [62]. The study was developed with stakeholders and interested parties from the EU and non-member countries. Although the study was completed, it did not propose a test procedure for evaluating the efficiency of water heaters.

In the summer of 2010, proposed ecodesign and labeling requirements, as well as transitional testing and calculation methods, were announced for water heaters. The EU's Regulatory Committee is expected to vote on the transitional testing methods in early 2011 [63]. The transitional methods are intended to be used until a standards body, such as the European Committee for Standardization (CEN) or the European Committee for Electrotechnical Standardization (CENELEC), promulgate standards for test procedures [64].

The proposed water heater test procedure is based on a 24-hour simulated use test. Ten different load profiles are available. Table 27 shows an early version of the load profiles along with the intended range of hot water supplied by the water heater being tested [65].

Table 27: Illustrative Load Profiles and Daily Volumes of Hot Water

Load	**Range of 'Specified Demand'**	
Profile	**(liters per day @ 60 °C)**	
XXS	<20l	Single point–not shower
XS	<50l	Single point, including shower
S	< 80 L	
M	35–150 L	
L	70–300 L	
XL	120–500 L	
XXL	150–650 L	
3XL	280–15,000 L	
4XL	550 L	

Each water heater is tested and rated under the largest load profile that it is capable of meeting. The load profiles consist of a multiple draws scheduled throughout a 24-hour period. Each draw is specified in terms of flow rate and useful energy content. For most draws, the useful energy content is measured once the delivered water exceeds a specified water temperature. For some draws, all the useful energy content is counted. The water must reach a specified peak temperature during the draw.The number of draws per day and delivered hot water energy varies according to the load profile. Different peak and useful temperatures are assigned to the draws in each load profile. Table 28 summarizes the parameters associated with the EU water heater test procedure load profiles. The equivalent parameters for the ASHRAE test procedure are shown for comparison.

In addition to the draws in the load profile, the transitional test protocol cycle comprises five stages. The first is a 24-hour stabilization period to allow the water heater to adjust completely to ambient test temperatures. For storage water heaters, the next stage is filling and heat-up. After the heat source cuts out, the water heater enters another zero-load stabilization period for 12 hours. The 24-hour load profile is applied after this second stabilization period. Following the 24-hour load profile is another 12-hour zero-load re-stabilization period. The filling/heat-up and stabilization stages are applied only to storage water heaters. The energy consumed during the stabilization periods is used to account for any energy surplus or deficit during the 24-hour measurement cycle. Figure 61 shows a schematic of the test cycle.

Table 28: Parameters associated with transitional EU test procedure for water heaters.

Load Profile	No. Draws	Delivered Energy	Max. Flow	Useful Temp.(ºF)		Peak Temp. (ºF)	
		(kBtu/day)	(gpm)	Min.	Max.	Min.	Max.
3XS	23	1.177	2	77	77	N/A	N/A
XXS	20	7.165	2	77	77	N/A	N/A
XS	3	7.165	4	95	95	N/A	N/A
S	11	7.165	5	50	113	131	131
M	28	19.943	6	50	104	104	131
L	24	39.767	10	50	104	104	131
XL	25	65.067	10	50	104	104	131
XXL	30	83.696	16	50	104	104	131
3XL	10	159.545	48	50	104	104	131
4XL	10	319.090	96	50	104	104	131
ASHRAE EF	6	40.632	3	135	135	135	135

Following the ecodesign philosophy, a water heater's energy efficiency is calculated as the ratio of the useful energy provided by the water heater as hot water to the energy required for its generation. The testing pattern represents a peak situation, e.g., weekends. On average daily field use is expected to be only 60% of the indicated hot water energy specified in the test procedure. To calculate the average annual heat load, a factor of 0.6 (60%) is applied for 366 days [22]. The energy required also takes into account hot water distribution losses and waste heat recovery.

Distribution losses are those heat losses that occur between the water heater and the point where the hot water is used. These losses reduce the rated energy efficiency of a water heater. The farther the water heater is installed from the end-uses of hot water, the greater the distribution losses. To approximate the impact of the likely installation location of a water heater, reference distribution losses are made dependent on the type of air intake, physical size and load profile of the water heater. If the water heater does not consume a fossil fuel, the air-intake is "none," and the distribution losses are low. If the water heater is fossil fuel fired and takes its combustion air directly from outdoors through a dedicated duct, the air intake is "room-sealed"; otherwise it is "open." An open air intake water heater is assigned the highest distribution losses. Physically larger water heaters and water heaters capable of meeting higher load profiles also have high distribution losses.

Waste heat recovery accounts for the space-heating benefits of the heat lost from a water heater located indoors. The heat recovery parameter is the assumed fraction of the waste heat from the water heater that is considered beneficial. The assigned heat recovery parameter, which ranges from 0% to 32%, depends on the energy source (electric or fossil fuel), the size of the water heater, and how noisy the water heater is.

In keeping with the life cycle assessment philosophy of ecodesign, the different types of energy used by the water heater are converted to source energy. A water heater's measured electricity use is increased by the EU average of the amount of primary energy used to provide the end-user with one unit of electricity. A conversion factor of 2.5 is used in the test procedure..

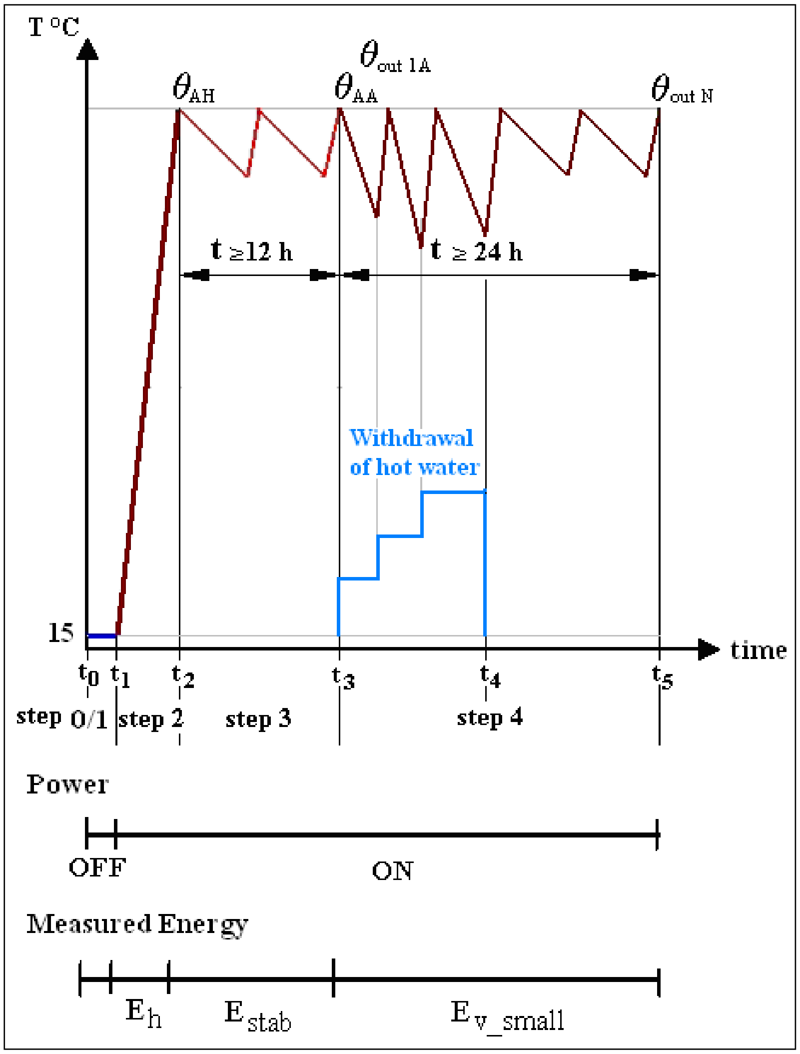

Figure 61: Schematic of EU test cycle for water heaters . [22]

International Organization for Standardization

The ISO has no test procedure for conventional water heaters. Part of four of the ISO test procedures for solar water heaters characterizes system performance by means of component tests and computer simulation. Some parts are relevant to testing conventional water heaters [23]. The procedure sets out a method of evaluating the annual energy performance of heated water systems using a combination of test results for component performance and a mathematical model to determine performance based on annual load cycle. The mathematical model recommended to evaluate the annual energy performance of the water heating system is the TRNSYS program. Many of the values used in the test procedure, such as temperatures or draw patterns, are not specified in the standard. They are to be specified by the certification or incentive program that references the standard.

The test procedures for determining the thermal capacitance of a water heater tank and the heat loss of the water heater are contained in Annex B, Store Performance. The thermal capacitance test involves measuring the temperature of the water drawn from the tank as it is purged all energy. The heat loss test is an extended cool-down period to determine how fast the water in the tank loses energy to ambient air. The ISO standard references the Australian standard for gas water heaters for determining thermal efficiency, startup heat capacity, and maintenance energy use (make-up for standby losses). As noted above, at this time the Australian standard is also being revised.

3.1.1.6 Comparing Current Efforts

Table 29 summarizes the differences among current and proposed test procedures for residential hot water heaters. The table helps illustrate the difficulties involved in comparing or attempting to harmonize test procedures for water heaters.

Table 29: Comparison of ASHRAE, EU, and Australian water heater test procedures.

	ASHRAE 118.2 (and DOE)	**European Union**	**Australia/New Zealand AS/NZS 4552.2 (draft)–** Minimum energy performance standards for gas water heaters; **AS/NZS4552.3**–Energy consumption test methods for gas water heaters; **AS/NZS 4234:2008**–Heated water systems: calculation of energy consumption
Status	Being revised	Awaiting adoption by European Council	AS/NZS 4552.2 in draft form; AS4552.3 to be published 2011; 4234:2008
Scope	Residential water heaters	Sanitary water heaters	Gas water heaters

	ASHRAE 118.2 (and DOE)	**European Union**	**Australia/New Zealand AS/NZS 4552.2 (draft)–** Minimum energy performance standards for gas water heaters; **AS/NZS4552.3**–Energy consumption test methods for gas water heaters; **AS/NZS 4234:2008**–Heated water systems: calculation of energy consumption
Scope limits	2–120 gallons, <75 kBtu/hr & <2gallons, <200 kBtu/hr	Provides drinking or sanitary hot water	For storage: ≤50 megajoules (MJ)/hr (47.4 kBtu/hr); for instantaneous ≤250 MJ/hr (236.9 kBtu/hr) (AS/NZS 4552.2)
Type of test	24-hour simulated use test	24-hour simulated use tests	Parameter determination followed by energy use calculation using TRNSYS
Number of draw patterns	1	10	Multiple depending on location and time of year (AS/NZS 4234:2008)
Daily load	64.3 gallons[33]	0.345–93.52 kWh (1.177–319.1 kBtu)	37.67 MJ (200 L water from 15.0–60.0 °C) (AS/NZS 4552.2)
Number of draws	6	3 to 30	8 for Australia, 10 for New Zealand; (AS/NZS 4234:2008)
Flow rate	3 gpm	2–96 liters/min. (0.53–25.4 gpm)	Varies by location and time of year (AS/NZS 4234:2008)
Draw type	10.7 gallons	1: sum energy after reaching useful temperature (Tm); 2: sum all energy, must reach peak temperature (Tp)	6 minutes each, flow rate adjusted to match fraction of daily load (AS/NZS 4234:2008)
Delivery temperature	135 °F	Tm = 25–45 °C (77–113 °F);	45 °C minimum in section 3.5.2;

[33] The 64.3 gallon draw is the DOE standard volume. The ASHRAE standard does not specify a volume quantity, other than referencing what the DOE standard uses in an annex.

	ASHRAE 118.2 (and DOE)	European Union	Australia/New Zealand AS/NZS 4552.2 (draft)–Minimum energy performance standards for gas water heaters; AS/NZS4552.3–Energy consumption test methods for gas water heaters; AS/NZS 4234:2008–Heated water systems: calculation of energy consumption
		Tp = 40–55 °C (104–131 °F)	60 °C in Appendix C (AS/NZS 4234:2008)
Logging interval	5 seconds	1 second	1/4 second tankless; 1 second storage; 1 minute standby (being considered)
Internal temperatures	6	No	1
Gain/loss	Calculate from internal temperatures	Pre- and post-test stabilization	Calculate from one internal temperatures
Discharge	No	No	From temperature-pressure relief valve as water expands during heating
Includes:			
Source energy multiplier	1	2.5	1
Distribution losses	No	Yes	No
Smart controls	No	Yes	No
Wasted water	No	No	Yes
Solar	No	Yes	Yes (AS/NZS 4234:2008)
Heat pump water heater	Yes	Yes	Yes, solar-boosted (AS/NZS 4234:2008); air source to be added
Combination unit	No	No	Excluded (AS/NZS 4552.2)
Outcomes:			
Primary rating	Energy factor (EF)	Energy efficiency	Annual energy consumption (AS/NZS 4552.2)
Recovery	Recovery efficiency	No	Recovery efficiency for storage;

	ASHRAE 118.2 (and DOE)	**European Union**	**Australia/New Zealand AS/NZS 4552.2 (draft)–** Minimum energy performance standards for gas water heaters; **AS/NZS4552.3–**Energy consumption test methods for gas water heaters; **AS/NZS 4234:2008–**Heated water systems: calculation of energy consumption
			Steady-state efficiency tankless;
Standby	Standby heat loss coefficient	Standing loss	Maintenance energy
Startup energy	No	No	Yes
Wasted water	No	No	Yes

3.1.2 DOE Energy Factors and Real World Efficiencies

This report section compares the energy efficiency of water heaters as determined from field measurements to their efficiency ratings in terms of energy factor (EF), which are established by the U.S. Department of Energy's (DOE's) test procedure. The field data derive from a study Davis Energy Group performed as part of the larger Public Interest Energy Research (PIER) Residential Water Heating Program being conducted for the Energy Commission under Contract # 500-08-060 [68]. The data set obtained through the field study provides an opportunity to compare determinations from the DOE EF test protocol against efficiencies measured during field use [47].

The field study monitored existing gas-fired water heaters in 18 California homes for as long as eight months. Then the original water heaters were replaced with new condensing and non-condensing storage and tankless units that incorporated advanced gas technologies. After the new units were installed, monitoring continued for four additional months. Recorded data comprised the water heater's gas and electrical energy consumption, water flow, inlet and outlet water temperatures at the water heater, and the temperature of the environment surrounding the water heater. The temperature and flow rate of the water were recorded at 4-second intervals when hot water was being drawn. The other data were recorded at 15-minute intervals [68].

The collected information was used to determine field conditions, develop daily hot water draw patterns, and calculate daily field efficiencies. Sufficient data were collected for 35 different water heaters to enable a comparison of the daily field efficiency relative to the rated efficiency from the DOE EF test procedure. Collected data represent a total of 6,039 days. Table 30 describes the types of data collected during the field study.

Table 30: Details of Data Collection

Monitoring Point	Measured Value	Interval	Sensor Description
Cold water inlet	Temperature	4 seconds*	Immersion temperature sensor in cold water line to water heater
Hot water outlet	Temperature	4 seconds*	Immersion temperature sensor in hot water line from water heater
Cold water inlet	Flow rate	4 seconds*	In-line turbine flow meter on cold water line to water heater
Ambient air temperature	Temperature	15 minutes	Air temperature sensor in area near water heater
Water heater gas line	Volume of gas	4 seconds*	Gas meter (with pulsing output) on gas line to water heater
Water heater electrical	Watt-hours	15minutes	True RMS power transducer on electrical supply to water heater

* Recorded when water was flowing.

The advanced gas water heater technologies assessed in the project included ENERGYSTAR™ storage units in the range of 0.67 to 0.70 EF, non-condensing tankless water heaters (TWHs), condensing TWHs, and condensing storage water heaters. Monitoring was initiated in April and May of 2010 and continued to June of 2011. Of the 18 sites, 17 underwent conversions to advanced water heaters, including 6 ENERGYSTAR storage water heaters, 3 TWHs, 5 condensing TWHs, and 3 condensing storage units [68]. Specifics of the water heaters are listed in Table 31.

Table 31: Water Heaters Used in Field Study

Site	Phase	Category	Make	Model #	EF/TE
LA1	Base	Tank	GE/Rheem	PG50T9XA	0.54
LA2	Base	Tank	Rheem	21V40-7NA	0.54
LA3	Base	Tank	GE/Rheem	SG60TT2YNG00	0.56
LA4	Base	Tank	Kenmore	153.335551	0.54
LA5	Base	Tank	Kenmore PowerMiser6	153.336351	0.57
LA6	Base	Tank	GE	PG40T09AQJ00	0.59
PG1	Base	Tank	Sears (Kenmore)	153.332461	0.57

PG2	Base	Tank	State Industries	GS650YOCTG	0.62
PG3	Base	Tank	State Industries	SEV40NXRT02CW	0.65
PG4	Base	Tank	Kenmore PowerMiser	153.336450	0.56
PG5	Base	Tankless	Rinnai	REU-V2532W-US	0.82
PG6	Base	Tank	GE	GELN1207Z188887	(A)
SD1	Base	Tank	State Industries	PRV40NRT3H	0.58
SD2	Base	Tank	American WH Co	FG6250T403NO	0.6
SD3	Base	Tank	Sears	153.330452	0.63
SD4	Base	Tank	GE		(B)
SD5	Base	Tank	GE	SG50T12AVH00	0.58
SD6	Base	Tank	State Industries	PRV30NRTSH	0.56
LA1	Advanced	Condensing tankless	Noritz	NRC111-DV (N-0842MC-DV)	0.93
LA2	Advanced	ENERGYSTAR storage	Rheem	42VP40FN	0.67
LA3	Advanced	ENERGYSTAR storage	Bradford White	U-4-TW-60T6FRN	0.67
LA4	Advanced	Tankless	Rheem (Paloma)	RTG-84DV	0.82
LA5	Advanced	Tankless	Nortiz	NR66-SV	0.83
LA6	Advanced	Tankless	Rinnai	R75LSe (VB2528WD-US)	0.82
PG1	Advanced	Condensing tankless	Navien	NP-240	0.95
PG2	Advanced	Condensing storage	Bradford White	EFR-1-60T1206EN	0.95
PG3	Advanced	ENERGYSTAR storage	AO Smith	GPVR-40	0.67
PG4	Advanced	ENERGYSTAR storage	Rheem	PDV40	0.67
PG5	Advanced	Condensing tankless	Rinnai	RC98HPe (KA3237WD-US)	0.93
PG6	Advanced	Condensing	AO Smith	HYB-90N	0.90

		storage			
SD1	Advanced	Tankless	Noritz	NR-71-SV	0.83
SD2	Advanced	Condensing storage	AO Smith	GPHE-50	0.90
SD3	Advanced	Condensing tankless	Navien	NR-240A	0.95
SD4	Advanced	Condensing tankless	Rinnai	RC80HPi (KA2530FFUD)	0.96
SD5	Advanced	ENERGYSTAR storage	Bradford White	D-4-504S6FBN	0.67
SD6	Advanced	ENERGYSTAR storage	AO Smith	GAHH-40	0.70

(A) No model number; serial number inadvertently recorded.

(B) No nameplate on water heater.

The efficiency ratings of the water heaters monitored during the base phase were determined by consulting historical appliance databases of the CEC [69]. Efficiency ratings for the new water heaters used in the advanced phase were provided by the manufacturers.

Data for the hot water draw patterns developed from the field data were processed using the same algorithms as applied to data from other field studies included in a larger database for hot water draw patterns [13]. The field efficiency of each water heater was calculated for each day for which there was a complete data set. Daily field efficiency was calculated as the total energy delivered as hot water that day divided by the total energy use of the water heater that day. If the water heater used both natural gas and electricity, energy use represents the sum of both energy sources.

For the field study, water flow was measured during more than 4 million 4-second recording intervals.

3.1.2.1 Data Cleaning

The field data contained a few extraneous or unusual data. Although the reasons for the unusual data were not identified, any days having anomalous data were removed from the data set.

One reason for excluding days was if total daily water efficiencies were missing or exceeded 100%. One house recorded 2 days that included missing efficiencies. At that same house total daily water heater efficiencies greater than 1 were recorded on a different 2 days. Efficiencies greater than 1 were recorded at other houses for 3 days. A total of seven days were excluded from the analysis because the efficiency data were missing or unbelievable.

During the field study, water flow was measured during more than 4 million of the four second recording intervals. A count of the number of intervals by equivalent flow rate is shown in Figure 62.

Extreme flow rates above 12 gallons per minute were considered to be outliers. Only a small number of intervals were recorded with a flow rate of more than 12 gallons per minute. Days with any recorded hot water flow rates greater than 12 gallons per minute were also excluded from this analysis. This happened for one day in each of four houses.

The other reason for excluding data was unbelievably low flow rates. A water draw was considered to occur for one or more contiguous recording intervals when no flow was recorded in the preceding and following recording intervals. During this field study, 374,000 draws were recorded. Of those, 134,326 were 4-second draws. Figure 63 shows the number of 4-second draws by volume.

The smallest volume recorded by the flowmeters used in this study was 0.002 gallons. If a draw contained only one recording interval and the total volume recorded was 0.002 gallons, that draw was ignored. Excluded from the data set were 17,306 4-second draws having volumes of 0.002 gallons, which were assumed not to be actual draws at all.

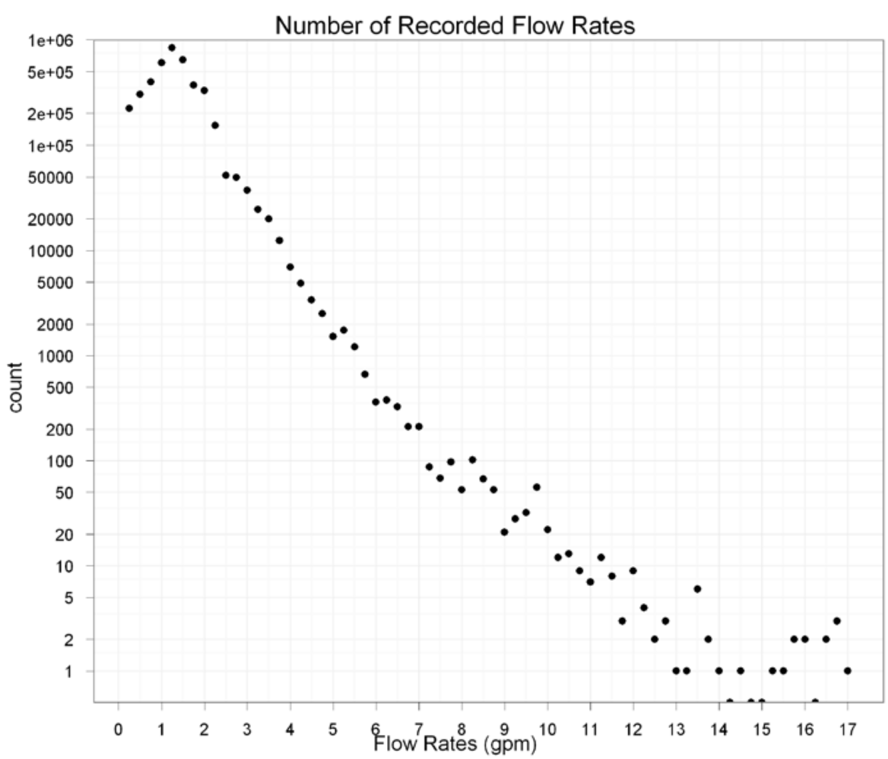

Figure 62: Count of Recording Intervals by Flow Rate

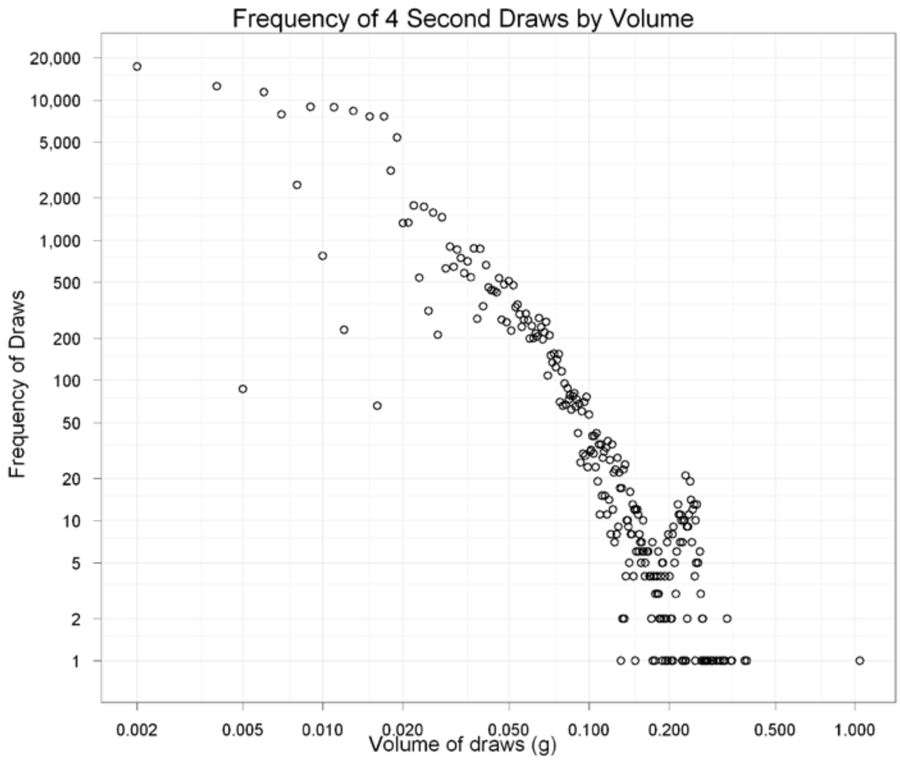

Figure 63: Frequency of 4-Second draws by volume

3.1.2.2 Results

Figure 64 presents histograms that show the daily field efficiency of each water heater monitored for the study in the Los Angeles region. The histograms show the number of days by daily efficiency recorded for each site for both the original (base) and new (advanced) water heaters. The dashed red lines show the DOE-rated efficiency of the water heater as EF or thermal efficiency.

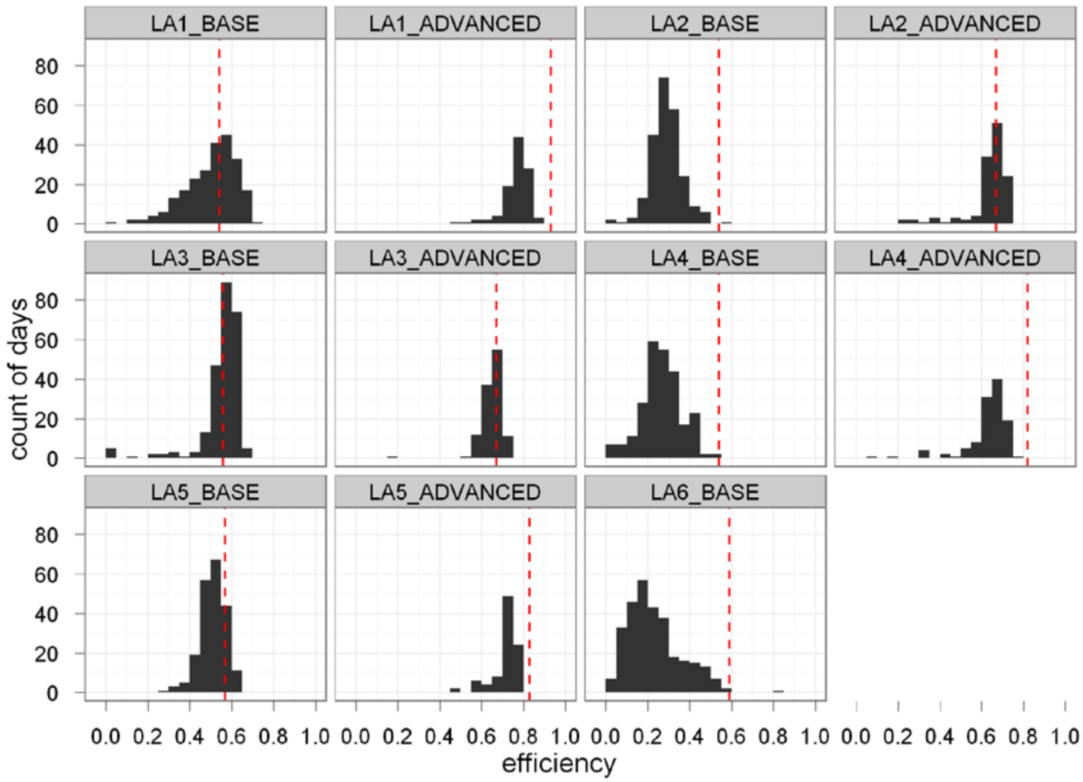

Figure 64: Histograms of Daily Efficiency

Figure 64 shows that the test procedure results do not consistently indicate field efficiency. Charts showing the measured daily field efficiency of all the water heaters monitored in this study are provided in **Error! Reference source not found.**. In the one case for which the rated efficiency was not available for a water heater, no red line appears.

To examine what might cause the frequent differences between field and rated efficiencies, one can compare parameters used in the draw patterns for the field and laboratory tests, such as total daily hot water use, number of draws, inlet temperatures, and outlet temperatures.

Figure 65 plots the number of draws and total volume of hot water used per day for the water heaters monitored for the study in the Los Angeles region. Each day appears as a black circle. The number of draws and total volume of hot water used in DOE's 24-hour test to determine the EF rating of a water heater is shown as a red cross.

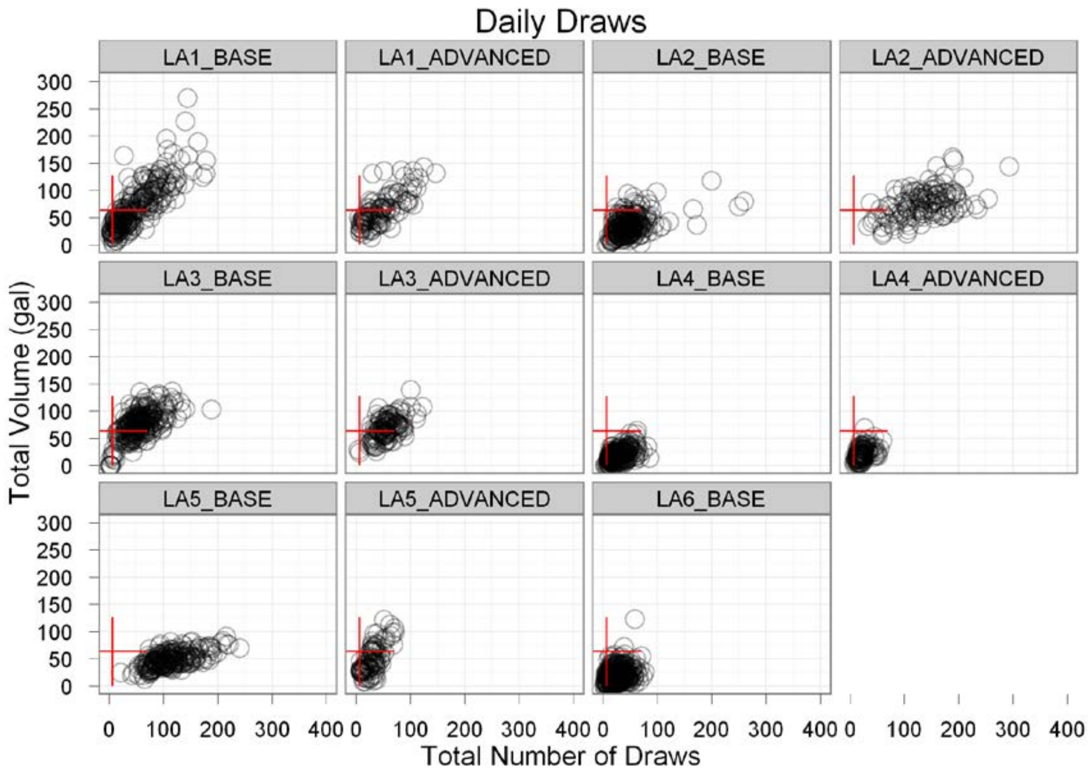

Figure 65: Number of Draws and Daily Volume of Hot Water Use

People clearly use hot water differently than it is used in the test procedure. In the field, the number of draws of hot water per day were consistently higher than the number of draws in DOE's EF test. Charts showing the measured number of draws and total volume of hot water used per day for all the monitored water heaters in the study are included in **Error! Reference source not found.**.

Another reason for the differences between laboratory and field results may be the water temperatures at the water heater. In the field study the inlet and outlet water temperatures were recorded when water was flowing. The average daily temperatures for each day were plotted on charts similar to the charts in Figure 65. For comparison, the inlet and outlet temperatures specified in the 24-hour EF test are shown as a red cross. The average of the daily temperatures is shown as a green cross. Figure 66 shows such charts for the water heaters for the field study in the Los Angeles region.

Inlet water temperatures in the field study are consistently higher than those used for the EF test. Plots of inlet and outlet temperatures for all water heaters in the study are presented in **Error! Reference source not found.**.

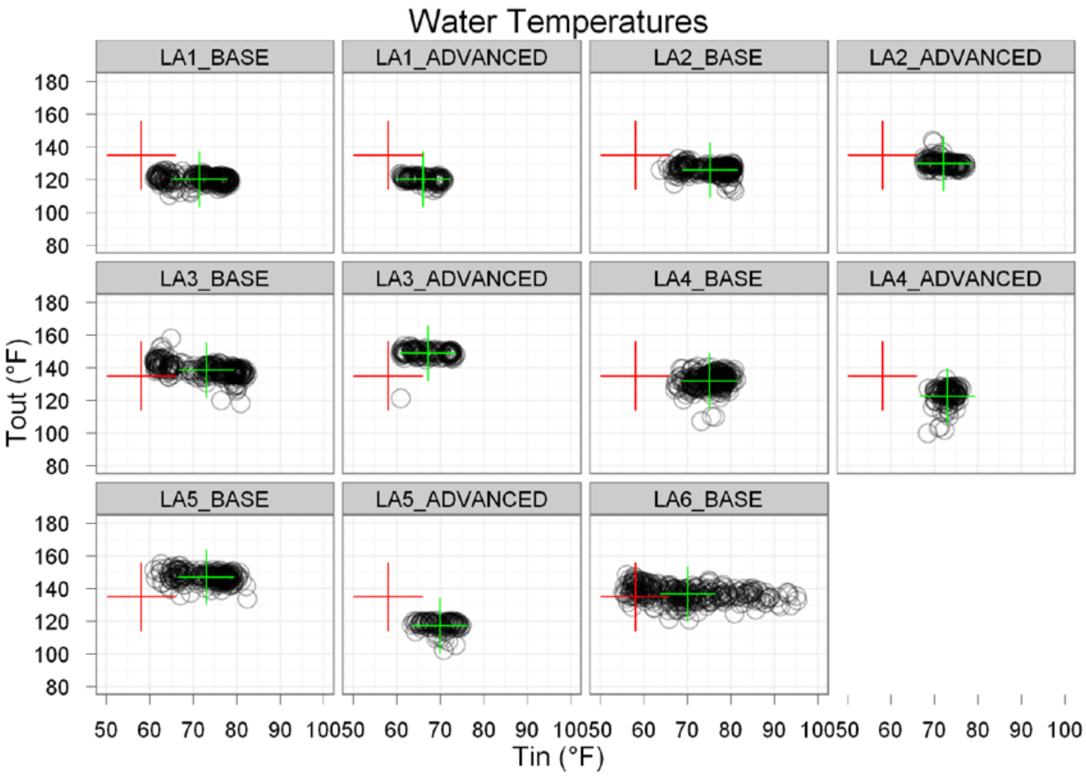

Figure 66: Water Temperatures from Field Study and Laboratory Test

Also of interest are distributional parameters related to total draw patterns, whether in the field or the laboratory. The distributional parameters include total volume per draw, time since previous draw, total duration of each draw, and flow rates recorded during all the monitored intervals. Each parameter can be displayed as a cumulative distribution of all the draws or all the recorded flow rates. This type of plot orders the value of the parameter for each event, *e.g.*, volume of hot water use per draw, in ascending order. The plot then shows the cumulative fraction of total events that are less than a given value. The dissimilarity between two patterns can be summarized as the maximum difference between the cumulative distribution function plots of the two sets of events.

On Figure 67, the cumulative distribution of draw volumes for each water heater is shown as a black line. The green line is the cumulative distribution of the volumes of all the draws monitored in the study. The red line is the cumulative distribution of the volume of draws in the EF test procedure. The vertical axis shows the volume of draws on a logarithmic scale, used because the range of volumes is so large. The horizontal axis is the cumulative fraction of draw volumes. The chart shows that all the draw volumes used in the EF test procedure are larger than about 95% of the draws recorded during the field study.

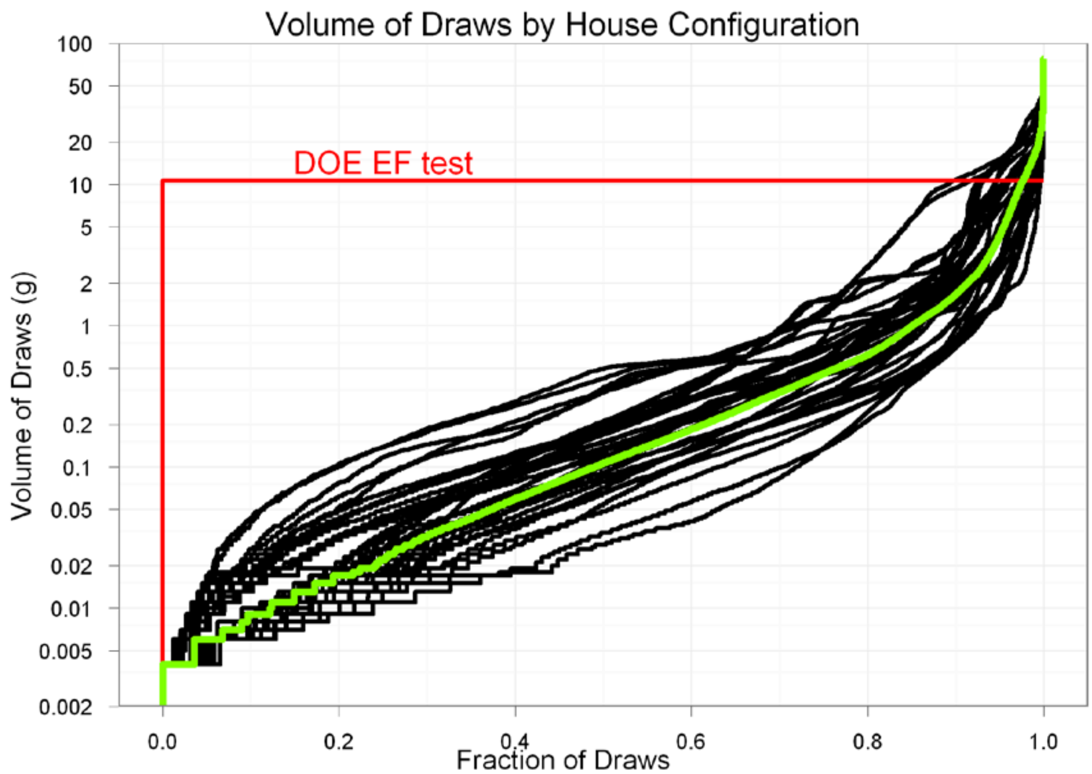

Figure 67: Cumulative Distribution of Draw Volumes

Figure 68 presents a plot of the cumulative distribution of the duration of draws. Just as draw volumes in the field generally were smaller than in the laboratory test, the durations of almost all draws recorded in the field are much shorter than those used in the EF test. The volume of draws is especially important when measuring the efficiency of tankless water heaters. The amount of residual heat left in a tankless water heater after a draw is relatively independent of draw length. Thus a tankless water heater will be less efficient for shorter draws. Nearly half the monitored draws lasted less than 12 seconds, compared to the nearly 4-minute draws in the test procedure.

The distribution of the time gaps between draws is shown in Figure 69, which indicates that more than 80% of draws occur within 20 minutes of the previous draw.

Figure 70 shows the cumulative distribution of flow rates during every recording interval when hot water was flowing. Almost all flow rates recorded during the field study are significantly lower than the flow rates specified in the EF test.

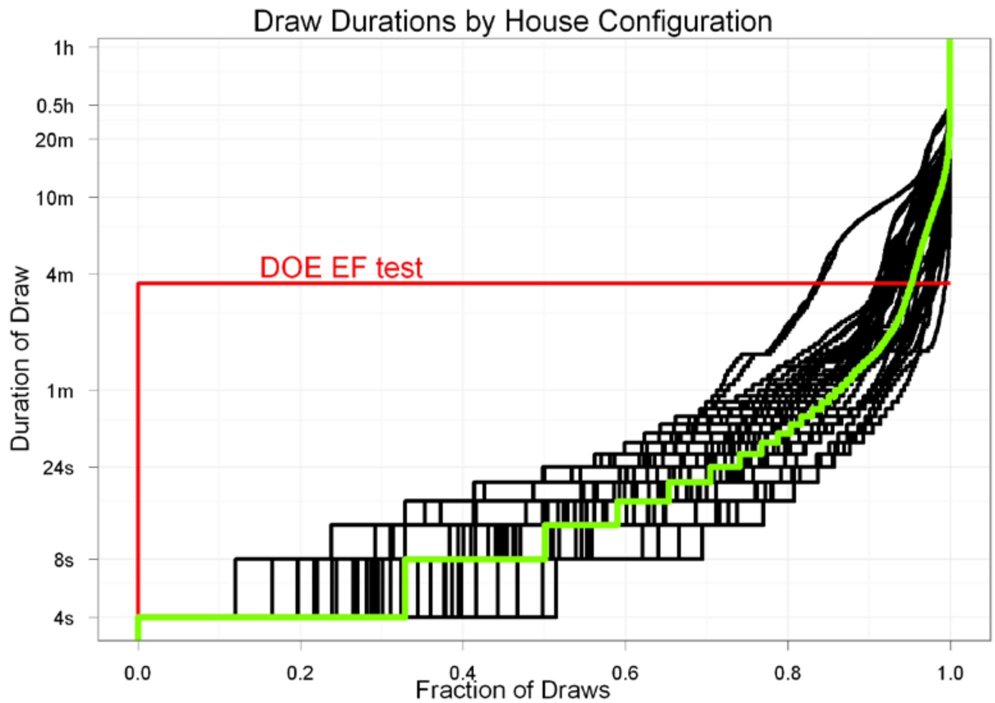

Figure 68: Cumulative Distribution of Draw Durations

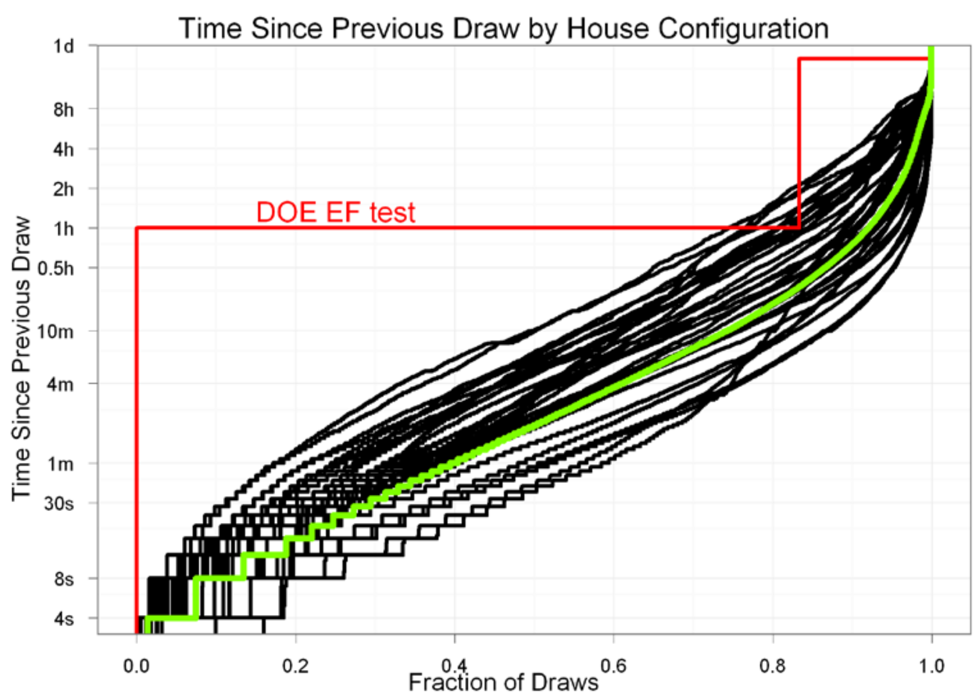

Figure 69: Cumulative Distribution of Time since Previous Draw

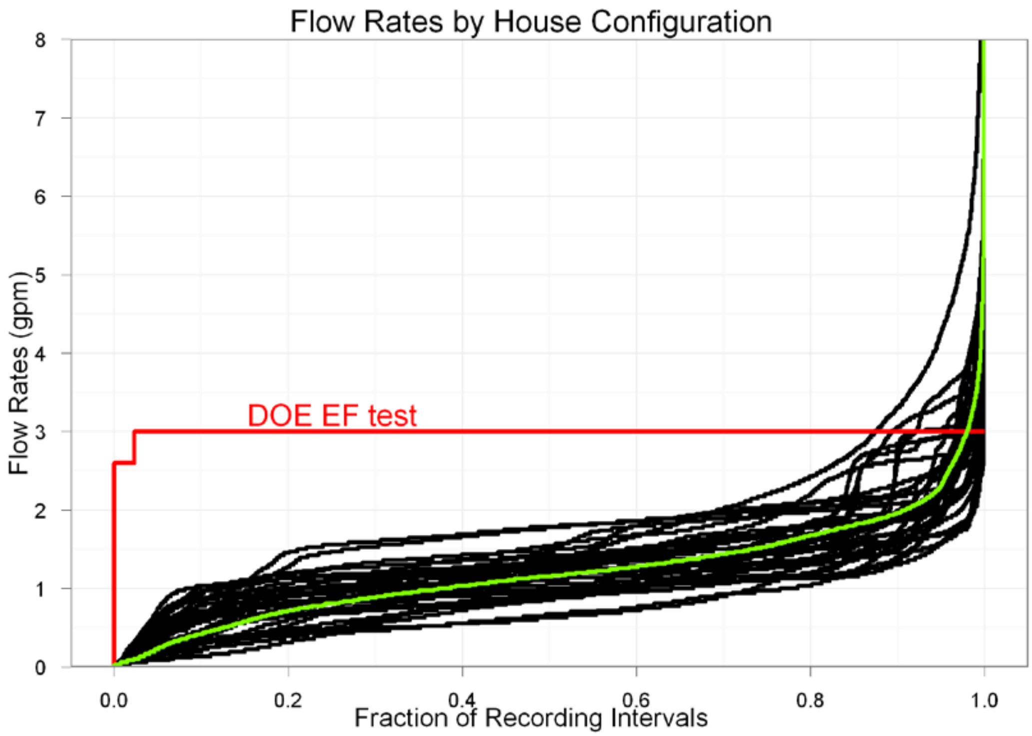

Figure 70: Cumulative Distribution of Flow Rates

3.1.2.3 Conclusions

Hot water use is driven primarily by occupant behavior. There is significant variation in hot water use and draw patterns between households. Even given this variation between households, the draw patterns used in the EF test differ significantly from those recorded during field use. To better match field usage, the EF test should include a larger number of shorter, smaller draws at lower flow rates clustered closer together in time.

3.1.3 DOE EF and ASHRAE 118.2 Standard Methods of Test Developments

ASHRAE Standards Project Committee (SPC) 118.2 is working to revise their Method of Testing for Rating Residential Water Heaters [48]. The U.S. Department of Energy (DOE) [70]; the Air-Conditioning, Heating, and Refrigeration Institute (AHRI); and the Canadian Standards Association (CSA) are also reviewing and amending test procedures for water heaters.

SPC 118.2 is revising the test procedure to make it more representative of efficiency performance in actual use and to provide for rating all technologies consistently. The committee, which began efforts in 2007, initially investigated the possibility of developing a lab test that would produce results that could be applied to an algorithm for calculating field efficiency. The input/output method, which is being considered as a test procedure for rating commercial boilers, initially was considered [71]. The effort was promising but would have to be expanded to incorporate losses incurred when the water heater is idle. Exploratory testing was done on several types of water heaters. The proposed method proved inadequate on electric storage water heaters, however, apparently because of changes in stored energy in the WH between the beginning and end of the test.

The committee then moved on to consider a simulated-use test with a 24 hour draw pattern. A simulated-use draw pattern also would be required to apply the results of a parametric test. To date agreement has been reached on using a simulated-use test that has a 24-hour draw pattern. The committee members still must agree on appropriate draw pattern(s). Currently the committee is defining broad characteristics to be described in detail in the final test procedure. As many as five different draw patterns will be developed for use on water heaters having different capacities. The development of the draw patterns will utilize field data as appropriate. Field data will be considered in developing the total daily volume of hot water use, total daily number of draws, flow rates, intervals between draws, and the durations of hot water draws for the simulated-use test draw patterns. Inlet and outlet water temperatures observed in field data will also be considered.

Other agreements to date are to use a draw pattern that minimizes the need for corrections between the initial and final energy states of a water heater and to consider the practicality and measurability of any hot water use draw patterns that are developed.

Still unresolved are the issues of how to deal with delivered water that is not at the specified temperature and how to determine which draw pattern a water heater is to be tested against.

DOE currently is reviewing and revising its test procedure for residential water heaters. The Department issued a request for information regarding test procedures for residential water heaters on October 12, 2011. Many of the questions posed in the request for information were the same ones the ASHRAE committee has been addressing. The National Institute of Standards and Technology is leading the technical effort to revise the test procedure for DOE. Originally, DOE anticipated releasing a draft test procedure for comment in the fall of 2012.

The Water Heater Section of AHRI has created a working group to address the DOE test method for residential water heaters. They are trying to develop a test procedure based on industry consensus that they will recommend to DOE. They are developing draw pattern(s) and investigating test results for a few different draw patterns. As of this date they have not released any recommendations.

Canada's Energy Efficiency Regulations for domestic water heaters specify different test procedures for gas-fired storage, gas-fired tankless, electric storage, oil-fired storage, and heat pump water heaters. The test procedures, developed by CSA, are used by the Natural Resources Canada (NRCan) Office of Energy Efficiency to establish minimum energy performance standards [72]. The test procedures are largely, but not completely, similar to those used in the United States. Currently CSA 191, performance of electric storage tank water heaters for domestic hot water service, is being revised. A request for public comments has been posted [73].

During the Fall of 2012, Congress was considering legislation that would direct DOE to develop a new uniform efficiency descriptor for water heaters, either commercial or residential, that are likely to be used in residential applications [74]. The uniform efficiency descriptor and accompanying test methods for covered water heaters would be published no later than 180 days after the enactment of the legislation.

Although all the efforts described above are being conducted independently, there is a fair degree of coordination. Members of the AHRI working group, NIST, and NRCan are active in ASHRAE SPC 118.2.

3.2 Title 24

The current Title 24 water heating compliance methodology is based on hourly calculations of water heating energy use based on assumed loads (dependent upon floor area and climate zone), water heater system type, and distribution system characteristics. The methodology for single family homes calculates an annual water heating budget based on these components and compares to a standard budget that is based on a single (minimum efficiency) small gas storage water heater with a "standard" non-recirculating distribution system. Key components of the 2008 water heating compliance methodology are highlighted here with full details included in **Error! Reference source not found.** (the Residential Alternative Calculation Methodology):

1. The climate zone representing the building location defines a monthly cold water inlet temperature.
2. Water heating end use (i.e. fixture) loads are based on a floor area based relationship which increase daily hot water use up to a building floor area of 2,500 ft^2, at which point usage is capped.
3. Distribution system performance is defined for a "standard" system with a resulting "Distribution System Multiplier" (DSM) of 1.0. Alternative distribution systems, including recirculation, home run, and conventional trunk and branch, are each represented with a unique DSM[34] to reflect performance relative to the "standard" case.

[34] These DSM values, ranging from 0.0 for a point-of-use distribution system, to 4.5 for a continuously operating recirculation loop system, were derived by completing multiple HWSIM runs on a total of six different distribution system layout. Results from the detailed HWSIM runs were used to develop the comparison to the "standard" distribution case, resulting in the final distribution multipliers that are applied on an hourly basis to the end use fixture loads.

4. Water heater performance for small storage gas and electric water heaters is based on a Load Dependent Energy Factor (LDEF) concept which reflects the effect of loads on the rated Energy Factor (EF) of the water heater. Gas tankless water heaters are derated from their EF rating by an 8% degradation, and heat pump water heater (HPWH) rated EF is derated by climate zone (i.e. weather) to reflect ambient temperature effects.

