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Disaggregating Hot Water Use and Predicting Hot Water Waste in Five Test Homes

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Definitions

ARIES	Advanced Residential Integrated Energy Solutions Collaborative Building America team
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
AWWARF	American Water and Wastewater Association Research Foundation
BA	Building America
CDH	CDH Energy Corporation, ARIES team member
CEC	California Energy Commission
DHW	Domestic hot water
ECM	Electronically commutated motor
EF	Energy factor
EPA	Environmental Protection Agency
GTI	Gas Technology Institute
Hot Water Use	Volume flow rate of hot water
HPWH	Heat pump water heater
HWSIM	Hot Water Simulation (software)
LBNL	Lawrence Berkeley National Laboratory
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
PEX	Cross-linked polyethylene (piping)
RECS	Residential Energy Consumption Survey
REUWS	Residential End Uses of Water Survey
TRNSYS	Transient System Simulation (software)

Executive Summary

Water heating is the second largest energy expenditure in homes in the Northeast, after space heating. Several energy-efficient water heating options are currently available, including more efficient tanks, tankless systems, and others. While it is important to make the equipment (or "plant") in a residential hot water system more efficient, the hot water distribution system also affects overall system performance and energy use. Energy wasted in heating water that is not used; that is, heat lost through piping and previously heated water that runs down the drain during a hot water draw while waiting for an acceptable temperature, is estimated to be on the order of 10%–30% of total domestic hot water energy use.

This project seeks to quantify the magnitude of hot water waste in existing Northeastern homes. This Building America (BA) project expands the field testing effort at several homes that are being tested as part of a water heating evaluation project sponsored by the New York State Energy Research and Development Authority). The BA portion of the work expanded the monitoring effort to focus on measuring the amount of hot water waste in five homes. The five monitored test sites include:

- Group 1—two baseline (or control) sites
- Group 2—one site where a conventional hot water tank was changed to a tankless system
- Group 3—two sites where the water heater and distribution system will be changed.

The last three test sites (Groups 2 and 3) will be monitored both before and after the changes are implemented.

Data logging equipment was installed at the five houses near Syracuse, New York and data collection commenced in December 2012. Data collection gathered 15-minute data as well as data collected at 5-second intervals during each hot water draw event. Procedures were developed to classify or assign each hot water use event to a fixture using temperature sensors installed on the distribution piping. This process was able to classify less than half of the water draws but typically about 95% of the hot water volume in each home. This classification process was achieved without the need to install flow meters for each fixture (which would have been cost-prohibitive and more disruptive to homeowners). The average number of events at each home ranged from 26/day to 180/day. Average hot water use ranged from 34 to 115 gal/day.

We also used pipe temperature sensors to determine the portion of hot water draw that was deemed useful. A temperature of 90°F at the fixture piping was selected as the threshold for gauging usefulness (other thresholds were also evaluated). The amount of hot water deemed useful ranged from a low of 75% ± 5% at Site 4 to a high of 91% ± 2% at Site 5—thus implying 9%–25% waste. Site 4 may have had a lower useful percentage in part be due to the fact that the sensors installed on cross-linked polyethylene (PEX) piping may have had a slower thermal response. As expected, the amount of hot water waste was found to be higher for bathroom and kitchen sinks and lowest for showers and washing machine draws. Overall, the probable error in the determination of "usefulness" was estimated to be ± 2% for Sites 1, 2, 3, and 5 with copper piping and ± 5% at Site 4 with PEX piping.

Three of the houses were retrofitted with water heaters (Group 2) and in some cases additional distribution improvements were implemented as well (Group 3).

At Site 3 (Group 2) a new tankless water heater was installed to replace a conventional gas-fired tank. The homeowners cut the number of water draws in half, but the volume of hot water use stayed about the same. The overall percentage of useful hot water delivered to the fixtures decreased from 90%–91% before the retrofit to 84%–86% with the tankless unit. The change is mostly explained by the 40-second startup delay for the tankless unit from a cold start. The homeowners at this site also purchased a high efficiency washing machine a few weeks after the retrofit. The pulsing nature and low volume of the appliance’s hot water draw cycles resulted in virtually no useful hot water being delivered to the appliance with the tankless unit. We also noticed unexplained burner cycling with the tankless unit at times, even though the flow rate was well above the cutout flow of 0.26 gpm.