Using this basic methodology the energy use for the "proposed" water heating system is compared to a prescriptive "standard" water heating system. Hourly energy use is converted to time dependent valuation (TDV) energy which recognizes a varying TDV value for gas and electric energy consumed for each climate zone and each hour of the year. The standard system is a natural gas water heater, and the relative TDV valuation of a BTU of gas energy vs. a BTU of electrical energy, creates a large performance penalty for electric resistance water heating[35]. HPWHs, with an effective efficiency roughly twice that of an electric storage water heater, generate a small compliance credit, despite the TDV penalties associated with electric consumption.

3.2.1.1 Changes for the 2013 Title 24 Standards

The CEC adopted the 2013 Title 24 Standards in mid-2012 and is currently developing the modeling tools, manuals, and forms to support the upcoming change which is scheduled to take effect January 2014.

Several general changes were completed to improve the alignment of predicted water heating energy use with actual energy use (as indicated by the Residential Appliance Saturation Survey (RASS)). HWSIM modeling completed in support of the 2013 Standards changes suggested that previously assumed distribution losses were underestimated. To remedy this, without changing the hot water volume through the water heater, end use loads were reduced to compensate for the higher distribution losses.

The 2008 methodology overpredicts RASS water heating energy consumption by ~15%. Based on the field monitoring effort undertaken in this PIER project, it is our impression that a significant factor in this discrepancy is the higher observed water heater cold water inlet temperatures relative to the monthly climate zone assumptions. Unfortunately the field study was very limited in geographical scope, suggesting that wholesale changes to the inlet water temperature assumptions would be speculative at best. Lowering the water heater set point represents an alternative to changing the inlet temperature. The DOE, in the development of the

[35] This is by design, since natural gas is widespread in California and the Title 24 standards are effectively pushing people to use natural gas, when available.

2001 RECS, utilized a survey of over 340 plumbing and hydronic heating contractors nationwide to determine typical hot water setpoints. Results of the survey indicated a "typical" estimated water heater setpoint of 124.2°F. Based on this, the assumed 2008 water heater setpoint of 135°F was reduced to 124°F, resulting in an improved alignment with RASS.

The key changes in the Title 24 water heating code that are being implemented for the 2013 Standards follow:

Single family systems (one or more water heaters serving a single dwelling unit):

Mandatory:

There are new mandatory requirements for gas or propane water heater installations. These requirements include having proper electrical outlet, vent category, and condensate drain feature to facilitate the use of high efficiency water heating equipment.

Pipe insulation is now required on all hot water distribution piping greater than or equal to ¾ inch diameter, as well as all piping from the water heater to the kitchen.

Prescriptive:

Where natural gas is not available an option for electric water heating is now allowed with a solar thermal water heating systems that has a solar savings fraction of at least 50 percent.

Performance:

The Point of Use Distribution multiplier now applies to systems with water heaters no more than 5 feet (of 3/4'" piping) from any point of use (10′ of ½", or 15′ of 3/8" are acceptable alternatives). This measure now requires HERS verification.

Compact distribution system design has been added as a new compliance option credit. To use this approach the furthest usepoint must be HERS verified (with a physical measurement) to be within a prescribed distance from the water heater.

Additional optional HERS verification elements have been added to offer credits for verified pipe insulation installation on both recirculating and non-recirculating distribution systems

Multi-family systems (One or more central water heaters serving multiple dwelling units):

Prescriptive:

Water heating recirculation systems are required to be designed with two recirculation loops. This measure must be HERS verified to ensure that two sets of recirculation loops are put in place from either the same or separate water heating equipment.

Solar water heating is required for all climate zones. The required solar savings fractions are either 20% or 35%, depending on the climate zone.

A demand recirculation control is the prescriptive requirement for central water heating systems.

Performance:

Temperature modulation recirculation control can be used for performance compliance. However, no credit will be given for timer control.

3.2.1.2 Future Title 24 Water Heating Research Needs

Equipment:

Condensing Gas Tankless water heaters

Field data from both the GTI PIER field monitoring project and the Minnesota CEE water heating project indicate that gas tankless water heater field performance is overestimated by their EF rating. This had been recognized in the 2008 Title 24 by derating the nominal EF of all gas tankless units by 8% (i.e., a 0.92 multiplier on the rated EF). Both of these field studies suggest that the 8% derating is reasonable for non-condensing tankless units, but appears to be too little degradation for condensing tankless units. This should be investigated in more detail to determine the need for derating condensing and non-condensing tankless units differently.

Improved HPWH modeling

HPWHs are currently modeled in a simplistic fashion using a climate zone specific adjustment on the annual rated efficiency (EF)[36]. From a national viewpoint, HPWHs represent a high profile energy efficiency opportunity. In California, the availability of natural gas combined with historically low natural gas prices and high electric rates makes HPWHs economically challenging for most customers. Countering that is the emerging zero net energy trend, which may direct residential designs to pursue all-electric options. Improved modeling of HPWHs would be valuable in better characterizing performance. Similar to distribution system performance, HPWH performance is best represented on a shorter than hourly time step, to properly represent short duration hot water loads and the resulting impact on the control of second stage resistance heating. Significant modeling efforts are underway at NREL and the Northwest Energy Efficiency Alliance (in coordination with Ecotope). The focus of this effort would involve developing a methodology that relies on a limited set of available HPWH performance descriptors to properly characterize the performance characteristics that have been observed in lab and field monitoring efforts.

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[36] See section E6 of Appendix A

In addition to improving HPWH modeling, a fundamental decision needs to be made whether the CEC wants to promote HPWHs as a viable component of Zero Net Energy new homes. If so, the current assumption that the standard water heating budget is based on a gas storage water heater needs to be revisited.

Combined Hydronic system modeling

Combined hydronic systems present an attractive option for high efficiency homes because these systems utilize one heat source to provide both space heating and domestic hot water. The rationale is that with a single heat source, the cost savings can be used to purchase a high efficiency heat source. Combined hydronic systems can deliver space heating via a hydronic fan coil, baseboards, radiant floors, or hydronic delivery to distributed fan coils. Currently, combined hydronic systems are handled in a simplistic manner. Water heating energy use, calculated independently of space heating energy use, is determined using the standard water heating calculation methodology. An effective heating "AFUE" is calculated based on the water heater recovery efficiency, pipe heat loss estimate, and water heater input rating.

With increasing interest in combined hydronic systems, it is important to improve how these systems are modeled in Title 24. Several research studies are underway looking at the laboratory and field performance of these systems[37]. Activities are also underway at ASHRAE (Standard 124) for updating testing and rating methods for combination systems. Developing a standard for combined hydronic system ratings for both heat sources and delivery systems is needed to accurately characterize performance of these systems. Performance data from the ongoing Minnesota CEE lab and field study monitoring twenty homes is providing valuable data on the impact of system airflow, water flow rate, and the resulting return water temperatures on overall system performance.

Hot Water Loads:

The 2013 fixture hot water loads are reduced from the 2008 assumptions, based on modeling suggesting higher than assumed distribution losses. The assumed 2013 hot water loads provide a reasonable match with RASS gas water heater usage data.

Several potential research questions that may need attention:

1. Is the current floor area dependency for hot water loads the best approach for defining usage?

[37] Research is underway (or completed) at GTI (for both NYSERDA and the BA-PIRC Building America team) and at the NorthernStar Building America team.

2. Is there data to better define new home hot water usage that reflects more water efficient showerheads, fixtures, and appliances?

3. Does accurate water heater cold water inlet temperature data exist (or can it be widely collected) to allow the existing monthly climate zone data to be adjusted?

Distribution Systems:

The area of distribution systems is a very important area for future research. Distribution system performance is very complicated and depends on a wide range of factors. The field study of California plumbing layouts completed in this project and the 2006 PIER project suggest that installations are highly variable and to a degree, dependent upon the configuration of the house[38]. The 2013 revisions attempted to move towards an improved design strategy, but resistance from the building industry eliminated one of the proposed components (limiting the length of 1" or larger piping). Future Title 24 improvements in this area should rely on the improved models being developed and the best available data on hot water usage patterns (and quantities) and installation practice. Education of the building community and the plumbing industry is vitally important to improve distribution system performance. The builder value of improved distribution systems can be significant in terms of reduced cost (less piping), reduced water use, and improved customer satisfaction due to reduced waiting times at remote fixtures. This effect will be magnified with gas tankless systems, where the startup time delay compounds any distribution system associated delays.

Distribution research in support of Title 24 improvements should include:

1. Field data collection of distribution system performance in both new and existing homes (Jim Lutz and Steven Lanzisera at LBNL are leading efforts in the deployment and testing of advanced low-cost wireless sensors that will facilitate this kind of work).

2. Lab testing of alternative distribution system configurations (typical layouts and "improved" layouts) with realistic draw patterns at various use points. The testing would explore the impacts of different flow rates, hot water and environment temperatures, usage patterns and quantities, and behaviors.

3. Validation of advanced modeling tools

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[38] To be clear, a compact house design with bathrooms and kitchens in close proximity to the water heater, does not necessarily translate into a "good" distribution system plumbing layout.

4. Complete a comprehensive modeling study to assess performance of alternative distribution system configurations on different plumbing layouts, with varying usage patterns.

3.2.1.3 Multi-Family Distribution Systems

Yanda Zhang of the Heschong Mahone Group was the key consultant supporting development of central system distribution system code requirements for the 2013 Title 24 update. He was contacted to provide his viewpoint on additional enhancement options specific to multi-family systems. He identified two key areas of research:

1. Optimize centrial system recirculation distribution system designs. This would require further investigation of plumbing design practices and performance comparison of different design options. For Title 24, it is also important to make sure that compliance inspection process is not overly complicated.

2. Evaluate alternatives to recirculation system designs, specifically for smaller multi-family buildings.

CHAPTER 4: SUPPORTING LABORATORY TESTS

One goal of the laboratory tests in this program was to better characterize high-efficiency gas-fired water heaters to support the integration of more accurate component models within the hot water distribution simulation program HWSIM. In addition, other tests explored performance details of selected water heaters through controlled laboratory conditions to help explain phenomena seen in the field evaluations and to help understand feedback from participating homeowners regarding their experiences with advanced storage and tankless water heaters. And finally, these supporting laboratory tests provided insight into alternative testing procedures (alternative draw profiles for example) and their impacts on current water heater ratings (Energy Factors).

Applied Energy Technology (AET) generated and analyzed laboratory datasets of hot water distribution piping thermal losses, while the Gas Technology Institute (GTI) and Pacific Gas & Electric (PG&E) Applied Technology Services (ATS) generated and analyzed laboratory datasets of various performance characteristics of high-efficiency water heaters, focusing on two classes of products:

- **High-Efficiency Storage Water Heaters** (PG&E) – Driven by both the change in EnergyStar® requirements, increasing the initial minimum Energy Factor (EF) from 0.62 to 0.67 in late 2010, and the coming change in the federal minimum efficiency standards, from an EF of 0.59 up to 0.62 in 2015[39], manufacturers have filled out their gas-fired storage water heater (SWH) product families to meet these efficiency requirements. In addition to new condensing, power/direct vent, and hybrid gas-fired SWH offerings, many new products are compatible with Category I venting, including features such as small combustion air blowers & inducers and powered vent damper. Unlike the most common minimum efficiency products, these products with EFs > 0.62 are powered and the impact and cost of this added electricity consumption has not been adequately quantified. In addition to providing datasets to update the most current software for simulating residential gas-fired SWHs, TANK [46], analysis of testing will focus on electricity consumption.

- **Tankless Water Heaters** (GTI) – Gaining popularity over the past decade, tankless water heaters (TWH) have enjoyed increasing market share due to their high-efficiency relative to standard gas-fired SWHs, marketing of "endless hot water", and incentive programs. Deficiencies in the delivered versus rated efficiency of tankless water heaters are a known

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[39] *Example is for a 40 gallon storage water heater*

issue [69, 76], due to the minimum draw rate requirements and startup sequence delays, however they remain a challenge to characterize analytically. To simulate the performance of TWHs, researchers have developed a robust single node model [75] which while complete in describing the steady state and transient heat transfer behavior of the TWH as a heat exchanger, implementing the model required an initial laboratory investigation. Some inputs may have sensitivity to test conditions (e.g. thermal capacitance) and some impacts of TWH controls are not captured (e.g. startup heating delays).

These two product classes of water heaters were evaluated using a variety test methodologies described in the following sections.

Water Heater Test Method

Tests performed on high-efficiency SWHs and TWHs are grouped into short term and long term tests. Short term testing includes the federal standard First Hour Rating (FHR) test for SWHs and a matrix of short term tests for TWHs. Long term tests, simulating daily usage, use the federal standard 24 Hour Simulated Use Test method, generating the Energy Factor (EF), and also non-standard draw patterns derived from field data [79], mid and low usage patterns with 64 gal/day and 30 gal/day respectively. Note that neither GTI nor PG&E Applied Technology Services operate laboratories certified as test labs for these federal standard methods of test. Therefore, while some reported results are from executing Department of Energy (DOE) test procedures, they are only relevant in relative comparison to experimental data from this project and are not directly comparable to First Hour Ratings (FHR) nor Energy Factors (EF) published elsewhere. Instrumentation used during testing is summarized in **Error! Reference source not found.**.

Daily Simulated Use Testing (24 Hour)

The currently accepted metric for the energy efficiency of residential water heaters is the Energy Factor (EF), which simulates a 24 hour hot water draw pattern with six regularly spaced equal magnitude draws followed by an extended standby period.

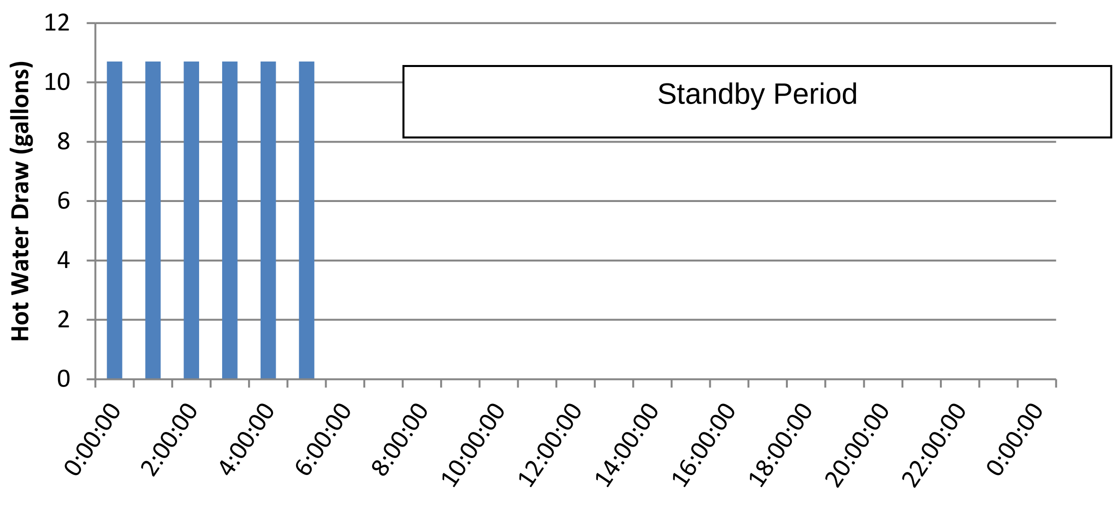

Figure 71: Visualization of DOE 24 Simulated Use Test Hot Water Draw Pattern

As any standardized test replicating anticipated usage, discrepancies exist between certified test results and performance observed during actual use. Additionally, as the current hot water draw pattern is front-loaded with large volume draws at 3.0 gpm followed by an extended standby period, as visualized in Figure 71, this pattern favors certain system configurations over another.

The term "EF" as calculated by the certified test procedure refers to specific test conditions and calculation procedures [46], and is indicated by EF (DOE). In all other cases where an estimated EF is calculated it will be indicated otherwise, using the ASHRAE Method of Test 118.2 or a simple delivered efficiency, defined as shown below. Hot water draw patterns can be broken down into individual "cycles" of draws proceeded by a standby or and/or recovery period, where each individual "cycle" varies in their draw magnitude, draw rate, and degree of intermittency. The simple delivered efficiency below sums through the *i*th cycle. Note that this delivered efficiency does not include adjustments for compensations for temperature under/overshoot as included in calculating the standard EF and that for TWH tests $\Delta Q_{storage} = 0$.

Equation 56: DOE EF Calculation

$$EF_{simple} = \frac{\left(\sum_i \rho_i C_p V_i \left(T_{del,i} - T_{in,i}\right)\right) + \Delta Q_{storage}}{Q_{in,total}}$$

In addition to the standard draw pattern shown in Figure 71, two additional more realistic hot water draw patterns are used for both SWHs and TWHs simulating a mid use of 64 gal/day, the same as the DOE draw pattern, and a lower use pattern at 30 gal/day. Details on the draw patterns are shown in **Error! Reference source not found.**. Note that while the daily volumes drawn are the same for the SWH and TWH mid/low draw patterns, the patterns are not.In the case of SWHs, a distinction is made between the total thermal energy output during the standard DOE draw pattern and the two non-standard draw patterns. The different thermal energy outputs, Q_{DOE} and Q_{Btu} differ in their treatment of the time-averaging of inlet and outlet water temperatures, namely the inclusion or exclusion of the first 15 seconds of temperature data. The two formulas are shown below, in this case for the DOE draw pattern, for which both are calculated[40]:

[40] The term *n logs* refers to the number of data samples logged

Equation 57: Total Thermal Energy during DOE Draw Pattern

$$Q_{DOE} = \sum_{i=1}^{6}\left[m_i \cdot C_p\left(\frac{\overline{T}_{out} + \overline{T}_{in}}{2}\right) \cdot \left(\overline{T}_{out} - \overline{T}_{in}\right)\right]$$

Equation 58: Total Thermal Energy during Non-Standard Draw Patterns

$$Q_{Btu} = \sum_{i=1}^{6}\left\{\sum_{j=1}^{n\log s}\left[m_j \cdot C_p\left(\frac{\overline{T}_{out} + \overline{T}_{in}}{2}\right)_j \cdot \left(\overline{T}_{out} - \overline{T}_{in}\right)_j\right]\right\}_i$$

The test control specifications for the standard DOE *24 Hour Simulated Use Test* are shown in the table below. Conditions are maintained as close to these standard conditions as possible in both laboratories with standard and non-standard draw patterns.

Table 32: DOE 24 Hour Simulated Use Test Control Specifications

Controlled Condition	DOE Specification
Ambient Dry Bulb Temperature	67.5 ± 2.5°F
Water Main Pressure	40 psig up to mfr. spec.
Water Main Temperature	58 ± 2°F
Water Draw Rate	3.0 ± 0.25 gpm
Water Heater Set Point Temperature	135 ± 5°F
Supply Voltage	Within 1% of mfr. spec.

Short Term Testing

As opposed to daily simulated use testing that characterizes the impact of usage volumes and patterns on the delivered efficiency, short term testing focuses on both steady-state and intermittent performance. The First Hour Rating (FHR) test, a standard certification [46], rates the hot water delivery capability of a storage water heater. The procedure begins with the storage tank at the prescribed average tank temperature, following recovery from a pre-draw and main burner cut out. A draw of 3.0 gallons per minute (gpm) is then initiated and sustained until the draw temperature drops by 25°F from the maximum delivered temperature for that draw. At this point, the draw ceased and the water heater is allowed to recover until the thermostat is satisfied and the main burner shuts off. Subsequent draw and recovery cycles are conducted within the same hour time frame; and the First-Hour Rating (FHR) is the total volume of hot water delivered over an hour. No other short term tests are performed on SWHs.

The balance of short term testing of intermittent performance and the definition of heat transfer characteristics of heat exchangers through steady state testing concerns only TWHs.

Defining the UA and Thermal Capacitance of TWHs

The thermal capacitance is the usable stored energy in the thermal mass of the TWH and the UA is the standby heat loss coefficient, which are needed to simulate the operation of the tankless water heater as described by Burch et al [75]. A quick series of tests were performed to derive these two parameters. Per the Burch study, the operation of the tankless water heater is broken into four modes: Steady State, Ramp-up, Environmental Decay, and Draw Decay. The testing leverages three of the four modes not including Ramp-up, which are described as follows:

Equation 59: Steady State

$$\eta_{Comb}\dot{Q}_{Gas} = \dot{m}C_P(T - T_{in}) + UA(T - T_{env})$$

Equation 60: Ramp-up

$$C\,{}^{dT}\!/_{dt} = \eta_{Comb}\dot{Q}_{Gas} - \dot{m}C_P(T - T_{in}) + UA(T - T_{env})$$

Equation 61: Environmental Decay

$$C\,{}^{dT}\!/_{dt} = -UA(T - T_{env})$$

Equation 62: Draw Decay

$$C\,{}^{dT}\!/_{dt} = \dot{m}C_P(T - T_{in}) - UA(T - T_{env})$$

Equation 63: Efficiency Definitions

$$\eta_{comb} = \frac{Q_{Gas} - Q_{FG}}{Q_{Gas}};\ \eta_{Th} = \frac{Q_{Water}}{Q_{Gas}}$$

Detailed Test

- *Initial Heat-up & Steady State:* Establish an extended draw of 3 gpm at a 130°F set point for no less than five minutes.

- *Standby Period:* Cease the draw, disable the tankless water heater (gas & power off) following the combustion blower post-purge, and begin a standby period. Over testing, a standby period of 0, 22.5, and 45 minutes are used[41].
- *Draw Down:* After the standby period, initiate a 0.5 gpm draw through the disabled tankless unit, record outlet temperatures until they are within 1°F of the inlet water temperature.

Through data analysis, the thermal capacitance *C* is calculated during the Draw Down period using the Draw Decay equation. As suggested by Burch et al., the water side heat transfer is an order of magnitude above that of the air side natural convective losses, thus for simplicity the final UA term is ignored during the brief Draw Down. During initial Steady State operation, the Steady State equation is used to estimate the UA value, with a known measured combustion efficiency (determined via gas analysis). For tests with a nonzero standby period duration, the Environmental Decay equation is used as a check for the estimation of both *C* and UA.

Focused UA Testing

An alternative approach to determine the UA is to supply heated water to the unit from an external source, and run it at a steady state condition with the power off and a low water volume. Under this scenario, the left-hand side of the 'Steady State' equation is zero, with no thermal input from combustion:

Equation 64: Steady State

$$0 = \dot{m}C_P\left(T - T_{in}\right) + UA\left(T - T_{env}\right)$$

When calculating the UA using this method, the volumetric air flow must be known. This was calculated by measuring the excess oxygen and flue gas temperature, in conjunction with a fuel analysis which yields the higher heating value of the fuel and fuel speciation (CH_4, C_2H_6, etc.).

Short Term Startup Tests

Unlike SWHs, which generates hot water in a batch process, TWHs are "on-demand" in that no hot water is available to draw immediately, there will always be a delay. When a TWH senses a hot water demand, a series of events must take place prior to the delivery of hot water (not necessarily in this order):

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[41] Note that with a standby period of 0 minutes, the draw is not stopped, but rather the fuel flow is cut to disable the tankless system while maintaining the normal post-purge blower operation.

- The inlet water must be determined to be of a safe temperature (e.g. < 180°F) and draw rate. On the latter, if the draw rate is below the minimum allowable (e.g. 0.5 gpm), the TWH will not permit firing if combination of the minimum firing rate and incoming water temperature would unsafely overshoot the thermostat temperature.
- Upon initiation, the combustion air blower must generate sufficient draft and the vent must be determined to be blockage-free.
- Upon opening of the gas valve, the fuel/air must be ignited and the flame must be proven.
- If proven, the controller estimates the hot water demand and adjusts the thermal input, by modulating the gas valve, staging the burners, and adjusting the blower speed.
- Depending on the magnitude or variation of the hot water demand, often there are other operations taking place (e.g. activation of cold water bypass valves).

Through this process and the distance the hot water travels through the TWH piping and distribution piping, the delays to deliver hot water are not trivial. TWH manufacturers are sensitive to this concern and have updated their products to reduce this delay. Over the past several years, the minimum firing has decreased substantially, units offered in 2010 fired between 20 – 200 kBtu/hr, now standard TWHs fire as low as 9.5 kBtu/hr. In addition, many manufacturers can operated in an "enhanced" standby mode, where for hot water draws within a certain amount of time, subsequent startups will skip some precautionary steps to reduce the delay to deliver hot water. The following draw pattern is used, with six one minute long draws spaced apart by longer durations, a 30 s delay, 60 s delay, 120 s delay, 300 s delay, and 360 s delay (Figure 72). Draw rate and set point temperature are varied for each test, with set points at 110°F and 130°F and draw rates at 0.7, 1.5, 3.0, and 3.5-4.0 gpm. The key output from this test is the delay to fire and to reach steady outlet temperatures for each draw, looking for an abrupt shift indicating the use of an "enhanced" standby mode.

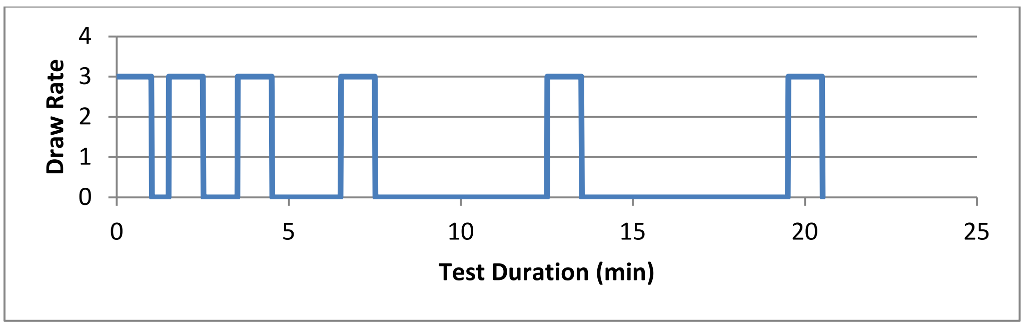


Figure 72: Visualization of Short Term Tests- 3.0 gpm Example

Two Shower Tests

With sophisticated controls, TWHs can modulate the supply of energy through varying the rate of fuel flow, air flow, and staging of numerous burners. Additionally, TWHs can adjust the demand as well. As end users, particularly through shower use, are more sensitive to small variations in temperature versus small variations in flow rate, the outlet temperature is the primary control target. In the case of insufficient capacity, TWHs will often restrict the water flow rate with a control valve, such that the thermostat goal can be met. In the case of temperature spikes or step changes in demand, often a cold water bypass valve is used to minimize outlet temperature overshoot/undershoot. This test uses this step changes in demand, simulating a shower coming on and off overlaid on a continuous shower, to (a) determine the effect on temperature over/undershoot and (b) detect any usage of bypass control by varying flow rates and water temperatures.

Table 33: Conditions for Two Shower Tests

Set Point (F)	High/Low flows (gpm)	Incoming Water Temperature (F)
120	3/1.5	58 - Normal
120	4/2	58 - Normal
120	4/2	95 - Elevated
140	4/2	58 - Normal

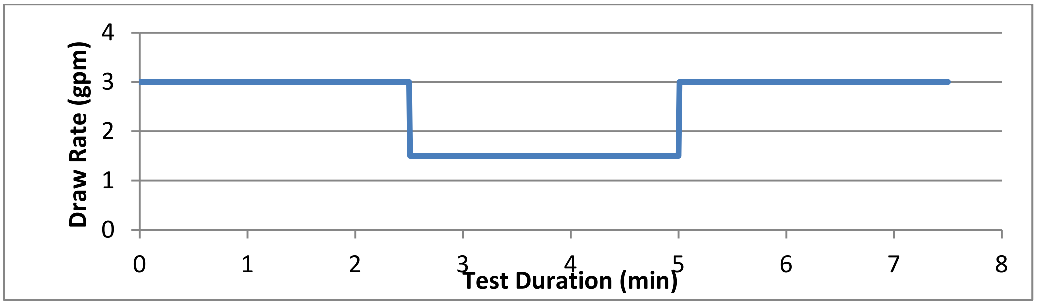


Figure 73: Visualization of Two Shower Test – 3.0/1.5 gpm Example

4.1 Storage Water Heater Laboratory Results

The purpose of testing storage water heaters is to compare how different styles of water heaters with varying energy efficiency features performed. The tests performed are the DOE First Hour Rating, DOE Standard Draw 24-Hour EF Test, GTI Medium Draw Profile, and GTI Low Draw Profile. With the exception of the 0.67 EF SWH, the intent was to test the spectrum of efficiency in a product line from one manufacturer, A.O. Smith in this case, selected due to their availability of both gas hybrid and condensing storage products.

Table 34: Storage Water Heaters Description and Model Number

Description	Model Number	Description
15 Year Old Water Heater	State SEV-40	Atmospheric combustion with pilot light that has been in the field since its manufacture
0.62 EF Atmos	AOS ProMax+ GVR-40	Atmospheric combustion with pilot light

0.67 EF Atmos/Vent Damper	AOS ProMax GCF-40	Atmospheric combustion with electronic ignition. Standby losses are mitigated with powered vent damper, activated during off-cycles
0.67 EF Power Vent	AOS ProMax GPVR-40	Powered combustion (induced) with combustion air drawn from indoors, with electronic ignition and PVC venting
0.67 EF Direct Vent	Rheem PDV40	Powered combustion (induced) with combustion air drawn from outdoors, with electronic ignition and PVC venting/air intake
0.70 EF Atmos/Fan Boost	AOS Effex GAHH-40	Slightly pressurized combustion (small blower), compatible with standard atmospheric venting, with highly restrictive flue baffle and electronic ignition
Hybrid	AOS Next Hybrid-90N	Powered combustion (blower) with electronic ignition, has high thermal input, small storage volume, condenses with secondary heat exchanger
Condensing Storage	AOS Cyclone BTX-80	Powered combustion (blower) for condensing unit with submerged helical coil flue, with electronic ignition

4.1.1.1 Storage Water Heaters Results and Discussion

The testing and analysis for the storage water heaters was performed by Pacific Gas & Electric (PG&E) at their Applied Technology Services Facility (**Error! Reference source not found.**), supervised by Robert Davis. For each unit listed in Table 34, a First Hour Rating (FHR) short term test is performed and three 24 hour tests are performed using the standard Dept. of Energy *24 Hour Simulated Use Test* ("DOE Standard EF") test procedure followed by the "Mid" and "Low" patterns described in **Error! Reference source not found.**). Table 35 shows a summary of results where **Error! Reference source not found.** through **Error! Reference source not found.** show a complete summary of tabular data derived from the daily simulated use testing for the DOE Standard EF, GTI Mid, and GTI Low draw patterns.

Observed previously for all SWHs, particularly emphasized in the evaluation of the alternative "Input/Output" method of test by the ASHRAE SPC 118.2, [76], the daily total hot water energy delivered, has a linear relationship with the daily total energy consumed for a given SWH. One can see that the DOE standard draw pattern and GTI mid draw pattern, of similar total volume drawn but otherwise quite different, result in very similar estimated EFs across products. With a smaller total volume drawn, thus a greater contribution of standby losses for a given output, the GTI low pattern results in universally lower efficiencies. Upon summarizing these results, Robert Davis of PG & E made the following observation:

"I think the draw profile really won't matter very much for storage tank systems, with the critical parameter being the temperature setpoints and the volume of water drawn. This is fairly well demonstrated by the test results between the standard EF test and the GTI medium use test being about equal.

Actually, following the linear input-output scenario, the GTI Medium use test should produce a number that is slightly higher than the standard because its draw amount is about 3% greater. Some of this may be hidden because there has been no mathematical adjustment for volume or temperature differences in the GTI test results."

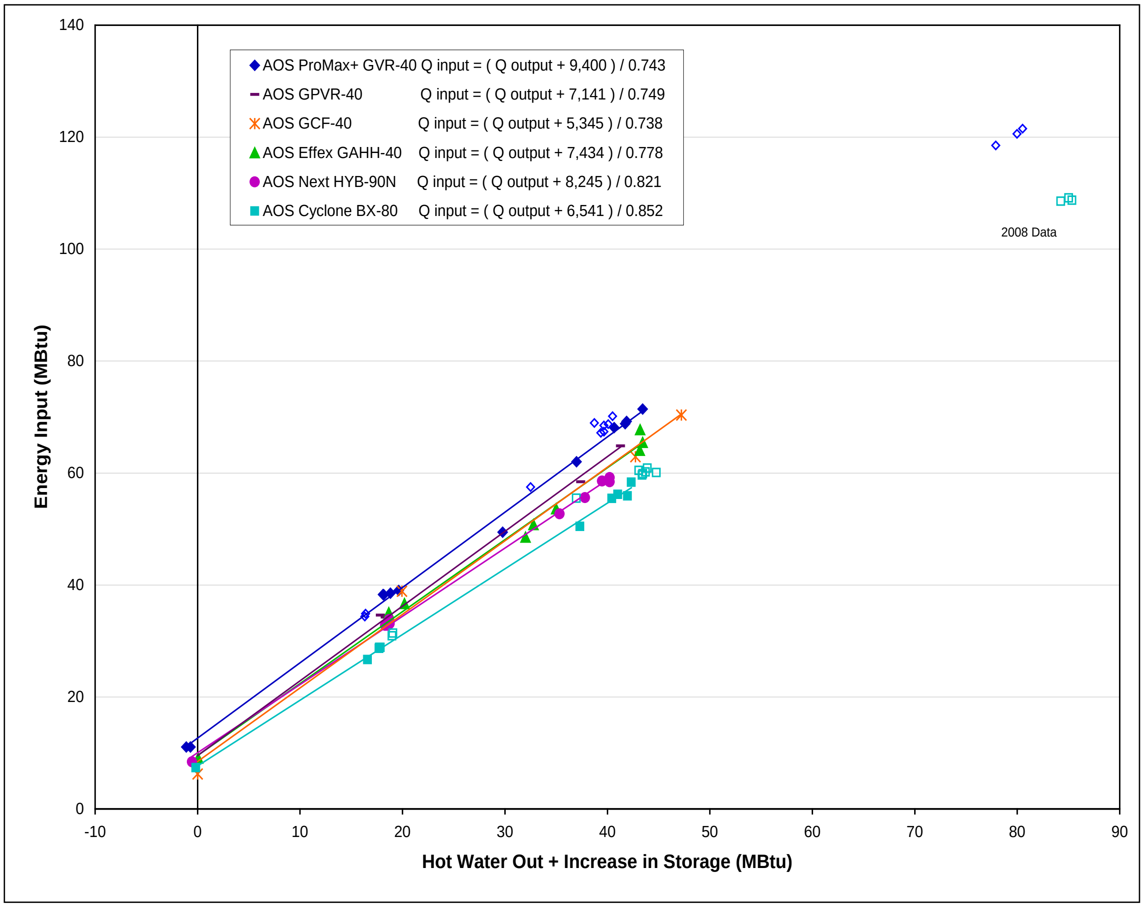
This linearity of results is also highlighted in Figure 74, whereby this "Input/Output" approach is used as an analytical technique. For smaller outputs, a single draw/recovery cycle or collection of cycles, a proportional thermal input is required, yielding the efficiency versus gallons drawn per day as shown in Figure 75, with the trend identified in Table 35 clearly presented.

Table 35: EF Results for Storage Water Heaters

Description	**DOE First Hour Rating**		**DOE Std Draw**[42]		**GTI Mid Draw**	**GTI Low Draw**
	Mnfr.	Test	Mnfr.	Test	Test	Test
"15 Year Old" Water Heater	63	80	0.64	0.59	0.60	0.44
0.62 EF Atmos	71	70	0.62	0.60	0.60	0.48
0.67 EF Atmos/Vent Damper	67	70	0.67	0.66	0.66	0.57
0.67 EF Power Vent	70	89	0.67	0.64	0.64	0.53
0.67 EF Direct Vent	73	76	0.67	0.64	0.64	0.53

[42] The EF results for the DOE standard draw have been adjusted according to the DOE standard procedures for operational offsets from the standard test conditions and the change in stored energy between the start and the end of the test. The GTI profile tests have only been adjusted for the change in stored energy.

0.70 EF AtmosFan Boost	70	77	0.70	0.66	0.66	0.54
Hybrid	189	130[43]	90%[44]	0.68	0.68	0.56
Condensing Storage	123	148	90%	0.74	0.73	0.62



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43 In manufacturer's test, First Hour Rating test was continuous, although it settles out at a temperature below the initial setpoint. In our tests, the delivery temperature did drop by over 25°F from the initial starting point, which resulted in two draw events. The test was incomplete since a third draw should have been started at the 60 minute mark, so this number is low. The manufacturer was consulted and it was suggested that an unwanted blockage existed in the recirculation loop, thus the results are not representative of a properly working product.

44 Both the Next (100,000 Btuh) and the Cyclone (76,000 Btuh) are rated with burner inputs above 75,000 Btuh, and thus are classified as EPACT units and have a thermal efficiency rating.

Figure 74: AOS Storage Water Heater Energy Input v Output Comparison[45]

When comparing all three 0.67 EF rated water heaters, the 0.67 EF Atmos/Vent Damper performs slightly better as compared to the others in that range, as the vent damper alone has a significantly lower power draw than the direct/power vent inducer. The average power when the unit is firing for the 0.67EF Atmos/Vent Damper is 5.9 watts, while it's approximately 178 watts for the 0.67 EF Power Vent and 0.67 EF Direct Vent requires approximately 145 watts when it is firing. Highlighting the differences in design tradeoffs between these three units with similar efficiencies, consider the difference in recovery cycles and total electrical energy consumed between the DOE and GTI-Mid 64 gal/day draw profiles (**Error! Reference source not found.**). Both power vent and direct vent models have an additional recovery cycle and a modest increase in electricity consumption as a result, leading to a drop in estimated EF. The atmospheric/vent damper unit has a marked increase in cycles however little change electricity consumption, with minimal impact on estimated EF.

[45] Additional data included from 2008 PG&E study of gas water heaters as indicated [76]

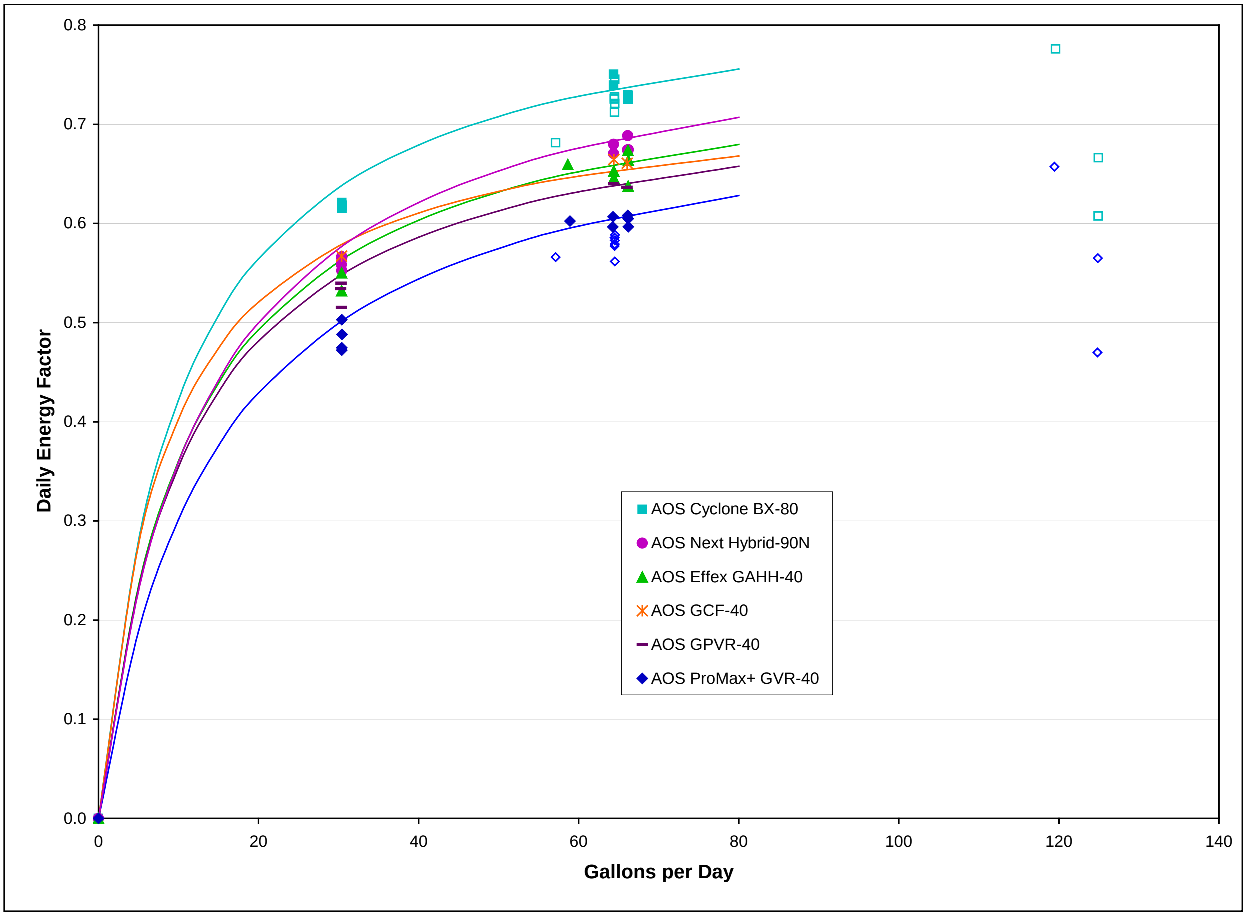

Figure 75: AOS Storage Water Heater Daily Energy Factor v. Gallons per Day Comparison

4.1.1.2 Cost Effectiveness of Storage Water Heaters

Depending on local market conditions and considering the variations observed for the three 0.67 EF models, the impact of increased electricity consumption for a given SWH EF can be an increased operating cost. Using the prices outlined in Table 36, a cost-effectiveness analysis will determine the magnitude of this increased operating cost.

Table 36: Natural Gas and Electricity Prices [80, 81]

Sensitivity Analysis		
2010 Mid Electricity Price[46]	0.1575	$/kWh
2010 Average Natural Gas Price[47]	0.9688	$/therm
High Electricity Price	0.1728	$/kWh
Low Electricity Price	0.1264	$/kWh
High Natural Gas Price	1.0479	$/therm
Low Natural Gas Price	0.8408	$/therm

Table 37: Estimated Annual Energy Operating Cost at 2010 Natural Gas & Electricity Prices

	15 year old water heater	0.62 EF Atmos	0.67 EF Atmos/Vent Damper	0.67 EF Power Vent	0.67 EF Direct Vent	0.70 EF Atmos/Fan Boost	Hybrid	Conde-nsing Storage
DOE Standard EF	$239.74	$231.25	$229.17	$219.74	$236.53	$194.31	$208.69	$194.01
GTI Mid Draw	$246.81	$246.10	$255.53	$244.03	$245.71	$242.43	$226.91	$206.41
GTI Low Draw	$141.08	$136.13	$144.06	$129.85	$134.35	$136.18	$132.16	$103.31

From an annual energy cost perspective, the condensing storage water heater is the most cost effective as it is the most efficient SWH. At the other end of the efficiency spectrum are the 15 year old and 0.62 EF atmospheric SWH which at times are as cost-effective, if not slightly more so, than 0.67 EF SWHs for the non-standard draw patterns. Certainly these two have the lowest installed cost, thus they are overall more cost-effective. Considering operating cost only, the

[46] Low, Mid, and High electricity prices correspond to 2010 annual averages from LADWP, PG&E, and SDG&E respectively.

[47] While an average residential price for natural gas is available from EIA for 2011, at the time of writing the most recent annual average residential electricity price is from 2010.

difference in the cost of electricity eliminates savings from reduced fuel usage for some of the 0.67 EF SWHs. Keeping things in perspective, these differences in annual operating cost are likely to be unnoticed by the end user.

4.2 Tankless Water Heater Laboratory Tests

As mentioned previously, the tankless testing is intended to (a) provided datasets for the validation of modeling tools and (b) investigate the nature of startup delays and other performance phenomena related to controls. Representative TWHs are selected for testing, all whole-house TWHs, including a non-condensing, two standard condensing, and a condensing TWH with a small onboard buffer tank. Details on the TWHs tested are shown in Table 38.

Table 38: Tankless Water Heater Description and Model Numbers

Description	Model Number	Firing Rate (Btu/hr)		Certified Performance			Unit Weight (lbs)	Water side volume (L, measured)
		Min	Max	EF	Max GPM	at ΔT (°F)		
Non-condensing	Paloma RTG-95DVN	11,000	199,900	0.82	4.3	77	54	0.875
Condensing 1	Rinnai RC98HPe	9,500	199,000	0.93	4.4	77	70.5	1.7
Condensing 2	Bosch Therm C 1050	19,900	175,000	0.92	4.2	77	74	0.92
Condensing with small 2 L buffer tank	Navien NR-240A	17,000	199,000	0.95	5.1	77	86	3.7

4.2.1 UA and Thermal Capacitance

For the non-condensing TWH, with a measured combustion efficiency of 86.7%, the following results are derived from the test outlined in the introductory section of this chapter. For tests with a nonzero duration standby period, the Environmental Decay equation is used as a check for the estimation of both C and UA. **Error! Reference source not found.** through **Error! Reference source not found.** in **Error! Reference source not found.** summarize the results of the Quick Thermal Capacitance Test and Focused UA testing, note that only one condensing TWH was evaluated for this testing, the Rinnai. A summary of critical simulation parameters is shown in Table 39, noting that due to the limitation that the condensing TWH did not have a maintenance mode whereby the blower could be operated independent of firing, the UA and C values are primarily estimated as averages from the DOE 24 Hour Simulated Use Test, with 1 second sampling.

Additionally, the pressure drop curves generate for all TWHs over the course of testing are summarized in **Error! Reference source not found.**.

Table 39: Summary of Modeling Parameters for TWHs

Input	Non-Condensing	Condensing		
Capacitance	12.9	5.9	Btu/F	Max output @ 77F rise
	6.9	2.5	Btu/F	Min output @ 77F rise
UA	32	28.3	Btu/hr-F	Max output @ 77F rise
		5.3	Btu/hr-F	Min output @ 77F rise
		8.7	Btu/hr-F	Blower Off - 130 F Inlet
	8	7.3	Btu/hr-F	Blower Off - 150 F Inlet
Thermal Efficiency	86%	95.4%		Max output @ 77F rise
		98.2%		Min output @ 77F rise
On-time delay	5	5.0	sec	
Power Consumption	55	160	W	Active – Average
	5	7	W	Standby - Average
	N/A	59	W	Active - Rated
		2	W	Standby - Rated

4.2.1.1 Short Term Tests

During the short term tests, as shown graphically in Figure 72 and in greater detail in **Error! Reference source not found.** and **Error! Reference source not found.**, two metrics are of primary concern: the delay to fire overall and variations throughout the testing, and observing the behavior of the thermal input modulation. A summary of the delay to fire, averaged over all tests for each of the six draws is shown in Table 40. The two condensing TWHs behave similarly, as described in detail in **Error! Reference source not found.**.

Table 40: Delay to Fire (s) Averaged Over All Tests - by Draw

Draw No.	Non-Condensing	Condensing 1
Draw 1	3.1	2.8
Draw 2	1.4	2.9
Draw 3	1.3	2.9
Draw 4	1.4	2.9

Draw 5	1.5	2.9
Draw 6	2.6	2.8

Using the mass flow meter to observe finer resolution changes in fuel flow rate, thus TWH thermal input modulation, **Error! Reference source not found.** through **Error! Reference source not found.** highlight the firing rates over the course of a cold start draw. Where the condensing 1 and 2 TWHs have similar smooth controls to reaching the target firing rate in most cases, the non-condensing TWH uses a hunt-and-seek method beginning from a fixed point. From a cold start, the controller assumes the necessary input is approximately 110,000 Btu/hr, and adjusts from there based upon feedback from the water-side sensors. However, when the unit operates in an "enhanced" standby mode, the impact of this hunt-and-seek delay is muted, as shown in **Error! Reference source not found.**.

4.2.1.2 Two Shower Tests

During the Two Shower tests, with complete results in **Error! Reference source not found.**, the delay to reach stable temperatures during and the temperature and flow variations observed following transitions are recorded. The summary of results over the four tests outlined in Table 33 are shown in Table 41. Complete results are shown in **Error! Reference source not found.** through **Error! Reference source not found.**.

Table 41: Summary of Two Shower Test Results

	Transition	Average Delay until Stable Temperature (s)	Temperature Departure during Transition	
			Overshoot (°F)	**Undershoot (°F)**
Non-condensing	Hi/Lo	19.8	5.6	0.8
	Lo/Hi	36.0	1.1	32.7
Condensing 1	Hi/Lo	29.8	6.7	0.8
	Lo/Hi	21.6	0.8	11.6
Condensing 2	Hi/Lo	23.7	13.7	15.3
	Lo/Hi	33.3	4.6	19.6
Condensing with BT (Inactive)	Hi/Lo	22.1	5.5	0.1
	Lo/Hi	32.5	0.4	8.8

4.2.1.3 24 Hour Simulated Use Tests

Reviewing the results in Table 47 first the trend observed with SWHs can be found whereby a lower daily hot water draw, in this case increasing the degree of intermittency, results in lower estimated EFs. To investigate the impact of the final TWH, with a 2 L buffer tank and a pumped recirculation loop, two GTI-Mid tests compare the impact of active (24 hr/day) or inactive maintenance of this hot water store. As described in greater detail in **Error! Reference source not found.** and **Error! Reference source not found.**, the TWH has 50 recirculation events which act to decrease the overall efficiency, but reduce the time to deliver hot water and increase the average delivered temperature. It is worth mentioning that with an inactive buffer tank in the water pathway, a 2 L tank with a diptube outlet 90% of the height, the average delivered temperature is lower and the delay longer than other TWHs.

Table 42: Summary of 24 Simulator Use Test Data

	EF	Estimated EF		Average Delivered T (°F)		
	DOE	Mid	Low	DOE	Mid	Low
Non-condensing	0.77	0.75	0.73	129.6	125.3	129.9
Condensing	0.92	0.90	0.87	127.5	123.7	123.8
Condensing with BT (Active)		0.67			126.4	
Condensing with BT (Inactive)		0.85			119.8	

4.3 Distribution Piping Laboratory Tests

Two different activities were performed under this task. One was a review of earlier AET lab testing techniques and results in support of improvements to the HWSIM code, including repeat testing of some previously tested piping configurations. The other was a new set of tests on bundled pipe.

4.3.1 Repeat Tests

As AET worked interactively with DEG in improving the HWSIM hot water distribution system model, several inconsistencies between lab test results and model results became apparent that suggested there may have been some inaccuracies in some of the early insulated pipe tests. As a result of this, AET undertook an extensive re-review of all the test procedures, analyses and results from all the various hot water distribution system lab tests AET had performed over the years. This involved review of many thousands of tests and analysis. While this review did not reveal any significant analysis errors, it did reveal a potential difference in results from the early test techniques and the later more refined test techniques. As a result, a comprehensive series of repeat tests (involving over 500 tests) were performed on the initial ¾ inch rigid copper pipe test rig (which had been saved intact), but modified to use the newer test techniques.

The older tests were performed using immersion thermocouples installed through pipe T's which stood a considerable height (2-3 inches) above the pipe, while newer tests were performed using direct penetration of the pipe sidewall by immersion thermocouples, and a special compression fitting developed by AET for that purpose. Moreover, early tests stored data at 5 second intervals while later tests stored data at one second intervals. Figure 76 through Figure 79 show the initial and repeat ¾ inch rigid copper pipe test setups.

Figure 76: Original ¾ Rigid CU Piping Test Setup, Bare, in Air

Figure 77: Original ¾ Rigid CU Piping Test Setup, Insulated, in Air

Figure 78: Retested ¾ Rigid CU Piping Test Setup, Bare, in Air

Figure 79: Retested ¾ Rigid CU Piping Test Setup, Insulated, in Air

Pipe heat loss results for the bare pipe configuration in air were similar between the initial tests and the repeat tests, being around 4 percent lower for the repeat tests, mostly due to the larger uncertainty bound in the early tests. However, pipe heat loss results for insulated pipe were 30-38% lower in the repeat tests compared to the initial tests (which is consistent with what the updated HWSIM model was predicting). While we are not exactly sure what caused this, it probably had something to do with extra turbulence generated by the pipe T's causing falsely low temperature readings as moving flow mixed with cooler stagnant flow in the upper parts of the T's. We know from test results that when pipe is insulated the temperature drop from one end to the other is fairly small, often less than one degree Fahrenheit, so this mixing effect could have a significant effect on apparent measured temperature and thus on computed heat loss. This is more so on insulated pipe than on uninsulated because the minor change in temperature (on the order of 0.1 F) represents a significant percentage of the total measured apparent temperature drop. While this effect was large on measured pipe heat loss UA values, it had no impact on measured water waste, which remained unchanged between the early tests and the repeat tests.

With this new understanding, updated heat loss UA curves were developed for both ¾ and ½ inch rigid copper pipe as functions of flow rate, and these results were more consistent both with HWSIM predictions, and with newer tests on other types of pipe which used physically the same pipe insulation. Only the early ¾ and ½ inch rigid copper pipe tests used pipe T's, and only the insulated results from those cases were at odds with all subsequent tests, which used the "through-the-sidewall" measurement approach. A summary of all the measured pipe heat loss UA values from all tests on all pipes is shown in Table 43.

Table 43: Pipe UA Value Summary (in-air unless noted)

NOMINAL PIPE SIZE Inches (mm.)	FOAM INSUL. THICK. Inches (mm)	ZERO FLOW UA BTU/HR FT F (W/m K)	HIGH-VALUE UA BTU/HR FT F (W/m K)
½ (13) Rigid CU	0	0.226 (0.392)	0.36 (0.624)
½ (13) Rigid CU-old	½ (13)	0.128 (0.222)	0.20 (0.347)
½ (13) Rigid CU-new	½ (13)	0.128 (0.222)	0.132 (0.229)
½ (13) Rigid CU-old	¾ (19)	0.116 (0.201)	0.19 (0.330)
½ (13) Rigid CU-new	¾ (19)	0.116 (0.201)	0.117 (0.203)
¾ (19) Rigid CU-old	0	0.388 (0.673)	0.44 (0.763)
¾ (19) Rigid CU-new	0	0.40 (0.694)	0.421 (0.73)
¾ (19) Rigid CU-old	½ (13)	0.150 (0.260)	0.25 (0.434)
¾ (19) Rigid CU-new	½ (13)	0.161 (0.279)	0.165 (0.286)
¾ (19) Rigid CU-old	¾ (19)	0.142 (0.246)	0.24 (0.416)
¾ (19) Rigid CU-new	¾ (19)	0.144 (0.250)	0.148 (0.257)
¾ (19) PAX	0	0.550 (0.954)	0.546 (0.947)
¾ (19) PAX	½ (13	0.199 (0.345)	0.199 (0.345)
¾ (19) PAX	¾ (19)	0.158 (0.274)	0.18 (0.312)
¾ (19) Rolled CU	0	0.334 (0.597)	0.334 (0.597)
¾ (19) Rolled CU	¾ (19)	0.138 (0.239)	0.16 (0.278)
¾ (19) Rigid CU-Buried Damp Sand	0	1.3 (2.25)	3.2 (5.55)
¾ (19) Rigid CU-Buried Damp Sand	¾ (19)	0.154 (0.267)	0.19 (0.330)
¾ (19) Rolled CU-Buried	0	1.2 (2.08)	2.8 (4.86)

Damp Sand			
¾ (19) Rolled CU-Buried Damp Sand	¾ (19	0.155 (0.269)	0.177 (0.307)
¾ (19) CPVC	0	0.44 (0.763)	0.52 (0.902)
¾ (19) CPVC	¾ (19)	0.148 (0.257)	0.17 (0.295)
¾ (19) PEX	0	0.535 (0.928)	0.585 (1.01)
¾ (19) PEX	¾ (19)	0.159 (0.276)	0.19 (0.329)
½ (19) PEX	0	0.438 (0.760)	0.438 (0.760)
½ (19) PEX	¾ (19)	0.13 (0.225)	0.13 (0.225)
3/8 (19) PEX	0	0.345 (0.598)	0.368 (0.638)
3/8 (19) PEX	¾ (19)	0.121 (0.210)	0.121 (0.210)
½ (19) PEX-Bundled	0-Bundled	0.71 (1.23)	0.71 (1.23)

4.3.1.1 New Tests-Bundled Pipe

In addition to the pipe retests, a significant new series of tests were performed comparing bundled vs single ½ inch PEX (high density cross-linked polyethylene) piping. The purpose of these tests was to quantify the impact on heat loss and water waste characteristics of bundling one hot water pipe with other unused water pipes, as is common practice in buildings using manifold distribution systems, as shown in Figure 80.

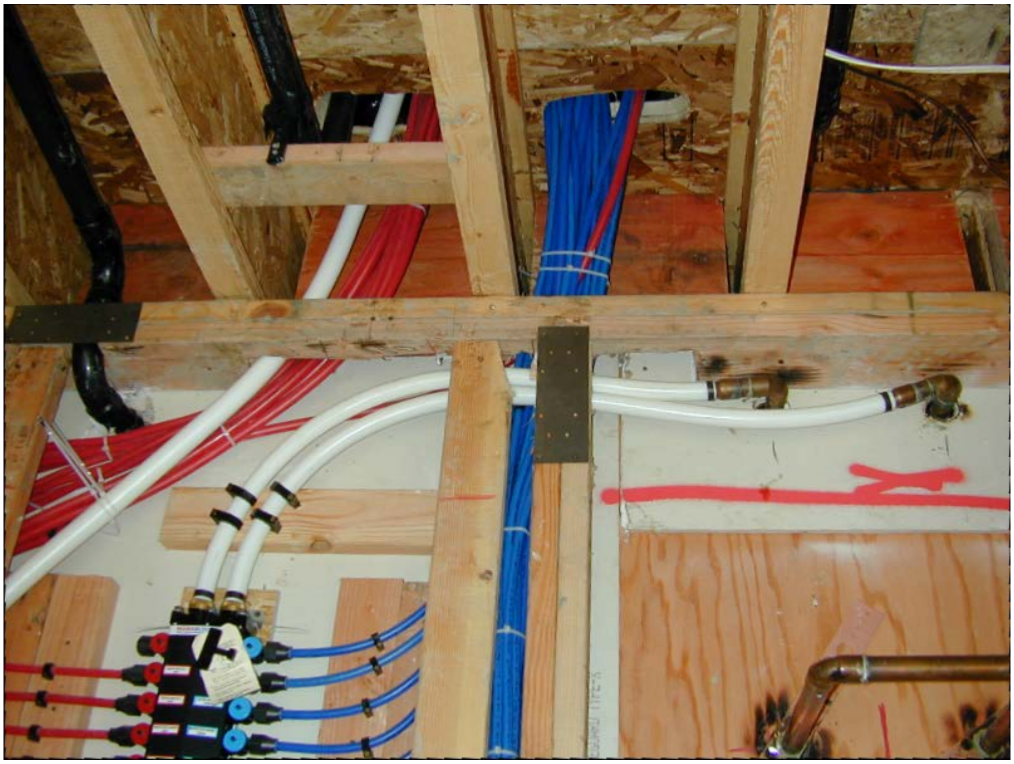

Figure 80: Bundled Piping as Seen in Real Buildings

Figure 81: ½ Inch Single PEX Piping 6-Pass, In-Air

Figure 82: 1/2 Inch Bundled PEX Piping 6-Pass, In-Air

The concern with bundled pipe is that this would increase the heat loss from the active pipe into the surrounding cooler pipes, resulting in both higher rates of heat loss and increased water waste compared to a single uninsulated pipe in air. Test results showed this to be a valid concern as discussed below.

The single pipe test configuration was a 6 pass serpentine arrangement having a total length of 125 feet, as shown in Figure 81. The bundled pipe configuration was similar, but had six water-filled non-flowing ½ inch PEX pipes fairly tightly bound around the active central pipe at approximately two foot intervals, as shown in Figure 82. Water in the surrounding pipes was at approximately room temperature at the beginning of each test.

Similar to tests previously performed on many other pipes, tests were performed at five different flow rates, two different entering hot water temperatures, and several air temperatures, and each test configuration was repeated at least 3 times, amounting to hundreds of tests.

Tests consisted of three phases during any one draw, including an initial “delivery” phase where hot water was traversing the pipe until “hot enough to use” water (defined as 105°F) reached the outlet, a “use” phase where a long steady draw was taken simulating hot water use during which heat loss measurements could be taken, and a “cool-down” phase, after the draw had ceased, while the pipe cooled back to ambient temperature. Fast response immersion thermocouples were inserted directly through the pipe side wall using a special compression fitting fashioned by the principle investigator. Thermocouples were located at the entrance to each pipe test section, at each U-bend, and at the outlet. Data were stored at 1 second intervals for all tests

Pipe heat loss (UA) factors were determined differently for the flowing vs zero-flow (cool-down) tests. To determine $UA_{flowing}$, the steady-state (or near steady-state) drop in temperature was measured from inlet to outlet in the pipe. The measured temperature drop and flow rate were then used to calculate $UA_{flowing}$ using Equation 65 [83].

Equation 65: Pipe Heat Loss (UA)

$$Q = (mCp)_w(T_{hot\ in} - T_{hot\ out}) = UA_{flowing}\ (T_{hot\ average} - T_{air}) = UA_{flowing}(LMTD_{flowing})$$

Where:

Q = heat loss rate

$(mCp)_w$ = mass flow rate of water times specific heat of water

$T_{hot\ in}$ = water temperature entering pipe

$T_{hot\ out}$ = water temperature leaving pipe

$T_{hot\ average}$ = log-mean average pipe water temperature

T_{air} = surrounding air temperature

$UA_{flowing}$ = pipe heat loss characteristic under flowing conditions (usually on a per unit length basis)

LMTD flowing = log mean temperature difference under flowing conditions

$LMTDflowing = [(T_{hot\ in} - T_{air})-(T_{hot\ out} - T_{air})]/\ln[(T_{hot\ in}-T_{air})/(T_{hot\ out}-T_{air})]$

Duration of the flowing pipe heat loss tests consisted of two phases; a transient phase while water temperatures at each measuring location were increasing as the pipe and surrounding materials (if any) were heating up to their final steady-state (or slowly changing quasi-steady-state) values and the air natural convection flows became established, and a steady state phase during which all temperatures remained relatively constant. The transient phase typically lasted 5 to 30 minutes (the longer times were needed when there was much surrounding thermal mass), and the steady state phase typically was run for 15-30 minutes once steady conditions were established.

To determine $UA_{zero\text{-}flow}$, the drop of pipe temperature was observed over time after flow was stopped. The known dimensions and properties of the pipe were used to calculate the effective mass times specific heat per foot of the pipes tested, including pipe, water, and insulation. The $UA_{zero\text{-}flow}$ was then calculated at each minute during the pipe cool-down process and the average value over an extended period was computed. Best consistency for comparisons was achieved by using $UA_{zero\text{-}flow}$ values computed during the time the pipe was cooling from its initial temperature down to the 105°F minimum usable temperature level. Equation 66 is used to calculate $UA_{zero\text{-}flow}$.

Equation 66: Pipe Heat Loss characteristic under Zero-Flow Conditions

$$Q = (MCp)_{pwi}(T_{pipe\ time\ 1} - T_{pipe\ time\ 2})/(\text{time interval}) = UA_{zero\text{-}flow}(T_{pipe\ average} - T_{air})$$

$$= UA_{zero\text{-}flow}(LMTD_{zero\ flow})$$

Where:

Q = heat loss rate

$(MCp)_{pwi}$ = (mass of pipe)(Cp_{pipe}) + (mass of water)(Cp_{water}) + (mass of insul.)($Cp_{insulation}$)

Cp = specific heat of the material

$T_{pipe\ time\ 1}$ = water temperature at beginning of time interval

$T_{pipe\ time\ 2}$ = water temperature at end of time interval

$T_{pipe\ average}$ = log-mean average pipe temperature over the time interval

T_{air} = air temperature

$UA_{zero\text{-}flow}$ = pipe heat loss characteristic under zero-flow conditions (usually on a per unit length basis)

$LMTD_{zero\ flow}$ = log mean temperature difference under zero-flow conditions

$LMTD_{zero\ flow} = [(T_{pipe\ initial} - T_{air})\text{-}(T_{pipe\ final} - T_{air})]/\ln[(T_{pipe\ initial}\text{-}T_{air})/(T_{pipe\ final}\text{-}T_{air})]$

It is important to note that for the bundled pipe configuration, the above equations do not strictly hold true. This is because when there is significant thermal mass close-coupled to the test pipe, conductive heat losses into the surrounding pipes are important, and they are not accounted for by this method. Moreover, when there is significant thermal mass nearby, the pipe never really reaches a steady-state heat loss condition, because the surrounding mass absorbs heat and heats up, reducing the apparent heat loss rate as time goes on. It is possible however, for simplicity of comparison purposes, to compute an "effective UA" for the bundled pipe configuration in the same way we do for single pipes without surrounding thermal mass. This "effective UA" will decrease with time as the surrounding mass heat up, but allows us to better understand how heat loss compares to the single-pipe configuration.

For the time, water (and associated energy) waste associated with the wait for hot water to arrive at fixtures, the amount of water passing each measurement station prior to reaching 105°F was recorded. After much investigation, it was decided that presenting the water waste results as the ratio of actual flow volume required to obtain 105°F water divided by pipe volume (AF/PV) gave the best resolution of the data. Given the AF/PV ratio and a flow rate, the time spent waiting for 105°F water to arrive could then be computed. Moreover, given knowledge of the water heater heat input efficiency and entering cold and leaving hot water temperatures, energy impact of the water waste could be computed.

Piping Heat Loss Test Results in Air

Figure 83 shows measured pipe heat loss UA factors vs time at one flow rate for two of the single-pipe tests compared to two of the bundled pipe tests at a similar flow rate. In both cases, there is an initial delivery-phase transient period where UA cannot be reliably computed as hot water traverses the pipe. Once that delivery-phase transient period has passed, we can see that for the single pipe configuration, the measured UA value varies only a minor amount with time. In comparison, the effective UA for the bundled pipe configuration starts with a much higher heat loss rate that drops with time, but always remains above that for the single pipe configuration. The high initial heat loss rate for the bundled pipe configuration is due to the high rate of conduction heat loss from the hot water in the center pipe to the cold water in the surrounding pipes. This means that bundled pipe configurations have much higher heat loss rates than single pipe configurations. Moreover, even after an extended period of time, the effective heat loss rate for the bundled configuration remains significantly higher than for the single pipe. This is because the bundle of surrounding pipes heats up, but then rejects the heat to the surroundings through its much larger heat transfer surface area, effectively permanently increasing heat loss as if the surrounding pipes were fins.

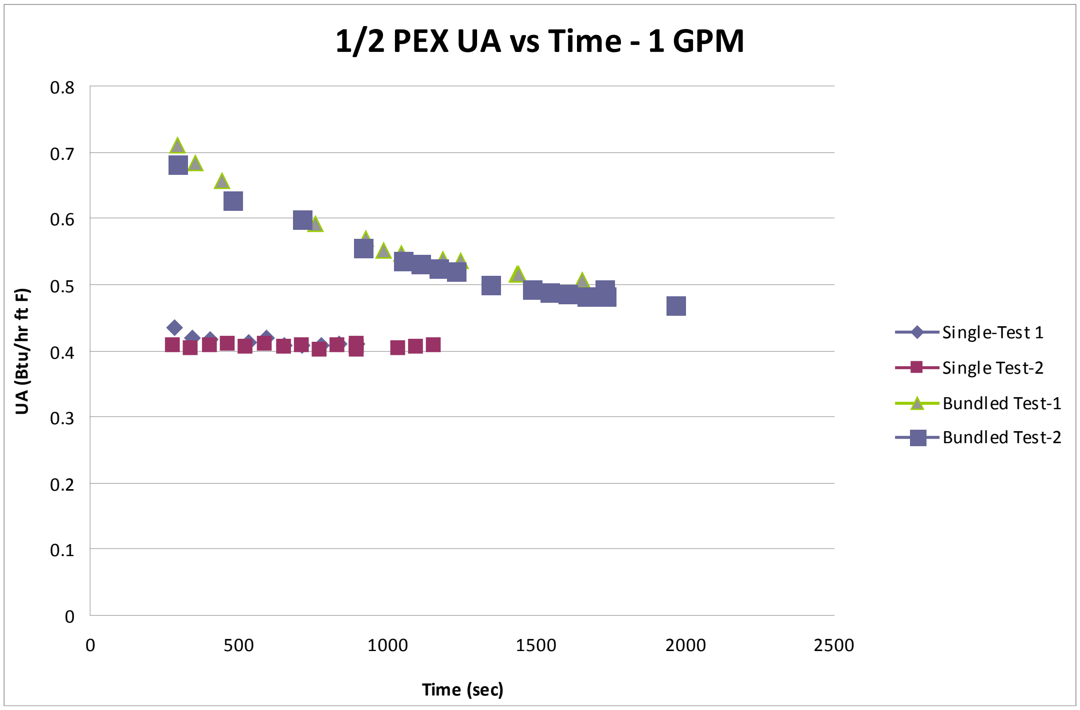

Figure 83: Single and Bundled Pipe UA Values VS Time-1/2 Inch PEX Piping

Figure 84 shows the initial high effective heat loss UA factors for the bundled pipe configuration compared to the single pipe configuration for other flow rates. We see that the initial effective heat loss rate for the bundled pipe configuration is about 0.7 Btu/hr ft F/0.42 Btu/hr ft F = 1.67 or 67% higher than the single pipe configuration. This means that for practical length draws, heat loss rate for the bundled pipe configuration is about 1.67 times higher than for the single pipe configuration, at essentially all flow rates.

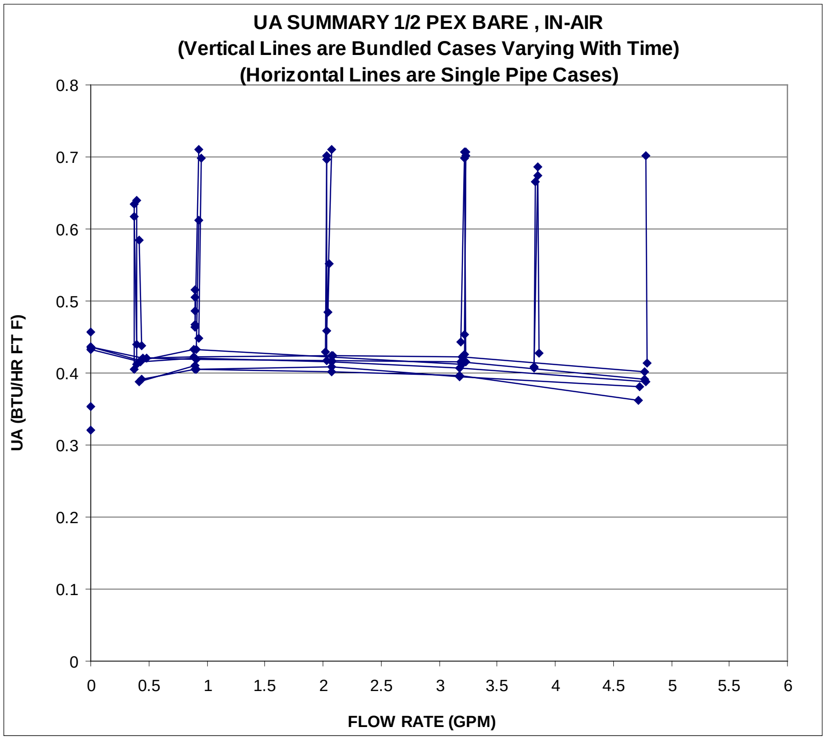

Figure 84: ½ Inch PEX UA VS Flow Rate

Additionally, under realistic duration draw events, which are usually less than 5 minutes, the surrounding pipes remain fairly cold, such that when flow ceases, the hot water pipe rapidly cools off, again at a rate of about 1.67 times that of the single pipe case. The time for the bundled pipe to cool down to below a usable temperature is on the order of typically less than 2-5 minutes. This rapid cool-down increases water waste and its associated energy waste while waiting for hot water to arrive at subsequent draws, because the bundled pipe is always the same or lower in temperature than a single pipe would be (lowers TDR as discussed below), resulting in a larger number of complete pipe purges to obtain hot water than for single pipe cases.

Water Waste Test Results In Air

Previous reports by AET describe the various flow regimes observed during the delivery phase transient, so that information will not be repeated here [23]. Rather, here we merely summarize the impact of the bundled pipe configuration on time, water, and energy waste during the delivery phase. When drawing conclusions about delivery phase waste it is important to compare cases at similar flow rates and temperature conditions

Temperature Difference Ratio or TDR = $(T_{hot}-T_{min\ use})/(T_{hot} - T_{pipe\ initial})$

where $T_{min\ use} = 105°F$.

Figure 85 and Figure 86 show AF/PV vs flow rate and length for TDR in the range of 0.365 – 0.407 for bare single pipe ½ inch PEX, horizontal, uninsulated in air. Figure 87 and Figure 88 show AF/PV vs flow rate and length for TDR in the range of 0.362 – 0.455 for bundled ½ inch

PEX, horizontal, uninsulated in air. Entering hot water was in the range of 135.7 – 138. 5°F for all plots. We note under conditions of higher flow rates and shorter pipe lengths, where less heat loss to the surroundings has time to occur, single-pipe and bundled pipe have similar AF/PV ratios. However, under conditions of lower flow rates (below 2 gpm) and longer pipe lengths (greater than 25 ft), where significant heat loss to the surroundings has time to occur, the bundled pipe configuration has significantly higher AF/PV ratios than does the single pipe configuration. The results mean that the bundled pipe configuration has higher time, water, and energy waste during delivery-phase flow than the single pipe configuration under most conditions of practical importance.

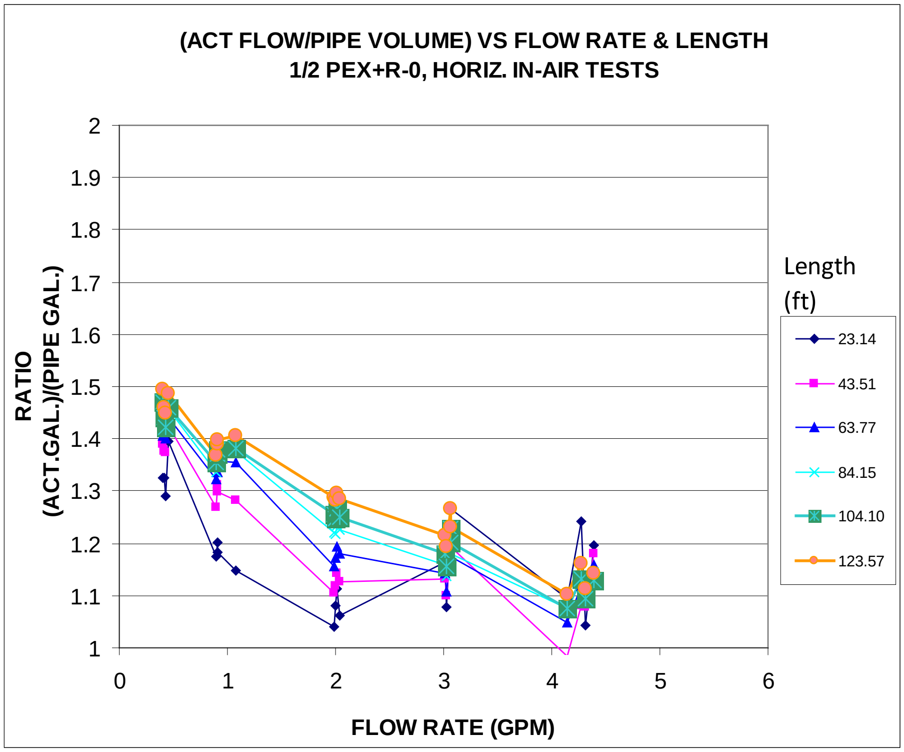

Figure 85: AF/PV Ratio VS Flow Rate & Length, ½ Inch PEX, Single Pipe in Air (TDR 0.365 – 0.407)

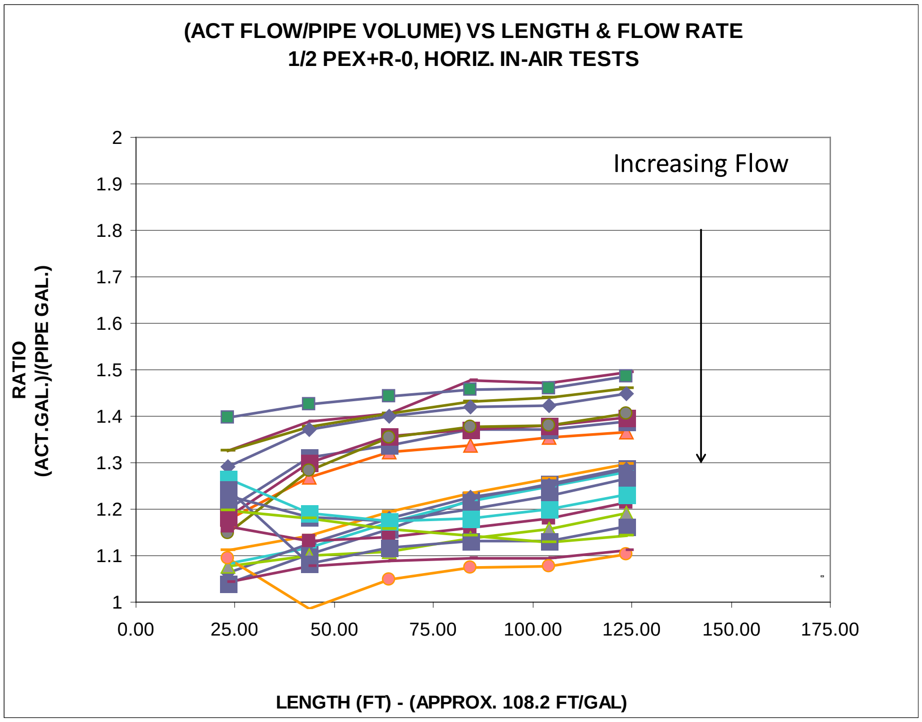

Figure 86: AF/PV Ratio VS Length & Flow Rate, ½ Inch PEX Single Pipe in Air (TDR = 0.365 – 0.407)

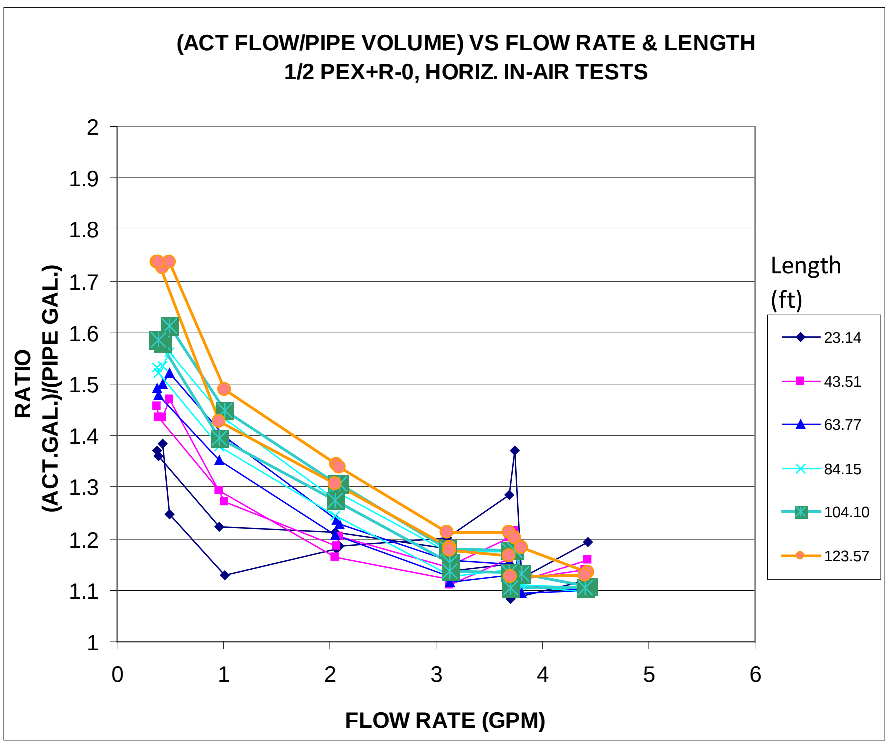

Figure 87: AF/PV Ratio VS Flow Rate & Length, ½ Inch PEX, Bundled Pipe in Air (TDR 0.362 – 0.455)

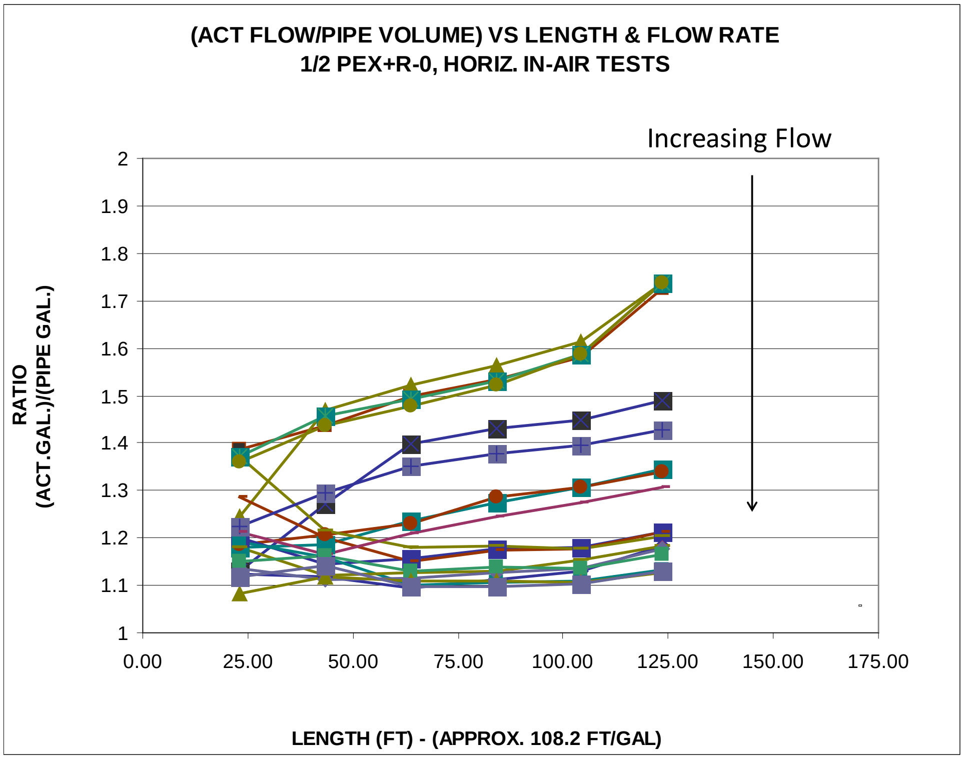

Figure 88: AF/PV Ratio VS Length & Flow Rate, ½ Inch PEX Bundled Pipe in Air (TDR = 0.362 – 0.455)

Overall Energy Waste Comparisons of Single vs Bundled Pipe in Air

Examples of how to compute energy waste associated with hot water distribution systems due to both heat loss and water waste are included in the Service Water Heating Systems Chapter of the 2007 and 2011 ASHRAE Applications Handbooks, and hence will not be repeated here. Suffice it to say that the findings presented here indicate that energy waste associated with bundled pipe systems is higher than for single pipe systems (at least for the particular pipe tested), having on the order of 2 – 50% higher energy waste under typical real-world pipe lengths and flow rates. The amount of energy waste varies significantly with draw durations and time between draws, which is why the energy waste difference is stated as a range. The lower end of the range of increase in energy use occurs when draw durations are short (just long enough to provide a little hot water, allowing little time for heat loss) and time between draws is long, such that the pipe cools off to below a usable temperature before each draw in either configuration. The higher end of the range of increase in energy use would be under a large number of moderately long draw durations (3-10 minutes) spaced a relatively short time apart (5- 8 minutes) such that cooled off water in the bundled pipe must be wasted to drain before each draw, whereas water in the single pipe does not.

4.3.1.2 Summary and Discussion of Lab Test Results

The comparisons between single and bundled pipe discussed above demonstrate that bundling uninsulated pipes tightly together results in increased heat loss rates and water waste, and thus higher energy waste than using single uninsulated pipes that are not bundled together. The increase in energy waste for the particular cases studied appeared to be in the range of 2 to as much as 50% higher energy waste for bundled pipe systems compared to single pipe systems.

The large body of hot water piping heat loss and water waste information that has been developed as a result of long-term funding support of such research by the California Energy Commission has led to rapid incorporation of such information into the ASHRAE Service Water Heating chapter, and thus unprecedented rapid dissemination to the design community. It has also provided a large body of data that has been used to improve accuracy of hot water distribution system models, such as HWSIM.

CHAPTER 5: FIELD TESTS AND SURVEYS

DEG led the field test and survey project, and teamed with Amaro Construction, Lutzenhiser Associates, and AET for their execution. The field test activity was comprised of three key elements:

- Monitoring of existing gas storage water heaters in 18 homes followed by replacement and monitoring of an advanced gas water heater;
- Assessment of California hot water usage behaviors through an on-line survey tool; and,
- Field documention of hot water distribution plumbing practice in 100 homes statewide.

A brief overview of the three projects follows, with detailed reporting in Sections 5.1 – 5.3.

Evaluations of water heater conversions in homes, from the very limited range of conventional 40 to 50 gallon storage water heaters to a wide range of higher efficiency condensing storage, tankless, and hybrid water heaters emerging in the marketplace were completed. The purpose of these field evaluations was to determine energy and hot water usage patterns before and after the higher efficiency upgrades. The field monitoring activities in this program provided detailed hot water usage data and water heater performance data, but the relatively small sample size (18 sites) and (intentional) broad selection of advanced water heaters limit the ability to make broad performance conclusions and observations. Clearly more field data are needed to bolster the findings in this report. Nonetheless, key project findings are summarized in the following sections.

Surveys of larger groups of homeowners and builders were also completed to understand broader hot water usage behavior among consumers as well as current distribution plumbing practices. Working closely with Southern California Gas (SCG), San Diego Gas & Electric (SDG&E), and PG&E, during the field site selection and these broader field survey processes, yielded informative demographics on residential water heating markets that will better match home hot water draw patterns and user behaviors to advanced water heater alternatives from among the much wider range of emerging versus conventional product offerings, thus allowing the utilities to better tailor their energy efficiency programs to consumers.

5.1 Baseline and Advanced Water Heater Field Tests

Water heating in California is a significant residential natural gas end use due to both a nearly 90% gas water heater saturation statewide and water heating's position as the largest residential natural gas end use, representing 49% of the 354 therm/year average household consumption according to the 2009 Residential Appliance Saturation Survey (RASS). Indications are that water heating's share of total gas use will only increase as space heating energy use continues to be reduced through a combination of increasingly tight Title 24 Building Energy Standards, improved furnace and duct efficiencies as part of HVAC retrofits, and a steady level of building envelope energy efficiency retrofits. Water heating is not yet following a similar trend, since efficiencies have been fairly static over the past thirty years as the atmospherically vented, center flue design has changed little beyond the incorporation of additional insulation.

The field monitoring efforts described in this report are part of a broader assessment of California residential water heating managed by the Gas Technology Institute. The field monitoring project involved selecting eighteen single family homes throughout California - six each in Pacific Gas & Electric (PG&E), Southern California Gas (SCG), and San Diego Gas & Electric (SDG&E) service territories - then nominally monitoring base case performance for four months, retrofitting advanced gas water heaters in the homes, and monitoring performance for another four months. Data collection involved recording water heater gas and electrical consumption, water heater cold water flow, water temperatures entering and leaving the water heater, and the environment temperature surrounding the water heater. During hot water draw events, water flow and temperatures were recorded at 4 second intervals. In addition "end of draw" records were logged with data summarizing all the key data captured during the period hot water was flowing, and a regular 15 minute interval data record was also logged.

The advanced gas water heater technologies assessed in this project include entry level EnergyStar™ storage offerings in the 0.67 to 0.70 EF range, non-condensing tankless water heaters (TWHs), condensing TWHs, and condensing storage water heaters. Monitoring was initiated in April and May of 2010 and continued into June 2011. Of the eighteen sites, seventeen underwent conversions to advanced water heaters including six EnergyStar water heaters, three TWHs, five CTWHs, and three condensing storage units[48].

Key project findings are summarized in the following four categories.

Hot Water Demand and Efficiency Implications

Monthly cold water inlet temperatures over a twelve month period ranging from May 2010 to April 2011 averaged 69.5°F, and ranged from 52.9 to 87.8°F. Southern California (SCG and SDG&E) sites typically had inlet water temperatures 7 to 8°F warmer than the PG&E Northern California sites.

The average number of hot water draws[49] was found to be 10 per person per day, ranging from 5 to 18. The average pre-retrofit water heater draw volume was 1.67 gallons.

[48] One of the three was a "hybrid" condensing tankless unit with limited storage (~25 gallons)

[49] A draw is defined as a continuous water heater flow event exceeding 4 seconds in length. Simultaneous draws at different use points would be represented as a single water heater draw event.

Hot water consumption averaged 56.4 gallons per day (gpd) over the full monitoring period, or 15.6 gpd per person. Individual average household hot water consumption varied widely across the different sites (from 21 to 138 gpd), with significant day-to-day variations observed at all sites.

Despite occupancy levels above the national census average household size, the annual hot water recovery load (combined water heater load due to end uses and piping losses) averaged 27,200 Btu/day. This average load is about 1/3 less than assumed in the Energy Factor test procedure. Explanations for this low recovery load include warmer inlet water temperatures, lower outlet water temperatures, and lower hot water consumption. The implications of these lower loads are significant for California, as we project a 0.06 reduction (~10%) in annual gas storage water heater efficiency from their estimated nominal Energy Factor (EF) levels.

Water Heater Performance and Economics

The average base case (i.e. existing) gas storage water heater energy use was projected at 188 therms per year, or slightly less than the 195 therms per year estimated for single family homes in the 2009 RASS. Of the total base case gas consumption, ~40 therms were attributed to the energy use required to maintain the storage tank in standby mode. All of the advanced water heaters were found to save energy, with the most dramatic savings occurring with tankless units, primarily due to the low observed recovery loads[50].

A graphical summary of the results are presented in the stacked bar graph shown in Figure 89. Annual gas energy savings are presented for three load cases (typical = 27,200 Btu/day, low = 14,000 Btu/day, and high = 40,500 Btu/day). Results are plotted by product class as defined below:

ESTAR = EnergyStar™ 0.67 – 0.70 EF non-condensing storage (average EF of the installed units = 0.675)

TWH = non-condensing tankless (average EF of the installed units = 0.82)

CTWH = condensing tankless (average EF of the installed units = 0.944)

CSTO = condensing storage (average thermal efficiency of the installed units = 91.6%)

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[50] High efficiency storage unit annual performance is also significantly degraded by low water heating loads.

Simple paybacks are plotted under both new and retrofit cost scenarios. The paybacks plotted include gas savings and incremental electrical consumption and are based on assumed residential rates of $1.20 per therm and $.15 per kWh. No incentives, tax credits, or maintenance costs are included in the payback calculation.

Projected annual savings for the EnergyStar™ products are under 30 therms per year, tankless savings range from 45 to 85 therms per year, and condensing storage savings range from 30 to 60 therms per year. Projected simple paybacks for new construction are between 9 and 15 years for tankless, and from 13 to 32 years for the storage products. In retrofit scenarios where implementation costs are considerably higher (especially for tankless), none of the projected simple paybacks were found to be less than 25 years. The economic results are discouraging, especially in the retrofit market, and indicate the need for increased production volumes and alternative equipment designs to reduce installed costs. Low California natural gas rates for the foreseeable future and high electric rates (a second order effect on savings) also contribute to a challenging environment for implementing efficiency.

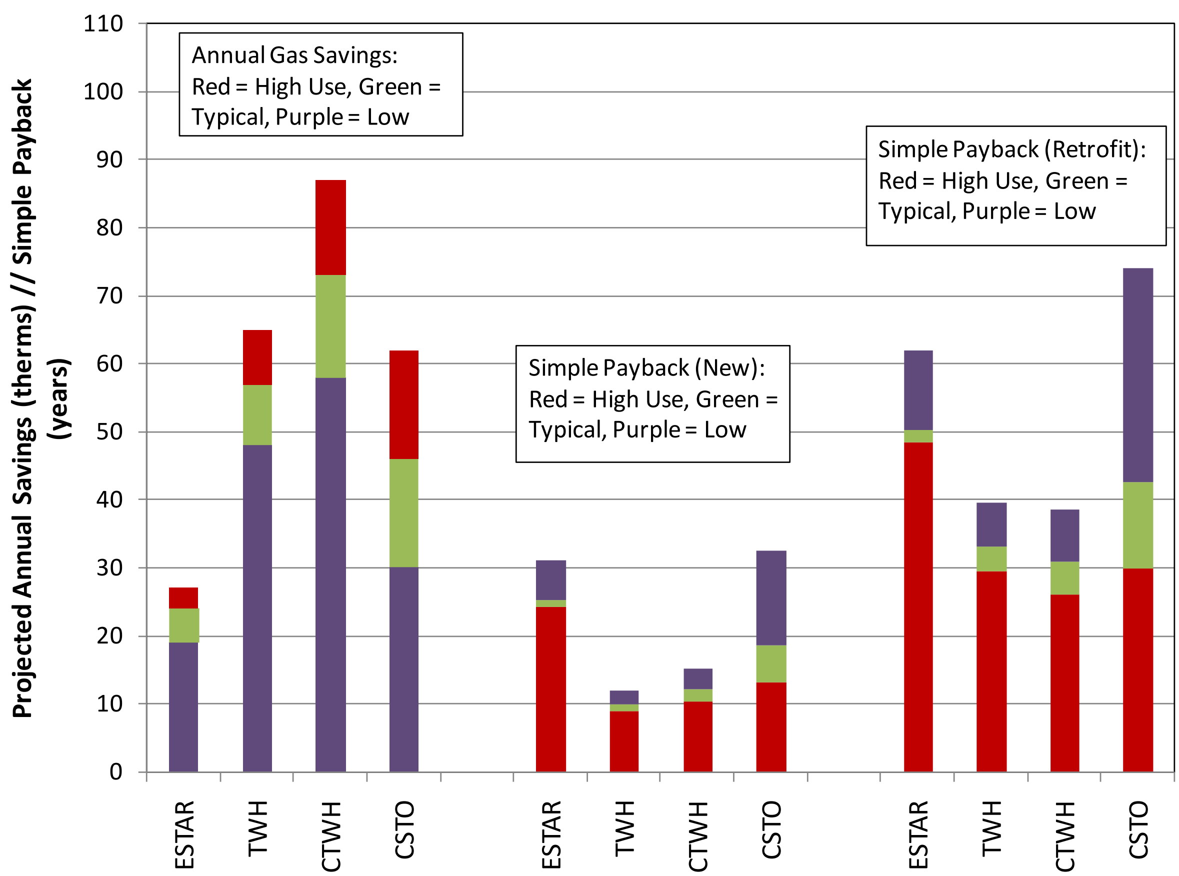

Figure 89: Projected Advanced Water Heater Savings and Simple Paybacks by Product Class

Customer Reactions to Advanced Water Heaters

In general, the seventeen homeowners who received advanced water heaters (at no cost) were satisfied with the units provided to them. One of the sites who received a CTWH did request that the unit be replaced with a standard storage water heater at the end of the project[51]. The only negative concern expressed by (some) customers who received a storage water heater replacement related to increased noise due to combustion air blowers. A few tankless customers had similar concerns related to noise, and also generally noted the well-documented issues related to increased hot water wait times, problems satisfying low-flow rate draws, and occasional cold water sandwich concerns. Overall these issues were not deemed problematic by any of the tankless households, with the exception of the site where the unit was removed. Positive tankless feedback was received from most respondents in terms of hot water capacity, stable delivery temperatures, compact physical size, and perceived energy savings.

Tankless water heaters were found to influence hot water usage behavior to some degree. The sites retrofitted with tankless units indicated an increase in average hot water draw volume from 1.40 to 2.09 gallons per draw, which was counteracted by an average 23% reduction in the daily number of draws. The net impact was that at four of the six tankless sites, there was essentially no change in the hot water recovery load between pre- and post, while two of the sites appeared to show higher hot water recovery load after the conversion. A broader study is needed to develop a better understanding of whether tankless water heaters result in greater hot water consumption in some households.

Recommendations

1. This project tested a sample of the emerging high efficiency products that are now on the market. With only eighteen field sites, further study by the California utilities is warranted to develop a more robust understanding of performance impacts under different climates and load profiles.

2. Evaluating customer satisfaction of these emerging technologies is an important step in directing future activities. Careful tracking of maintenance needs and the associated costs is needed to better define the overall economics of the different technologies.

[51] Their dissatisfaction could be attributed to perceived miscommunication with the plumber, aesthetic concerns over the gas line and venting appearance, as well as some performance concerns.

3. The CEC and California utilities should stay abreast of new and emerging water heater technologies. The costs for many of these products should come down in the years ahead as production volumes increase. Other new technologies better suited to retrofit applications will also likely be entering the market in the next few years. These systems should be carefully studied in both laboratory and field settings.

4. Evaluate combined hydronic systems as a strategy to improve high efficiency water heater cost effectiveness. These systems offer the advantage of utilizing one high efficiency heat source to provide both space and water heating. New product offerings from several manufacturers are expected in the near term.

5. Direct future Title 24 field research towards better quantifying hot water loads, cold water inlet temperatures in various locations statewide, and also identifying water heater setpoints at several hundred sites. This data can inform how water heating is modeled within the Title 24 code. The data collected here provides a start on that process.

5.1.1 Background

Water heating is a significant residential load in California. According to the 2009 Residential Appliance Saturation Survey, 49% of the 354 therm/year California household usage can be attributed to water heating, exceeding space heating. With 87% of California households heating water with natural gas [19], identifying cost-effective energy efficiency options for water heating represents a high priority strategy in reducing residential energy consumption. To address this, the Gas Technology Institute is managing a comprehensive set of interrelated projects to better understand and promote efficiency opportunities through a combination of field monitoring, laboratory evaluations, modeling activities, behavioral surveys, codes and standard activities, and industry outreach. This report addresses field monitoring activities in support of the GTI Residential Water Heating Program.

The field monitoring activity represents a central activity of the GTI Residential Water Heating Program in an effort to better characterize California single family household hot water energy use and hot water use patterns, and assess the anticipated savings and cost-effectiveness for emerging gas water heater technologies. The advanced water heater technologies evaluated in the field project included EnergyStar rated gas storage water heaters (0.67 to 0.70 Energy Factor), non-condensing and condensing gas tankless water heaters, condensing gas storage water heaters, and emerging hybrid products which combine storage and tankless features. The results of this project are valuable in assessing the performance of these new technologies in the field, better understanding usage patterns and hot water profiles, and providing project partners Pacific Gas and Electric (PG&E), Southern California Gas Company (SCG), and San Diego Gas and Electric (SDG&E) with representative end use information for supporting their energy efficiency programs.

Typical center flue gas storage water heaters found in California homes have rated Energy Factors ranging from about 0.55 to 0.62, depending on vintage. However, the assumed hot water recovery load of ~ 41,000 Btu/day in the Energy Factor test is likely high for most California households resulting in lower than rated field efficiencies due to standby losses being a larger fraction of overall consumption. Improving the efficiency of the California water heater stock could have a significant impact on California natural gas consumption, greenhouse gas emissions, and air pollution impacts.

5.1.1.1 Objectives

The key objective of the field monitoring effort was to assess the performance impacts of advanced gas water heating technologies in eighteen California homes. Given that the scope of the field monitoring was limited to eighteen homes and a range of equipment was to be installed, the results are not intended to provide statistically definitive performance comparisons. The goal was to develop robust quantitative data for initial technology performance assessments to be expanded on in future, more targeted studies.

Specific project objectives included:

1. Develop a monitoring plan that will provide high resolution data of water heater performance including submetered energy consumption (gas and electric), hot water flow, and water heater inlet/outlet temperatures.

2. Select six single family field sites with each of the utility partners PG&E, SCG, and SDG&E. Secure monitoring access agreements with homeowners.

3. Install and commission monitoring hardware on existing installed hot water heaters.

4. Coordinate with Gas Technology Institute project manager on selection of advanced water heaters for individual sites.

5. Select plumbers for advanced water heater installation and coordinate installation activities with homeowners. Secure permits at all sites.

6. Install and re-commission monitoring equipment after advanced water heater installation.

7. Collect a minimum of four months of data in both base case and advanced water heater mode.

8. Provide monthly summary monitoring reports and survey occupant satisfaction related to advanced water heaters.

9. Decommission monitoring systems.

10. Complete monitoring project report.

5.1.1.2 Methodology

Monitoring Plan

The initial step in the implementation of the field monitoring project was developing a monitoring plan consistent with the scope and project budget. Since the focus of the field monitoring was to assess the advanced gas water heating technologies relative to standard gas storage water heaters, we directed the monitoring effort on understanding the energy use and heat flows at the water heater, and ignored downstream effects related to gaining a more detailed understanding of hot water system performance in terms of end uses and distribution losses. Although the latter information is important in better understanding overall system performance, the project focus was centered on determining the field performance of the advanced water heating technologies themselves.

The full project monitoring plan can be found in **Error! Reference source not found.**. An overview of the monitoring strategy follows.

The primary aim of this monitoring project was to collect data that will describe the in-situ operating efficiency of conventional storage gas water heaters (representing existing water heater stock in California) and advanced residential water heater technologies that have higher nameplate efficiencies, but have not yet been widely monitored in the field.

This information will be helpful in developing a preliminary assessment of economic viability, as well as identifying system performance characteristics that are most significantly affected by operating patterns identified in the field. By monitoring the energy flows into the system (gas and electric consumption), and the energy output to the distribution system, an overall site efficiency can be calculated. In addition to quantifying the thermal performance of the base case and advanced water heaters, we also surveyed the homeowners to understand their reaction to these new technologies. In the case of storage water heaters, hot water delivery characteristics are expected to be similar to their existing water heater, however tankless water heaters do exhibit different performance characteristics.

Key field data recorded for evaluating and comparing water heating system performance, and methods for obtaining the data are listed in Table 44.

Table 44: Monitoring Point Description

Monitoring Point	Sensor Description	Used For
Cold water inlet temperature	Immersion temperature sensor in cold water line to water	Calculating hot water delivered energy (Btu's)
Hot water outlet temperature	Immersion temperature sensor in hot water line from water	Calculating hot water delivered Btu's & outlet temp stability
Domestic hot water flow rate	In-line turbine flow meter on cold water line to water heater	Calculating hot water delivered Btu's, and when a draw occurs
Water heater ambient	Air temperature sensor located in area near water heater	Determining standby loss as a function of temperature
Water heater gas use	Gas meter (with pulsing output) on gas line to water	Measuring gas energy consumed
Water heater electrical usage	True RMS power transducer on electrical supply to water	Measuring parasitic electric energy usage

Davis Energy Group has developed extensive experience with Data Electronics programmable data loggers over the past twenty years. For this project, the DT 50 datalogger provided sufficient analog and digital channels to handle the proposed sensors to be monitored. The logger is fully programmable allowing for customized scanning and logging intervals, a feature which is highly desirable in capturing short duration hot water flow events. Specifications on the installed monitoring sensor are listed in Table 45.

Table 45: Sensor Specifications

Application	Type	Mfg/Model	Signal	Accuracy
Air temperature	Type T thermocouple	Gordon special limits of error	Millivolt	±0.5°C
Water temperature	Type T thermocouple	Gordon 20CTOUH Immersion probe	Millivolt	±0.5°C
Electric use	Power transducer	Continental Control Systems WNB-3Y-208P	1.3 pulses/ watt-hr	±0.5%
Gas use	Gas meter	American AC-250	10 pulses/ft^3	±1.0%
Water Heater Inlet Water Flow	Turbine flowmeter	Onicon F1300	Approximately 500 pulse/gal	±2.0%

The flow meter was scanned continuously at four second intervals to detect hot water draw events. To filter out the effect of normal water system pressure fluctuations, two consecutive four second intervals with positive flow were needed to initiate high resolution logging. The four second logging recorded hot water volume, and water heater inlet and outlet temperatures for the full duration of the hot water draw event[52]. Once the hot water draw event stops, the datalogger will write an event record which will characterize the draw event with the following data:

- **Cold water inlet temperature**: Both average and end of draw cold water temperatures
- **Hot water outlet temperature**: Average, maximum during draw, and end of draw temperatures

[52] Note that simultaneous end use draws may be represented as a single water heater draw event. This complicates the determination of what a draw represents. Is it a single continuous demand of hot water (which could be multiple uses), a demand for hot water at a use point, or satisfying a particular end use (whereby a shaving "draw" event could be comprised of multiple short uses over a five minute period).

- **Hot water draw volume**: Total hot water volume, and volume at a temperature > 105°F (assumed minimum use temperature[53])
- **Time**: End of draw time, total draw duration, draw duration with temperature <=105°F
- **Thermal energy delivered during the draw**: Calculated with four second temperature and flow data
- **Gas consumption during the draw:** The last data stream is recorded at a regular fixed interval monitoring, which will occur every 15 minutes. This fixed interval logging will present average or summed values over the previous 15 minute time interval. This recorded dataset includes:
    - Average water heater environment temperature
    - Gas and electrical energy consumption over the period
    - Hot water thermal energy delivered
    - Total hot water flow volume
    - Burner firing fraction (fraction of 15 minutes)
    - Number of burner starts during the period

Datalogger memory was sufficient to store more than a week of data, so that loss of communications will generally not interrupt the stream of data. The datalogger was powered by a low voltage power supply with battery backup to protect against data loss during power outages. Datalogger PCMCIA memory cards were installed at sites more than 100 miles from Davis Energy Group's office to provide added backup. Comma-delimited ASCII data was downloaded nightly to a central computer and screened using software to insure that the data falls within expected ranges. Out-of-range data was flagged and investigated to determine whether a sensor or monitoring error exists or logging equipment has failed. Several times a week, the data was uploaded into EXCEL spreadsheets to further verify data integrity through data sums and graphical rendering.

[53] For storage water heaters, there should be little or no difference between the two recorded volumes, unless the storage tank is depleted. For tankless heaters, there will likely be a difference if the heat exchanger is not hot.

Site Selection

Project utility partners (PG&E, SCG, and SDG&E) were intimately involved in the site selection process. After initial field monitoring planning discussions with the GTI project manager, we approached the utility project liaisons to coordinate the site selection process. The Sempra[54] project manager immediately suggested that selecting candidate sites from utility personnel would be a preferred approach, since it would provide candidates who would likely be more amenable to participating in a project requiring a level of coordination and support that may be beyond what the average homeowner would be willing to provide. This approach was reviewed with GTI and all parties agreed that it would be a prudent way to proceed with site selection. The Sempra project manager sent an internal email to company employees requesting their participation in a project where they would be provided a free advanced gas water heater provided they agreed to participate in monitoring, which entailed providing access and completing hot water use surveys[55]. Approximately 150 employees responded to the participation request. They provided information on house location, house size, family size and ages, water heater type, water heater distance to gas meter, and other pertinent information. The information was cataloged, and a candidate list of ten sites each for both SCG and SDG&E were compiled, based on variations in the demographic factors, and also homeowner response to house access issues and their flexibility in accepting a yet to be specified water heater.

Each of the ten candidate sites in the SCG and SDG&E service territories were visited to provide an initial assessment of homeowner interest, current water heater installation, and potential venting, gas line, and electrical issues. Photos were taken of the existing water heater location, layout of the garage (or water heater surroundings), and gas meter location. This information and a rough layout of the house were used to reduce the list of ten candidates down to a preferred list of seven or eight sites. Further communications with the prospects occurred to better understand their receptiveness in participating, availability of house access during the monitoring period, and concerns over potential advanced water heater selections. Final selections were made with the homeowners provided an access agreement outlining the responsibilities and expectations for both parties (homeowner and DEG). Final selection of the twelve Sempra sites (six in SCG and six in SDG&E service territories) was completed in April 2010.

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[54] Sempra is the parent company for SCG and SDG&E

55 The one stipulation was that the advanced water heater would be selected for them, and at the end of the project they would not have the option of requiring project funding to support conversion to a conventional unit.

The PG&E internal site selection process started later than the Sempra process, but the six site selections were also completed by the end of April 2010. The first PG&E selected site was that of a Davis Energy Group employee. This approach was undertaken to allow us to test and debug the monitoring setup and customized datalogger programming[56] prior to broader implementation in the remaining seventeen homes.

Figure 90 shows the approximate geographic location of the six San Diego area sites. Similarly, Figure 91 and Figure 92 plot the location for each of the Los Angeles-area and PG&E Northern California sites, respectively.

Table 46 summarizes basic site information for the 18 selected sites. The Site ID is used throughout the report to identify the site. All but one site had an existing gas storage water heater installed. Site PG5 had an existing non-condensing gas tankless water heater[57]. With the exception of site SD4, all water heaters were in reasonable condition, with two of the units being of 1980's vintage, seven from the '90's, and eight from 2000 or newer. The SD4 homeowner needed to replace their existing leaking gas storage unit with a dated replacement unit provided by an acquaintance prior to installation of the monitoring equipment. This replacement unit did not have a nameplate, hence the vintage is unknown.

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[56] Datalogger programming is fairly sophisticated in the handling of the short 4 second time interval data. The programming manipulates the 4 second data to generate both the "event" records and the 15 minute data.

[57] This site was selected to make an interesting base case for comparison with a future condensing gas water heater.

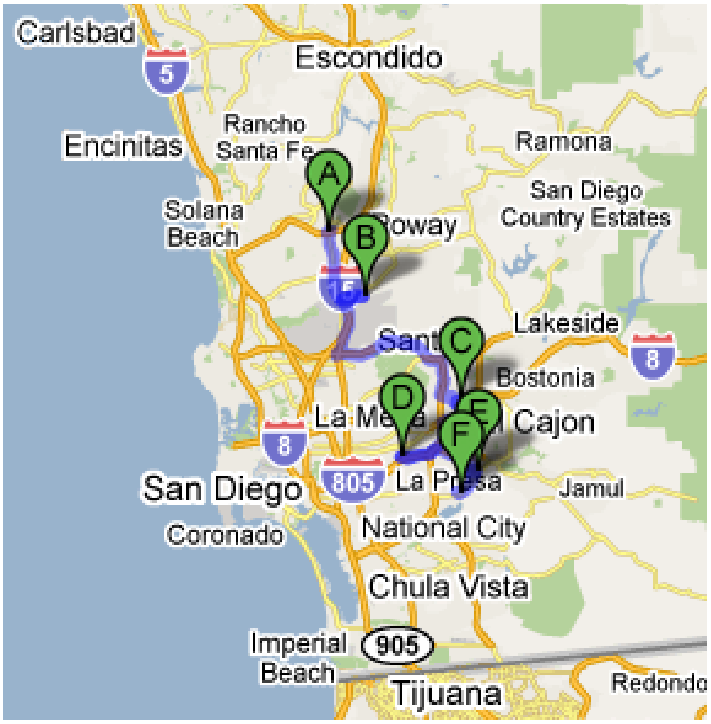

Figure 90: Location of San Diego Area Field Test Sites

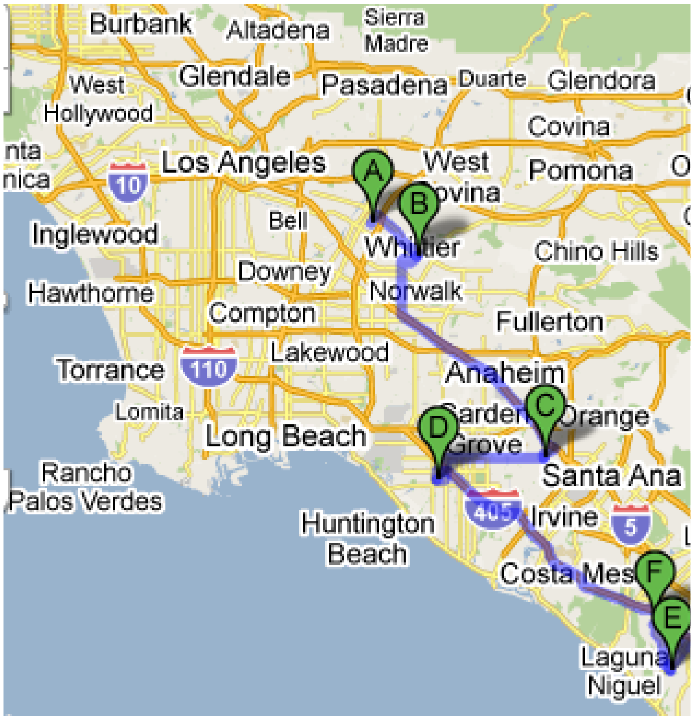

Figure 91: Location of Los Angeles Area Field Test Sites

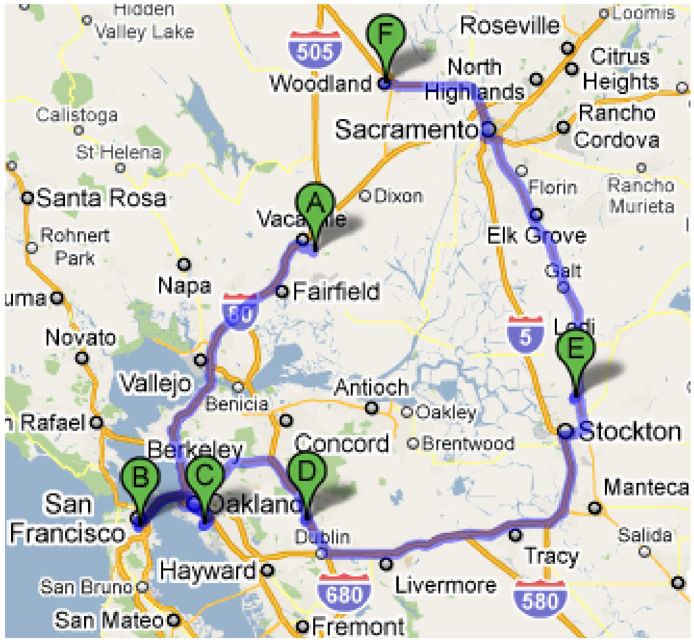

Figure 92: Location of PG&E Field Test Sites

Table 46: Field Test Site Characterization

Site ID	Location	House ft²	Age of Occupants*	WH Type, Btu/hr	WH Vintage
SD1	El Cajon	2450	40, 38, 7, 4	40 gal, 32 kBtu	1982
SD2	San Diego	2507	38, 35, 7, 4	50 gal, 40 kBtu	2004
SD3	Spring Valley	2000	63, 61	40 gal, 40 kBtu	1998
SD4	Spring Valley	1700	23, 23, 2	50 gal	No Nameplate
SD5	San Diego	2400	49, 48, 17, 14	50 gal, 40 kBtu	2008
SD6	San Diego	1600	36, 34, 6, 4	30 gal, 33.5 kBtu	1987
LA1	Aliso Viejo	2000	54, 54, 25, 27	50 gal, 40 kBtu	2000
LA2	Huntington Beach	2970	54, 53, 19	40 gal, 34 kBtu	1996
LA3	Laguna Niguel	2750	54, 48, 19, 16	60 gal, 50 kBtu	2006
LA4	Santa Ana	2100	58, 60	50 gal, 40 kBtu	1991
LA5	Pico Rivera	980	62, 62, 29, 29, 1	30 gal, 33.5 kBtu	1998
LA6	Whittier	1800	59, 34, 12, 8, 6	40 gal, 38 kBtu	2006
PG1	Woodland	1500	37, 35, 2	40 gal, 32 kBtu	1996
PG2	Stockton	2823	53, 47, 25, 22, 19, 16	50 gal, 40 kBtu	2004
PG3	Vacaville	1586	26, 24	40 gal, 40 kBtu	1994
PG4	San Ramon	2230	53, 50, 22	40 gal, 35.5 kBtu	1999
PG5	Alameda	1800	55, 58, 25	Tankless, 199 kBtu	2003
PG6	San Francisco	2206	45, 45, 14, 16	40 gal, 40 kBtu	2007

"*" Age and number of occupants at start of monitoring

Monitoring System Installation

The first monitoring installation was completed at the home of a DEG employee in mid-April 2010. This site was chosen to allow the team to get the system installed, check for any installation issues, and fully test and debug the datalogger monitoring program, which was customized for this application. The following photos depict the key monitoring components found at all the sites. Figure 93 shows the datalogger, power supplies, and modem with the water heater ambient temperature sensor located in the plastic case to the left of the water heater. Figure 94 shows the piping assembly that was installed to provide sufficient straight pipe length for accurate flow sensing, as well as the immersion thermocouples on the hot and cold water lines. Figure 95 shows the gas meter with pulse counter (10 pulses/ft^3) installed on the gas line feeding the water heater. Power monitors were also installed when the advanced water heaters were installed, to record electrical energy usage.

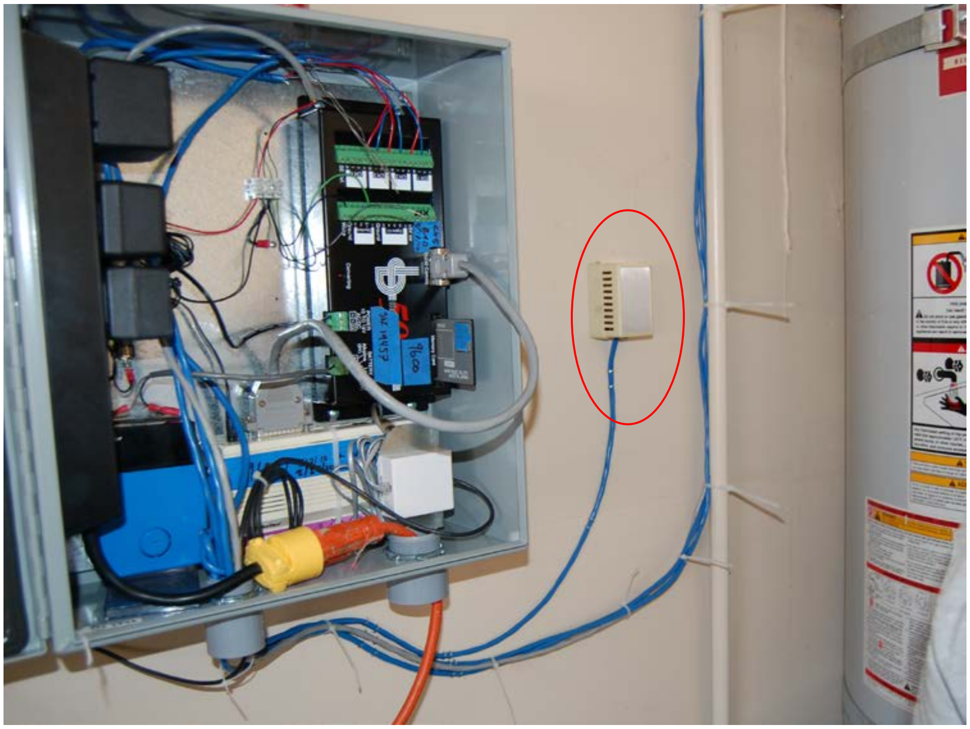

Figure 93: Datalogger Box (with Adjacent Ambient Temperature Sensor)

Figure 94: Flow Meter Assembly with Hot and Cold Immersion Thermocouples

Figure 95: Gas Meter (for water heater sub-metering)

The twelve southern California sites were installed two sites a day, over a six day period in mid-May. The remaining PG&E sites were installed by the end of May. Immediately upon completion of the monitoring installation, the installed data acquisition system for each site was queried remotely to verify modem communications, as well as for verifying sensor outputs (flow vs. volumetric measurements, reasonable temperature readings[58]). After completing this checkout, the logging program was remotely downloaded to the datalogger. The program is unique to each site as the flow meter calibration factor varied slightly for each meter (~ 500 pulses per gallon).

Data Handling and Review

Data from all eighteen sites were downloaded on a nightly basis to a dedicated computer located at DEG's office. The downloaded data was automatically separated into three distinct data streams:

- 4 second data during hot water flow (cold and hot water temperature, and hot water flow);
- 15 minute interval data (gas and electrical energy use, energy delivered, ambient temperature); and
- End of draw "event" data (detailed data describing draw length, energy, temperatures)

The downloaded data were then passed through a range check program to determine if sensor values were outside of an expected range (e.g. cold water inlet temperature below 40°F). On a daily basis, the range check output file would be reviewed to determine if the data download had actually occurred, and if any sensors were out of range. Data download problems occurred on an infrequent basis, due to computer problems, but were generally easily remedied by a manual download process. On some occasions, the problem was at the monitoring site end requiring a manual reset of the modem in the field. Out of range data was manually reviewed to determine if the reading appeared faulty, or if unusual conditions contributed to the recorded event. In any case, if service was deemed necessary, DEG would dispatch a technician to the site to investigate and correct the problem. A PCMCIA card installed in virtually all of the loggers

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[58] All of the immersion thermocouples were lab calibrated prior to installation in the field.

provided an additional level of assurance that data loss would not occur if communications were lost for a longer period of time[59].

Several times a week, data from all eighteen sites would be reviewed in an EXCEL spreadsheet that compiled daily summary totals including energy use, energy flow from the water heater, number of hot water draws, total daily hot water flow, and daily "thermal efficiency", defined as follows:

Equation 67: Thermal Efficiency

$$\text{DailyDeliveryEfficiency (thermal)} = \frac{\Sigma \text{ 4 second flow x 8.33 x } (\text{Thot-Tcold}) \text{ [Btus]}}{\Sigma \text{ Daily Gas Use [Btus]}}$$

Data from each subsequent day would be appended to the existing dataset to provide a cumulative record for each site. The daily record was useful in seeing both trends with prior data and seasonal changes in usage patterns.

Advanced Water Heater Equipment Selection

A number of quantitative and qualitative factors were considered in making the advanced water heater selections for retrofit at each of the 18 sites, including:

1. Site code issues related to advanced water heater retrofit
2. Proper sizing to meet existing base case demand for hot water
3. Homeowner concerns regarding advanced technologies
4. Program team needs for applying diverse set of advanced water heaters

Regarding point 1, despite prescreening visits, one site (LA6) ultimately proved to have code issues that were too costly for the program budget to address. This site was not retrofitted with an advanced water heater but was retained for continued base case monitoring.

On point 2, the existing water heater specifications (shown in Table 46) and the base case monitoring of hot water demand (see average gal/day in Table 47) provided adequate guidance for selection of retrofit advanced water heaters that would ensure existing water hot water capacity needs would be met. Tankless units were matched to the lower hot water draw homes

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[59] The installed memory card could store a minimum of two weeks of additional data. In rare cases, the datalogger would lock up, resulting in more extended data loss.

out of the 18 sites, to avoid the high standby loss and poor overall efficiency to be expected with a storage water heater in such applications.

Addressing point 3, interactions varied greatly with individual homeowners as preliminary advanced water heater selections were presented to them. Only a few of the homeowners raised issues with the preliminary advanced water heater selections made for them. Those issues related to either concerns perceived or experienced (even by others – neighbors, relatives, etc.) with reliability of particular makes of storage water heaters or peculiarities of tankless water heater operation. Issues were expressed with tankless water heater delays in delivery of hot water and cold water sandwiches, along with maintenance timelines and protocols that are not well established. All these issues were addressed and with some limited reassignements of advanced water heater selections by homeowners, the program team was able to achieve a diverse set of advanced water heater product category applications in this limited 18 site test.

Table 47: Advanced Water Heaters Installed by Site

Site ID	Gal/ Day	WH Type	Manufacturer Make & Model	Product Description
SD1	25	TWH	Noritz NR-71-SV	20 - 180 kBtuh, 0.83 EF, indoor/outdoor NR71 (N-0631S) series model
SD2	63	CSTO	AO Smith GPHE-50	50 Gallon, 76 kBtuh, 90% TE, power PVC vent Vertex model
SD3	22	C TWH	Navien NR-240A	17 – 199 kBtuh, 0.95 EF, indoor/outdoor, direct vent, no min flow (0.5 gal storage)
SD4	22	C TWH	Rinnai RC80HPi KA2530FFUD	9.5 – 157 kBtuh, 0.96 EF, indoor Ultra Line Tankless Water Heater model
SD5	71	ESTAR	Bradford White D-4-504S6FBN	50 Gallon, 40 kBtuh, 0.67 EF damper equipped Category I vent Defender model
SD6	38	ESTAR	AO Smith GAHH-40	40 Gallon, 40 kBtuh, 0.70 EF, fan assist atmospheric Category I vent Effex model
LA1	68	CTWH	Noritz NRC111-DV N-0842MC-DV	11 – 199 kBtuh, 93% TE (no certified EF), indoor, direct vent NRC111 series model
LA2	32	ESTAR	Rheem 42VP40FN	40 Gallon, 36 kBtuh, 0.67 EF, power PVC vent, ultra low NOx 10ng/J model
LA3	81	ESTAR	Bradford White U-4-TW-60T6FRN	60 Gallon, 40 kBtuh, 0.67 EF, power PVC vent, ultralow NOx 10ng/J model
LA4	20	TWH	Rheem (Paloma) RTG-84DV	11 - 180 kBtu, 0.82 EF, indoor direct vent, 84 tankless series model
LA5	42	TWH	Noritz NR66-SV	20 - 140 kBtuh, 0.83 EF, indoor/outdoor NR66 (N-0531S) series model
LA6	17	NA	NA	NA

PG1	45	CTWH	Navien NP-240	17 – 199 kBtuh, 95% EF, indoor/outdoor, direct vent, 0.5 gpm minimum flow
PG2	127	CSTO	Bradford White EFR-1-60T1206EN	60 Gallon, 120 kBtuh, 95% TE, power/direct PVC vent ultralow NOx 14ng/J model
PG3	55	ESTAR	AO Smith GPVR-40	40 Gallon, 40 kBtuh, 0.67 EF power PVC vent ProMax model
PG4	36	ESTAR	Rheem PDV40	40 Gallon, 40 kBtuh, 0.67 EF direct PVC vent model
PG5	58	CTWH	Rinnai RC98HPe KA3237WD-US	9.5 – 199 kBtuh, 0.93 EF, outdoor Ultra Line model
PG6	103	CSTO	AO Smith HYB-90N	30 Gallon, 100 kBtuh, 90% TE, power PVC vent NEXT Hybrid model
LA6	dropped this site from retrofit plans due to code issues			

Per point 4, Table 47 identifies the installed advanced water heaters by site and breaks those selections down by equipment category and particular manufacturer make and model with a short product description. Hot links to detailed on-line product specification sheets are contained in **Error! Reference source not found.**. Currently the energy efficiency programs at the California utilities incentivize only Energy Star and higher rated water heaters (> 0.67 EF storage water heaters and 0.82 EF tankless water heaters). This Energy Star level established the minimum level of performance for the advanced water heater selections. Above that level, selections covered a range of products from condensing storage, condensing tankless, and even an emerging condensing hybrid (smaller firing rate tankless and smaller volume storage combination), some of which are not covered by the EF rating procedure and carry a thermal efficiency (%TE) rating instead. The number of advanced water heaters in each of the categories is listed below:

- Six (6) Energy Star non-condensing storage water heaters (0.67 – 0.70 EF) (ESTAR)
- Three (3) (0.82 EF) Energy Star non-condensing tankless water heaters
- Two (2) condensing storage water heaters (CSTO)
- Five (5) condensing tankless water heaters (CTWH)
- One (1) hybrid water heater (treated as a CSTO)

5.1.1.3 Results

Overview

Monitoring began in late April 2010 at the first PG&E site (PG1) and continued until June 2011 (see Table 48 for high level data summaries by site). Given the original project budgets, the plan was to collect four months of base case data and four months of advanced water heater data. In reality, closer to 12 months of data were collected at most sites, primarily due to extended delays in selecting plumbing contractors, delivering water heaters to the plumbers, and coordinating the installations with both the plumbers' and homeowners' schedules. Overall data availability in the base case period was ~95% and 99% in the post-retrofit period.

Table 48 summarizes the monitoring periods for each of the eighteen sites, as well as the availability of monitoring data from that site. As note previously, site LA6 was never converted to an advanced site, as significant existing code issues would have made a permitted replacement very expensive[60].

Table 48: Summary of Base and Advanced Water Heating Monitoring Periods

Site ID	Base Monitoring Period	Data Availability	Advanced Monitoring Period	Data Availability
SD1	5/20/10 – 12/29/10	100%	12/30/10 – 6/13/11	100%
SD2	5/19/10 – 1/19/11	92%	1/21/11 – 6/13/11	99%
SD3	5/21/10 – 2/15/11	87%	2/17/11 – 6/27/11	97%
SD4	5/21/10 – 12/16/10	100%	12/18/11 – 6/10/11	100%
SD5	5/19/10 – 1/12/11	100%	1/14/11 – 6/10/11	100%
SD6	5/20/10 – 1/5/11	99%	1/7/11 – 6/8/11	100%
LA1	5/22/10 – 1/30/11	100%	2/2/11 – 6/9/11	100%
LA2	5/18/10 – 1/27/11	100%	1/28/11 – 6/6/11	100%
LA3	5/22/10 – 2/7/11	97%	2/8/11 – 6/7/11	100%
LA4	5/18/10 – 2/13/11	100%	2/14/11 – 6/12/11	100%
LA5	5/17/10 – 1/26/11	97%	1/28/11 – 6/6/11	99%
LA6	5/17/10 – 6/8/11	89%	n/a	
PG1	4/10/10 – 2/7/11	95%	2/9/11 – 6/30/11	98%
PG2	5/13/10 – 2/20/11	92%	2/27/11 – 6/30/11	95%
PG3	5/11/10 – 1/17/11	81%	1/18/11 – 6/16/11	100%
PG4	5/27/10 – 1/13/11	87%	1/14/11 – 6/7/11	100%

[60] There were significant plumbing and electrical code violations that would have been flagged by an inspector. In addition the gas line upsizing was more expensive than anticipated.

PG5	5/28/10 – 1/13/11	100%	1/14/11 – 6/9/11	100%
PG6	5/27/10 – 1/20/11	86%	1/23/11 – 6/8/11	99%

During the course of the monitoring, issues occasionally arose which resulted in data loss. The problems varied from discharged back-up batteries, scrambled modems, flow meter problems[61], damaged thermocouples, power outages, and datalogger issues. In most cases, these problems would be evident the morning after the data download, although some errors took longer to isolate. DEG would immediately begin diagnosing the problem to determine the course of action. Often a system or modem reset would solve the problem. In other cases, a site visit would be in order. The latter might result in a longer period of data loss, depending if the datalogger was continuing to collect data.

In addition to the monitoring, the homeowners were required to participate in several surveys. A companion piece of the GTI Residential Water Heating Program was the development and deployment of a hot water behavioral survey intended to glean information from 400+ California households on how they use hot water and the "performance" characteristics of their existing hot water system. During the development of the survey tool, the 18 homeowners were asked to complete a beta version of the survey tool, both to gather behavioral data and to test the survey tool prior to broad release. In addition, two brief satisfaction surveys were given to the homeowners after the advanced water heater was installed. The first, given just a few weeks after installation, was primarily to assess satisfaction with the equipment installation, as well as to gain initial thoughts on any performance changes with the new water heater. The second survey was given at the end of the advanced water heating phase, and explored in more detail the occupant's response to the new system in terms of hot water delivery, waiting times, recovery capacity, temperature stability, aesthetic issues, etc. A summary of the second survey can be later in Results (Customer Response to Advanced Water Heaters), with the full responses provided in **Error! Reference source not found.**.

Characterization of Seasonal Effects, Hot Water Loads, and Usage Patterns

An important part of the data collection effort was to secure high resolution field data from actual California households to better characterize how and when people use hot water. Historically this type of detailed data has been lacking as monitoring efforts normally don't focus on short interval data logging. Jim Lutz of LBNL has been developing a database of high resolution hot water usage data from various projects over the past twenty years. Data from this

[61] In some cases, the flow meter turbine would be affected by entrained solids in the supply water.

project will feed into that database as well as inform on general hot water usage patterns for the eighteen homes. Hot water loads are known to be highly variable both day-to-day within a household, as well as from one household to another. Gaining a better understanding of when people use hot water, how clustered or dispersed their usage typically is, and how usage varies seasonally, all factors into better information for hot water generation and distribution models, which to varying extents show performance differences under different usage patterns.

Data presented here is intended as a high level overview of the hot water usage data. Detailed evaluation of the data is beyond the scope of this project, but its availability offers the potential for more detailed, future analysis.

Figure 96 plots average monthly cold water inlet temperatures *during periods when hot water draws were occurring*. Results are averaged by location (LA, PG&E, and SD) with individual sites shown in Homeowner Post-Installation Survey **Error! Reference source not found.**.

Average annual temperatures for the PG&E sites of 64.2 degrees were recorded, with southern California temperature 7-8° higher. The seasonal swing from mid-winter low to mid-summer high was roughly 15-16°F in both Northern and Southern California. The observed cold water inlet temperatures were found to be considerably higher than the assumed temperatures specified in the Title 24 water heating compliance calculations[62]. This has implications both in terms of the recovery load and the ratio of hot and cold mixing needed to satisfy an end use, such as a 105°F shower condition.

[62] LA and San Diego area climate zones assume annual average cold water temperatures of 61-64°F and Northern California temperatures are 57-60°F.

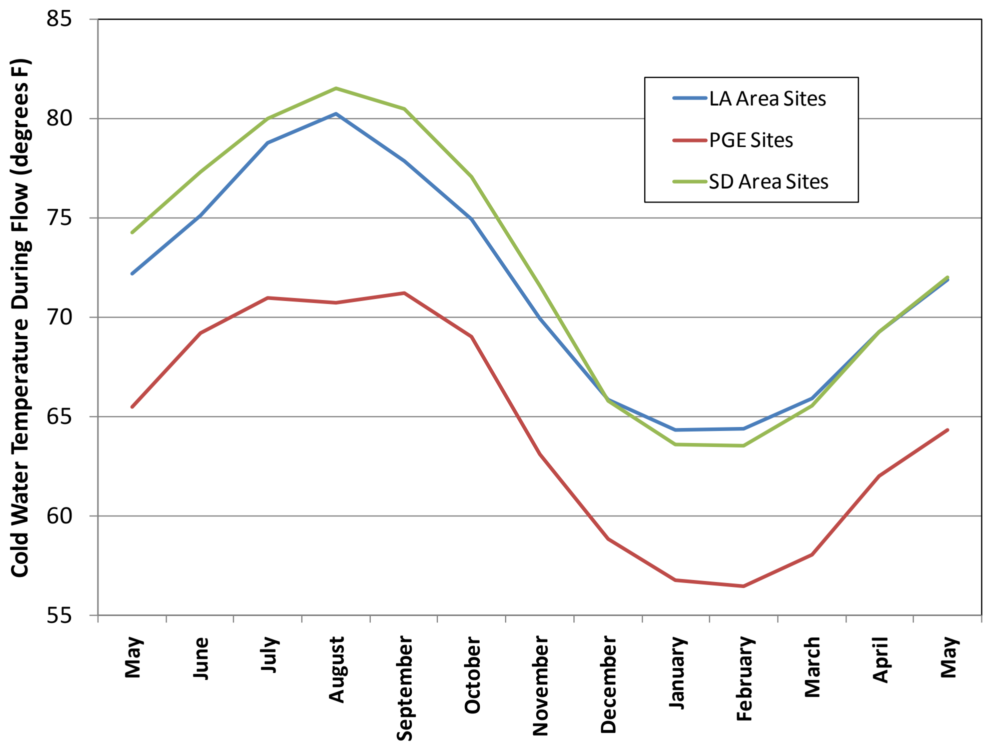

Figure 96: Monthly Average Cold Water Inlet Temperature During Flow Events

Figure 97 plots monthly average water heater environment temperature by utility area. (Plots for individual sites can be also found in Homeowner Post-Installation Survey (Completed ~ 3 months after equipment install) **Error! Reference source not found.**.

The temperatures are fairly comparable to the cold water inlet temperatures and exhibit an average 15°F seasonal variation. Averaging over the May 2010 to April 2011 period indicates an average temperature of 69.5°F, ranging from 65.5°F for PG&E sites to 71-72°F for the SD and LA sites.

Figure 98 plots the average daily hot water usage data for each of the sites over its entire monitoring period, beginning with the lowest usage site (LA4) on the left and the highest usage site (PG2) on the right. Note LA2 had an extended period of questionable flow data and is excluded. Hot water usage for all sites averaged 56.4 gallons per day, or 15.6 gallon per day, per person. The X-axis labels in Figure 98 include the standard deviation in daily hot water usage, which for most sites is roughly half of the mean consumption. Each of the site usage bars is comprised of different color elements, which indicate the frequency of six daily hot water volume ranges as a contributor to the site overall average. For example, site PG5 usage is comprised of approximately an equal number of days with usage of 10-30 gallons, 30-50 gallons, and 50-70 gallons, with very few days less than 10 gallons or greater than 100 gallons. The comparison between sites is interesting to note fairly significant differences in usage characteristics, further highlighting the high level of variability in hot water loads.

Figure 99 plots the daily hot water loads (in gallons per day) for all 18 sites over the duration of the monitoring period. The plotted data demonstrates both the significant day-to-day hot water usage variation, as well as seasonal variations. Thirty day moving average trend lines for roughly half the sites are shown to help highlight usage pattern changes over time. Some sites are fairly steady with only a seasonal variation present, while others show repeated fluctuations in usage. Finally, some sites clearly show the impact of a change in the number of residents in the household during the course of the monitoring (as highlighted in the red box) identifying a site where an additional two people joined the household in late January 2011.

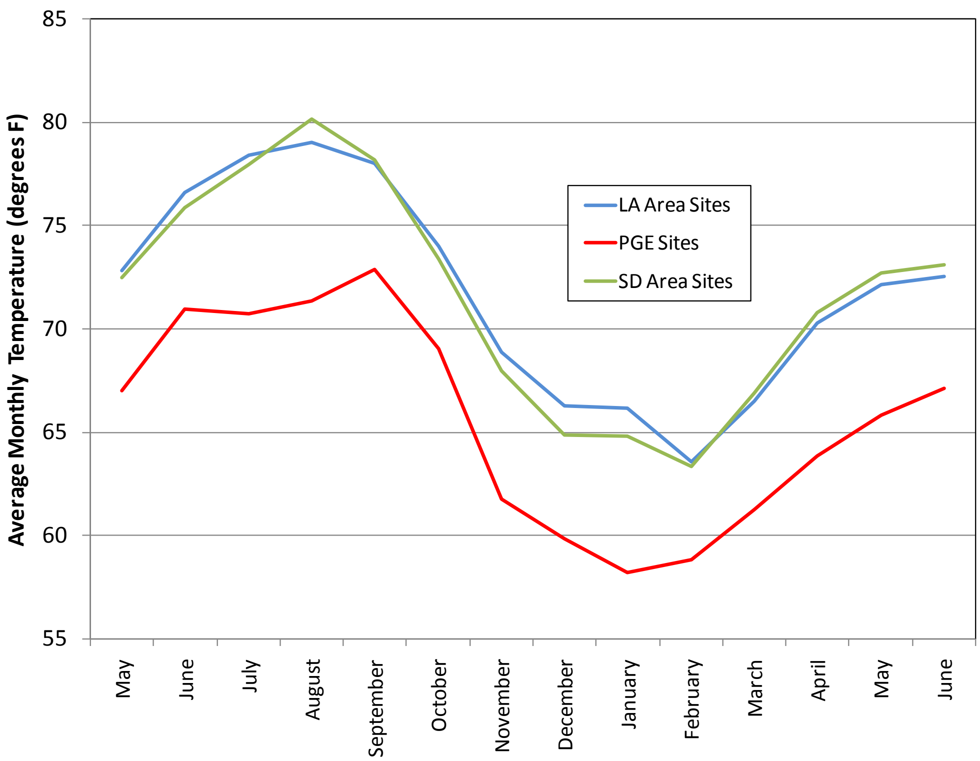

Figure 97: Monthly Average Water Heater Environment Temperatures

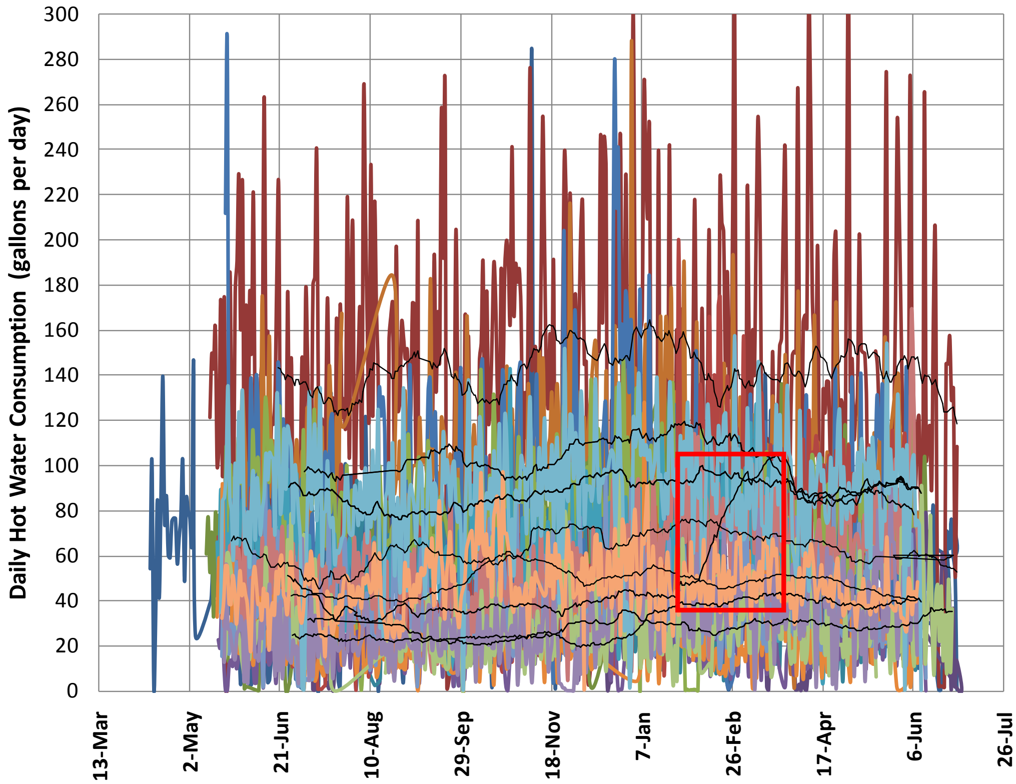

Figure 98: Average Daily Hot Water Consumption by Site

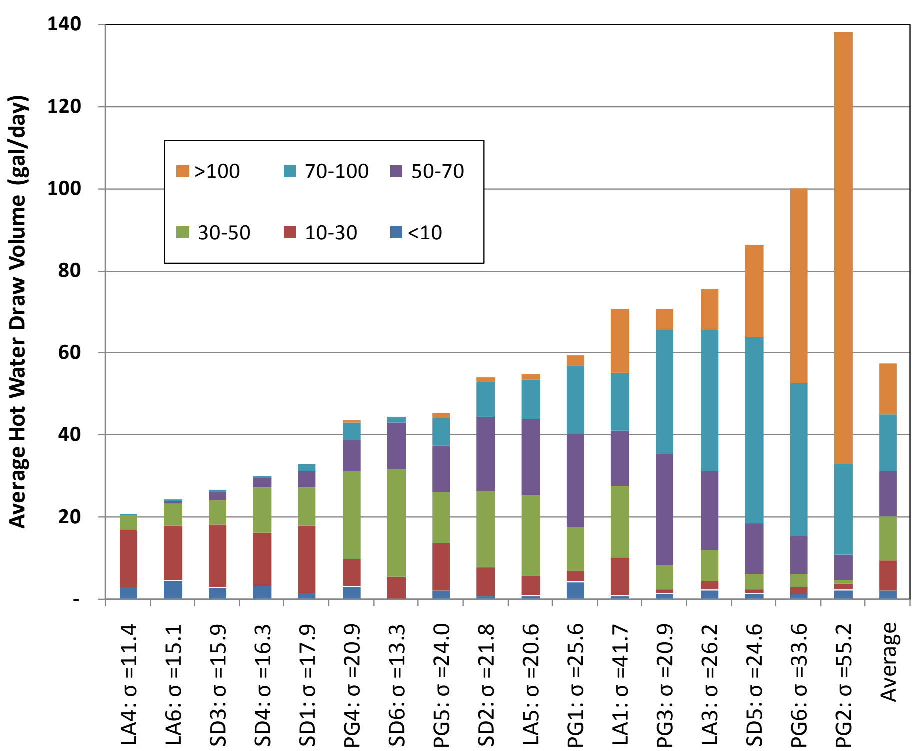

Figure 99: Daily Hot Water Load Magnitude by Site

Figure 100 separates all the hot water individual draw events by sites and characterizes them by the time interval between the start of that draw and the end of the prior draw. The X-axis data again presents the bars from low use to highest hot water use sites. This type of data is informative in the development of hot water usage profiles, in terms of time intervals between draws. It also informs as to the potential benefits of pipe insulation on the distribution system. Clearly draws separated by more than 60 minutes will have little or no benefit from pipe insulation, since nearly all entrained energy will be lost. Similarly draws within one minute (and potentially 10 minutes) will only have small benefits from pipe insulation, depending upon the configuration of piping and where the prior draw occurred.

Figure 101 presents the same data but plots draw volume in terms of time between draws. This is a better indicator of energy impacts than just looking at the number of draw events. From this perspective, the right-most "average" bar shows that ~30% of hot water volume occurs more than 60 minutes after the prior, and ~45% occurs within 10 minutes. Again, the ~30% would see no benefit from pipe insulation, and the ~45% of the volume under ten minutes would see a reduced benefit, depending upon the layout of the distribution system and at which fixture the draws occur. Only about 15% of the average draw volume occurs between 10 to 60 minutes of the prior draw, a prime target for reducing distribution system losses with insulation.

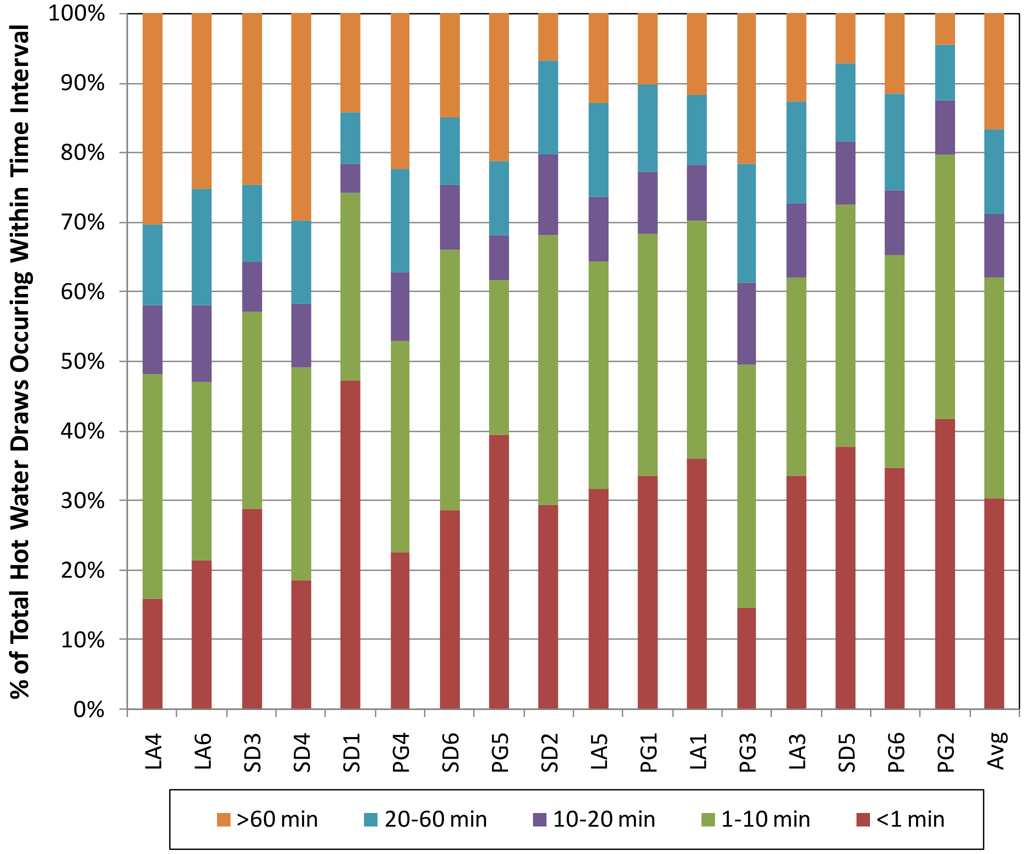

Figure 100: Characterization of Time Between Hot Water Draws in Terms of # of Draw Events

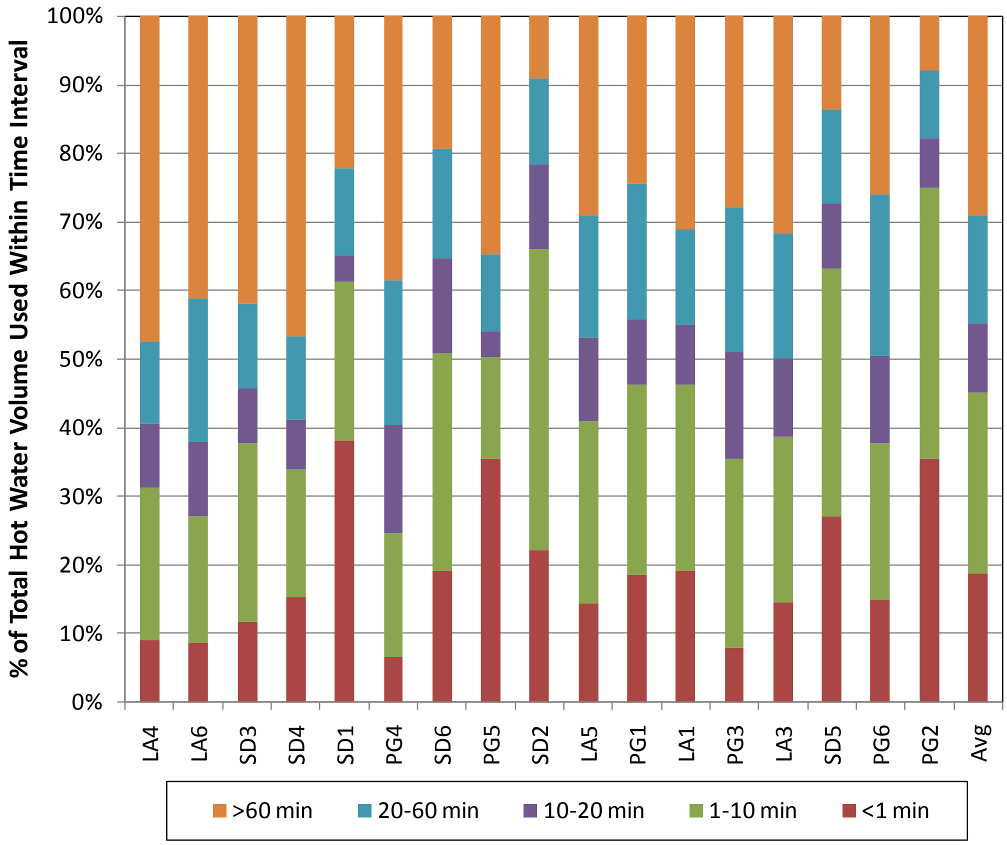

Figure 101: Characterization of Time Between Hot Water Draws in Terms of Volume

Figure 102 presents data characterizing the average hot water volume per draw event for pre and post retrofit. Three groups are plotted. The leftmost (storage water heaters) represent the six sites that were converted to advanced storage water heaters from their original storage water heaters. Tankless represents six sites that were converted to tankless from their original storage water heaters. The third grouping represents the remaining five sites, all of which experienced a change in occupancy during the "post" and are therefore separated from the more "controlled" sites. Average "pre-retrofit" draw volume for the seventeen retrofitted sites (excludes LA6) was found to be 1.67 gallons[63], with the six storage and six tankless sites

[63] Note: The draw event as defined in this study, reflects one continuous volume of hot water demand, and in reality may represent multiple simultaneous draws.

averaging 2.28 and 1.40 gallons (pre-retrofit) per draw, respectively. Site PG3 stands out with average draw volumes roughly double the average of the other sites.

For the six sites that were retrofitted with advanced storage water heaters, the change in pre-to-post average draw volume (2.28 gallons pre- vs 2.17 post) was fairly small (showing modest increases or decreases), with the exception of site SD6, which demonstrated a significant decrease. Conversely, all six tankless water heater sites show a fairly significant increase in average draw volume (a 49% increase from 1.40 gallons to 2.09 gallons). Despite the small sample size, this seems to indicate some level of behavioral change among the tankless sites.

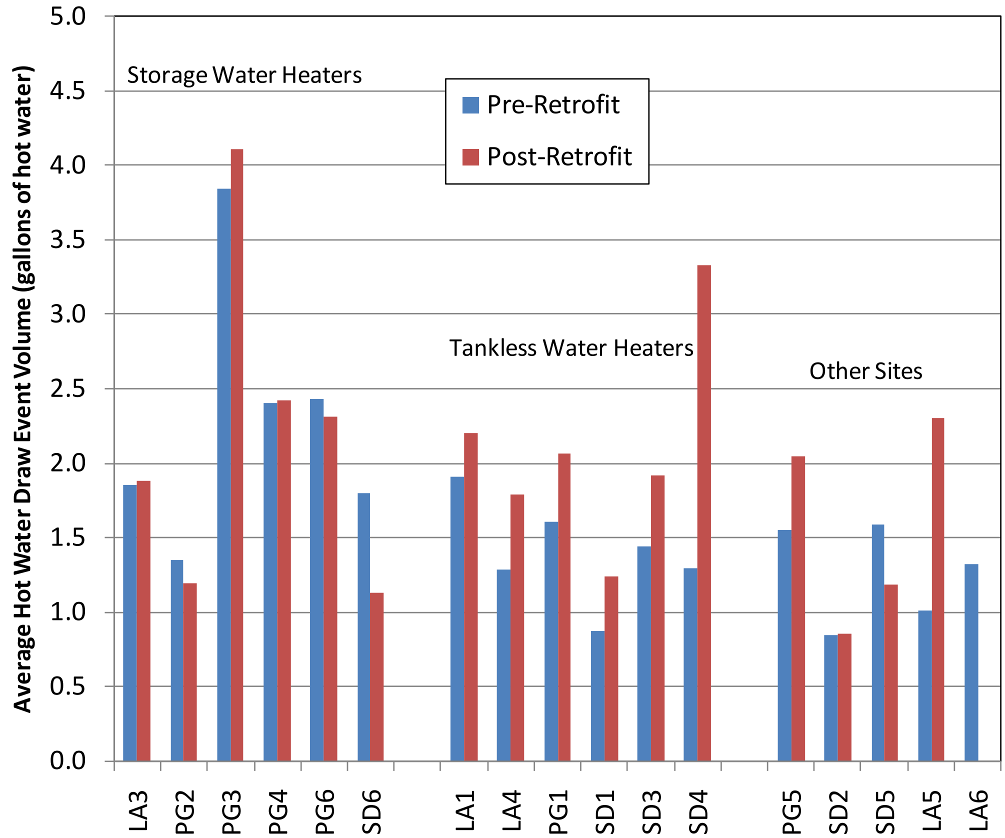

Figure 102: Average Draw Event Hot Water Volume by Site

Figure 103 plots the corresponding "number of daily draws" in the same manner as Figure 102. For all seventeen sites, the average daily pre-retrofit draws per day totaled 36.5, or 10.0 draws per person per day. Site PG2, the highest gal/day household, had by far the highest number of daily draws at 104, or slightly over 17 per person per day. Post-retrofit draw data averaged over the six advanced storage water heater sites showed a small 4% increase in daily draws (from 42.4 to 44.3 draws per day). For the six tankless sites, average post-retrofit draws per day were reduced at all six sites from 27.4 to 21.1 per day (23% reduction). Similar to the consistent increase in average tankless draw volume, the reduced number of draws was consistent at all six sites, suggesting behavioral changes from the occupants.

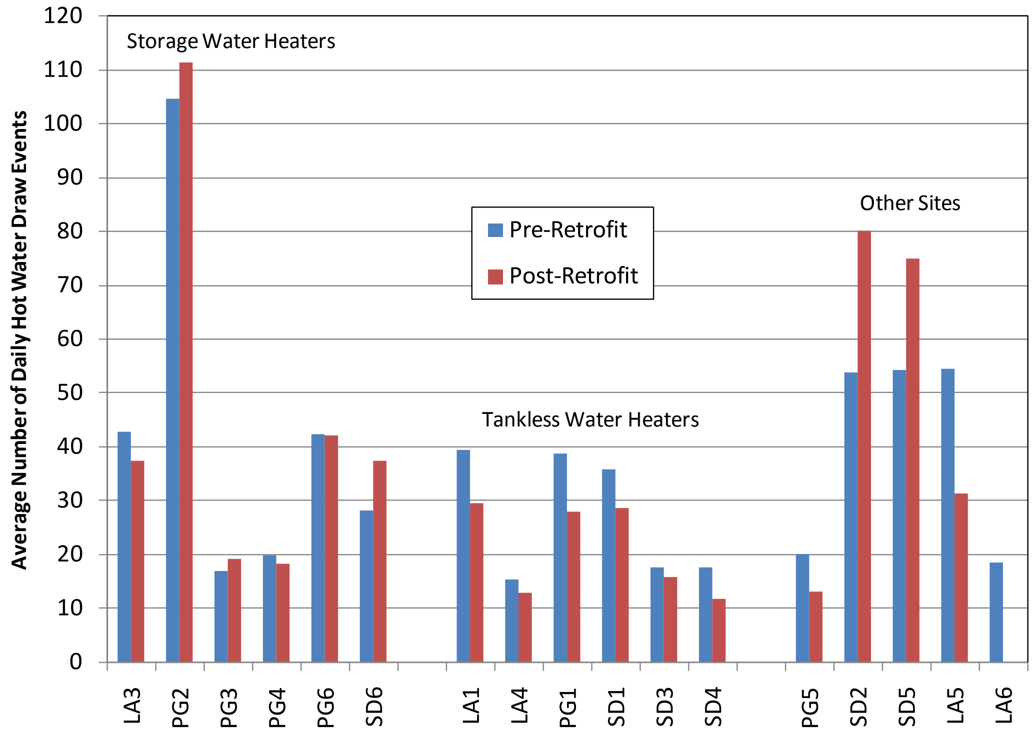

Figure 103: Average Daily Draw Events by Site

Performance of Base Case and Advanced Water Heaters

The period of base case monitoring for most sites stretched from mid-May 2010 to January or February 2011, resulting in data collection in all seasons of the year. The average base case data collection duration was 246 days. Despite the fact that some sites had more missing data than desired, a robust gas usage profile was developed for each site, for each month, over the full base case period. The 10 pulse per ft^3 gas resolution (~100 Btu/pulse) allowed us to easily discern the differences between pilot energy and firing energy[64]. With all the collected base case gas use data, we could sort the data into the two data streams: pilot energy and firing. Actual pilot energy use rate could be calculated by summing all the pilot energy data points and dividing by the total number of hours of pilot-only operation. For each water heater monitored,

[64] During standby operation, we would observe 1 to 2 gas meter pulses per 15 minutes (~100-200 Btu/ 15 minutes). When the water heater fired, the rate would typically increase to 70+ pulses per 15 minutes.

we could then define the annual energy that would be consumed in the absence of any hot water loads.

Determining annual base case water heating energy use could be completed in various ways. With data available over a ~8 month period, one could simply extrapolate usage for the missing months based on monitored months with similar conditions (loads and cold water inlet temperatures). Or one could utilize average monitored hot water loads over the 8 months and apply a site-specific load-dependent water heater efficiency to calculate usage. Both of these approaches have inherent inaccuracies. For simplicity, the former approach was taken, given the high degree of variability in loads, both day-to-day and seasonally[65]. Figure 104 plots annual projected base case water heater energy consumption and annual pilot energy consumption. (Site PG5 was an existing tankless site and therefore annual calculated pilot energy was equal to zero.) Average projected annual water heater usage for all storage water heater sites average 188 therms (and 183 therms when including the tankless site PG5). Average storage water heater base usage varied from 108 therms at site SD3 to 293 therms at site PG2. By utility area, San Diego usage averaged 149 therms/year (3.5 occupants per site), LA sites 201 therms per year (3.8 occupants per site), and PG&E storage sites 219 therms per year (3.5 occupants per site).

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[65] If this approach were to introduce an error of say 15% over the four month extrapolation period, the net impact on the annual usage estimate would be on the order of 5% ([8 months x 0% + 4 months x 15%]/ 12 months).

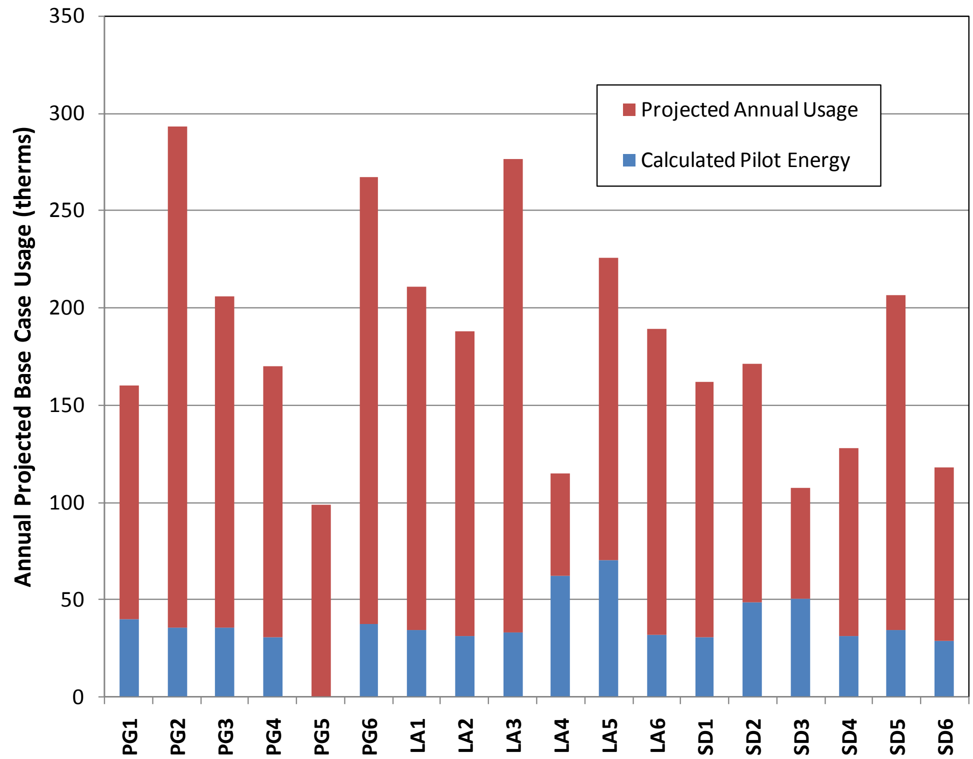

Figure 104: Projected Base Case Annual Usage and Pilot Energy

Annual projected pilot energy averaged 39.5 therms for all the storage water heaters. There was however, a fair amount of variation, with projected usage ranging from 29.1 to 70.7 therms. Site LA4 is projected to consume more pilot energy annually than needed to meet the recovery load, highlighting a key performance concern of storage water heaters in low load situations. Average annual projected pilot energy represents 21% of the 188 therm per year average consumption. Assuming a representative 76% average water heater recovery efficiency, another 35 therms/year can be assigned to combustion inefficiencies. The remaining 113 therms per year represents the average water heater recovery load (end use plus distribution losses).

Figure 105 and Figure 106 plot base case (pre-retrofit) and post-retrofit hot water usage and water heater outlet temperature (i.e. "setpoint"). These data offer some insight on how occupants change usage or other behaviors in response to a change in technology, for example converting to a tankless water heater. Of course these effects are interwoven with other factors, primarily changes in occupancy. The plotted data shows side-by-side pre and post hot water usage (two bars for each site, with pre on the left), with average water heater outlet temperature shown with a red marker immediately above the corresponding pre- and post bars. Figure 105 shows all sites with the exception of LA6 (no retrofit completed) and LA2 (extended period of questionable flow data). Site X-axis labels include a "T" notation for those sites with a tankless water heater. Interestingly, some sites such as PG1, are very consistent in both pre- and post hot water usage and outlet temperature, even accounting for the potential load-changing impacts associated with a conversion to a tankless water heater. Other sites were found to be much more variable, with much of the variation being a change in occupancy at the house (sites PG5, LA2, LA5, SD2, and SD5).

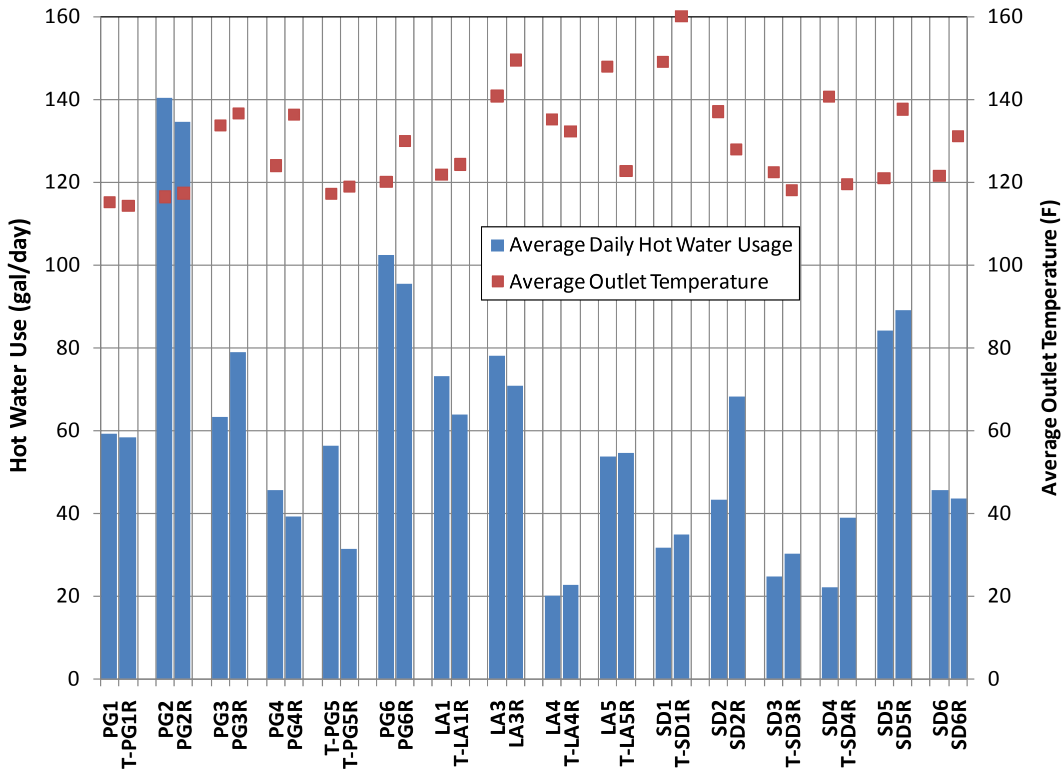

Figure 105: Pre- and Post Retrofit Hot Water Usage and Outlet Temperature Data

Figure 106 focuses in more closely on the eleven sites that had stable occupancy throughout the full monitoring period. The graph separates sites that were retrofitted with storage units to the left hand side of the graph and those with tankless units to the right. For the storage water heater sites, one can determine (with the exception of site PG3[66]) a fairly stable pattern of hot water usage, or a compensating change in outlet temperature from pre- to post-retrofit periods. The tankless data for the six sites to the right show more variation. Although four of the six sites indicate comparable usage or usage changes offset by outlet temperature changes, sites SD1 and SD4 show potential increases in usage that cannot be fully explained by setpoint changes,

[66] Site PG3 experienced no change in occupancy, but a final homeowner survey indicated house construction projects in the post-retrofit period with a resulting perceived increase in showering.

indicating that behavioral changes with the tankless unit may have occurred at these households.

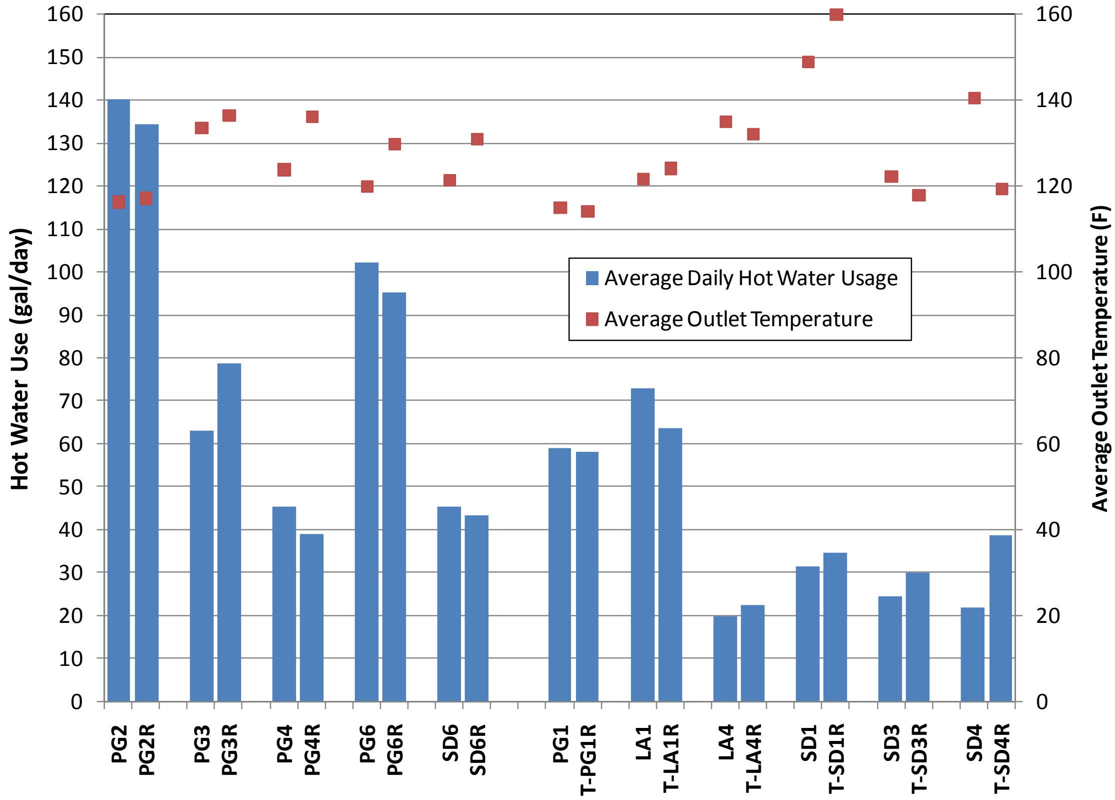

Figure 106: Pre- and Post Comparison for Stable Occupancy Sites (Usage and Setpoint)

Figure 107 plots the energy leaving the water heater for the 500 highest “energy content” hot water draws monitored at SD4, both pre and post. One can clearly see that most of these draws show a considerably higher energy content with the tankless unit that with the base case storage water heater. The duration of these 500 draws increased from an average of 407 seconds to 512 seconds. Although longer showers may be the case for SD4 and possibly SD1, there are four other sites where this behavior was not observed. Based on this limited dataset, the only conclusion one can draw is that further study is needed to see if increased usage with tankless units is the norm or just an anomaly. Figure 108 plots average monthly recovery load for each of the three utility areas. Seasonal variations in load and differences between Northern and Southern California climates are evident. The horizontal purple line shows the EF test recovery load of 41,000 Btu/day. Only January and February usage in PG&E territory are shown to exceed that level.

Table 49: Pre- and Post-Retrofit Daily Average Recovery Load by Site

Site	Advanced WH Type	Avg Daily Recovery Load Base Case	Post-Retrofit	% Difference Post vs Pre	Comments
PG1	CTWH	22,600	22,200	-2%	
PG2	CSTO	54,200	54,600	+1%	
PG3	ESTAR	31,100	45,000	+45%	
PG4	ESTAR	22,400	26,500	+18%	
PG5	CTWH	20,800	13,800	-34%	Adult moved out 1st week Jan'11
PG6	CSTO	44,100	52,800	+20%	
LA1	CTWH	29,200	28,100	-4%	
LA2	ESTAR	16,000 *	30,600	n/a	Additional adult arrives 2/7/11
LA3	ESTAR	41,800	46,600	+11%	
LA4	TWH	8,900	9,800	+10%	
LA5	TWH	31,600	23,600	-25%	3 moved out 4/9/11
SD1	TWH	17,500	23,800	+36%	
SD2	CSTO	21,700	33,100	+52%	2 addl adults beginning Jan '11
SD3	CTWH	9,400	11,200	+19%	Includes some buffer tank heating
SD4	CTWH	11,400	16,200	+42%	
SD5	ESTAR	29,700	43,000	+45%	Spouse stopped work Dec '10
SD6	ESTAR	16,500	20,100	+22%	
Avg TWH & CTWH		16,500	18,500	+12%	Except PG5, LA5
Avg CSTO & ESTAR		35,000	40,900	+17%	Except LA2, SD2, SD5

* "pre" recovery load data low to sporadic flow meter issues resulting in under-reporting of hot water use

Table 49 presents average daily recovery load (in Btu/day), both before and after the advanced gas water heater retrofit. The table highlights the vast difference among sites as well as differences in recovery load before and after the retrofit. Average recovery load over all the sites was 27,200 Btu/day, or approximately 1/3 less than the 41,000 Btu/day assumed in the EF test. Excluding sites with significant changes in occupancy, the average tankless recovery load increased 12% after the retrofit (from 16,500 to 18,500 Btu/day) and the average storage water heater site increased 17% (from 35,000 to 40,900 Btu/day). Part of this can be explained by colder average inlet water temperatures during the "post" period relative to the "pre" period. The tankless sites are of most interest in this regard, since one might well expect a change in usage as a function of the delivery characteristics of the unit. Looking at sites PG1, LA1, LA4, and SD3, one sees a very small change in daily recovery load. However, sites SD1 and SD4 stand out based on their significant increase in daily recovery load.

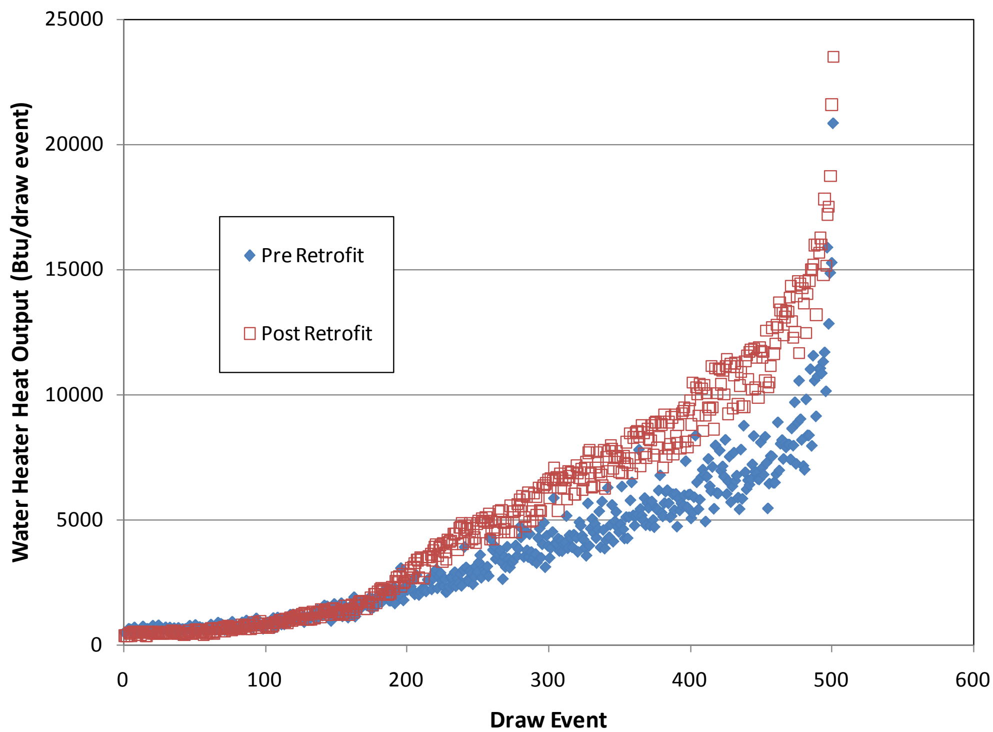

Figure 107: SD4 Comparison of Highest Energy Content Hot Water Draws (pre and post)

Table 50 presents monitored pre and post delivery efficiencies, on both a traditional gas-only basis, and a Gas/Elec calculation where electrical usage is added to the numerator on a site energy basis. Delivery efficiency is analogous to an EF value, with the distinction being that it is site-specific and not tied to the EF test parameters. Values are reported to three significant figures to improve the resolution between the Gas and Gas/Elec values. Base case values (for all sites but the tankless base case site PG5) range from a low of 0.333 (SD4) to a high of 0.698 (PG2). This wide range highlights the issue with gas storage water heaters in California. While the high load PG2 site (~138 gal/day) demonstrates very good performance for a standard atmospheric water heater, low SD4 loads contribute to very poor performance. Post-retrofit delivery efficiencies are a minimum of 0.10 higher, ranging up to 0.55 higher. The addition of electrical energy in the delivery efficiency calculation reduces the calculated “Gas efficiency” by an average 0.014, although the impact can be as large as 0.03. Note the PG6 retrofit was a hybrid tankless/storage unit with interconnecting piping equipped with an electric circulation pump.

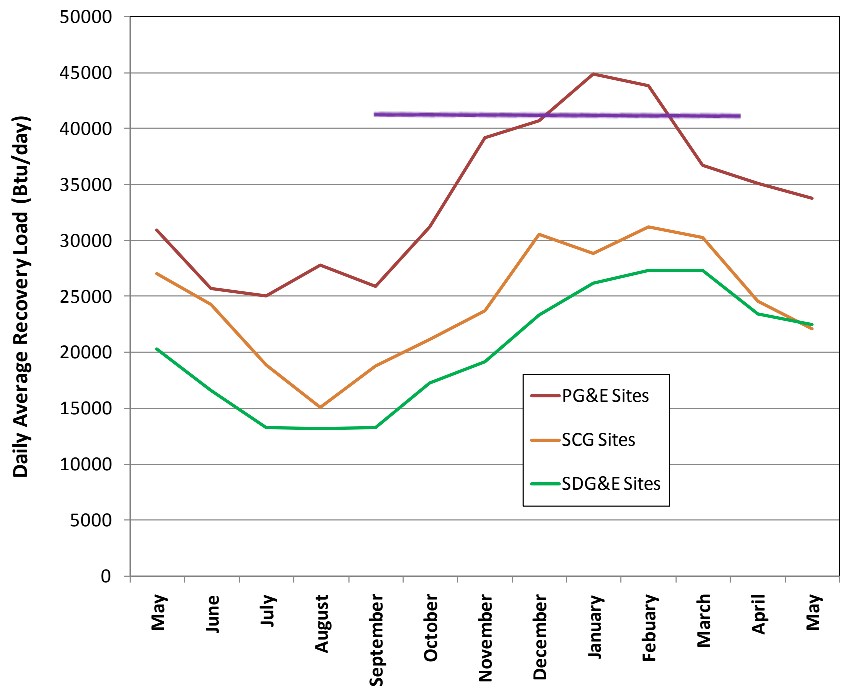

Figure 108: Average Monthly Hot Water Recovery Load

Table 50: Comparison of Pre and Post Delivery Efficiency

Site	Advanced WH Type	Average Delivery Efficiency Base Case	Post- Gas	Post- Gas/Elec	Projected Annual kWh
PG1	CTWH	0.520	0.806	0.780	99
PG2	CSTO	0.698	0.832	0.823	80
PG3	ESTAR	0.608	0.736	0.723	113
PG4	ESTAR	0.490	0.587	0.577	62
PG5	CTWH	0.769/0.754*	0.808	0.796	58/26 *
PG6	CSTO	0.626	0.725	0.709	215
LA1	CTWH	0.529	0.761	0.731	113
LA2	ESTAR		0.684	0.675	113
LA3	ESTAR	0.580	0.670	0.658	128
LA4	TWH	0.281	0.681	0.657	37
LA5	TWH	0.530	0.752	0.741	47
SD1	TWH	0.420	0.730	0.719	58
SD2	CSTO	0.490	0.711	0.703	58
SD3	CTWH	0.337	0.724	0.698	62
SD4	CTWH	0.333	0.882	0.865	37
SD5	ESTAR	0.567	0.637	0.636	22
SD6	ESTAR	0.544	0.637	0.627	77

* PG5 had existing TWH. Base Case represents Gas / G/E efficiency; Annual kWh = pre / post

Input-Output curves were generated for each site for both base case (pre) and post-retrofit performance. In generating the curves, daily gas energy consumed was plotted against daily water heater recovery load as shown for site LA1 in Figure 109. Plotted datapoints represent days with complete data records for that day. In the example plot shown, the advanced gas condensing tankless water heater (CTWH) shows a clear performance benefit relative to the existing atmospheric water heater. The Y-axis intercept (14,459 Btu/day for base case, 746 Btu/day for CTWH) nominally represents the standby energy consumption at zero recovery load. A complete set of curves for each site can be found in **Error! Reference source not found.**.

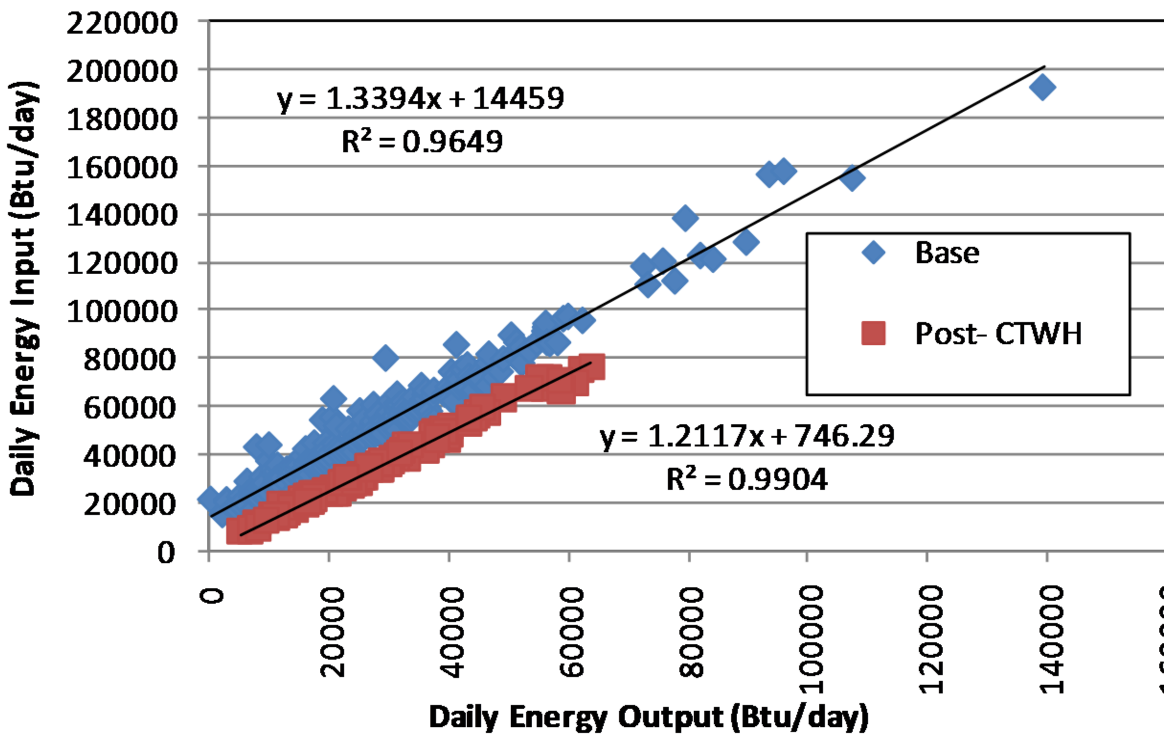

Figure 109: Sample Input-Output Curve (daily gas energy used and thermal energy delivered)

To obtain a better understanding of performance by product class, the individual site input-output curves were averaged together by product type. This defined a single relationship for the existing water heaters, as well as each class of advanced water heater (EnergyStar 0.67-0.70, tankless, condensing tankless, and condensing storage). These aggregated relationships were then used to calculate delivery efficiency as a function of recovery load, as shown in Figure 110. This rendering of the results highlights performance variations as a function of recovery load. The figure shows a vertical dashed line at the average observed recovery load of 27,200 Btu/day, as well as one standard deviation below and above (a "low" level of 14,000 Btu/day and a "high" level of 40,500 Btu/day). Interestingly the mean load + one **σ is** very close to the EF's daily recovery load. Of the monitored sites, two were found to have usage below the "low" level and three were found to have usage above the "high" level.

Since significant variations in recovery load were observed among the sites, the decision was made to present savings estimates for the different technologies at three usage levels: the average usage (27,200 Btu/day), and one standard deviation above and below the mean. Keep in mind that these projections are representative of the particular products monitored and may vary.

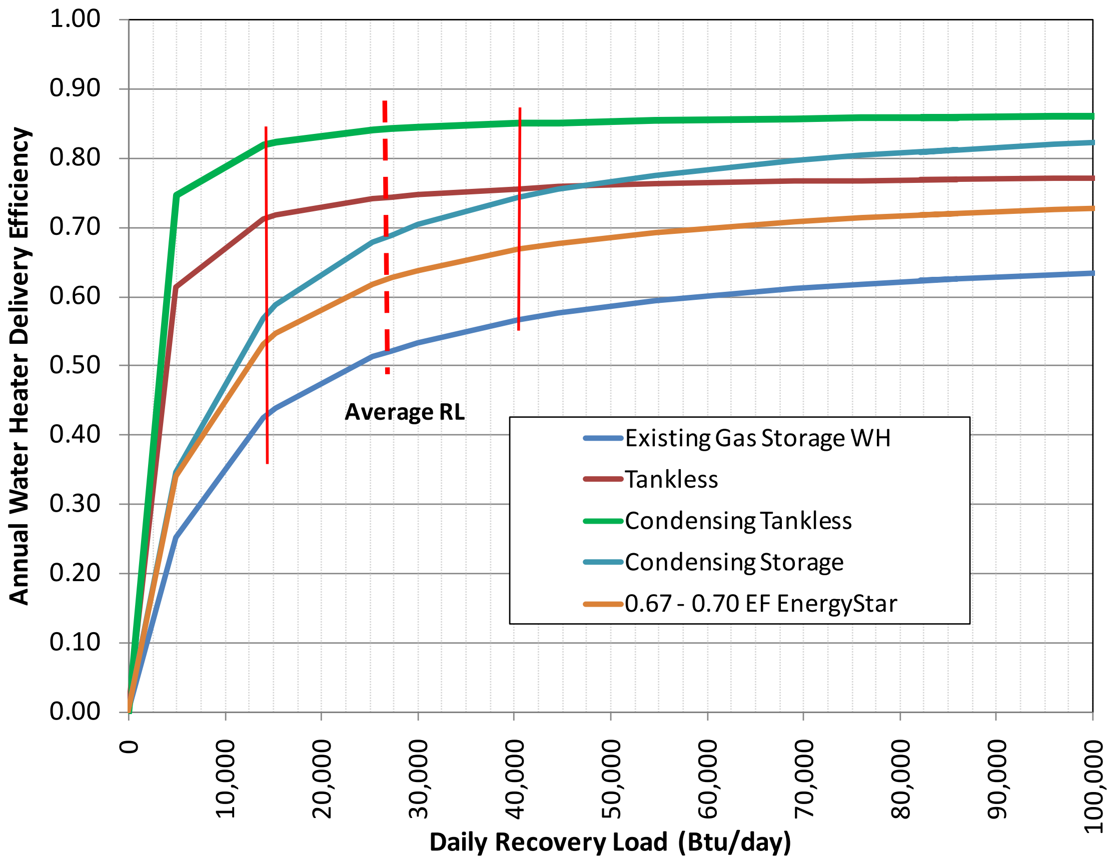

Figure 110: Projected Load Dependent Thermal Delivery Efficiency

Table 51 projects annual gas usage for each of the water heater types at the three usage levels based on the thermal efficiency relationships shown in Figure 110. Base case consumption for the typical use case shown is projected at 191 therms, very close to the average monitored base case consumption of the 18 sites. As shown in both Figure 110 and Table 51, tankless unit projected performance demonstrates a significant advantage over the other technologies at low recovery loads. As loads increase the condensing storage combustion efficiency benefit begins to overcome the standby loss, to the point at which its projected efficiency equals non-condensing tankless at a recovery load of approximately 43,000 Btu/day. Annual electric consumption is also estimated in Table 51. The red highlighted values represent the monitored electrical usage as it aligns with the observed recovery loads. Adjustments for the other cases were made on approximations of electrical consumption during firing modes and standby modes. Again, actual usage will vary based on the selected product.

Table 51: Projected Use and Savings by Product Type

WH Type	Annual Projected Usage Low Use	Annual Projected Usage Typical Use	Annual Projected Usage High Use	Annual Projected Savings Low Use	Annual Projected Savings Typical Use	Annual Projected Savings High Use
Gas Use (therms)						
Base	120	191	261	n/a	**n/a**	n/a
EnergyStar	101	167	234	19	**24**	27
TWH	72	134	196	48	**57**	65
CTWH	62	118	174	58	**73**	87
CSTO	90	145	199	30	**46**	62
Electric Use (kWh)						
Base	0	0	0	n/a	**n/a**	n/a
EnergyStar	66	**86**	106	(66)	(86)	(106)
TWH	**47**	54	68	(47)	(54)	(68)
CTWH	**67**	87	108	(67)	(87)	(108)
CSTO	96	**118**	140	(96)	(118)	(140)

The red highlighted values represent the monitored electrical usage as it aligns with the observed recovery loads.

5.1.1.4 Discussion

With the introduction of the latest Energy Star labeled offerings, storage water heaters at the minimum 0.67 EF level come equipped with electronic ignition to eliminate the inefficiency of a pilot. Atmospheric combustion units also have motorized center flue vent dampers to further limit standby losses. Such units are compatible with existing Category I/Type B venting left over from the earlier, less efficient storage water heater installations. Power vent and direct vent units with induced draft combustion fans are also offered at this efficiency level, but require new PVC venting installations. However, one common attribute among all these wide ranging Energy Star storage water heater offerings is the requirement for electrical power, which can add to the installation cost if a new outlet is required. Furthermore, these electric parasitics will tend to partially offset the gas savings.

A comparatively limited number of condensing storage water heaters are also entering the marketplace. The greater than 75,000 Btu/hr firing rates of the current offerings preclude the certification of an EF, but this work and the work of others, indicate an increasing efficiency advantage over the non-condensing Energy Star storage water heater offerings under higher hot water load applications.

Despite the lack of a manufacturing base in the Americas, tankless water heaters have been making substantial inroads into the marketplace that is still dominated by storage water heaters. Presently all U.S. storage water heater manufacturers do brand one of the foreign makes as their own, while most of those same foreign manufacturers also sell directly into the U.S. marketplace. Earlier on, non-condensing tankless water heaters represented the only higher efficiency option available and certified EF ratings of 0.82 appeared to offer significant gas savings potential. However, this work and work by others, has shown that under real world hot water draw profiles, cycling losses not well represented in the standard EF test draw profile, reduces the realized efficiency in the field.

Condensing tankless water heaters, which recently entered the U.S. marketplace in the last two years or so, do appear to maximize the operating savings potential. However, certain performance issues persist with the tankless products overall, including longer delays for hot water delivery due to the firing startup sequence of operation, cold water sandwich due to low/intermittent hot water draws and minimum flow rate requirements for firing, and concerns regarding maintenance, reliability, and longevity with the compact heat exchanger and mineral buildup. Tankless products also typically require the most site modifications during installation to incorporate power/direct venting (sometimes with manufacturer specific kits), upgrades from ½' to ¾" or larger gas piping to accommodate the higher firing rates, the condensate line to a sanitary drain, and condensate neutralization system.

The results presented in this study highlight several key issues. Based on the 18 home sample in this study, average observed water heating loads are roughly 1/3 lower than assumed in the EF test. This has several significant broad implications. First, lower loads generally translate into lower energy savings potential for advanced technologies. Secondly, storage water heaters, whether standard atmospheric, EnergyStar, or condensing storage, all carry an efficiency penalty in the form of standby loss. As shown in Figure 111, a standard center flue atmospheric water heater's energy use starts at ~40 therms per year (as noted on page 27) at zero load, and increases linearly with load based on the assumed combustion efficiency (76%). As loads increase, standby energy slowly decreases, and combustion inefficiency and recovery loads linearly increase. Applying the low usage estimate used in Table 51 (~ 5.1 MBtu/year), the standby energy use represents nearly 40% of the annual water heater energy usage. As loads increase, this percentage falls and the efficiency value increases.

Looking at overall performance by product class, Table 52 summarizes average nominal and observed efficiencies and recovery load (Rec Load) from the field study. The Base water heaters are estimated at an average 0.56 EF. Recovery loads for all product types, except for CSTO, were well below the 41,050 Energy Factor test level. This is especially true for the eight tankless units, which were below 50% of the EF level. Monitored field efficiencies range from 0.50 to 0.77, with the highest observed efficiencies for the condensing technologies. Adjusting the observed efficiencies to bring them in line with the EF recovery load (based on Figure 110), one finds that most of the product types would demonstrate higher performance (from 0.015 to 0.06 EF point increase) if actual loads were in line with the EF test. The final column in the Table indicates that the field performance of both conventional atmospheric storage units and Energy Star storage units appear to be consistent with their ratings. TWH units are projected to perform at 10% below their rating, close to the 8% degradation currently applied in the Title 24 water heating methodology. CTWH units are slightly worse at 84% of nominal. Finally CSTO appear to operate at 80% of their rated thermal efficiency (TE). Since thermal efficiency does not account for standby effects, this comparison isn't intended to indicate a gross over-rating, only that TE is not a good indicator of seasonal performance, especially in average or low-load situations.

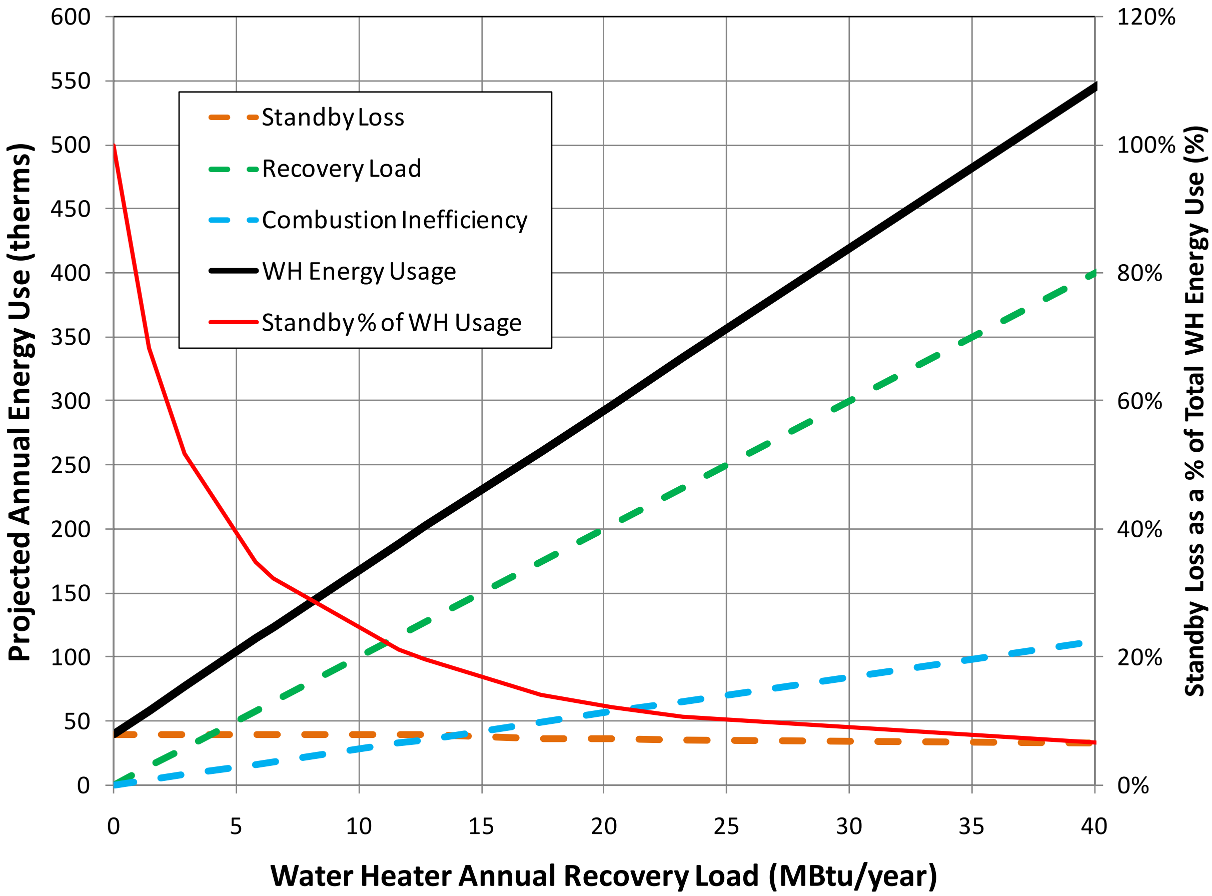

Figure 111: Breakdown of Standard Atmospheric Water Heater Energy Use with Load

Table 52: Comparison of Monitored Field Efficiencies to Rated Efficiencies

Product Type	Rated Efficiency	RecLoad kBtu/day	% of EF RecLoad	Monitored Field Eff	% of Rated Eff	Efficiency Correction	Adjusted % of Rated Eff
Base	0.56 EF*	25.8	63%	0.504	90%	+ 0.06	101%
ESTAR	0.675 EF	35.3	86%	0.649	96%	+ 0.015	99%
TWH	0.820 EF	19.1	47%	0.706	86%	+ 0.03	90%
CTWH	0.944 EF	18.3	45%	0.774	82%	+ 0.02	84%
CSTO	0.916 TE	46.8	114%	0.745	81%	- 0.01	80%

"*" estimated for the various vintage units monitored

Installation Costs

As part of the program, the advanced water heaters were graciously donated by the participating manufacturers, while installation costs were covered by this program. Although informative, our sense is that the limited sample of installed cost data should not be construed as being representative of the broader market for several key reasons. First, some of the plumbers indicated that they wouldn't have recommended installing the assigned water heater to the selected site, due primarily to added complications with the installation process (e.g. venting issues). However, it could be indicative of the significant market barriers, i.e., added costs that could limit conversion of conventional storage water heaters to advanced equipment installations. Secondly, permits were required at all sites. This may or may not be standard practice for the plumbers, but does represent added cost and time coordinating with the building department. Finally, there was some level of coordination expected between DEG, the plumbers, and the homeowners in this process. The plumbers often had to provide some support in terms of reinstalling flow meters and gas meters during the retrofit. All three of these factors contributed to some degree to higher costs than one might normally anticipate.

Table 53 summarizes the average, maximum, and minimum of the installation costs charged by the plumbers participating in this project. These costs are higher than those reported in the EPA's *EnergyStar® Residential Water Heaters: Final Criteria Analysis* document published in 2008[67].

Table 53: Field Site Installation Cost Summary (not including equipment)

	Average	Maximum	Minimum
EnergyStar (# = 6)	$1,500	$2,134	$1,096
Condensing Storage (#=3)	$2,360	$1,930	$3,140
Tankless (# = 8)	$2,800	$3,395	$2,403

With input from several cost sources, including the EPA document, a recent ACEEE Water Heater Technology Assessment[68], and cost quotes collected as part of ongoing Davis Energy Group retrofit activities, we compiled approximate typical new and retrofit cost assumptions for the advanced gas technologies assessed in this study. Clearly the costs presented are rough estimates for any one technology class, but are intended to provide general guidance on the

[67] http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/water_heaters/WaterHeaterAnalysis_Final.pdf

[68] http://aceee.org/research-report/a112

question of cost effectiveness. Actual installed incremental costs for any one technology will vary in pricing based on a wide variety of factors including capacity, specific make and model, and contractor familiarity with the technology. Table 54 summarizes the new and retrofit costs and estimates simple paybacks based on representative average electric and natural gas prices of $.15 per kWh and $1.20 per therm, respectively, and the savings presented in Table 51. The paybacks shown look only at net energy savings[69] and do not account for any incremental maintenance costs, or potential incentives which could reduce the incremental cost. New construction projected simple paybacks are much better than projected retrofit paybacks, since many of the key site implementation issues are trivial or low cost in new construction situations. At the typical usage level, new construction tankless paybacks are projected at 10-12 years, with paybacks exceeding 19 years for the high efficiency storage options. Under high use retrofit scenarios, projected paybacks for the storage technologies are comparable to the tankless paybacks, but all exceed 25 years. Growth in market share for these emerging technologies will lead to reduced production costs, increased competition among manufacturers and installers, and increased familiarity among installation contractors.

Table 54: Estimated Simple Paybacks (Years) for Advanced Gas Technologies without Incentives

	Est. Incremental Cost		Low Use		Typical Use		High Use	
WH Type	New	Retrofit	New	Retrofit	New	Retrofit	New	Retrofit
EnergyStar	$400	$800	31	62	**25**	**50**	24	48
TWH	$600	$2,000	12	40	**10**	**33**	9	29
CTWH	$900	$2,300	15	39	**12**	**31**	10	26
CSTO	$700	$1,600	32	74	**19**	**43**	13	30

Combustion Condensate Disposal

Condensate disposal for the condensing water heater products is an issue that is currently handled in different ways by various local building jurisdictions. To provide more information on the subject, an investigation into the code requirements for condensate disposal was conducted with the assistance of project PAC member Adam Muliawan with the International Association of Plumbing and Mechanical Officials (IAPMO) and in accordance with the 2009 Uniform Mechanical Code (UMC):

- Points of discharge of combustion condensate piping include:

[69] Average advanced water heater electrical consumption is projected at ~80 kWh/year, or ~$12 annually.

- The tailpiece of a lavatory (must be in a space or dwelling served by the appliance).
- The drain and overflow of a bathtub (muse be in a space or dwelling served by the appliance; the drain and overflow shall be provided with an access panel, even if there is no slip joint – required by the UPC).
- A floor sink.
- A gravel pit (shall be restricted to small residential units and the soil shall be the type that will absorb the condensate. This method shall not be used with clay or expansive soil).

Disposal of combustion condensate in a sanitary drain can present significant installation issues for warmer climate installations in garage or exterior closet/wall applications (like most of our field tests). So Adam provided the following clarifications on gravel pit disposal:

- The clause "restricted to small residential units" – is there a quantitative condensate volume limit?
    - Currently there is no quantitative volume limit. Yes, the representative 100 gal/year of combustion condensate used in a single family home water heater would qualify for a gravel pit disposal.
- Does the code require neutralization of the acidic combustion condensate for gravel pit disposal?
    - No, the code does not require neutralization of the acidic combustion condensate for gravel pit disposal.
- Is a soil test required to qualify for gravel pit disposal?
    - No, a soil test is not required to qualify for gravel pit disposal, unless the Authority Having Jurisdiction requires it. See Section 116.5 of the 2009 UMC.

Customer Response to Advanced Water Heaters

A recent tankless water heater study by the Minnesota Center for Energy and Environment[70] provided in-depth, same site, monitoring of storage and tankless units in the Minnesota homes.

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70 http://www.state.mn.us/mn/externalDocs/Commerce/CARD_Natural_Gas_Tankless_Water_Heater_Study_100510053932_DomesticWaterHeatingReport.pdf

The report addressed several issues related to the performance of tankless water heaters: impact on the quantity of hot water used, and behavioral impacts due to a change from storage to tankless. Based on the data collected, the authors determined that there was no statistical difference in hot water usage with the storage water heater and the tankless water heater. When using the tankless units, homeowners were found to increase flow rates relative to data collected during the storage monitoring, since tankless water heaters require a minimum flow rate to trigger the burner firing. Follow-up surveys indicated that homeowners were three times as likely to categorize hot water wait times as "unfavorable" with the tankless unit as with a storage unit. They also were 40% more likely to recognize tankless units as providing more consistent hot water temperatures during draws, and 2.5 times more satisfied with the tankless unit in terms of not running out of hot water. Of the ten field sites, eight of the sites wanted to keep their tankless unit at the end of the monitoring, with only one site indicating that they did not want the tankless unit.

With this information as a backdrop, this project also looked at surveying the test sites for satisfaction and water use characteristics. As part of the field monitoring project, homeowners at the field sites were obligated to respond to surveys provided by DEG. The first survey delivered to the homeowners was the beta version of the behavioral survey developed by Lutzenhiser Associates. This survey was designed to assess household hot water usage patterns, characteristics of their existing water heater and distribution system (in terms of waiting time, ability to provide hot water, etc), and individual behaviors as it relates to showering, sink use, and appliance usage. The survey, ultimately administered to over 500 households in California, was tested on the 18 field sites to get initial usability feedback. Additionally, within a few weeks after installation of the advanced water heaters, a very brief survey was given to the homeowners, mainly to assess initial reactions to their new water heater and their assessment on how satisfied they were with the plumber's installation process. Finally towards the end of the advanced water heater monitoring, more detailed feedback was solicited from the homeowners.

The following questions comprised this final customer survey:

1. With some households we are aware that there has been a change in the number of people living there. Can you please describe to the best of your ability, the approximate dates of these changes, and how long they lasted?
2. Any performance issues with your new water heater? (e.g. varying temperatures during shower, ability to handle multiple draws, etc.)
3. After living with your new water heater over the past several months, what performance attributes do you like (relative to your old water heater) and what attributes do you not like?
    a. Likes
    b. Dislikes

4. With some of the monitored houses we have seen a change in hot water usage and the number of daily hot water draws. Some of this may be due to occupancy changes. Outside of that effect, if you feel your behavior has changed in response to your new water heater, please describe behavioral changes and what types of hot water draws are most affected?

5. For those of you with tankless water heaters, we are interested in following up with you again to assess any behavioral changes you may have implemented as you have become more familiar with your unit. Please answer the following questions:

    a. How has the minimum flow rate performance of your water heater affected how you use hot water? (By minimum flow rate, I mean that the unit will not fire unless a certain flow of hot water is passing through the tankless unit.)

    b. Do you feel that the minimum flow rate issue is an inconvenience or actually makes you think more about when you need hot water?

    c. Do you feel that any of your usage patterns have been affected by the unit? Sink draws, showers, others?

    d. Have you noticed any occurrences of the "cold water sandwich"? This is when you may start a shower with warm water, but it then gets cool before it comes up to temperature? Please describe.

    e. What is your best guess on how much longer you wait for hot water?

6. Traditionally, standard gas storage water heaters have received little or no maintenance over their lifetimes. Some of the advanced gas water heaters (e.g. tankless) may require more maintenance over their lifetime. Please describe what maintenance activities you anticipate performing and at what interval (annual, every other year, etc.)?

Full responses from all the sites can be found in **Error! Reference source not found.**. The following summary presents survey responses to key questions that probe at performance changes, with primary interest focused on distinctions between sites that remained storage water heaters, and those that were converted to tankless water heaters.

Question 1: Comment on the ability to supply hot water for multiple uses at the same time

Sites with Conversions to Storage Technologies: consensus "equal or better than before"

Sites with Conversions to Tankless Technologies:

> LA1: A little disappointed. When 2 or more people take a simultaneous shower, one does not have hot water. That was not the case with the previous water heater.
>
> SD1: Once we get hot water to bathrooms, no problems running two showers at the same time.

SD3: New system appears to supply ample hot water to multiple areas of home at the same time.

PG1: Haven't fully tested it for large demands but given the size of this unit don't expect any issues for possible future heating coil.

PG5: Works fine to meet two showers, sink, and DW demand at same time.

Question 2: Comment on the ability to maintain stable outlet hot water temperatures

Sites with Conversions to Storage Technologies: “equal or better than before”

Sites with Conversions to Tankless Technologies:

LA1: Temperature seems to change often, between hot &lukewarm, back to hot. Not very consistent.

LA4: No problems noticed.

SD1: We can run a large tub full of water and the temperature is stable. If we turn water on & off when washing dishes or in a shower, we notice a small amount of cooler water in the lines.

SD3: The system appears to maintain stable hot water outlet temps.

SD4: Very consistent so far.

PG1: It has seemed stable so far, at least equal to or better than our old storage heater.

PG5: Excellent *(….. previously had TWH…..).*

Question 3: Comment on the change in hot water wait times (at remote usepoint)

Sites with Conversions to Storage Technologies: “equal or better than before”

Sites with Conversions to Tankless Technologies:

LA1: It takes twice, almost 3x as long to get the first bit of hot water (up to 45 seconds, sometimes 60) .

LA4: It seems to take the same time for the hot water to reach the faucet. There is a slight delay after adjusting the temperature higher.

LA5: It is taking more time for the water to come out hot when using first time in the morning. We have gone from 10-15 to 25-30 seconds to get initial hot water.

SD1: I have noticed an increase in the time that it takes to get hot water in one of our showers at the end of our run. I would guess that at least additional 15 seconds (or 30) when the pipe and slab are cold.

> SD3: To avoid waste, we always collect water in a bucket at the most remote outlet (shower off our bedroom). With the old WH, we consistently collected 1.5 gals of water. Now with the new tankless water heater, we are collecting over 2 gallons of water.
>
> SD4: It seems longer to me than it actually is, but I believe it has increased by about 10-15 seconds.
>
> PG1: Not noticeable since wait times were so high already.
>
> PG5: Longer by a good 5 seconds, possibly longer that that *(prior TWH site).*

Question 4: Have you had to modify your hot water usage patterns with the new unit?

Sites with Conversions to Storage Technologies: generally "…no…", but one comment of "need to adjust temperature downward during shower "

Sites with Conversions to Tankless Technologies:

> LA4: Not that we noticed. If the water flow is that low or the water is turned off quickly, we seem to live with it or just not notice.
>
> LA5: Only when taking a shower. The wait is a little longer.
>
> SD1: It takes longer to obtain hot water when taking a shower. When washing dishes, we tend to wash them faster in order to avoid a delay in cycling the hot water on or off. These changes are not minor.
>
> SD3: Since we are now collecting more water (in buckets), my wife and I are taking back-to-back showers, and we try to start the kitchen dishwasher and the laundry room washing machine when there is already hot water primed in the pipes.
>
> SD4: If I am going to just wash my hands with no other adjacent hot water usage, and the pipes have cold water to start, I will now just use cold as there is no point in heating water that won't make it to the faucet during the handwashing. No behavior change otherwise.
>
> PG1: No necessary changes. I can hear the heater firing now so it reminds me to leave the hot side off in situations where HW won't have time to get to the fixture and also to turn the flow down until the heater modulates down in low flow situations i.e. dish and hand washing. The low flow threshold is just below my lowest use so it always comes on.

5.1.1.5 Conclusions and Recommendations

The field monitoring activities completed from April 2010 through June 2011 provided a significant amount of detailed hot water usage data and water heater performance data. A pre- and post data collection methodology provides interesting insights into how hot water usage behavior may change within a household in response to a new water heating technology. The relatively small sample size and (intentional) broad selection of advanced water heaters limit the author's ability to make broad performance conclusions and observations. Clearly more field data are needed to bolster the findings in this report.

Key project findings are summarized in the following four categories.

Hot Water Demand and Efficiency Implications

Monthly cold water inlet temperatures over a twelve month period ranging from May 2010 to April 2011 averaged 69.5°F, and ranged from 52.9 to 87.8°F. Southern California sites typically had inlet water temperatures 7 to 8°F warmer than the PG&E Northern California sites.

The average number of hot water draws[71] was found to be 10 per person per day, ranging from 5 to 18. The average pre-retrofit hot water draw volume was 1.67 gallons.

Hot water consumption averaged 56.4 gallons per day (gpd) over the full monitoring period, or 15.6 gpd per person. Household hot water consumption varied widely across the different sites (from 21 to 138 gpd), with significant day-to-day variations observed at all sites.

Despite occupancy levels above the national census average household size, the annual hot water recovery load averaged 27,200 Btu/day, or about 1/3 less than assumed in the Energy Factor test procedure. This was due to warmer inlet temperatures, lower outlet water temperatures, and lower hot water consumption. The implications of these lower loads are significant for California, as we project a 0.06 reduction (~10%) in annual gas storage water heater performance from their estimated nominal EF levels.

Water Heater Performance and Economics

The average base case (i.e. existing) gas storage water heater energy use was projected at 188 therms per year, or slightly less than the 195 therms per year estimated for single family homes in the 2009 RASS. Of the total base case gas consumption, ~40 therms were attributed to the energy use required to maintain the storage tank in standby mode. All of the advanced water heaters were found to save energy, with the most dramatic savings occurring with tankless units, primarily due to the low observed recovery loads[72].

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[71] A draw is defined as a continuous water heater flow event exceeding 4 seconds in length. Simultaneous draws at different use points would be represented as a single water heater draw event.

[72] High efficiency storage unit annual performance is also significantly degraded by low water heating loads.

A graphical summary of the results are presented in the stacked bar graph shown in Figure 112. Annual gas energy savings are presented for three load cases (typical = 27,200 Btu/day, low = 14,000 Btu/day, and high = 40,500 Btu/day). Results are plotted by product class as defined below:

ESTAR = EnergyStar™ 0.67 – 0.70 EF non-condensing storage (average EF of the installed units = 0.675)

TWH = non-condensing tankless (average EF of the installed units = 0.82)

CTWH = condensing tankless (average EF of the installed units = 0.944)

CSTO = condensing storage (average thermal efficiency of the installed units = 91.6%)

Simple paybacks are plotted under both new and retrofit cost scenarios. The paybacks plotted include gas savings and incremental electrical consumption and are based on assumed residential rates of $1.20 per therm and $.15 per kWh. No incentives, tax credits, or maintenance costs are included in the payback calculation.

Projected annual savings for the EnergyStar™ products are under 30 therms per year, tankless savings range from 45 to 85 therms per year, and condensing storage savings range from 30 to 60 therms per year. In lieu of tax credits and utility incentives, projected simple paybacks for new construction are between 9 and 15 years for tankless, and from 13 to 32 years for the storage products. In retrofit scenarios where implementation costs are considerably higher (especially for tankless), none of the projected simple paybacks were found to be less than 25 years. The economic results are discouraging, especially for the retrofit market, and indicate the need for increased production volumes and alternative equipment designs to reduce installed costs. Low California natural gas rates for the foreseeable future and high electric rates (a second order effect on savings) also contribute to a challenging environment for implementing efficiency.

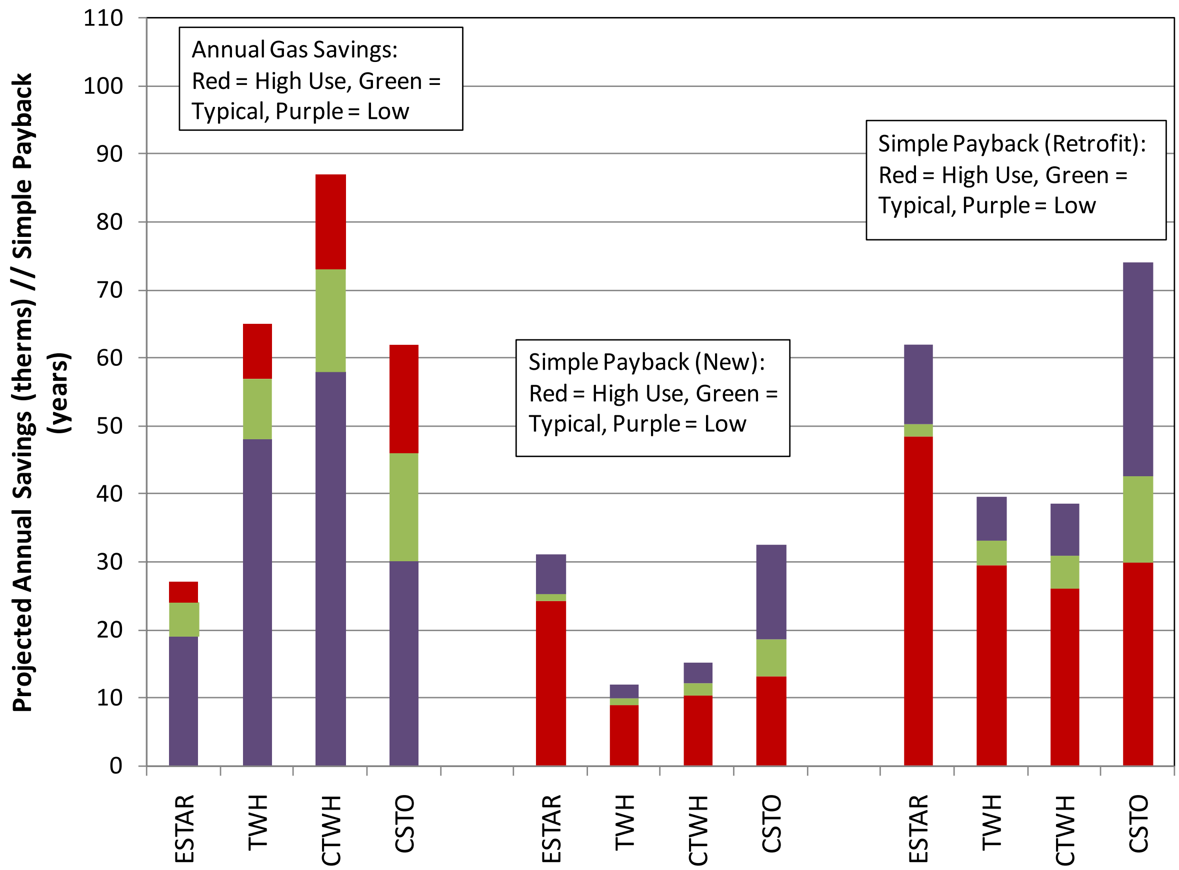

Figure 112: Projected Advanced Water Heater Savings and Simple Paybacks by Product Class

Customer Reactions to Advanced Water Heaters

In general, the seventeen homeowners who received advanced water heaters (at no cost) were satisfied with the units provided to them. One of the sites who received a CTWH did request that the unit be replaced with a standard storage water heater at the end of the project[73]. The only negative concern expressed by (some) customers who received a storage water heater replacement related to increased noise due to combustion air blowers. A few tankless customers had similar concerns related to noise, and also generally noted the well-documented issues

[73] Their dissatisfaction could be attributed to perceived miscommunication with the plumber, aesthetic concerns over the gas line and venting appearance, as well as some performance concerns.

related to increased hot water wait times, problems satisfying low-flow rate draws, and occasional cold water sandwich concerns. Overall these issues were not deemed problematic by any of the tankless households, with the exception of the site where the unit was removed. Positive tankless feedback was received from most respondents in terms of hot water capacity, stable delivery temperatures, compact physical size, and perceived energy savings.

Tankless water heaters were found to influence hot water usage behavior to some degree. The sites retrofitted with tankless units indicated an increase in average hot water draw volume from 1.40 to 2.09 gallons per draw, which was counteracted by an average 23% reduction in the daily number of draws. The net impact was that at four of the six tankless sites, there was essentially no change in the hot water recovery load between pre- and post, while two of the sites appeared to show higher hot water recovery load after the conversion. A broader study is needed to develop a better understanding of whether tankless water heaters result in greater hot water consumption in some households.

Recommendations

- This project tested a sample of the emerging high efficiency products that are now on the market. With only eighteen field sites, further study by the California utilities is warranted to develop a more robust understanding of performance impacts under different climates and load profiles.
- Evaluating customer satisfaction of these emerging technologies is an important step in directing future activities. Careful tracking of maintenance needs and the associated costs is needed to better define the overall economics of the different technologies.
- The CEC and California utilities should stay abreast of new and emerging water heater technologies. The costs for many of these products should come down in the years ahead as production volumes increase. Other new technologies better suited to retrofit applications will also likely be entering the market in the next few years. These systems should be carefully studied in both laboratory and field settings.
- Evaluate combined hydronic systems as a strategy to improve high efficiency water heater cost effectiveness. These systems offer the advantage of utilizing one high efficiency heat source to provide both space and water heating. New product offerings from several manufacturers are expected in the near term.
- Direct future Title 24 field research towards better quantifying hot water loads, cold water inlet temperatures in various locations statewide, and also identifying water heater setpoints at several hundred sites. This data can inform how water heating is modeled within the Title 24 code. The data collected here provides a start on that process.

5.2 Hot Water Use Behavioral Survey

5.2.1 Survey Overview

During the summer of 2010, the Gas Technology Institute, Davis Energy Group, and Lutzenhiser Associates collaborated on a research effort for the purpose of developing a more detailed knowledge of residential consumer hot water use. We were interested in surveying California homeowners to gather data on hot water usage patterns and use practices, technologies, and knowledge regarding water heating and water heating technology choices. Two surveys of current natural gas water heating customers in California were completed in the Fall of 2010 and the early Summer of 2011; respondents included 146 Pacific Gas and Electric (PG&E) Company employees and 443 Southern California Gas (SCG) customers, respectively.

Background

With little prior research to draw upon, the research team developed a series of questions to ask of consumers in this relatively uncharted research area. The task was also challenging because – as in other types of residential energy end use research – the ultimate object of inquiry is invisible. Electricity and natural gas flows are hidden from view and only through periodic billing (monthly in this case) do consumers have any idea how much energy they are using, let alone for what purposes. Water use and hot water use are actually a bit more obvious, than, say, refrigerator energy use. But still they are buried in the realm of habit and the taken-for-granted. As such, they are difficult to recall and likely subject to some level of uncertainty in estimating, for example, water use at the sink or length of showering for different members of the household.

To address at least some of these "invisibility" issues, and to assist respondents with the rather technical language used in the survey, our survey instrument provided several visual cues. Pictures of typical tank and tankless gas water heaters were imbedded in the online survey, along with pictures of typical single-lever and dual-control faucets, faucet water restrictors and, aerators. The results of these surveys offer an initial assessment of how homeowners interact with their system and perceptions of their hot water use patterns. Results also suggest that innovative ways of communicating could be used to better support future inquires.

Our data are far from perfect and all of our results should be interpreted with care. This is particularly true in any generalizations that the reader might want to make to larger populations and over-arching patterns of water use and persons' routine practices. With those caveats taken seriously (we hope), the survey nonetheless has broken new ground. It also allows us to consider future improvements in residential behavioral surveying that attempts to capture and measure aspects of hot water use. It raises a set of new research questions that should be pursued in the future to continue to refine hot water use models and to better inform hot water energy efficiency programs and policies.

Respondent Groups Compared

When comparing the two respondent groups, we found that the PG&E employee group was demographically different than the SCG customer group. Compared to the SCG respondents, the PG&E group had higher income levels, a higher percentage of white/Caucasians, and fewer households composed of adults with children. Incidentally, fewer of the households in the PG&E group had a whirlpool/jetted bathtub. Also, as one might expect, the PG&E employees from the company's Integrated Demand Side Management group were generally more aware of water heating technologies, were more likely to report an estimate of their annual cost of water heating, and more proactively adjusted water heater settings (especially while on vacation) than did the SCG customer survey pool. However, despite these differences, the two groups were similar in their overall hot water use behaviors. The following conclusions were made across the households in both respondent groups:

- Nearly two-thirds let hot water run continuously while washing or rinsing dishes;
- Only around one-quarter of respondents waited for hot water to arrive at bathroom or kitchen sinks (SCG customers were somewhat more likely to wait for hot water in the bathroom than PG&E group);
- At least one-third of all laundry loads used cold water exclusively; however, ~20% of laundry loads used a hot water wash cycle (PG&E 17% and SCG 24%);
- Most frequently, average household shower length was between 5-10 minutes (34% of showers taken by SCG group and 48% of all showers taken by PG&E group);
- In the SCG group a small (14%), but relatively higher percentage than in the PG&E group (5%), of showers last "more than 15 minutes;" and
- Respondents rarely adjusted or delayed using hot water to avoid running out (86% SCG and 78% PG&E group);

In the future, households said they were most likely to replace their water heater upon failure (not before) – 85% in both SCG and PG&E groups. Key findings from the larger SCG customer sample are summarized here. Findings from the smaller PG&E employee sample are presented later in the report.

Summary of Findings - SCG sample

Much of the full report takes an in-depth look at the larger and more robust SCG respondent sample. Some key findings from this group include:

- Most respondents knew the type (predominately tank or tankless), age, and location of their water heater, but fewer (~70%) knew the volume of their tank heater, and ~50% did not know whether or not their pipes were wrapped with insulation.
- Routine maintenance of water heaters among households was low; most had never drained their storage tank and replacement of the magnesium anode rod was rare.

- Awareness of water heating options (other than standard tank models) was relatively low. About half were aware of tankless water heaters, fewer (under 40%) were aware of solar heating, and very few (under 10%) were aware of condensing tank or hybrid tank heaters.
- Replacement of heaters was not common (under 20% in past two years), generally occurring upon failure. Many of these households make their own decision about replacement type, but 55% were influenced by a plumber or contractor.
- Several factors were important during the replacement decision. Almost all considered energy cost (or energy efficiency), capacity and recovery time, the warranty period, and initial cost. Fewer (under half) considered discounts or rebates, brand names, and space availability.
- When thinking about future water heater replacements, "future replacers" were more likely than "recent replacers" to think they would make the replacement decision on their own, would replace with the same type and size of unit, and would replace the unit themselves. However, 42% of these future replacers thought they would consider a different size (4%) or type (38%) than their current model.
- Few households had more than one kitchen sink (~10%). In many cases kitchen sinks didn't appear to be used very often (fewer than five hot water uses per day, as indicated by 33% of respondents). ~20% of households didn't have a dishwasher; 36% of those who had dishwashers ran them 3 or more times a week,
- We did not ask respondents how many bathrooms they had; instead, we asked for a count of bathroom sink faucets. There was wide variation in bathroom sink faucets (few had one bathroom faucet, ~35% had 2 bathroom faucets, and ~50% had three of more faucets somewhere in the house). Overall, hot water uses at bathroom and kitchen sink were similar.
- For almost all, the kitchen wait-time for arrival of hot water was one-minute or less. For a handful of SCG households, wait times for hot water arrival in the bathroom were slightly longer than in the kitchen.
- SCG respondents (26%) more often said they "rarely wait" for hot water than usually waited (22%) to arrive before finishing their kitchen washing-up. This contrasts to bathroom behavior where 20% of respondents "rarely" and 33% "usually" waited for the hot water to arrive.
- Regardless of relatively short wait times, many respondents finished washing-up before the arrival of hot water.
- To draw warm water, those with single-lever faucets most often set the handle to "full hot" then adjusted the lever (and the water temperature) after the hot water arrived; those with a dual-control faucet most often turn on the hot knob first then turned on the cold water tap to adjust the temperature. A small percentage of dual-control faucet-user

(~7%) opted to only use cold water at the kitchen and bathroom sinks. This latter finding may likely occur only in milder climates, such as California.

- The number of bathroom faucets varied, but few had only one while ~41% had 3 or more. Bathrooms with tub/shower combinations were common, as were bathrooms with only a shower (no tub). Bathrooms with only a tub were rare (and then only in homes with more than one bathroom), and fewer than 20% had bathrooms with separate tubs and showers.
- Overall, 13% of households used both tubs and showers while 87% took showers exclusively.
- Most respondents were satisfied with their current water heater performance (74% of rating were "excellent" or "good"). And nearly one-half (46%) of SCG respondents gave their current heater high ratings for cost of operation (another 27% said the cost was "adequate"). Overall, sufficient amounts of hot water were supplied without undue noise, and generally, at an acceptable cost.
- Most households (~80%) indicated that they have had discussions about not wasting water, while fewer (~60%) had discussed not wasting hot water.

Future Research

The following is a brief summary of topics addressed in our conclusions and recommendations regarding future research. Details for each may be found in the full report.

1) Improving the accuracy of consumer recall and reporting.
2) Improving sample generalizability to larger consumer populations.
3) Improving our understanding of the structure of behavior and choice.
4) Improving our understanding of consumption differentials.
5) Keep abreast on customer satisfaction on emerging efficient technologies.

5.2.1.1 Background and Methodology

In this opening section of the report, we describe the research process, methodology and samples, including an overview of goals and timelines. The overall purpose of the research was to develop a more detailed knowledge of residential consumer hot water usage patterns, practices, technologies, knowledge, and water heating technology choices. The primary approach used was a survey of current natural gas water heating customers in California. Two different samples were used in the research: a sample of Pacific Gas and Electric (PG&E) Company employees and a sample of Southern California Gas (SCG) customers in single family homes. Survey development took place during the summer of 2010 and data collection was completed in two waves in the Fall of 2010 and early in the Summer of 2011.

PG&E Process and Sample

We reviewed existing literature on residential hot water use and found them very limited in regards to the issues presented in the survey. We also reviewed prior surveys of residential customers and compiled initial lists of questions about equipment, behaviors and attitudes. Working with Davis Energy Group (DEG) and Gas Technology Institute (GTI) staff, we defined the primary research interests related to natural gas water heating equipment, dwelling characteristics, consumer knowledge of water heating technologies and sources of trusted advice, experience in managing and maintaining water heating equipment, hot water use practices, and experiences with and attitudes toward water heating technologies. Survey questions were developed and pretested among a small group. A paper version of the web-based survey was also delivered to the 18 customers who participated in the related DEG/GTI water heater field test. Feedback on the survey instrument was gathered from those respondents.

A version of the survey was developed for web delivery and was tested by DEG and GTI staff. Pacific Gas and Electric Company (PG&E) agreed to participate in the project by contacting a sample of Integrated Demand Side Management (IDSM) staff and asking them to voluntarily and anonymously participate in the survey. The PG&E web survey was launched on November 22, 2010 and closed several weeks later in mid-December. A total of 146 IDSM staff ultimately completed the survey.

SCG Process and Sample

For the Southern California Gas (SCG) survey, we started with the web survey instrument used for the prior PG&E IDSM employee survey. SCG company staff then suggested revisions and additions. The revised instrument was reviewed and tested by the research team and SCG, and invitation text was developed in conjunction with SCG staff and approved in early June 2011. Our target final sample size was 400 completed surveys.

The survey was launched on June 10, 2011 and closed on June 30th. SCG supplied a customer list from which invitations to participate in the survey were sent to 3,653 SCG customers assumed to be residents of single-family detached housing units on the basis of address information. Of that number, 197 invitations were determined to be undeliverable (non-existent email address, spam blocked, etc.). A reminder note was sent on June 21st to all of those who had not responded. By the close of the survey, 1,802 recipients had received but not opened their invitation email, and another 1,188 opened the invitation but did not choose to participate in the survey. A total of 466 customers started the survey, with 23 answering only a few questions before quitting, while another 43 answered a majority of the questions, and 400 customer households completed the entire survey. Table 55 summarizes the sample and disposition.

Our target sample size of 400 was exceeded by about 10%. The dataset that was used in the analysis contains 443 cases (all of the complete and mostly-complete cases). This represents 13.5% of the overall sample and a 28% response rate from those customers who opened their invitations.

Table 55: SCG Sample and Disposition

Total invitations sent	3,653
Undeliverable	197
Delivered but not opened	1,802
Opened invitation, did not start the survey	1,188
Started survey, but quit after a few questions	23
Completed a majority of questions, but quit before the end	43
Completed all survey questions	400

Comparison of Samples to Population

Social surveys commonly evidence biases because everyone selected in a sample may not complete the survey and everyone who starts the survey may not finish or may not answer all of the questions. If the non-responders are similar to the responders, there would be no sample bias. But because responders tend to be different in important ways from non-responders, it is important to try to understanding biases in survey datasets. We compared both the PG&E employee sample and the SCG customer sample to U.S. Census data. The differences between the PG&E employee sample and census distributions were striking, particularly along income lines. We also imagine that, as energy conservation professionals, PG&E employees are more aware of energy savings opportunities and are likely to be more willing to act upon them.[74] It would not at all be appropriate to combine the two samples, given these differences. As a result, we used the PG&E sample primarily as a pilot test of the survey instrument used to gather data from the more random SCG customer sample.

SCG Sample Comparisons to Census Data

Comparing the demographics of the sample to be used in analysis to census population parameters suggest that there are biases—specifically, biases toward higher incomes, a more Anglo and older aged sample. Further analysis is required to better identify these and other possible biases. However, the sample does seem generally representative of the SCG customer

[74] Differences between the PG&E and SCG samples are discussed in greater detail later.

population, with no particular groups strikingly under-represented. Here are some comparisons of the SCG sample to Census data.

Income

The median household income in the six most populated Southern California counties (not counting San Diego, since it was not in the sampling area) is about $57,000/year. The median income in the survey sample is about $75,000. So lower income households are under-represented and any attempts to generalize to the larger population should take that into account. However, a closer look at Census values for subgroups of homeowners and residents of single-family units is required, since these groups would be expected to have higher incomes. However, the ways in which census data are collected and reported do not generally report information on income and age differences between occupants of different housing types. While we did not conduct an exhaustive search of census source files, we have concluded that the effort would consume more time and resources than warranted with limited prospects for success. We know that our sample is biased, but we have reason to believe that the biases within single-family housing are somewhat smaller than suggested by a comparison of the sample to population income distributions.

Owner/renter Status

About 35% of all Southern California housing units are single-family detached units. The remainder includes du/tri/four-plexes, condos, townhomes, and apartments. The vast majority of the single-family detached units are owner-occupied (83%). In the survey sample, we focused primarily on detached units, screening out customers whose addresses included unit or apartment numbers. So we would expect nearly all of the surveys to have been completed by occupants of single-family detached houses. That was the case of 87% of the survey respondents, although a small number of others live in attached units. Duplexes/tri-plexes may vary little from detached units in terms of plumbing and technology options. Only 11 respondents claimed to live in buildings with 5 or more units, which was taken into account in the analysis. In the survey sample, 78% of the respondents are homeowners and 22% are renters, which is very similar to the mix of 83% owners and 17% renters of single-family detached units in the general population of Southern California.

Household Size and Age

Average sample household size of 3.3 members is very similar to the Southern California population average of 3.0 persons per household.

A comparison of percentages of respondents in the oldest and youngest age categories shows that about 38% of cases in the survey sample have members age 65 and older (vs. 22% of the population) and about 50% have children under the age of 18 (vs. 42% of the population). Our sample is both older and younger than the general population—something not too surprising since we're not trying to mirror the population as a whole, but the population of single-family detached (and largely owner-occupied) housing.

Race and Ethnicity

Table 56 shows that the ethnic diversity of the sample is similar to that of the population, with several notable differences. The survey sample is more Anglo (63% vs. 55% of the Southern California population as a whole) and less Hispanic (23% vs. 41%). Percentages do not sum to 100% and the Hispanic origin question is asked separately—i.e., we used the Census categories in the survey questions, asking persons to report race and Hispanic ethnicity separately, making it possible for a person to report being Hispanic and at the same time White, Black, American Indian, etc.

Table 56: Race and Ethnicity Comparison

Race / Ethnicity	Survey Sample	Southern California
White	63%	55%
Black or African American	9%	8%
American Indian	2%	1%
Asian	14%	10%
Pacific Islander	2%	<1%
Hispanic ethnicity	23%	41%

Knowledge and Interest

The SCG survey was drawn from a group of customers who opted to receive online information from the utility. Their interest in energy-related information may present a bias in terms of their awareness of water-related issues and knowledge of energy-efficient actions related to water heating. This bias cannot be confirmed without a general population survey for comparison of survey responses. Furthermore, as discussed above, this group is unlike the general population in the SCG territory across several demographic characteristics. Because of these issues, we obviously cannot recommend that SCG survey results be used to represent the general population of the service territory.

5.2.1.2 Findings: Summary of Responses in Key Topic Areas

In this section, we present a detailed analysis of SCG survey responses. We will not present a similar detailed analysis of the smaller PG&E survey. However, as noted above, in a later section of this report we present a broad comparison of the two samples, specifically pointing out areas where their response patterns are similar and where they differ.

Key areas to be summarized here include building and occupant demographics, domestic hot water (DHW) system characteristics, behaviors and usage reported, system replacement experiences and opinions, occupant assessments and experiences with current equipment.

Building and Occupant Demographics (SCG)

As planned, the majority of our SCG respondents lived in single-family homes, with 12% reporting that they live in non-detached homes (see Figure 113). [75]

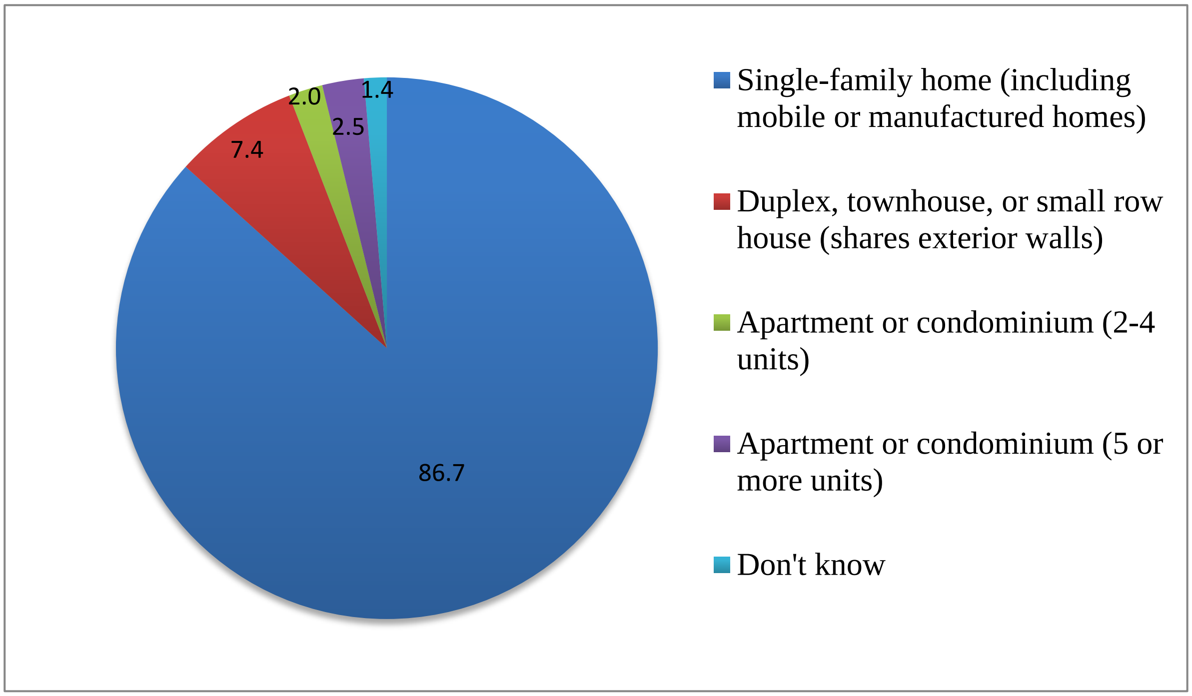

Figure 113. Dwelling Type (n=443)

Over half (60%) of SCG respondents had lived in their home for more than five years. About one-fifth each were newer homeowners (20% in their home for two years or less) and homeowners who had lived there for between two and five years (23%).

In terms of home style, the majority (60%) were one-story homes, followed by 38% two-story above ground and only 1% being three story residences. Most commonly, homes were

[75] The SCG customer file used for sampling did not differentiate between single-family detached and other types of housing units. We excluded any cases with addresses that would indicate an apartment number. However, there was no way to exclude attached units with unique numbered addresses. Therefore, a small number of households in attached units are included in the final sample, since housing characteristics should have little to do with many variables of interest, such as dishwasher or clothes washer use or shower/tub use.

constructed on slabs (60%), however 31% of respondent homes were on a foundation with a crawlspace, indicative of older home vintages. Six respondents (fewer than 2%) had a basement and 30 (7%) didn't know their foundation type.

As to be expected, most (75%) of homeowners reported living in older homes – 43% were 30 or more years old and another 32% were between 12 and 20 years old. A much smaller percent of respondents (17%) said their homes were built since 2000. 7% of the respondents did not know when their homes were built.

The size of respondents' homes varied considerably, as seen in Figure 114. Most (81%) of the homes had three or more bedrooms (half with four or more) while fewer than 3% had only one bedroom.

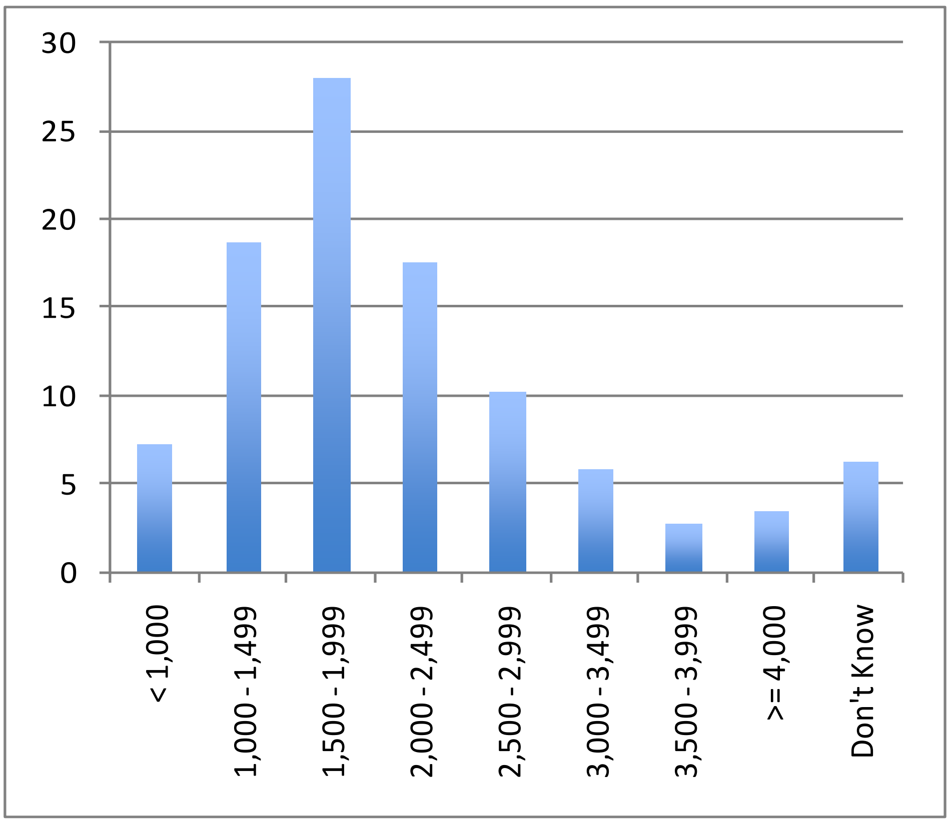

Figure 114: House Floor Area (square footage, n=443)

Hot Water System and Appliance Characteristics

In the next two sections of this report we first discuss reported water heating system types, followed by a discussion of homeowner decisions about, and installation of, water heater replacements. For visual reference, our online survey displayed pictures of typical tank and tankless gas hot water heaters.

Descriptions of domestic hot water systems were similar across the households in the SCG sample. Almost all (94%) had a "tank only" water heating system, however 28 respondents (6%) had tankless systems. Nine respondents (2% overall) had a combination system consisting of tank and tankless water heaters. As is often the case in California, the majority (73%) of homeowners reported tank water heaters located in the garage or outdoor closet. When located in the home, tank heaters are generally accessibly located in an interior closet or in the basement. However in three percent of cases, water heaters were less accessible (in attics or crawlspaces). A small number of respondents reported other, non-specific locations for tank heaters. Most (43%) of the 28 tankless heaters reported were attached to outside walls; another 29% were in garages or in outside closets and a few were located indoors (closet or attic). Only five respondents mentioned having solar water heating (two specified pool heating).

Over one-quarter (29% of 424 reporting) said they didn't know the volume of their tank water heater. Among 299 SCG respondents reporting water heater size, about three-quarters (221 or 74%) said they had a 40-50 gallon tank heater. Among the remaining households reporting tank volume, thirteen percent each reported having "less than a 40 gallon tank" or "over 50 gallon" tank.

As seen in Figure 115, about one-fifth of the homeowners didn't know the age of their tank water heater. Self –reports suggest that, like tankless models, almost all tank heaters are less than 10 years old. Most homeowners (72%) had never drained their tank heater to clear out debris. Although 50 homeowners (11%) had done so, another 13% didn't know if they had drained the tank or not. When homeowners do drain their tanks, about half do so regularly (from every six months to every two years); the other half had drained it once or twice. Magnesium anode rod replacements appear to be rare events – only nine homeowners reported ever doing this type of maintenance.

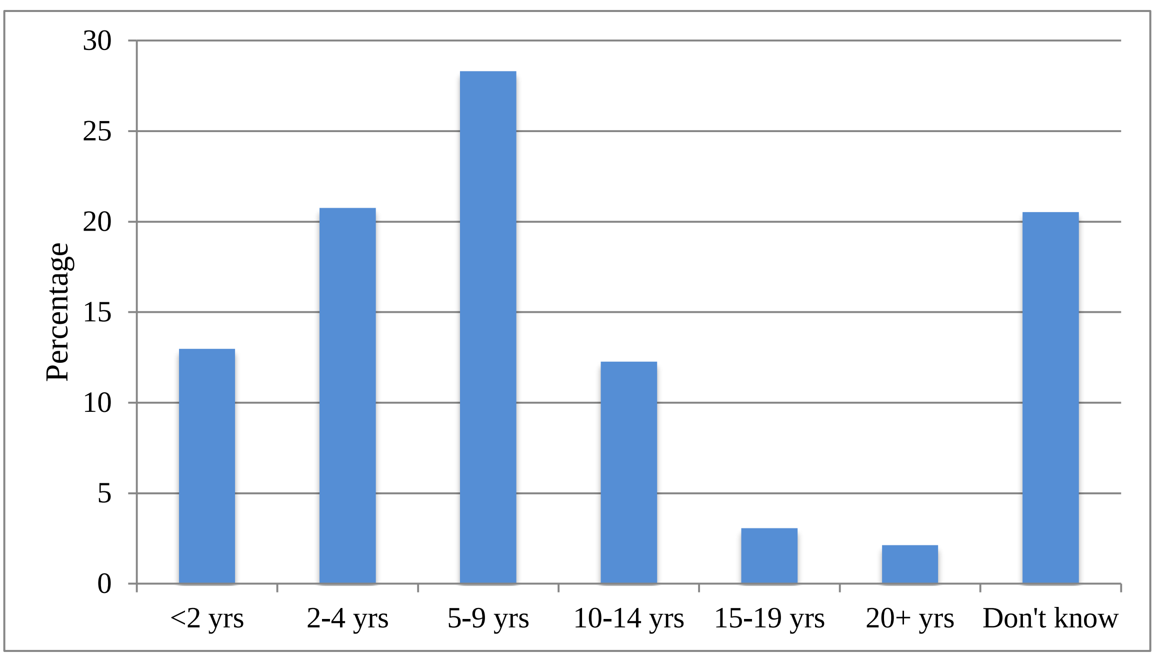

Figure 115: Reported Tank Water Heater Age (n=424)

In terms of customers' awareness of alternatives to tank water heaters, almost 50% were aware of tankless/on-demand water heaters. However, awareness of a broader range of domestic water heating options appeared to be low at the time of our SCG survey. Fewer than 10% of respondents were aware of condensing tank heaters or hybrid tank (tank and tankless combo) option; and fewer than 40% were aware of solar hot water heating.

Awareness of the presence of pipe wrap is also low among respondents – nearly half didn't know if their pipes are wrapped or not. Among those reporting on pipe wrap, just over 60% of these cases said their pipes were not wrapped while about 20% said they were wrapped "but only close to the water heater" and 20% said they were "entirely wrapped."[76]

The SCG survey also suggests that for many people, the location of water piping may be a bit of a mystery. Just over 25% of SCG respondents said they don't know where their water pipes were located. Among those reporting a location, over half said that their pipes were "mostly in the crawl space or basement" (30%) or "mostly in the walls" (26%). Overall, few (16%) said pipes were mostly in the attic. Recall that nearly two-thirds (263) of SCG respondents reported slab foundations. Among 196 of those with slab foundation reporting on the location of their water pipes, the majority (81%) thought that their pipes were "mostly in walls," "most in the attic," or "between floors," (respectively, 34%, 24%, and 22%). Less than one-fifth (18%) of those with slab foundations who reported a location thought their pipes were "mostly under the slab floor."

System replacement experiences and opinions

In the following section we'll summarize homeowner motivations for recent water heater replacements. Homeowners reported on who installed the new equipment, what influenced their choice of equipment, where the unit was purchased, and if the type and size of the new water heater was similar or different than the old model.

Recent Water Heater Replacements

Among respondents, few (57 or 17%) reported replacing their water heater within the past two years ("recent replacers"). A handful (10) of these households replaced the unit themselves while the majority had the new water heater installed by a plumber or other contractor. The majority of these replacement decisions were guided by a plumber or warranty company; however, twenty-two (40%) of these homeowners made the decision about which unit to buy on their own.

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[76] This estimate may just be representative of visible piping.

As seen in Figure 116, “recent replacers” reported that several factors were important when deciding on a replacement heater. Almost all of these homeowners considered energy cost (or energy efficiency); capacity and recovery time; the warranty period; and initial cost. Among “recent replacers,” somewhat fewer (roughly half) were also concerned with discounts or rebates; brand names; and space availability.

As we might expect, the majority of these households (86%) replaced the unit upon failure. The remaining households that replaced water heaters did so to upgrade to a more energy-efficient unit. Few households in this group mentioned replacing the unit as part of a house remodel or because the unit was old and rebates were available.

Over half the time (56% of the 57 reporting), the new units were purchased from a “big box” store such as Home Depot or Lowes. Alternatively, homeowners (15 or 26%) purchased their new heater from a “contractor supply house.” Among the ten remaining respondents, five mentioned purchasing through a plumber, three through a home warranty company, one person simply said the tank was “replaced under warranty,” and one respondent purchased their replacement tank at a used appliance store.

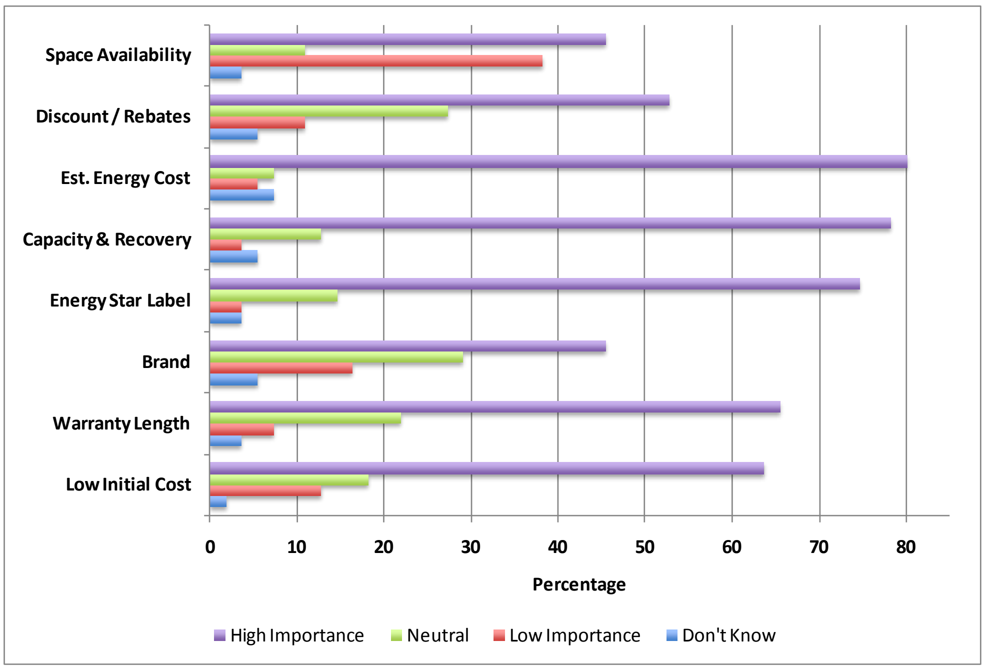

Figure 116: Importance of Factors in Water Heater Replacement Decision for Recent Replacers

Just under half of the time (47%), households that recently replaced a water heater opted to install the same type and size of water heater. Most of the other households put in the same type of water heater – installing larger volume units two-thirds of the time. However, a few (9 or 16%) of the reported replacements were of different type than the old unit – about two-thirds were high-efficiency (HE) tank type heaters and one-third tankless heaters. In only one instance was fuel switching reported, a switch from a gas to an electric water heater.

Future Water Heater Replacements

Similar to those who have replaced water heaters in the past two years, 85% of 290 responding homeowners who have not recently replaced a unit anticipated replacing it only when it fails. Among those (44) reporting they anticipate replacing the unit prior to failure, most (36) would do so to get a more energy-efficient unit. Very few mentioned insufficient hot water, a home remodel, or rebates as a reason for replacement prior to failure.

Homeowners thinking about a future water heater replacement also differed from those who made recent replacements in some interesting ways. Those thinking about future replacements were more likely than the recent replacers to say that they will decide which heater to buy rather than relying on a plumber's suggestion (76% versus 40%). In addition, these homeowners more often plan to replace the unit themselves compared to those who recently replaced a unit (respectively 33% versus 18%). And nearly 60% of homeowners currently intend to replace their current water heater with one like their current model (same type and size), a somewhat higher percentage than among those who made recent replacements (respectively 58% versus 47%).

Responses suggest that homeowners will consider a variety of options, in particular tankless/on-demand models. Consideration of tankless models was mentioned twice as often as the consideration of HE tank models, and three times more often than adding a solar system.

Among homeowners who have not replaced a water heater in the past two years (342), awareness of federal, state, or utility company incentives is relatively low for HE gas hot water heaters (30%) or solar water heaters (26%).

Appliances, Fixtures and Hot Water Usage Behaviors

In this section we discuss appliances, such as clothes and dishwashers, as well as fixtures in kitchens and bathrooms, and for each we explore how respondents used them. We start our exploration in the laundry.

Clothes Washing

The majority (63%) of the 435 SCG respondents reporting on this topic had top-loading washing machines. Just over one-third (35%) had front-loaders, and 3% did not have a clothes washer. The frequency of washes, using any one of the following categories of water temperatures, ranged from zero to 30 loads per week. Overall, households reported doing an average of 2.4 loads of laundry per week per person.

Figure 117 presents the breakdown of aggregated SCG household reports of 2,977 weekly loads of laundry (6.84 average weekly loads per household). Just under two-thirds of these loads were washed using the most energy-efficient method – that is, cold water for both the wash and rinse cycles (35%) or warm wash and cold rinse cycles (26%). The remaining loads, about 40% of the total, represented combinations of less efficient clothes washing cycles: hot/cold (13%), hot/warm (13%), warm/warm (15%) cycles.

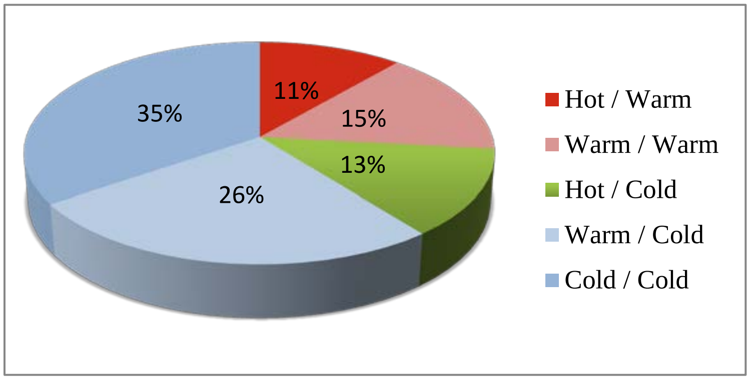

Figure 117: Percentage of SCG Reported Wash/Rinse Temperatures (n=435)

Water Use in the Kitchen and Bathroom Sinks

We asked respondents to report on their hot water use in the kitchen and bathroom, including number of faucets in each location, how often they are used in a typical day, faucet type, wait times for hot water, and how warm water is typically drawn. For visual clues, our online survey provided respondents with typical pictures of single-lever and dual-control faucets, low flow restrictors, and an aerator.

Faucets and Flow Restrictors

A large majority (87%) of SCG respondents had one sink faucet in the kitchen and another 10% had two kitchen faucets. About one percent each did not have a kitchen sink, didn't know the number, or had three sinks in the kitchen. Over three-quarters of the kitchen sink faucets (81%) had single-lever controls, 17% had dual-controls (2% didn't know the faucet type). One-quarter of kitchen sinks were reported to be without a faucet aerator and just over one-half (55%) were thought not to be "low-flow" (pictures of a typical aerator and flow restrictor were displayed in the survey).

Numbers of bathroom sink faucets ranged from zero (possible entry error) to 12, with one case each at the extreme ends of this range. In future studies, it would be useful to know the number of bathrooms in the home to better understand this wide range in reports. However, on average, these reports are likely to be accurate given that four faucets would be reported for a home with two bathrooms, each with double sinks with dual-controls. While conceivably accurate, the 13 cases reporting seven or more bathroom sinks could be miscounts that included tub and shower faucets in addition to sink faucets. As seen in Figure 118, multiple sink faucets were much more likely to be reported than a single bathroom faucet. Most often (35%) SCG respondents had two bathroom faucets (two sinks), but almost one-half of 424 reporting had three or four-plus bathroom faucets (23% and 26%, respectively).

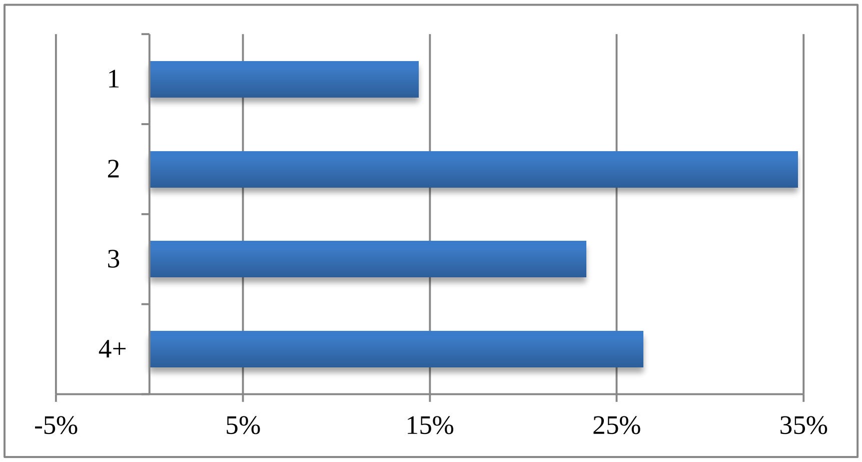

Figure 118: Number of Bathroom Sink Faucets (SCG, n=424)

Unlike in the kitchen, where the majority of faucets are single-lever, we found dual-control faucets to be the norm (only 40% of bathroom sinks were reported to be single-lever).[77] In contrast to kitchen faucets, more of the bathroom faucets were reported as not having aerators (25% versus 39% without, respectively). In all, just over one-half of bathroom faucets had aerators (53%) and were low-flow (56%). The remaining respondents reported not knowing about aerators (8%) or low-flow restriction (14%).

Kitchen and Bathroom Sink Use and Wait Times

We were quite specific in our instruction to respondents regarding how to report kitchen water use – in this case, "use" was defined in terms of "events." The survey instruction read:

A "use" as equal to one event or operation, for example hand washings (count each), breakfast dishes (1 event), other dishwashing (1 event each), miscellaneous clean up (1 event each time), etc.

As seen in Figure 119, kitchen and bathroom sink usage is quite similar. Two-thirds of the SCG survey respondents used kitchen and bath sinks 10 or fewer times during the day.

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[77] Dual-control faucets were presumed to be installed absent reports of single-lever handles.

Figure 119: Frequency of Hot Water Use At The Kitchen & Bathroom Sinks

	Kitchen Sink* (n=417)	**Bathroom Sink **** (n=417)
< 5 uses per day	33.3%	26.6%
5 – 10 uses per day	33.6%	40.6%
10 - 15 uses per day	15.6%	19.5%
15 - 20 uses per day	9.1%	7.4%
20 - 25 uses per day	4.1%	3.7%
> 25 uses per day	4.3%	2.2%
Total	100%	100%

* Counting hand washing, dishwashing, cooking, and meal preparations.

** Reported use data only for a single (most used) bathroom.

However, given our definition of use, it is worth noting that these percentages do not represent the number of actual water-draws occurring at these sinks. We did not attempt to collect this level of detail because of the high likelihood of recall bias.

Among 417 reporting on kitchen wait-times for the arrival of hot water, few (8%) said that they had a wait time of over one minute for the arrival of hot water at the kitchen sink (12 or 3% of this group waited more than 2 minutes). Bathroom sink wait-times for the arrival of hot water were similar to kitchen wait-times, however at bathroom sinks wait-times were somewhat longer with 12% reported one-minute or longer waits.

In Figure 120, we display respondent waiting behavior at the kitchen sink, specifically whether they actually waited for the hot to arrive or “sometimes finished washing before it really got hot.” A statistical reading of Figure 120 supports the view that there is a negative relationship between respondents’ behavior relative to hot water arrival times in the kitchen – that is to say, as hot water arrival-times increased, respondents were more likely to make the decision to wait for its arrival. The relationship between bathroom sink hot water arrival times relative to waiting behaviors were similar to those at the kitchen sink.

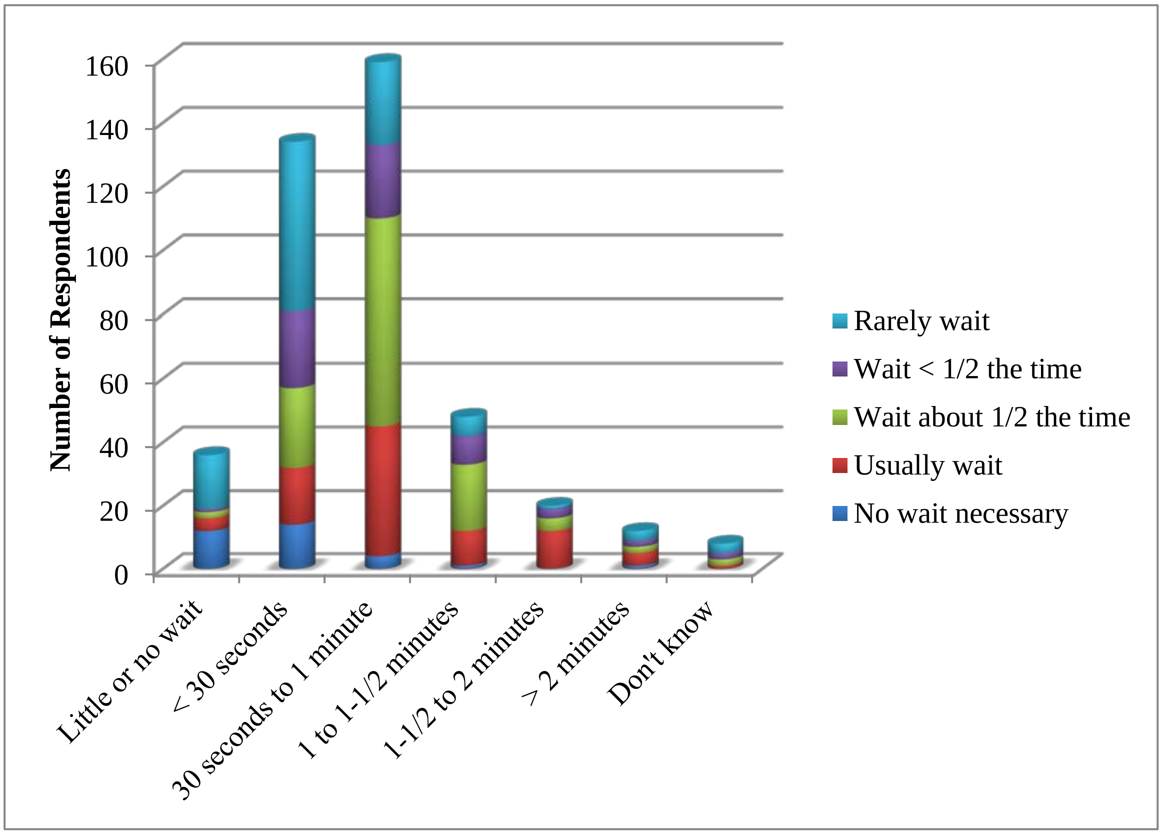

Figure 120: Kitchen Sink Hot Water Arrival Times by Waiting Behaviors (n=417)

Overall, we find it interesting to note that SCG respondents more often (26%) said they "rarely wait" for hot water than usually waited (22%) to arrive before finishing their kitchen washing-up. This is in contrast to the bathroom where 20% of respondents "rarely" and 33% "usually" waited for the hot water to arrive. The fact that a reasonable fraction of the population rarely wait suggests that they are happy using cold water, and ideally should not have even drawn hot water from the water heater.

Dishwashing Behaviors

This section and the next conclude our exploration of kitchen hot water use with a summary of dishwashing behavior and a discussion of how respondents position single-lever and duel handled faucets to draw hot water.

Just over 80 percent of 416 SCG respondents said they never or rarely fill the kitchen sink with warm water for washing dishes (respectively 46% and 35%). Most of the remaining respondents filled the sink for dishwashing once a day (with only 3% doing so more than once a day). Perhaps somewhat surprisingly, just over one-fifth (22%) of the SCG respondents said they let the hot water run continuously while washing or rinsing the dishes. About one-half (48%) let the hot water run "sometimes," while 30% never let it run during dishwashing.

In part, low levels of dishwashing in the sink can be explained by the high percentage (78%) of respondent households having dishwashers. Table 57: shows the frequency of dishwasher operations.

Table 57: Frequency of Dishwasher Use Per Week (7 days, n=416)

Frequency	Percent
I don't have a dishwasher	22%
Less than 1 time per week	19%
1 -2 times a week	23%
3 - 4 times a week	20%
5 - 6 times a week	13%
More than 1 time per day	3%

Those with dishwashers (323) also reported on pre-rinse behaviors, with all but 7% saying that they pre-rinse dishes prior to loading the dishwasher. About one-fifth of the respondents each pre-rinse dishes in hot water or cold water, while one-half pre-rinsed using warm water. A small remaining group (16) said they pre-rinse using various temperatures of water.

Drawing Warm Water from Kitchen and Bathroom Faucets – Single-Lever and Dual Handled

We asked people to think about how they used the single-lever faucets in their homes to draw warm water (in the SCG survey no distinction was made between kitchen and bathroom practices. Figure 121 shows that just under one-half (47%) of the cases respondents first set the lever to full hot, while the other one-half set the lever somewhere between full-hot and the middle of the hot-to-cold range.

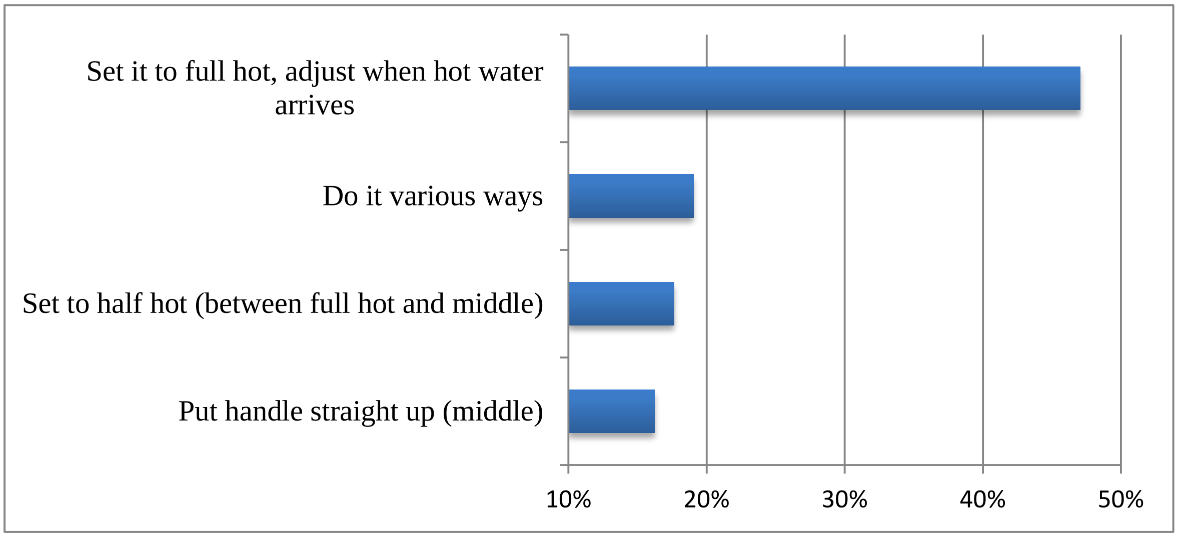

Figure 121: Single-lever Faucet Position To Draw Warm Water – All Locations (SCG n=362)

Warm water draws from dual-control faucets in the kitchen and bathrooms were reported separately for each location. From these reports it appears that faucet control practices may be engrained – become habit – because reported practices in the kitchen and bath were almost identical across dual-control fixtures (see Figure 122).

In the majority of cases when respondents wanted warm water they first turned on the hot water tap then added cold water after the hot water arrived at the sink (66% kitchen, 70% bathroom).

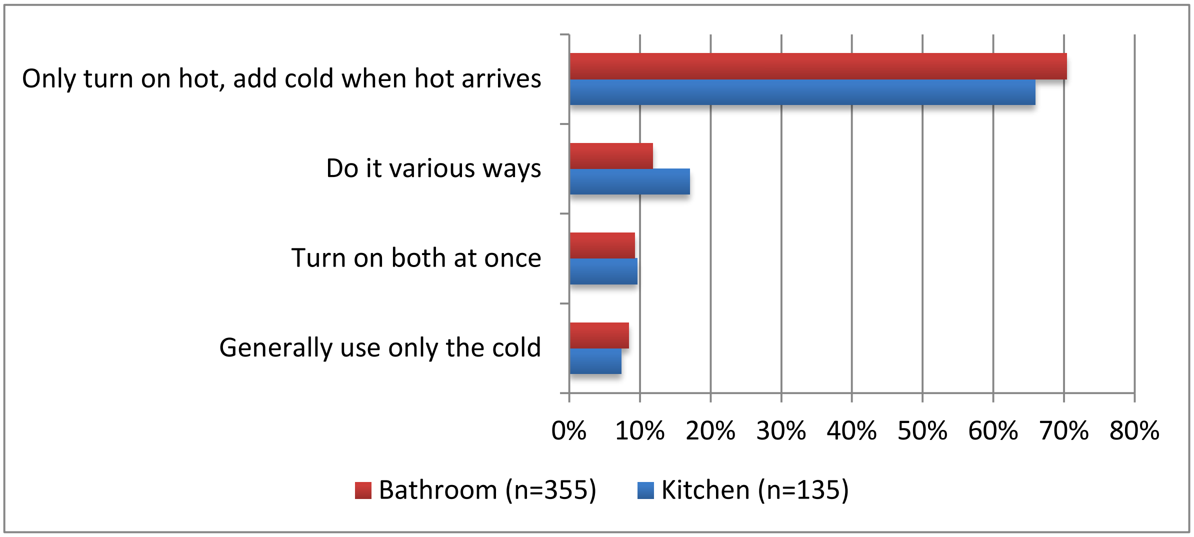

Figure 122: Dual-Control Faucet Position To Draw Warm Water (SCG n=375)

Of interest is the small percentages of respondents who "generally used only cold water" – seven and eight percent of respondents with dual-control faucets in kitchen and bathrooms, respectively. Our first inclination was to think that these households were most likely to come from those where the wait for hot water was quite long. We were only partially correct. Further analyses revealed that 43% (16 of 37 mostly cold water users) had little (under 30 seconds) or no wait for hot water in either location.

We found it interesting that two-thirds from each of the groups of respondents reporting on single-lever or dual-lever faucet practices ventured reports that other household members drew warm water from the two different styles of faucets in the same way the respondent did (approximately 54% the same, 9% differently). The remaining approximate one-third of respondents from each reporting group reported not knowing this level of detail about others in the household.

Tub and Showers: Types, Size and Behavior

We asked respondents to tell us how many of the types of tub and/or shower combinations they had. In all, 403 SCG respondents reported that they had 766 bathtub(s) and/or shower combination with the majority (52%) of households reporting two bathrooms. Similar percentages of these households had one or three bathrooms (respectively 19% and 16%), while a surprising number (57 or 14%), if accurate, reported having four or more bathrooms.

Table 58 displays the combination of bathtub and shower configurations reported in various sized homes. Fewer respondents report having bathrooms with "bathtubs only" or with "separate tub and shower."

Table 58: Number of Bathrooms by Percentage of Bathtub/Shower Combinations

	Types of Tub and/or Shower Combinations				
Number of Bathrooms	Tub with Showerhead	Shower Only	Separate Tub and Shower	Tub Only	Total
1	8%	1%	1%	0%	10%
2	24%	18%	6%	1%	49%
3	8%	7%	4%	1%	19%
4+	7%	6%	6%	3%	22%
Total	46%	31%	18%	5%	100%

Self-reports suggest that over one-half of the showerheads were "low-flow" – with 56% reporting low-flow for "separate tub and shower" configurations and 68% reporting low-flow heads on "tub(s) with showerhead" configurations."

Almost all (92% of 404) SCG respondent households had a standard sized bathtub (specified as 30" x 60"). Two-thirds (67% of 404) of these households had one standard tub, while diminishing percentages of the remaining households reported having between two and four standard bathtubs (an average of 1.3 standard bathtubs per respondent household). Ninety-two (23% of 404) respondents said they had a whirlpool or jetted bathtubs, with most (88) of these households reporting one jetted tub, however four households (two each) reported having two or three jetted bathtubs in the home. In addition, these respondents reported that 98 (@16%) of their bathtubs were "jetted or large-volume." [78]A summary of reported bathtub use is displayed

[78] In all, 404 respondents reported 497 standard-sized bathtubs and 98 "jetted or large-volume" bathtubs. Our calculations indicate that when SCG respondents reported on separate tub and shower combinations they recalled a total of 526 tubs; however when asked only about the number of standard and jetted tubs (497 and 98 respectively)

in Figure 60. As we can see, the majority (58%)of surveyed SCG households did not use their bathtubs. And reports revealed that jetted or high-volume tubs were used even less often than standard sized tubs (90% non-use vs. ~60% non-use). Across SCG households reporting bathtub use, the weighted average weekly use suggests that approximately 40% of those households use standard-sized bathtubs about four times per week. However, actual weekly use of any type of bathtub ranged from between .25 to 40 uses per household across the SCG respondents reporting use of bathtubs (use at the high-end of this range use reported by a seven-member family). Year-around, households with children under the age of seventeen report more use of their standard-sized tubs than do household with adults only.

Table 59: Seasonal Bathtub Use by Type

	Standard-sized Tub(s)		**Jetted or Large-Volume Tub(s)**	
	Summer (n=404)	***Winter*** (n=404)	***Summer*** (n=402)	***Winter*** (n=404)
Number Reporting Use	149	169	41	53
Average Number of Weekly Uses	4.1	3.7	3.6 (2.6 w/o high outlier)	3.0
Range of Weekly Uses	0.5 - 16	0.5 - 21	0.25 - 40	0.25 - 28
Percent No Bath Taken	63%	58%	90%	87%

* Weighted average among households reporting bathtub use.

Household Showering Behaviors

Next, we explore reported showering behavior (number and length of showers, and routine showering away from home that would tend to reduce home hot water use). To better understand the range in household showering activity, we asked respondents to estimate the weekly number of household showers taken at 4 varying lengths of time. In general, households appear to be able to report this level of detail, however in at least two cases the frequency of showers reported stretch the imagination. Both were dropped from our analysis as outliers (a 4-member household reporting a total of 360 showers on average per week and a 3-member

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this group reported on a total of 595 bathtubs. This difference may be due to recall error or may be accounted for by standard sized, jetted tubs. Future research should further specify the definition of whirlpool or jetted tubs.

household reporting 91 showers per week on average). Household showers ranged from between one to 75 times per week, with half of the households taking 13 or fewer showers per week, and the other half showing from 14 to 75 times. As we would expect, number of showers and the number of persons in the household are significantly correlated.

A total of 401 households reported showering activity across one or more of the time lengths specified – only two households reported no showering activity.[79] On average, households reported taking showers in two out of the four length-options; only 59 respondents reported household showers taken in all four periods. From these data we calculated the total number of household showers, average number of showers taken overall, and average numbers of showers taken per household at the various lengths of time. We estimate that, on average, each person took 4.9 showers per week (calculated using cases reporting both showering activity and household size).

Table 60: Showering Behavior by Length of Shower (n=401)

	Average Length of Showers			
	Less Than 5 minutes	***5-10 minutes***	***10-15 minutes***	***More Than 15 minutes***
HHs Reporting Shower Lengths	228	301	223	125
Weekly Average Per HH	6.2	8.4	6.6	5.0
Range in Weekly Showers	1 – 30	1 – 48	1 - 35	1 - 25
% of HHs Reporting No Showers in this Category	43%	25%	44%	69%

"HHs" = households

From the data displayed in Table 60, we see that a larger number of 5-10 minute showers are taken than are shorter or longer length showers. And showers in excess of 15 minutes are not the norm.

Across these households we found a wide range of variation in the amount of time members spent showering – on average 133 minutes per household per week or 8.8 minutes per shower. At the lower end of this range, one quarter spent between 4 and 50 minutes per week showering, and another one-quarter spent from 52.5 to 99.5 minutes per week showering. In the upper ranges, one-quarter of these households spent between 100 and 174.5 minutes per week

[79] 38 partial completes did not respond to questions this far along in the survey.

showering, while the remaining quarter spent 175 to 809 minutes per week in the shower (Figure 125 and Figure 126 provide additional details on the distribution of shower length per person per week and per shower, respectively).

Bathroom shower wait-times for the arrival of hot water were longer for more households than the wait-time reported at bathroom sinks. Twenty-eight percent of 404 SCG respondents reported a "1-miniute" to "more than 2-minute" wait versus 12% reporting a one-minute or longer wait for hot water at the bathroom sink.

Occupant Assessments and Experiences with Current Equipment

Even though the survey was quite detailed in terms of the data considered above, most households continued to the end of the survey, providing answers to an additional set of equipment-related questions. In this section we discuss respondents' ratings of current water heating equipment, reported temperature settings and adjustments made, estimates of annual cost for hot water, household discussions about hot water, and concern over wasting water.

In Figure 123 we see that with the exception of operating cost, SCG household were generally satisfied with individual performance criteria, as well as with the overall performance of their current hot water heating equipment.

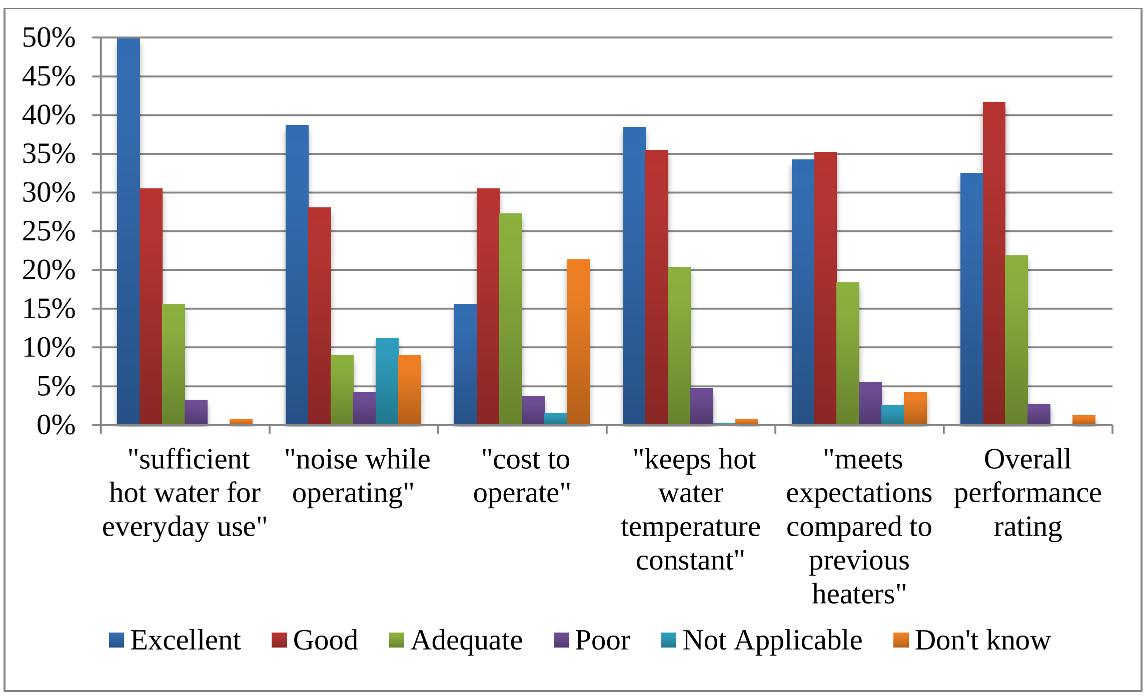

Figure 123: Satisfaction with Current Water Heater in Past Six Months (n=403)

Water Heater Temperature Settings and Adjustment Behavior

In addition to the other images we've mentioned above, the online survey also provided a picture of a typical gas water heater setpoint dial. To reduce survey length, we opted not to suggest that the respondent check their water heater setting prior to responding.

With 401 SCG households responding to the question, almost one-quarter (23%) said they didn't know the hot water heater temperature setting. Approximately one-third each said that it was "hot" (37%) or "medium" (30%). Small percentages reported "very hot" settings (4%), "low" settings (3%) or a specific temperature. Eleven respondents reported specific temperatures ranging from 115 to 140 degrees Fahrenheit (mean 121.4 degrees, median and mode[80] 120 degrees).

Respondents were asked if they ever changed the setting on the water heater, and few did. As seen from Table 61, most (76%) households reported never changing the settings and only 63 (16%) did so prior to going on vacation.

Table 61: When SCG Households Changed Water Heater Settings (n=403)

	Percentage
Never change HW Heater setting	76%
Vacation	16%
Higher in Winter than Summer	9%
When guests arrive	9%
Set back at night (routinely)	0.2%
Raise temperature prior to heavy use	0.5%

Also, a very large proportion of respondents (86% of 403) reported that they "never" adjusted or delayed using hot water to avoid running out. However, on a weekly basis ~6% (23) of these respondents reported making modifications in their hot water use to avoid running out of water. [81] Another 8% made some adjustments in hot water use "less than once per month." By way of follow-up, for less than half of the cases (20 of 48 reporting), making adjustments to avoid running out of water was more of an issue in the winter than the summer.

While most SCG households (63% of 402) reported that they never run out of hot water, nearly two-fifths had run out at various times in the past, including

[80] Mode is a statistical measure of the most common number reported.

[81] Of the 23 households reporting, nine made adjustment "about once a week," 10 made adjustments "2 - 5 times a week," and four households made adjustments ">5 times per week" to avoid running our of water.

- 19% during the winter when two or more people shower in a row (less of an issue in the summer, only 8% reporting this issue for that time),
- 17% when there are multiple demands at once (clothes and dish washing, or showers),
- 13% when there are guests or additional people in the home,
- 7% after someone takes a bath, or for
- 3% when the power went out.

In addition, few (25%) SCG households reported grouping hot water uses together to take advantage of hot water in the lines.

Overall, 62% of SCG respondents reported having none of the following devices: recirculation pumps, "rain" showerheads, showers with multiple showerheads, or water softeners. Only 2% (8 of 402 reporting) of SCG households had recirculation pumps that always run; another 5% (20) had recirculation pumps that run only when needed. "Rain" showerheads were popular with 17% (70) of these SCG respondents. [82] And few (11% each) had a shower with multiple showerheads or water softeners. None of these SCG respondents had hot water space heating.

The majority (71% of 397 responding) of the SCG households readily admitted that they "don't know" how much it costs them annually for heating hot water. The 115 households who ventured an estimate reported annual costs that range from $10 to $1700 per year.[83] On the face of this wide variation, we might suppose that people just don't have a very good handle on the cost of water heating. However, when number of persons in the household is considered (Table 9), we see that, on average, smaller households report lower annual estimates than larger households. This suggests that at least the small percentage (29%) of households venturing a guess had some understanding of the relative cost.

[82] In future research, "rain" showerhead should be defined. Our aim was to get an indication of the market penetration of deluge-type showerheads. However, this relatively high response suggests that respondents may have reported showerhead with lots of holes and more of rain effect vs a jet effect.

[83] The Davis Energy Group estimates that single-family households in California have annual average water heating costs of between $150 and $200.

Table 62: Estimated Household Annual Water Heating Cost (n=115)

Number in HH	Estimated Annual Cost	N Reporting
1	$167	16
2	$326	34
3	$248	19
4	$461	18
5	$438	14
6+	$512	14

Awareness of Water Use

The majority (80%) of 398 SCG households responding told us that household members have talked about saving water in general, but fewer (60%) have ever discussed not wasting hot water. Figure 124 displays household level of concern expressed over wasting water. In all, over one-half (56%) of the SCG households were "somewhat" to "very" concerned. In general, we found that lower income households were somewhat more likely to be concerned over wasting water than the higher income households, however the difference was not statistically significant.

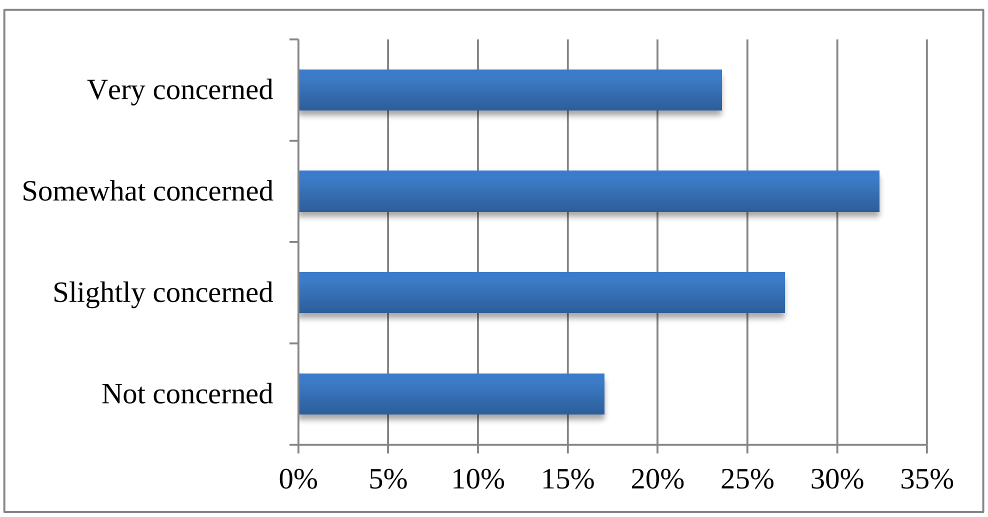

Figure 124: Level of Concern Over Wasting Hot Water (n=399)

5.2.1.3 Differences Across Respondent Subgroups

In addition to the analyses presented above, we compared the SCG and PG&E respondent groups on over two-dozen household characteristics. Cross tabulations were used to explore some of the similarities and differences between these groups using key demographic characteristics such as household composition, income levels, and age of adults in the household. In addition, we considered subgroup differences within the more robust SCG customer sample. We found that the two surveyed groups (PG&E IDSM employees and SCG customers) are quite different from each other in terms of income and race/ethnicity. They also differ across several home-related characteristics. Regardless, the two groups' hot water use is often similar, specifically in the kitchen where two-thirds ran water "usually" or "sometimes" continuously while washing dishes, and rinsed dishes in hot/warm water prior to loading in the dishwasher. The difference between the groups regarding making water heater adjustments may be explained in part by higher degrees of awareness of energy-efficiency practices among the PG&E staff. However, we cannot confirm these from the survey data.

Comparison of PG&E and SCG Samples

First listed in

Table 9 Table 63 are demographic characteristics, followed by a listing of home features. The table concludes with comparisons of awareness of hot water-related issues and hot water-related behaviors.

Table 63: Comparison of SCG and PG&E Respondents Across Demographic, Home/Appliance Characteristics, Awareness, and Hot Water-Related Behaviors (Bolded where Difference is Greater Than 10%)

Characteristic or Behavior	SCG Percent (n=397 to 443)	PG&E IDSM Percent (n=146)
Demographics		
Homeowner	78.1	72.8
Lived in home 5+ years	57.1	51.8
2009 Income in $100K-$125K range	12.0	20.8
2009 Income $125K or more	19.0	**43.8**
Hispanic origin	22.6	13.5
White/Caucasian	62.7	**79.2**
HH composition – Two or more adults plus one or more children	**38.1**	18.5 (65% reporting)
House / Appliance Characteristics		
1-story home	**60.9**	40.2
Slab foundation	**60.5**	49.1
Basement	1.4	**12.5**
Small home (1,000-1,500 Sq. Ft.)	18.7	27.7

Water heater in garage	**52.4**	37.5
Have a front loading clothes washer	34.5	**51.9**
Have tankless water heater	6.3	7.7
Awareness		
'Don't know' volume of tank heater	29.5	21.6
Heard of solar water heating	58.5	**85.2**
Heard of tankless water heater	74.9	**92.6**
Heard of condensing water heater	7.4	**34.3**
"Very" concerned about wasting hot water	23.6	18.8
Those who "*Don't know*" what water heating costs per year –	**70.8**	53.1
Guesstimated cost of water heating per year	$10-$1,700 ($349 on avg)	$25-$900 ($251 on avg)
Behaviors		
More likely to replace heater upon failure	84.8	84.1
Never run out of hot water	62.7	58.3
Let hot water run continuously while washing or rinsing the dishes	69.4	66.7
Pre-rinse dishes in hot/warm water	69.3	61.9
Actually wait for hot water in the bathroom	32.5	27.3
Actually wait for hot water in the kitchen	21.8	17.6
Percent of laundry loads cold wash & cold rinse	34.6	42.3
Percent of laundry loads hot wash & warm or cold rinse	24.0	16.6
Have a whirlpool/jetted bathtub	**22.8**	13.0
Avg. jetted bathtub use per week - winter	3.0	1.6
Most common shower length (minutes)*	5-10	5-10
Percent of all showers lasting *more* than 15 minutes	11.1	4.8
Never adjust or delay using hot water to avoid running out	86.4	78.4

Never change water heater temp settings	**75.9**	56.7
Change water heater temp while on vacation	15.6	**28.9**

* For more information on showering, see distribution of shower lengths below.

From this comparison, we can see that the SCG and PG&E IDSM respondent groups are quite different in terms of demographics. Overall, the PG&E respondents had higher incomes and were less racially diverse than the SCG group. The two groups also lived in different types of houses. The SCG group was more likely to have the water heater located in the garage and to have a jetted tub. PG&E respondents were more likely to have front-loading clothes washers and change the setting on the water heater, especially when on vacation. As we would expect, the utility employees were more familiar with hot water heater options and were more likely than the SCG group to venture a guess about their cost of heating hot water. Despite these differences, the two groups were very similar across most water-using behaviors.

Differences Between Demographic Groups within the SCG Sample

To inform marketing efforts, the following analysis takes a closer look at which households types were least aware of hot water heating options, which households replaced their old water heater with a different type of heater in the past two-years, and which households say they would consider buying a tankless hot water heater when they replace their current model.

Differences in Water Heating Technology Awareness and Attitudes

Table 64 shows technology awareness and attitude differences across demographic subgroups. Marketing efforts appear to have raised the general awareness of tankless hot water heaters – evidenced by 75% of SCG respondents knowing about this option. However, fewer (59% of 399) of these households reported being aware of solar water heating. Furthermore, comparison across demographic subgroups reveals that levels of solar water heating awareness varied among the 41% of all respondents who are unaware of solar water heating. The lowest awareness levels were found in minority households and among those with the lowest incomes (50-53% unaware of solar). The highest awareness levels were found among households composed of "more than one adult, without children" and in the highest income group (only 35% and 36% respectively being unaware of the solar option). Lack of awareness of tankless water heating options ranged from a low of 14% unaware within the highest income group to a high of 47% unaware among Asian respondents.

For 13% of the respondents getting "a more energy-efficient water heater" was a consideration during their recent replacement process (among other reasons such as unit failure). Among households with "more than one adult and no children" fewer (8%) than the overall average reported being motivated by the desire to get a more efficient unit. However, more than twice the percentage of Hispanics (29% compared to the overall average of 13%) reported replacing their water heater, in part, to get a more efficient unit.

Table 64 also shows that only 13 percent of SCG respondents reported replacing their water heater with a "different type of heater." This suggests a low level of innovation when it came to water heater replacements - households were much more likely to get another heater like the model being replaced. Willingness to innovate appears to be lowest among the lowest and middle-income groups, as well as among African Americans. On the other hand, the highest income group appears to have been the most willing (22%) to purchase a different type of replacement water heater in the past two-years.

The last four rows of Table 64 summarize SCG respondent subgroups' opinions about future hot water heater replacements. Overall, about one-third (32%) of respondents thought they would replace their own water heater. With the exception of Hispanics (44% likely to self-replace), most demographic subgroups within the SCG group reported similar percentages likely to replace a future water heater on their own. At this time, consideration of solar heating options (28%) lags considerably after consideration of HE tank models (49% overall).

Table 64 Awareness and Willingness to Consider New Technologies Varies by HH Composition, Income, and Ethnicity/Race (Percentage within Subgroup)

	Adults w/o children (n=163)	Adults with children (n=169)	< $50K (n= 106)	$50-100K (n= 109)	>$100K Hs-hold income (n=124)	Hispanic (n=90)	White (n= 250)	Black (n= 36)	Asian (n= 58)	**Overall**
Unaware of Solar (n=165 of 399)	35%	50%	53%	38%	36%	54%	36%	50%	53%	41%
Unaware of Tankless (n=98 of 399)	21%	30%	43%	20%	14%	39%	16%	31%	47%	25%
EE *part* of motivation in recent WH replace (n=53)	8%	18%	27%	0%	9%	29%	8%	25%	20%	13%
Replaced with diff WH type (n=53)	8%	18%	0%	0%	22%	14%	14%	0%	10%	13%
Likely to self-replace WH (n=258)	33%	32%	34%	37%	32%	44%	35%	30%	27%	32%
Would consider tankless (n=107)	93%	82%	83%	90%	87%	80%	93%	75%	92%	86%
Would consider HE tank (n=107)	62%	39%	61%	43%	46%	45%	51%	25%	54%	49%

	Adults w/o children (n=163)	Adults with children (n=169)	< $50K (n= 106)	$50-100K (n= 109)	>$100K Hs-hold income (n=124)	Hispanic (n=90)	White (n= 250)	Black (n= 36)	Asian (n= 58)	**Overall**
Would consider solar (n=107)	26%	30%	17%	27%	36%	25%	27%	13%	54%	28%

Percentages based on the number of respondents reporting in each category, not the total number in the subgroup listed in the top row of the table.

Willingness to consider tankless heaters, HE tank, and solar hot water heating options roughly mirror respondents' awareness of these alternatives. Consideration of tankless heaters during future replacements was high among all demographic subgroups. However, compared to the other demographic subgroups displayed in Table 64, African Americans may be less willing to consider other water heating technologies.

Percentages based on the number of respondents reporting in each category, not the total number in the subgroup listed in the top row of the table.

5.2.1.4 Consumption Patterns

In the final phase of our analysis, we looked at hot water consumption measures, including total household and per person patterns of showering, bathing, laundry hot water use, dish washing, and hot water draws at sinks. In the absence of metered water use data, we rely solely on self-reports. Future analysis could incorporate hot water volume and energy estimates for various end uses (showers of a particular duration, a dish washing cycle, a hot water wash cycle, etc.).

We present a series of histograms that show the distributions of cases across the SCG sample. The horizontal (X) axis records the magnitude of the variable of interest (e.g., total number of showers, reported, total minutes of showering, etc.). The vertical (Y) axis reports numbers of cases or percentages of cases found at each interval of the X-axis variable. We have removed a small number of outlier cases from several of the figures to improve the clarity of the display.

Figure 125 shows the distribution of total number of showers per week reported by SCG households. We can see considerable variation, from none to nearly 60 showers per week.

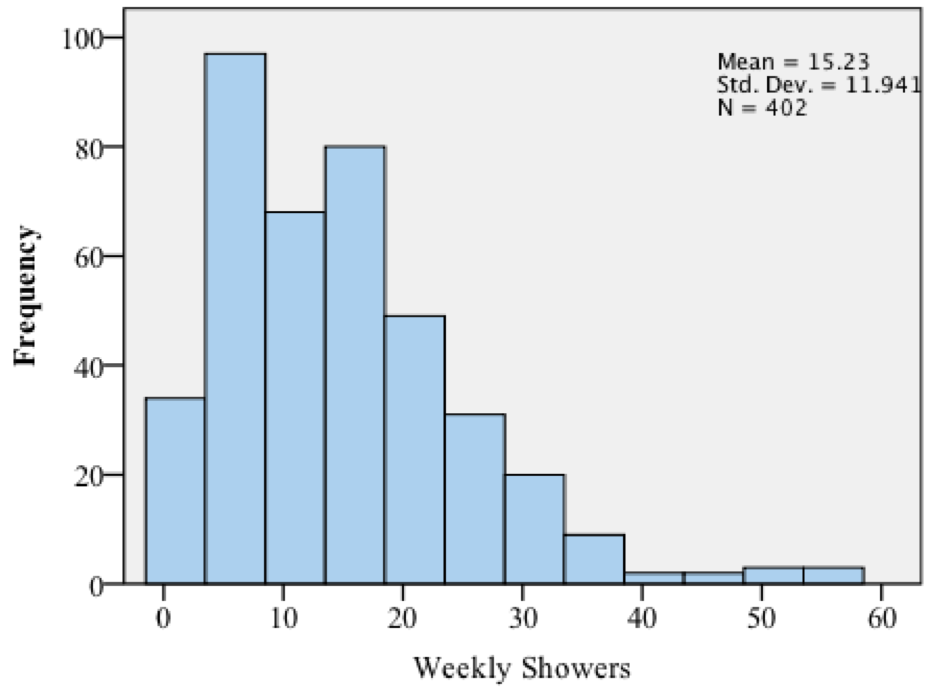

Figure 125: Total Number of Showers Reported per Household (per week)

Figure 126 displays the average numbers of showers taken weekly by those who routinely shower. We did not ask our respondents how many showers they take per day. However, if we assume that the 81% households reporting seven or fewer routine showers per week are taking no more than one shower per day, we might also assume that the remaining 19% of respondents are, on some occasions, taking more than one shower per day.

It is also interesting to consider the total amount of time reported showering per week by households and per person within different households. Recall that respondents were asked to report numbers of showers of different lengths. This information was used to construct an aggregate time-spent-showering estimate. The distribution of this variable is presented in Figure 127. It shows a considerable range, from only a few minutes per week to 600 minutes. The high-end reports may be valid (i.e., not respondent data entry errors), since they occur in very large households.

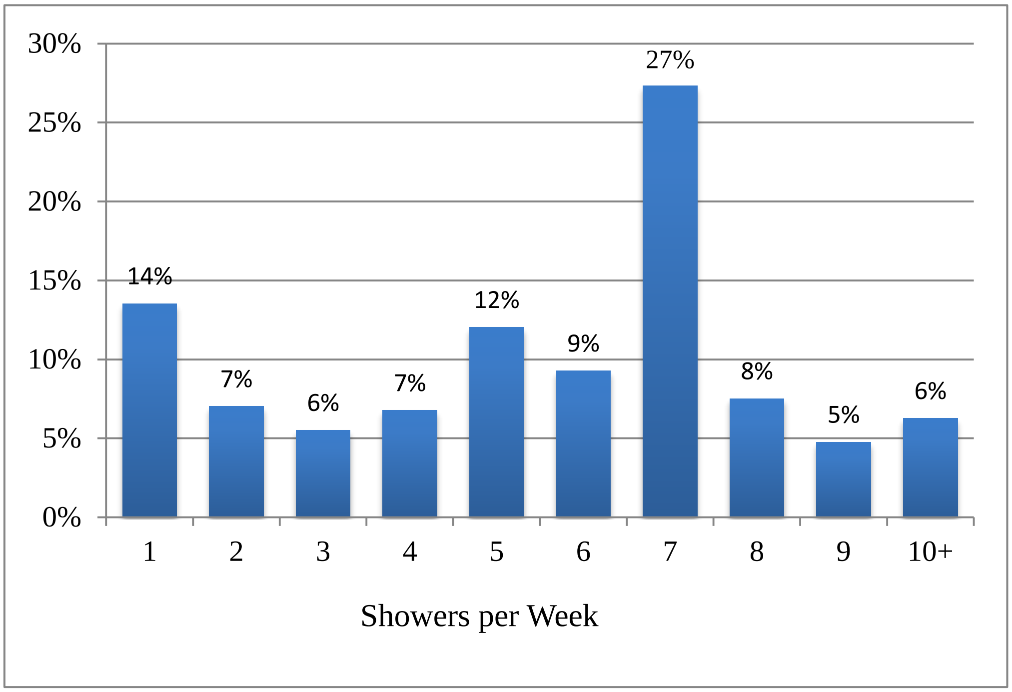

Figure 126: Distribution of Showers Taken per Person per Week (n=399)

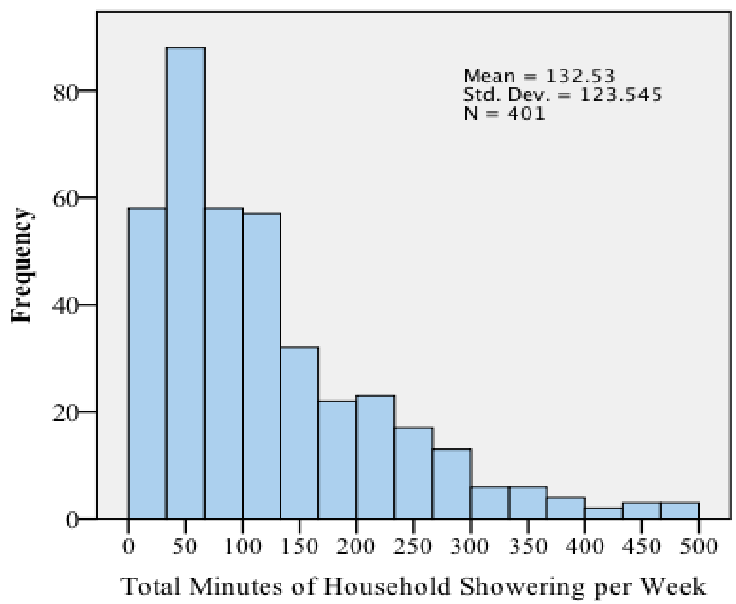

Figure 127: Distribution of Total Time Showering Per Week Per Household

In an effort to take household size into account, we also constructed a measure of total time spent showering per person within households. The distribution of cases for that variable is reported in Figure 128. Rather than simply explaining the variation in household total time showering by controlling for household size, this per person measure also shows considerable variation – from only a few minutes to several hours.

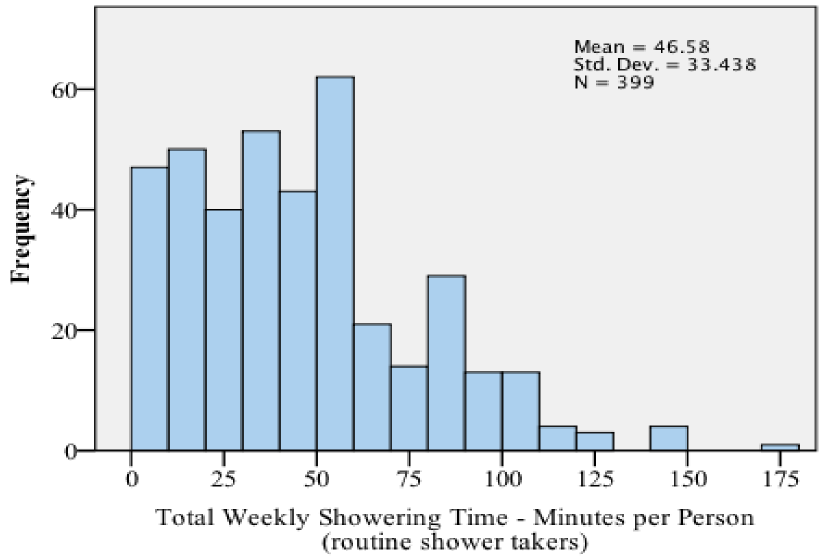

Figure 128: Total Weekly Showering Time Per Person

A more granular way to look at this information is to construct a distribution of average shower length for individuals within households (i.e., a different per person measure). The results are shown in Figure 129, which also displays a fairly wide range of shower times around a sample mean of ~8.5 minutes. [84]

We also explored the distributions of cases on the other major hot water usage categories, but do not report them here, since their incidence is relatively infrequent (e.g., bathing in a tub, dishwasher operations, sink draws). Clothes washing loads are somewhat more frequent and variable, but since many do not use hot water, their frequency is less relevant.[85] As a result, there is not a usefully wide range for this sort of analysis (the averages and some range information are reported earlier in this report).

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[84] Numbers of shower were reported for 4 general lengths of time: "LT 5 minute," "5-10 minutes," "10-15 minutes," and "GT 15 minutes." To calculate average weekly shower length, midpoints were first assigned to each period: 3.5 minutes, 7.5 minutes, 12.5 minutes, and 17.5 minutes, respectively.

[85] We do not display a distribution of clothes washing loads here because earlier in this report we presented a comprehensive analysis of laundry loads by water temperature.

We also performed exploratory analyses of all of the end uses, from showering and bathing to dish washing and sink draws, using a variety of statistical techniques that compared the incidence of hot water use behaviors across demographic subgroups (including income, home ownership, household age/size composition, and ethnicity). Our methods included cross-classification, comparison of means, and multiple regression. Somewhat to our surprise, we did not identify any significant differences between demographic groups (including the often-cited effects of children on household consumption). The analysis was not exhaustive, however, and further analysis may yet uncover better information on the sources of variation of hot water use in the sample.

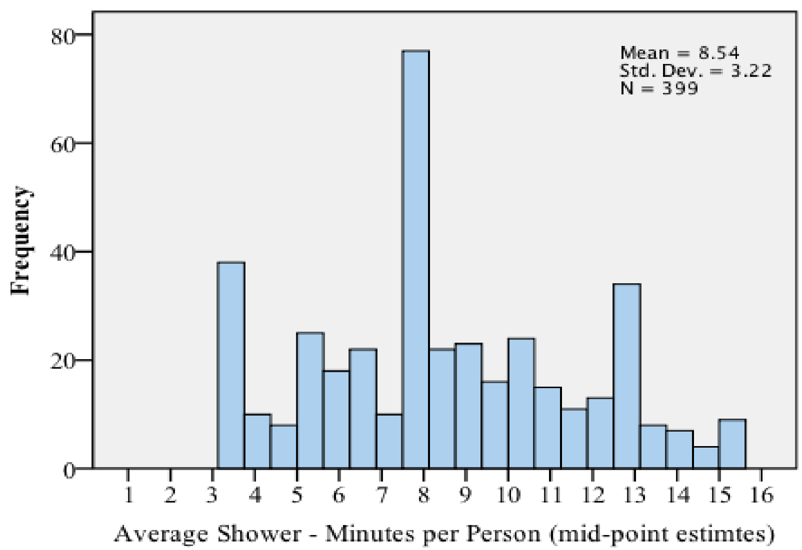

Figure 129: Average Length of Shower by Routine Shower Takers

5.2.1.5 Future Research

This research was a unique attempt to get a better understanding of routine hot water usage by residential customers. With little prior research to draw upon, the research team developed a serious of new questions to ask of consumers in relatively uncharted territory. The task was also challenging because, as in other types of residential energy end use research, the ultimate object of inquiry is invisible. Electricity and natural gas flows are hidden from view and only through periodic billing (monthly in this case) do consumers have any idea how much energy they are using, let alone for what purposes. Water use and hot water use are actually a bit more obvious, than, say, refrigerator energy use. But still they are buried in the realm of habit and the taken-for-granted. As such, they are difficult to recall and likely subject to considerable error in estimating water use at the sink or length of time showering for different members of the household.

To address at least some of these "invisibility" issues, and to assist respondents with the rather technical language used in the survey, our survey instrument provided several visual cues. Pictures of typical tank and tankless gas water heaters were imbedded in the online survey, along with pictures of typical single-lever and dual-control faucets, faucet water restrictors and, aerators.

At the outset of our project, all of the researchers (and supporters of this research) were confident that utility employees would be able to answer our questions about the more technical aspects in the survey. Specifically we expected them to be more aware than the "average" household of various hot water heating equipment options on the market and of the cost of heating water. However, we were less sanguine about general levels of knowledge related to water pipe locations, temperature settings, wait times, and the frequency of household hot water uses. The results of these surveys strongly suggest that people are able to provide useful information about their home's water heating technology and distribution system, as well as daily and weekly water use habits of household members. Results also suggest that innovative ways of communicating could be used to better support future inquires. Some suggestions are listed below.

Our data is far from perfect and all of our results should be interpreted with care. This is particularly true of any generalizations that the reader might want to make to larger populations and over-arching patterns of water use and persons' routine practices. With those caveats taken seriously (we hope), the survey nonetheless has broken new ground. It has also allowed us to consider future improvements in residential behavioral surveying that attempts to capture and measure aspects of hot water use. It also raises a set of new research questions that should be pursued in the future to continue to refine hot water end use models and to better inform hot water energy efficiency programs and policies.

The following are our conclusions and recommendations regarding further research:

1) Improving the accuracy of consumer recall and reporting. Further innovations in data collection instruments and approaches can be imagined:

    - An interview approach would lead the respondent through the house to imagine activities and count features such as numbers of tubs and sinks in different locations.
    - Something along these lines could also be developed for an interactive web survey. For example, asking first how many bathrooms the home has, then ask about the features and fixtures in each bathroom.

2) Improving sample generalizability to larger consumer populations. As an exploratory research project, our study used samples of convenience from which we cannot generalize with confidence. The limits of self-selected samples (e.g., utility employees, customers who have volunteered to receive email utility information) limit the modeling and customer communications and efficiency program options available to users of these data.

    - Randomly selected samples from the general consumer population would be more expensive to recruit, but would increase the usability of the data from future hot water surveys.
    - Larger and more heterogeneous samples would allow analyses in which hot water technology, use and decision-making patterns are more easily detected, and from which customer market segmentation typologies can be derived.

3) Improving our understanding of the structure of behavior and choice. It is clear from our preliminary analysis that simple demographic variables are not sufficient to explain the sources of variation in reported hot water use. Other factors (group dynamics, psychology, situational conditions and constraints) are at work. Also, more refined demographic measures may be required (e.g., employment status, finer distinctions in age and household composition).

   - Use depth interviews to inform future survey design and question selection.
   - Explore the use of alternative data collection methods to collect fine-grained data, including: diaries, cell phone polling, and online focus groups.

4) Improving our understanding of consumption differentials. What are the implications for actual hot water demand and natural gas consumption of the behaviors and choices reported by survey respondents?

   - Use existing data on measured hot water use and survey self-reports collected in the early stages of this study from 18 households to explore the alignment (and misalignment) of self-reports and actual demand.
   - Use data from new unobtrusive measurement technologies in conjunction with improved surveys in a larger sample (e.g., 100) of households to determine accuracy and estimate error tendencies of self-reports, and to identify the actual consumption implications of different hot water use practices, technologies and retrofit/replacement choices.

5) Keep abreast on customer satisfaction on emerging efficient technologies. New technologies are gaining market share and assessing customer acceptance will be an important effort moving forward.

   - The IOU's should follow up with customers participating in rebate programs to assess both short term and long term satisfaction, reliability, and maintenance needs.
   - Periodic focus groups should be held with plumbers to gather their perspectives on technology implementation issues and customer satisfaction.

5.3 Single Family Construction Plumbing Layout Practices Survey

5.3.1 Background and Objectives

The efficiency in delivering hot water from the water heater to the use points in a home is dependent upon many factors including:

1. hot water usage characteristics (loads magnitude, profile, flow rates, and end use temperature);
2. the configuration of the hot water distribution system (HWDS);
3. piping installation issues (layout, pipe material type and diameter, insulation);
4. location of hot water piping (garage, underground, crawlspace, basement, exposed to attic air, buried in attic insulation, between floors, interior or exterior wall cavities);
5. location of hot water fixtures relative to the water heater(s);
6. pipe environment temperatures;
7. water heater setpoint;
8. patterns of use of individual fixtures; and
9. recirculation system design and controls (if installed).

Clearly characterizing HWDS thermal losses is a complicated issue requiring both validated simulation tools and accurate specification of the above parameters. Collecting a representative sample of data in some of these areas will be very challenging. The focus of this study revolves around better understanding how HWDS are configured in new California homes (in terms of pipe materials, length, diameter, location). From that viewpoint, this study addresses issues 2-5 identified above.

New homes being built in California have more amenities and are typically larger than homes built twenty to thirty years ago, although the house size trend has reversed to an extent with the housing market downturn. Another trend that has been occurring is an increase in the number of hot water consuming fixtures. Homes with three or more bathrooms (and multi-sink vanities) are increasingly common. More use points, high flow rate fixtures, and increased house size all contribute to more and larger diameter hot water piping in new homes. This has implications both in terms of energy usage (greater heat loss), customer satisfaction (longer hot water wait times), and water waste (more entrained water is dumped before hot water arrives at the fixture).

To better understand how hot water distribution systems (HWDS) are being installed, Amaro Construction and Davis Energy Group completed a field survey of new production homes throughout California. The goal of the survey was to quantify the HWDS plumbing layout in these homes and also to try and gather anecdotal feedback from plumbers and building superintendents on industry trends. This work builds on a 2006 field survey of sixty California production homes that is presented in a 2008 PIER report (Lutz, 2008). A summary of the survey plan is included in **Error! Reference source not found.**.

In this study we have characterized HWDS as one of the four following types:

- conventional trunk and branch (either copper, PEX, or CPVC)
- PEX parallel piping systems with a single central manifold feeding either 3/8" and ½" lines or exclusively ½" lines which serve individual use points
- Hybrid systems (a variation of the trunk and branch system that includes elements of a trunk and branch system as well as in-line mini-manifolds, which are located along the trunk lines to serve groupings of use points.
- Recirculation systems (a central loop with a pump and controls that activate pump operation based on either a timer, temperature input, or a demand- initiated signal)

5.3.1.1 Field Survey Methodology

The goal of the field survey was to gather a snapshot of current HWDS installation practice in California production homes. Although not intended to be statistically significant, the survey effort does capture current industry trends and installation practices.

Unlike the 2006 survey fieldwork, which took place during an extended California construction boom, this field work occurred from late 2009 through late 2011, a period during which the California housing market was severely depressed. Despite increased difficulty in finding homes we strived to gather sites from a broad geographic area and from as many plumbers as possible. In addition, extra efforts were made to find sites that fell into the four HWDS types.

The majority of the construction sites where the surveys were undertaken had on-site model homes, however in the current streamlined environment there were often no sales staff or construction superintendents available on-site. In some cases we could obtain floor plans either from a sales brochure or via the Web. In other cases, we would have to draw out approximate floor plans as part of the survey process, and then document the plumbing layout on the hand drawn floor plan.

The key element of the survey process involved measuring every section of installed hot water piping in the home with a tape measure.[86] Additional data collected included pipe material

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[86] A pipe section is denoted as a unique combination of pipe material, diameter, pipe location (e.g. attic, garage, etc.), and insulated or not.

type, diameter, location, and the presence of thermal insulation. The location of major components such as the water heater, trunks, manifolds, etc. were sketched on the floor plan. Pictures were also taken to document site observations including installation quality, hot water use points, underslab plumbing, pipe locations, and bundling of tubing.

All recorded lengths reflect actual installed piping measurements, with two exceptions. Since water heaters were typically not yet installed, an additional 1.5 feet of length was added to the as-built measurement to account for the piping from the garage stub-out to the water heater. Also, an estimated length of pipe was added for sinks, dishwashers, and clothes washers to represent the final length of piping to the use point.

For central manifold systems, the measurement of the main line from the water heater to the manifold terminated at mid-height of the manifold. An additional volume was added to account for the larger internal manifold diameter relative to the main line .

5.3.1.2 Results

The 97 houses surveyed included installations from 20 different plumbing contractors. Sites were geographically located as described in Table 65. The majority of the sites were located in climate zone 12 (greater Sacramento area), with a significant number in the inland Los Angeles area. Figure 130 plots the three key areas where sites were concentrated.

A condensed summary of key information by site can be found in **Error! Reference source not found.**.

Figure 131 plots the conditioned floor area for the surveyed houses relative to the sixty houses surveyed in the prior PIER study. Conditioned floor area averaged 2,119 ft2, or 13% less than the 2006 dataset. Fifty-five percent of the houses were single story (average floor area equal to 1,844 ft2) and 45% were two-story (average floor area equal to 2,480 ft2). On average there were 2.42 (vs. 2.84 in 2006) bathrooms per house and 11.66 hot water use points [87] (vs. 12.85 in 2006). Figure 132 and Figure 133 plot the bathroom and use point data as a function of floor area.

[87] Combination tub/shower was treated as two use points.

Table 65: Site Location Summary

Climate Zone	Number Of Sites	Location
7	2	Carlsbad, Chula Vista
8	3	Yorba Linda
10	29	Menifee, Temecula, Moreno Valley, Beaumont, Murietta, Poway
11	10	Roseville, Rocklin
12	35	Folsom, El Dorado Hills, Rancho Cordova, Davis, Manteca, Livingston
13	19	Bakersfield, Fresno
15	1	Palm Desert

Figure 130: Location of Survey Site Concentrations

<img src="http://www.digital-topo-maps.com/county-map/california-county-map.gif">
Map Courtesy of Digital-Topo-Maps.com

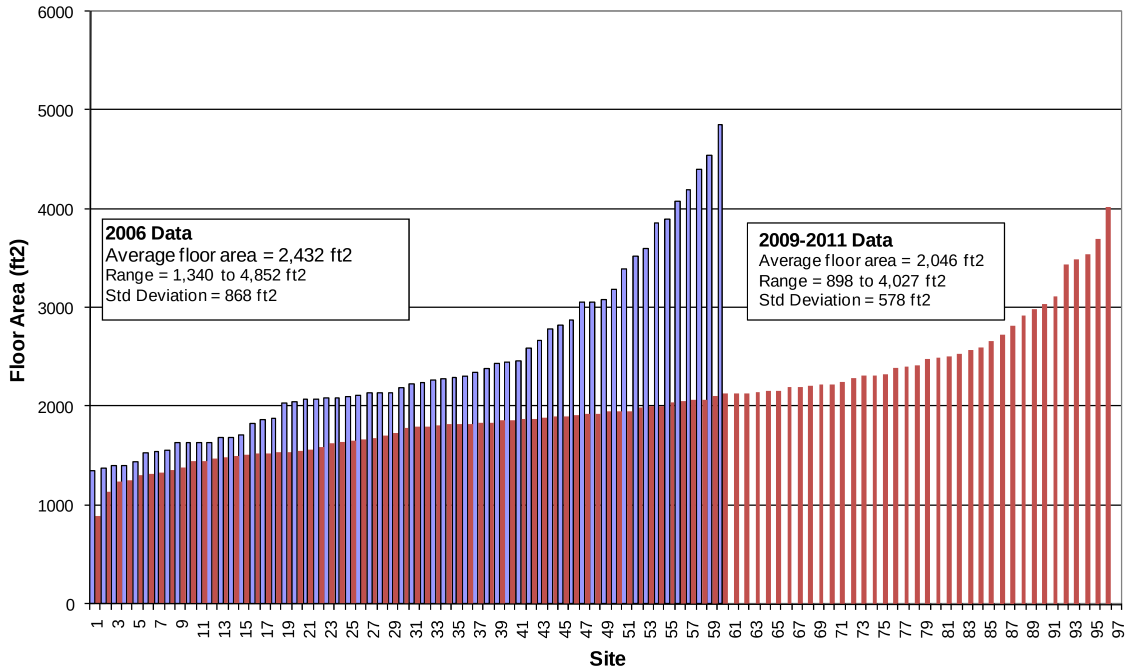

Figure 131: Comparison of Survey Site Floor Area (2006 vs 2009-2011)

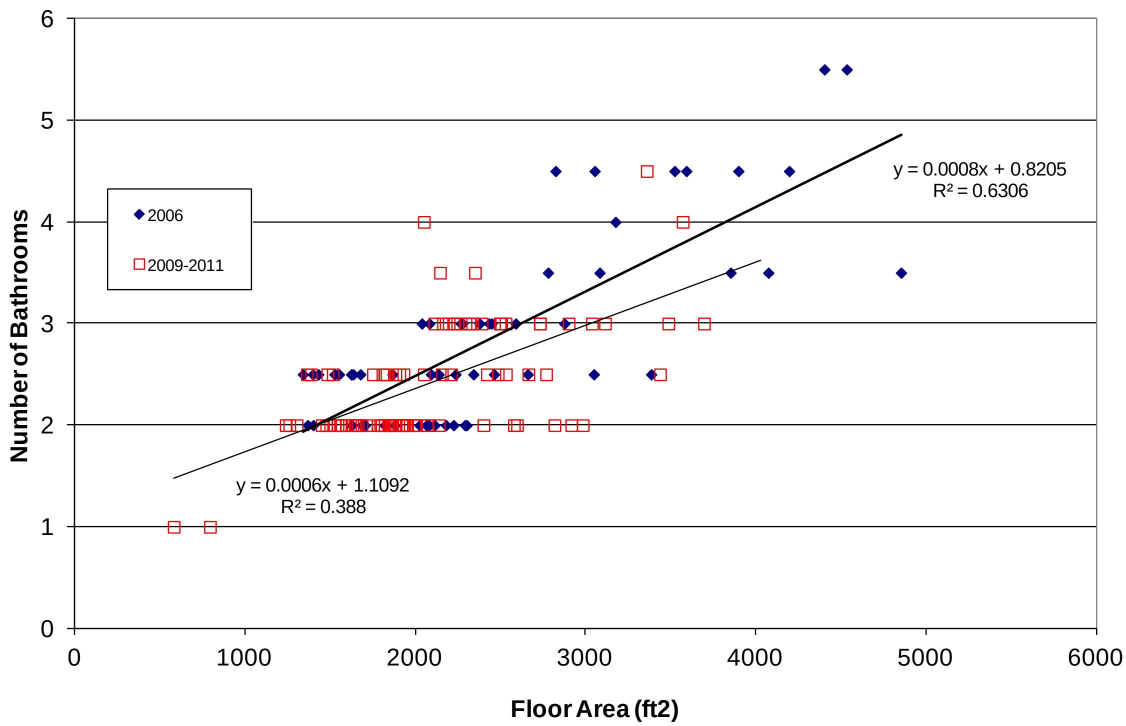

Figure 132: Comparison of Number of Bathrooms (2006 vs 2009-2011)

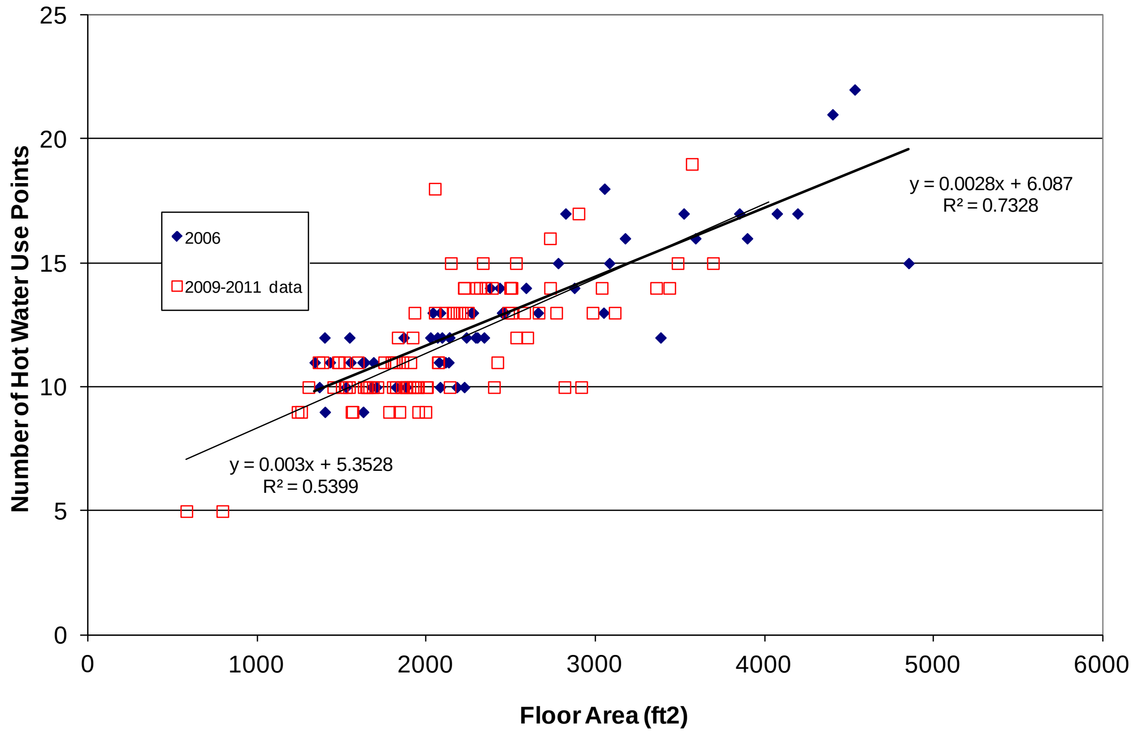

Figure 133: Comparison of Number of Hot Water Use Points (2006 vs 2009-2011)

The primary plastic piping material seen in California in recent years is cross-linked polyethylene piping (PEX), although CPVC pipe also was found to have a small market presence in recent field plumbing surveys. California's statewide acceptance of PEX in the California Plumbing Code in 2009, the rising cost of copper over the past ten years, and ongoing concerns over liability due to solder joint failures and pipe pitting have been the primary factors leading to the widespread use of PEX. Plastic pipes have other apparent non-cost advantages over copper, with a primary benefit being that for a given nominal pipe size, the plastic pipes have considerably less entrained volume per 100 feet of pipe length. Figure 134 plots the entrained volume in "gallons per 100 feet" for copper (type L and M), PEX (SDR 9), and CPVC (SDR 11). An additional relationship to look at is the relative volume of smaller to larger diameter piping. Relative to ½" PEX, ¾" PEX contains nearly twice the volume per foot, and 1" PEX contains 3.25 times as much. The entrained volume of water that remains in a pipe after a hot water draws is one indicator of energy and water waste associated with the distribution system. As a general rule, the larger the entrained volume to a use point, the greater the energy waste, water waste, and hot water wait time.

Somewhat counter intuitively, plastic pipe has been found to have higher heat loss than copper pipe. The primary explanation for this is plastic pipes emit higher levels of radiant heat than other forms of pipe. Plastic pipes have high surface emissivities of roughly 0.90, while copper often has a much lower emissivity, with values as low as 0.02 for shiny new pipe, and as high as 0.78 for fully oxidized pipe. Another complication for in-situ heat loss is whether the pipe is exposed to the thermal environment. For example, PEX piping buried in attic insulation wouldn't exhibit the higher radiant heat transfer that is observed if the pipe is "in air".

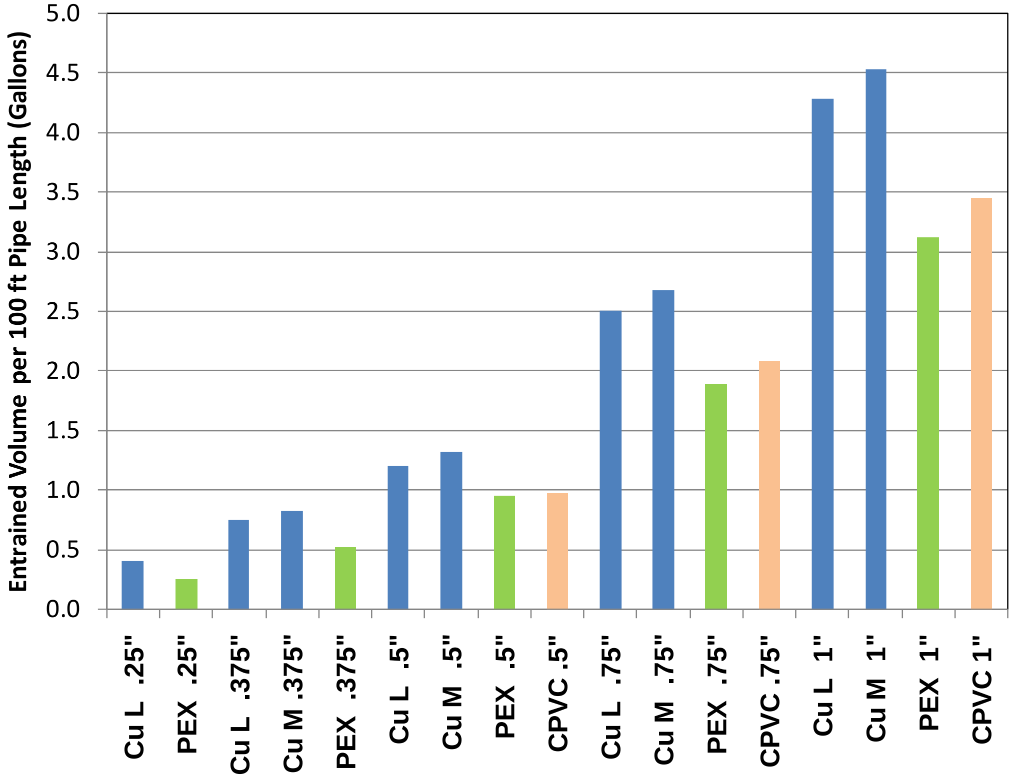

Figure 134: Entrained Pipe Volume Comparison- Copper vs. Plastic Pipe

Of the 97 surveyed sites, all but ten sites used primarily PEX piping. Six of the remaining ten used copper. The six sites were from two different projects. Four remaining sites used CPVC in a locality where PEX did not have local approval at the time of permitting. (Since that time other nearby projects in the same town were using PEX piping.) Copper piping was more prevalent in the 2006 survey, especially in Southern California. This no longer appears to be the case, and the expectation is that high copper prices have essentially priced copper piping out of the production home market.

Table 66 summarizes the observed hot water distribution systems. The system types are distinguished between trunk and branch, home run systems with a central manifold, hybrid systems, and recirculation systems. Hybrid systems are characterized as systems that combine manifolds with trunks that the feed individual manifolds. One example of a hybrid system is represented in Figure 135. In this example, a single trunk line feeds three manifolds which each serve a different part of the house. The first two manifolds are fed with a 1" line, with the last manifold fed by a ¾". These types of systems were the most commonly observed. How these systems are laid out is of primary interest, since there are many possible combinations.

Table 66: Observed HWDS Types

System Type	Number
Conventional Trunk and Branch (rigid pipe)	24
Home Run Central Manifold (PEX)	3
Hybrid Systems w/ PEX Piping	63
Recirculation Systems (copper)	7

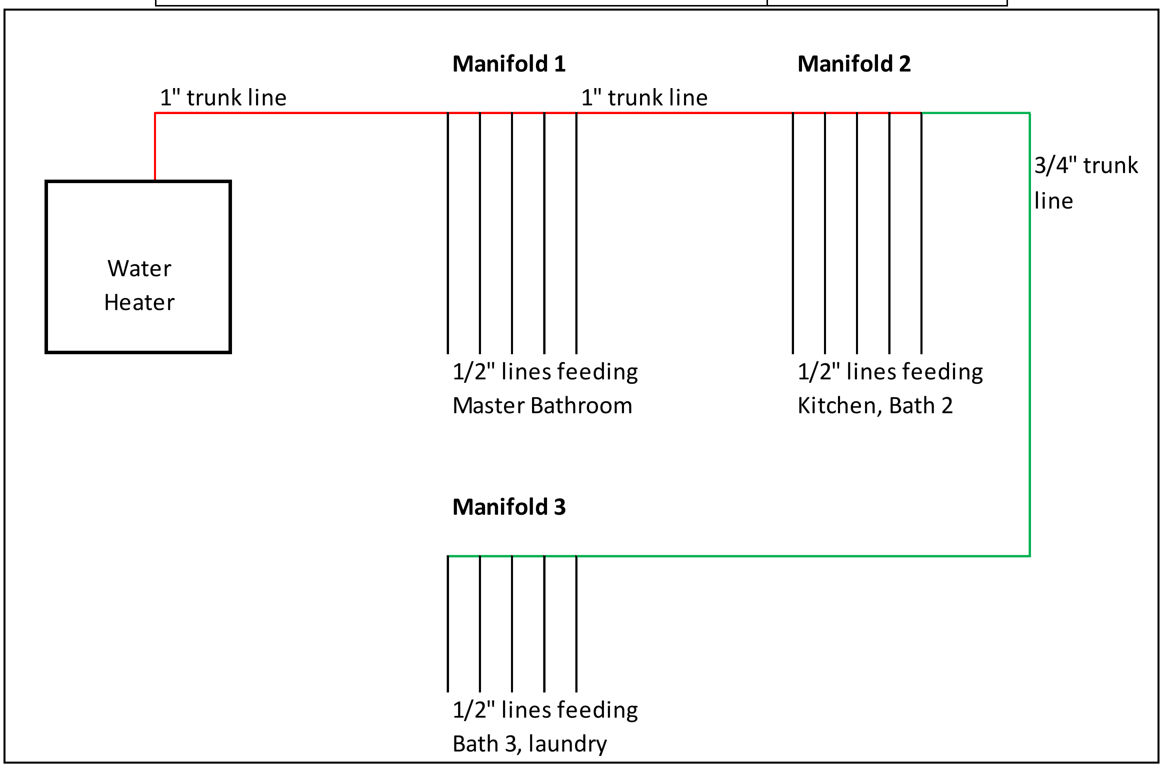

Figure 135: Hybrid System Example Layout

Table 67 reports the average volume of water entrained in the piping between the water heater and all the end use points for the different HWDS types. This metric is used to characterize the efficiency of the HWDS system, realizing that it only represents one performance aspect of the system. Different HWDS types react very differently to load patterns and usage levels, with simulations or field measurements being the only approach to quantifying performance. For example a demand recirculation system may have a larger entrained volume than a corresponding trunk and branch system, however the control operation and use patterns result in a more efficient distribution system.

Table 67 "average volume" values are dependent upon the configuration of the house, the size of the house, and the sizing and layout of the HWDS. The normalized "per 1000 ft^2" entry removes floor area differences between the samples. Conventional trunk and branch was disaggregated into rigid pipe (copper and CPVC) and PEX to determine if there might be a difference attributed to the piping material. This was not discernible, although the sample size is small. Interestingly, the hybrid systems and recirculation systems also demonstrated "per 1000 ft^2" average volumes very close to the conventional trunk and branch systems. Home run systems were the smallest volumetric system, although the sample was only three sites.

Table 67: Average Entrained Hot Water Volume to End Use Points

System Type	Number of Sites	Average Volume (gallons)	Average gal/1000 ft^2 of Floor Area
Conventional Trunk and Branch (rigid pipe)	6	0.78	0.47
Conventional Trunk and Branch (PEX pipe)	18	0.91	0.48
Home Run with Central Manifold (PEX)	3	0.54	0.29
Hybrid Systems (PEX)	63	0.97	0.45
Recirculation Systems	7	1.18	0.43

Table 68 compares the Table 67 findings to the sixty home surveys completed in 2006. The conventional trunk and branch, and hybrid systems look very similar (on average) between the two datasets. The 2012 home run sample is considerably lower than the 2006 finding, but the small dataset (only 3 sites) makes it difficult to draw any conclusions[88]. Recirculation systems surveyed were also found to be considerably smaller than those surveyed in 2006. The amount of 1" pipe (as part of the loop) was considerably less in the 2012 sample, which would certainly influence that result. Again, with the small sample, it is not easy to determine precisely what is happening with these installations.

[88] The 2008 Title 24 Standards limit the water heater to manifold distance to 15 feet maximum length. All three surveyed sites met that critieria, while the 2006 sample averaged over 20' in length.

Table 68: Comparison to 2006 Findings

System Type	Average gal/1000 ft² of Floor Area	
	2006	2012
Conventional Trunk and Branch	0.49	0.48
Home Run with Central Manifold (PEX)	0.39	0.29
Hybrid Systems (PEX)	0.43	0.45
Recirculation Systems	0.82	0.43

Figure 136 plots the average entrained pipe volume for each of the survey sites, broken down by HWDS type. What is most noticeable is not the variation with floor area, but how much variation there is for a given floor area. For example, at 1,800 ft², average entrained pipe volumes vary from 0.5 to 1.50 gallons. This clearly indicates that house design (as it affects water heater location relative to hot water use points) and actual plumbing layouts are the major factors affecting what gets installed.

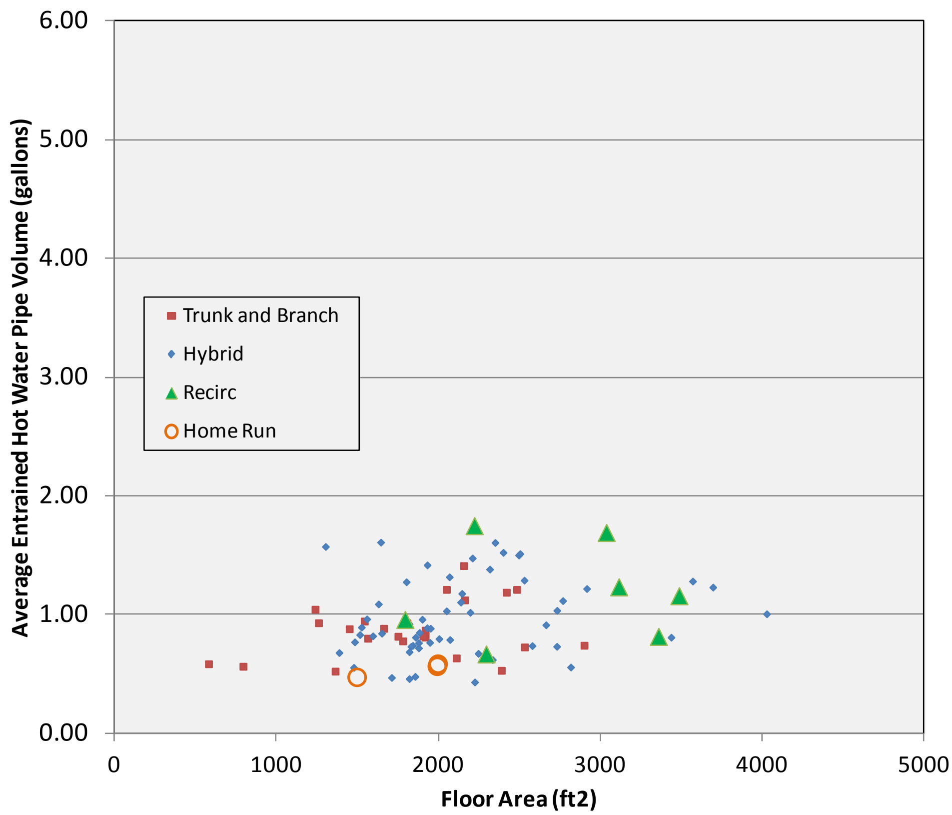

Figure 136: Current HWDS Survey Sample Entrained Pipe Volume by System Type

Figure 137 plots the current data combined with the 2006 dataset. This presents a similar conclusion, with the primary difference being that the 2006 recirculation sites were much larger than observed in the current survey. Figure 138 and Figure 139 provide additional data supporting the contention that it is very difficult to define "typical" installation practice. Figure 138 shows the maximum measured pipe run as a function of floor area, and Figure 139 plots the length of 1" piping as a function of floor area. For both of these, one would expect some reasonable correlation with floor area.

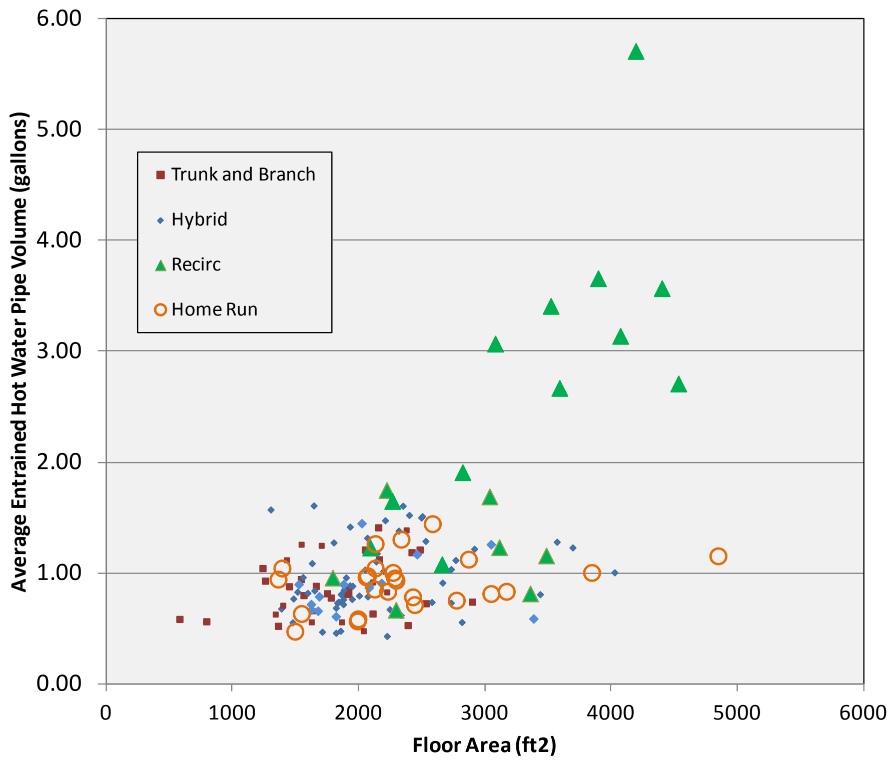

Figure 137: Entrained Pipe Volume by System Type (Combined Dataset)

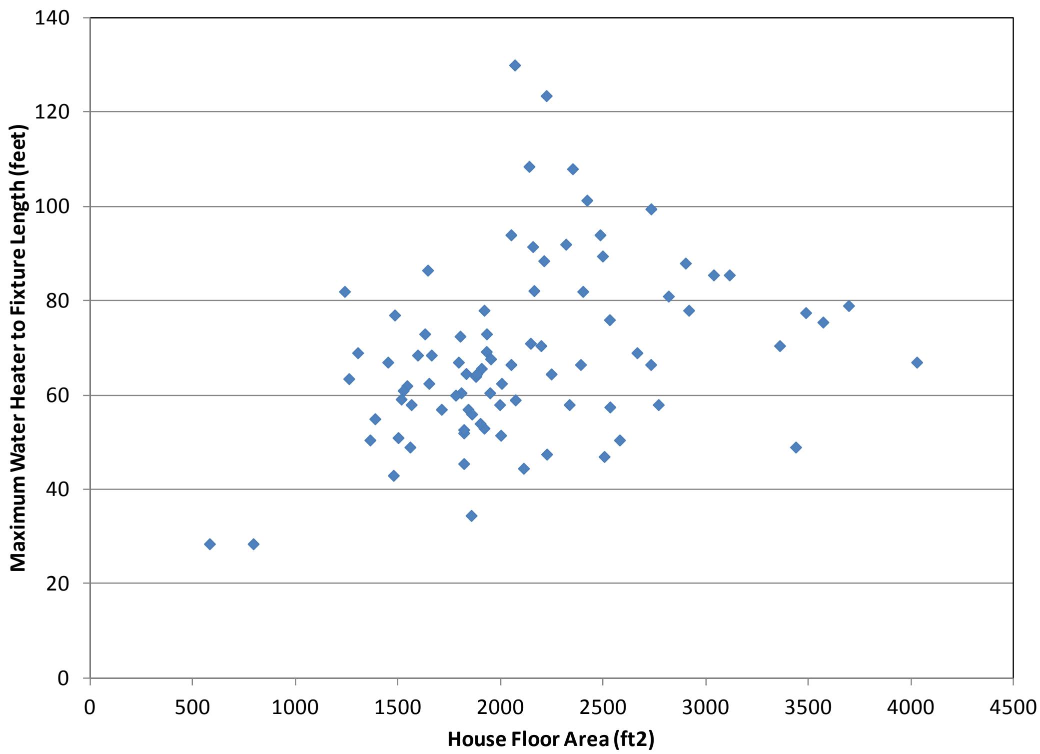

Figure 138: Maximum Measured Piping Length from Water Heater to Use Point

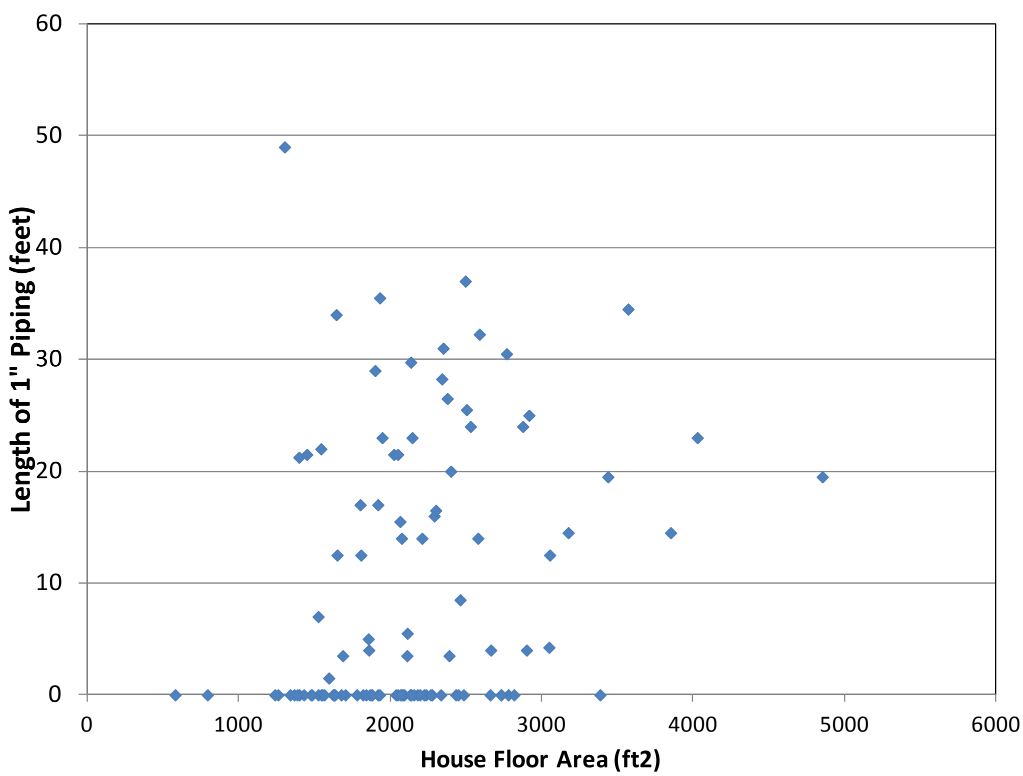

Figure 139: Total Measured One Inch Piping Length (non-recirc systems)

Other observations from the field:

- Virtually all of the plumbing that was installed in the attic was estimated to be located within the blown attic insulation depth. (This was estimated based on the height of the piping over the rafters, and accounting for the expected insulation depth.) Allen Amaro, the field surveyor, estimates that roughly 95% of the piping would be below the nominal height of the blown insulation. This is significant since PEX piping that is in the insulation would not exhibit the radiant heat losses observed by Applied Energy Technology in the laboratory setting.
- One plumber indicated that it takes approximately two person-days to complete the rough plumbing installation for both hot and cold water in a typical 2000 ft^2 house. Clearly spending a little more time and working off a plumbing design could greatly improve the performance of the HWDS. Our understanding is that hot water wait times remains a major complaint of many new home buyers. This problem will only get worse as the saturation of gas tankless units increases, since these units increase time delays when starting from a cold condition.

5.3.1.3 Conclusions and Recommendations

The following conclusions were generated based on the plumbing survey field experiences:

1. PEX has effectively replaced copper piping as the material of choice. This is largely cost driven. It is not clear if CPVC will make inroads in the California market.
2. Average entrained pipe volumes are fairly consistent with the 2006 survey. For a typical 2000 ft^2 house, the average entrained volume is close to one gallon of water. There is large room for improvement in this regard.
3. Home run systems are much less common than in 2006. Again, this appears to be driven by cost. The mini-manifold systems are the predominant system types.
4. Installation issues lead to significant variability in the installed HWDS. There are many instances when a much more direct path can be followed, but for whatever reason, the installer chose not to.
5. The need for training is critical to improve knowledge among the installers.
6. Builders need to recognize that there is value in good design. Good design begins with the architectural design and water heater location. Locating the water heater as centrally as possible is the first step in minimizing the energy and water waste inefficiencies of the HWDS. Efficient (ie. minimizing length and diameter) installation of the layout is also important.
7. Residential plumbing designs should be required.
8. Systems of all types were generally not efficiently installed. The following summarizes findings on each of the system types:

Trunk & Branch and Hybrid Systems

Avoiding and/or minimizing the use of one inch piping in residences is the most important improvement that could be implemented in both trunk & branch and the hybrid systems. This data suggests the use of 1" pipe is not necessarily based on plumbing design, but based on what the plumber preferences. One plumber reported that he uses 1" pipe over ¾" pipe because it delivers hot water to the fixture faster. Installers seem to put little value on reducing pipe length despite the benefits of reduced hot water waiting time (less callbacks). Designing a system with an emphasis on reducing piping length would have lower material costs, lower installation labor costs, and would provide better performance. Installers tend to run trunks parallel to framing rather than straight to where the hot water is needed; this trend adds about 40% to the length of the trunk.

Home Run Central Manifold Systems

Eliminating excessive pipe length is also the most important improvement that can be made to home run manifold systems. This is because this is where the large diameter piping (¾" or 1") is used, and most of the system entrained volume occurs. Minimizing this length will greatly improve "cold start" hot water waiting times and water waste. The 2008 Title 24 Standards now require that the maximum water heater to manifold distance be limited to 15 feet. The three home run systems identified in this survey had water heater to manifold lengths of 9.5, 11.5, and 13.5 feet. Shorter distances are possible. The 2013 Title 24 Standards provide for a small credit for home run systems that are shown to have a maximum water heater to manifold length of five feet.

Another pipe length reduction opportunity exists for two-story houses. Some, but not all, plumbers tend to run the piping to the attic and them back down to the first floor – even if the draw point is only 10 feet away. The preferred approach would be to remain between floors.

Bundling the PEX piping was done to consolidate the tubing in one location and improve the aesthetic of the piping. Section 4.3: Distribution Piping Laboratory Tests of this report studies the energy impact of tightly bundling hot and cold piping together. A field study assessing additional distribution losses under real world draw patterns would provide further data.

Hot Water Recirculation Systems

Eliminating excessive pipe length is also a major issue for recirculation systems, although this was not as evident in the 2012 sample of seven homes. The problem of oversized distribution systems is more pronounced for recirculation since excess pipe length is often large diameter piping (3/4" or 1"). For continuous or timer controlled loops, the large loop size has significant energy impacts. For the preferred demand recirculation approach, the data reinforces the need to fully understand how these systems are installed and controlled.

CHAPTER 6: OUTREACH

Affiliated International Management (AIM) led the outreach project. Outreach was accomplished through utility hosted workshops with the purpose of disseminating the findings from the preceding program projects. The workshops were provided by the International Association of Plumbing and Mechanical Officials (IAPMO) and GreenPlumbers® USA, an innovative, non-profit venture based in California that trains plumbers to promote the benefits of energy efficiency and water saving technologies. Working with the participating utilities in this program, AIM, IAPMO, and GreenPlumbers® USA completed a series of nine (9) in-state workshops that targeted the plumbing trades, homebuilding professionals, and code officials.

6.1 Workshop Materials

The purpose of this task was to develop the materials used in the outreach workshops.

This task began early on during the project with the subcontractor, Affiliated International Management, LLC (AIM) participating in the regular monthly project review meetings and in periodic discussions with the other members of the team. As interim results from the research became available, AIM began gathering the data so that it could be incorporated into the presentation materials.

In late 2011, AIM developed a detailed outline of the planned presentation. The plan was for a full-day workshop, relying primarily on a slide presentation intermixed with interactive exercises. The result was a 6- to 7-hour class during an 8-hour day.

The information that was shared during the presentations came primarily from the research conducted during this research program. However, all of the members of the GTI project team, and some of the Program Advisors were involved in hot water research prior to this agreement or were involved in other activities concurrent with this program, so there was a larger pool of information to rely on in developing the course materials. It seemed advisable to draw from as many relevant sources as possible to develop the materials so that the participants in the classes could obtain the clearest picture of what constitutes best practices in hot water systems.

Because the course content was new, and the intent was to target the workshops to professionals involved in hot water, AIM/IAPMO decided to use the three seminars held in the spring of 2012 to refine the materials and the order of presentation in the class. This feedback resulted in reducing the number of slides in the presentation, and grouping them into topics such as patterns of use, hot water distribution, circulation, water heaters, etc. AIM/IAPMO also decided to present the research results normally seen only by researchers in hot water to the attendees and, let them come up with what they thought best practices should be.

Each class also included three interactive exercises involving the attendees. In one exercise, the attendees were given 18 pieces of tubing that ranged in diameter from ¼ inch to 2 inches, and lengths from six inches to 25 feet. The participants were told that each segment contained the same volume of water, and they were asked to guess the length of pipe and volume of water. They stood up, stretched out the coils, and held up the rigid sections. Guesses ranged from one cup to one gallon; the correct volume was one cup. The purpose of this exercise was to give people a tangible sense of how many feet of pipe represents how much water. This is important because one of the best practices is to reduce the volume of water in the piping between the source(s) of hot water and the uses they serve.

The second exercise involved laying out the floor plan of the wet rooms of a small house (or an apartment) on the floor of the classroom using blue painter's tape for the walls and masking tape of different widths to represent pipe of different diameters. The students were tasked with measuring the water, energy, and time efficiency of the hot water distribution system. AIM/IAPMO started with a traditional trunk and branch layout, measured the performance, and asked the students to improve the performance. Options included moving the single water heater; installing two or more water heaters; using electric heat trace; and changing the layout to a home run central manifold, a distributed manifold, or a circulation system. The pros and cons of each approach were discussed and evaluated.

The third exercise was a method of determining the approximate layout of the hot water distribution system in situations where the piping is not visible--a case common in houses with slab foundations, water heaters located in garages, or in houses with the water heater in a finished basement. Students were given three cards:

1) Location of hot water use (for example, the master bathroom shower or the kitchen sink);
2) Volume for a cold start (this represent the volume of water that runs down the drain when the trunk line to the hot water use location has cooled); and
3) Volume for a hot start (this represent the amount of water that runs down the drain when the trunk line is already primed with hot water).

Large differences in volume between hot and cold starts indicated the location is far from the trunk line. Participants were asked to stand around the room so that the distance from the water heater was relative to the volume for the cold start number on their card. Then they were asked to determine what type of hot water distribution system the numbers on their cards indicated. Finally, without changing position, the students were given new cards with the same hot start volumes but different cold start volumes and they were asked determine what type of hot water distribution system had been installed.

With all of this information, the students are then asked what they think the best practices for hot water systems should be. While no class came up with all of these practices, each came up with most of the list.

1) Understand the hot water use patterns
    a) The key is that residential hot water use is an extremely variable event that occurs within windows of opportunity based on the schedules of the occupants
2) Understand the "service(s)" of hot water desired by these occupants

a) What customers want is “hot water now,” to “never run out in their shower,” safety, and reliability. Provide these services in the most water conserving and energy efficient way

b) It does not make sense to discuss the efficiency of the system until it can provide these “service(s)

3) Understand that it is a system of interactive components that provides the “service” of hot water

    a) All of the components need to work well together for the system to be effective

4) Locate source(s) of hot water close to the uses

    a) Sometimes the source of hot water is a water heater or boiler, sometimes it is the supply portion of a circulation loop or a heat traced pipe

5) Keep the volume from the source(s) to the uses small

6) Minimize pressure drop and optimize velocity in the piping

7) Insulate hot water piping

    a) All of it because the patterns of use are so variable and likely to change over the life of the piping within the building

8) Prime trunk lines with hot water shortly before use

    a) Demand controlled pumping systems are the most energy efficient way to do this

9) Utilize (hot) water use efficient fixture fittings and appliances

    a) Lowering flow rates and reducing fill volumes without improving the hot water distribution system will result in frustrated users and reduced savings

10) Capture waste heat from hot water running down the drain and use it to preheat incoming cold water

11) Combine energy requirements for water heating and space heating into one thermal engine

    a) In thermally-efficient housing, which can be found in all climate zones, the emphasis should be on the water heating load

12) Select water heaters (or boilers) matched to these uses and patterns

    a) Because residential hot water use is so small and in general declining, it is difficult to pay off the difference in cost between a more efficient water heater and the least efficient model that is most commonly installed. Select the water heater and then maintain it so it lasts a very long time.

Implementing all of these best practices, in the order presented above, will result in providing the "service" of hot water in the most water and energy efficient way.

6.2 Workshop Presentations

The goal of Task 6: Outreach was to conduct nine separate day-long best practice training workshops in conjunction with California utilities for plumbers, homebuilders, code officials and others.

The focus of IAPMO/Green Plumbers Training, in Task 6.2 was to:

- Coordinate with Affiliated International Management (AIM) and the participating utilities to schedule nine in-state day long workshops.
- Complete mailings and e-mailings to secure registered attendance at the workshops.
- Provide all necessary logistical to execute the nine workshops. It should be noted that the original contract for Task 6.2 was amended to extend the workshop completion schedule to October 15, 2012.

6.2.1 Summary

IAPMO/Green Plumbers Training (GPT) approached this project as a new construction scenario with practical applications for structured plumbing and hot water efficiency, wherein targeted attendees would be plumbing engineers and designers, plumbing contractors, architects, and home builders. However, the course also includes potential solutions for retrofit projects, therefore service plumbing contractors and building energy professionals were included in the mailing lists.

GPT began with the Green Plumbers' national e-mailing lists of more than 65,000 plumbing professionals, and culled the list to approximately 12,000 California plumbing professionals. Solicitation letters were sent to California building associations, including the American Society of Plumbing Engineers (ASPE); ASHRAE; California Association of Building Energy Professionals (CABEC); California Plumbing, Heating, Cooling Contractors Association (CAPHCC); California Building Industry Association (CBIA); California Chapters of the American Institute of Architecture (AIA): and IAPMO's California Chapters. Letters for the Spring workshop sessions were generic, followed by personal solicitation letters for the Fall series.

IAPMO/Green Plumbers Workshop Statistics are showcased in Table 69. Workshop sessions were conducted in two separate time frames, including three workshops in Spring 2012 in San Francisco, Ontario, and San Diego, and six workshops in Fall 2012 in San Ramon, Stockton, Ventura, Downey, San Diego, and Los Angeles.

Total attendance at the nine workshops was 222, averaging just under 25 per class. The highest attendance occurred at the final workshop at Los Angeles Trade Technical College, with more than 80 professionals and students attending. The specific outreach letters were very productive, as more than one-third of attendees reported having heard of the workshops through their industry trade association. In addition, another 22% reported receiving workshop information from sponsoring utilities.

Table 69: IAPMO/Green Plumbers Workshop Statistics

Workshop	Date	Sponsor	Location	Attendees	Total
#1	24-May-12	PG&E	San Francisco		15
				5 energy	
				9 prof/eng	
				1 plbg/contr	
#2	7-Jun-12	SoCalGas	Ontario		22
				17 prof/eng	
				4 energy	
				1 plbg/contr	
#3	18-Jun-12	SDG&E	San Diego		
				21 prof/eng	39
				9 energy	
				8 plbg/contr	
				1 student	
#4	11-Sep-12	PG&E	Stockton		8
				3 energy	
				3 plbg/contr	
				2 prof/eng	
#5	13-Sep-12	PG&E	San Ramon		
				5 energy	11
				3 plbg/contr	
				3 prof/eng	
#6	18-Sep-12	SoCalGas	Downey		4
				4 prof/eng	
#7	20-Sep-12	SoCalGas	Ventura		
				2 energy	4
				2 prof/eng	
#8	8-Oct-12	SDG&E	San Diego		
				15 prof/eng	22
				3 plbg/contr	
				4 energy	
#9	11-Oct-12	SoCalGas	LATTC		
				89 students	97
				(plumbing)	
				5 prof/eng	
				3 energy	

Totals					222
				90 students	
				(plumbing)	
				35 energy	
				78 prof/eng	
				19 plbg/contr	

The utility partners for this project were Pacific Gas & Electric (PG&E) Company, and Sempra Utilities. Delaina Wilhelm of PG&E; Joe Shiau of Sempra (SoCalGas & SDG&E); and other staff at the utilities assisted with venue reservations and catering.

Organizational sponsors included the California Association of Building Energy Professionals (CABEC); California Association of Plumbing, Heating, Cooling Contractors (CAPHCC): and the American Society of Plumbing Engineers (ASPE). These sponsors publicized the workshops in their newsletters and emails.

As a result of the varied degree of interested organizations, it is no surprise that the bulk of our registrants were building energy professionals, plumbers and/or plumbing contractors, and plumbing engineers, and designers. Survey respondents were appreciative of the course material, with 65% reporting that they expected to change future work practices as a result of the workshop. More than 85% said that the use of a taped floor plan and piping exercises made the program more interesting and understandable.

Survey comments were overwhelmingly favorable, although some participants could see a challenge in educating plan checkers to understand implementation. Other comments:

- "Excellent seminar. I will use this information in my work."
- "The instructors have a wealth of knowledge and shared it freely."
- "The ideas shook the foundations of presumed knowledge surrounding hot water efficiency that facilitates current plumbing industry water heating equipment sales."
- "Some courses are just academic; this one is applicable in a very useful way."

6.2.1.1 Outcomes

The primary result of this task was to provide the research information gathered from experts over the course of three years, in a comprehensive workshop series that reached over two hundred professionals. Perhaps a more long-term result is that the research information contained in the presentation, which was modified and improved over the course of the nine workshops, is available online and can be disseminated to a much larger audience.

Two very positive specific outcomes are:

1) The change in venue for the final workshop to Los Angeles Trade Technical College (LATTC), where a large number of students were able to see first-hand the practical value of the research. In addition the course materials will be integrated into LATTC's ongoing plumbing curriculum, and potentially the LATTC plumbing laboratory will be used for structured plumbing demonstrations.

2) The decision by the American Society of Plumbing Engineers (ASPE) to award CEUs for the course content at its chapter offerings throughout the United States.

In summary, the research outcomes of the three year CEC/GTI project have resulted in valuable information on hot water efficiency that will ultimately become benchmarks in the plumbing industry.

The final version of the presentation used in the workshops can be accessed using this link: http://www.greenplumberstraining.org/documents/bestpractices_residentialhotwatersystems.pdf

GLOSSARY

AIM - Affiliated International Management

ASHRAE - American Society of Heating, Air-Conditioning, and Refrigerating Engineers

AET - Applied Energy Technology

ATS - Applied Technology Services

DEG - Davis Energy Group

DOE - Department of Energy

EPRI - Electric Power Research Institute

Energy Commission - California Energy Commission

EF - Energy Factor

EIA - Energy Information Administration

GTI - Gas Technology Institute

HERS - Home Energy Rating System

HWSIM – Hot Water SIMulation

IAPMO - International Association of Plumbing and Mechanical Officials

LBNL - Lawrence Berkeley National Laboratory

PG&E - Pacific Gas & Electric

PAC - Project Advisory Committee

PIER - Public Interest Energy Research

RASS - Residential Appliance Saturation Survey

SDG&E - San Diego Gas & Electric

SCG - Southern California Gas

SPC - Standards Project Committee

SEGWHAI - Super Efficient Gas Water Heater Appliance Initiative

TANK – gas-fired, central flue water heater simulation

TRNSYS - TRaNsient SYstems Simulation

WH – Water Heater

EQUATIONS

ΔH_C = Fuel calorific value (higher heating value)

$\Delta H_{C,L}$ = Lower heating value of the combustible gas

ΔT = Temperature range of the smoothing function

σ = Stephan Boltzmann constant

ε_B = Emissivity of tank bottom

ε_G = Emissivity of flame

μ_G = Flue gas viscosity

$(\varrho V)_G$ = Mass velocity of the flue gas

α_F = Flame spreading angle

A_B = Area of the base of the storage tank

AF_{ST} = Stoichiometric air fuel ratio

b_B = Width of the area of the base struck by hot gas

C = Thermal capacitance of the heat exchanger

C_F = Circumference of the flue

$\dot{c}_g$ = Energy flow rate of the flue gas

c_p = Specific heat of the heated fluid

$c_{p,g}$ = Mean specific heat of the flue gas

D_F = Diameter of the flue

D_M = Average of the tank and flue diameters

D_T = Diameter of the tank

$\frac{dT_i}{dt}$ = Rate of change of temperature of a specified node in the heat exchanger

EA = Excess air in the flue gas

f = Represents the smoothHeaviside function from the LBL Buildings Library

$h_{C,B}$ = Convection coefficient between the hot gas and the base

$H_1(i)$ = Smoothing function comparing the temperature of the current segment to the temperature of the segment below

$H_2(i)$ = Smoothing function determining the position of the segment below the current segment relative to the stratification layer

h_F = Heat transfer coefficient describing the convective heat transfer between the hot gas and the flue wall

H_{mix} = Segment representing the top of the mixing zone in draw heat transfer calculations

$h_{R,B}$ = Radiation coefficient between the hot gas and the base

i = Index value used to identify different points in an array

k_G = Thermal conductivity of the flue gas

L_{BRN} = Height of the burner assembly

L_{FLU} = Length of the flue

$\dot{m}$ = Mass flow rate of the heated fluid

$\dot{m}_G$ = Mass flow rate of gas

$\dot{m}_{In}$ = Hot water draw mass flow rate

nSeg = Total number of segments used to describe the storage tank

N = Number of nodes used to describe the heat exchanger in the simulation with respect to time

$N_{tu,B}$ = A description of the effectiveness of heat transfer between the hot gas and base of the storage tank

$\dot{Q}_B$ = Rate at which heat is transferred from the hot gas in the burner to the base of the storage tank

$\dot{Q}_{Consumed}$ = Rate at which heat enters the tankless water heater

$\dot{Q}_{Delivered}$ = Rate at which heat is transferred to the fluid

$\dot{Q}_{Draw}(i)$ = The heat transfer impacts of a hot water draw on a specific segment

$\dot{Q}_{Environment}$ = Rate at which heat is lost to the environment

$\dot{Q}_{Flu}(i)$ = Heat transfer through the flue for a given segment

$\dot{Q}_{In}$ = Rate at which heat enters the burner in the form of natural gas

$\dot{Q}_{In,Seg}(i)$ = Heat entering a specific segment

$\dot{Q}_p$ = Heat consumption rate of the pilot light

$\dot{Q}_{R,FE}$ = Rate at which heat is lost from the hot gas to the floor via radiation

$\dot{Q}_{Rated}$ = Maximum rated input heat rate of the heater

$\dot{Q}_{Required}$ = The rate at which heat needs to be delivered to the heater fluid to meet the set temperature

$\dot{Q}_{Seg}$ = Heat added to each section below the stratification layer

Q_{Stored} = Amount of heat stored in the heat exchanger relative to 0°C

$\dot{Q}_{Str}(i)$ = Heat flow in a segment below the stratification layer

$\dot{Q}_{Str,Tot}$ = Total heat flow below the stratification layer

T_{AD} = Adiabatic flame temperature

T_{Amb} = Ambient temperature

T_{DB} = Dry bulb temperature

$T_{F,0}$ = Temperature of the hot gas as it enters the flue from the burner

$T_F(i)$ = An array used to identify the temperature of the hot gas in the flue at every segment in the storage tank

T_i = Temperature of the specified node (node i)

T_{i-1} = Temperature of the previous node (the node before i

T_{Inlet} = Temperature of fluid entering the tankless heater

T_{Out} = Outlet temperature

T_{Set} = The set temperature of the tankless water heater

$T_{Wat}(i)$ = Temperature of water in a specified segment

$T_{Wat}(In)$ = Temperature of the fluid entering the heater

$T_{WL}(i)$ = An array used to identify the temperature of the flue wall (hot gas side) at every segment in the storage tank

$T_{WL,Avg}(i)$ = The average temperature of the flue wall below a given segment

$T_{WL,B}$ = Temperature of the base of the tank

$T_{WL,Eff}$ = Effective flue wall temperature used for calculation of heat transfer through the flue

UA = Heat loss coefficient of the tankless water heater

$(UA)_B$ = Combined effective heat transfer coefficient between the base of the storage tank and hot gas

X(i) = Position of a specified segment relative to the stratification layer

X_n = Placeholder in an equation representing one half of the difference in tank and flue gas diameters

η_p = Efficiency of the pilot light

η_{SS} = Steady state efficiency of the tankless water heater

γ = Control signal determining how much heat enters the burner

$\gamma_{\dot{m}}$ = Control signal returned from the minimum flow rate check

γ_P = Control signal returned from the power signal check

γ_{PID} = Control signal returned from the PID controller

$\gamma_{\dot{Q}}$ = Control signal returned from the minimum heat rate check

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Water heater selectrion criteria

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Heat pump water heater measure guideline

http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/measure_guide_hpwh.pdf

Combined hydronic system expert meeting

http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/expt_mtg_combi_systems.pdf

Combined hydronic integration with tankless water heaters

http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/measure_guide_combi_systems.pdf

Laboratory testing of advanced water heaters

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