Site 1 (Group 3) had both a new heat pump water heater installed as well as distribution system improvements. The hot water supply line was shortened by 177 in. since the new location was closer to the center. A recirculation pump was installed that included an internal time clock as well as an internal thermostat. The pump pulled return water from two remote locations on the first floor (the kitchen and the half bath). On average the pump ran about 3 minutes/day to prime the hot water lines during periods when hot water usage was expected to be high. The useful portion of hot water delivered increased from 82% before the retrofit to 91% after. The largest improvement was in the kitchen area. More modest improvements for other fixtures (not served by the pump) were also noted due to the shorter supply trunk (i.e., 28%–35% for the master sink and 49%–66% for the bath 2 sink).

Site 2 (Group 3) had a new condensing water heater installed with a Taco SmartPlus recirculation pump. The pump was set to operate in the smart mode where it anticipates hot water use based on the previous 7-day operating pattern. The pump was observed to operate about 200 minutes/day, or about 14% of the time. This excessive runtime resulted in significant thermal losses. While this water heater unit was observed to have an effective energy factor of 0.85 in the laboratory, it operated at 40%–70% efficiency at this site depending on daily hot water use. The poor field performance of this system was linked to increased thermal standby losses of 15–16 MBtu/day due to pump operation. The pump had no perceptible impact on the amount of hot water use at the site; however, the large variations in hot water use throughout the pre- and post-retrofit periods may have obscured the impact of the retrofit.

Overall, there were some indications of improved hot water “usefulness” at the fixture for one of the two retrofitted sites. However, no direct reduction in hot water use or energy use was measured. Therefore, no energy cost savings were observed to offset the installed cost of $500–$1,000 to implement these distribution system improvements. Monitoring is expected to continue beyond this initial test period to confirm these findings.

1 Problem Statement

1.1 Introduction

Water heating is the second largest energy expenditure in existing homes in the Northeast, after space heating (RECS 2005, Table 13). Historically, efforts to improve residential efficiency have focused on space conditioning, often neglecting water heating improvements. Several new or recently refined water heating technologies are now available on the market including: solar water heaters; gas-fired, tankless units; and heat pump water heaters (HPWHs). Tax credits are currently available for some of these systems that are expected to boost consumer interest.

Current U.S. Department of Energy rating procedures to determine the energy factor (EF), or efficiency, of these systems may be poor indicators of actual energy use, in part because the amount and timing of water use greatly impacts the performance and relative efficiency ranking of these systems. Better information is needed to help consumers, manufacturers, and installers understand the efficiency, costs, and environmental impacts of both new and conventional domestic hot water (DHW) systems for retrofit and new construction applications.

While it is important to make the equipment or "plant" in a residential hot water system efficient, the hot water distribution system also affects overall system performance and energy use. Energy wasted in heating water that is not used—that is, heat lost through piping and heated water that runs down the drain during a draw while waiting for an acceptable hot temperature—is estimated to be on the order of 10%–30% of total DHW energy use (Klein 2006; Chinery 2006; Lutz 2005; Hendron et al. 2009).

1.2 Background

Several technologies and approaches have been identified to reduce hot water distribution system losses and waste, including:

- Floor plans that organize or "stack" kitchen and bathrooms to minimize the length of hot water piping runs
- Structured plumbing arrangements that use trunk/branch arrangements
- Recirculation pumps that operate on demand to prime trunk piping (by pumping water back to the DHW tank using either a dedicated return line or a cold water line).

These approaches and technologies have been successfully applied and demonstrated in gut rehab or new construction projects, mostly in California and other western states. Less effort has been aimed at determining which approaches are most appropriate for existing buildings and DHW retrofit applications in northeastern homes—the focus of this effort. Existing northeastern homes differ from western homes in ways that may affect the costs, efficacy, and practicality of DHW distribution retrofit approaches. For example, many northeastern homes are significantly older than their western counterparts. Older plumbing systems may contain galvanized steel, cast iron, or even lead pipes that are less common in newer western homes. Likewise, older plumbing designs may still be in use in older northeastern homes. Increased age also increases the likelihood that plumbing has been affected by past renovations, complicating the system, and by corrosion that can restrict flow, especially in iron and steel pipe. Northeastern homes are far more likely to have basements where the piping is easily accessible (compared to under slabs or in the attic in the West), but exposed to colder temperatures if those basements are unheated. Differences in home layout also affect DHW distribution: Western homes tend to be shorter and more spread out, while older northeastern homes, especially in towns and urban areas, are often narrow and tall with baths and kitchens stacked upon each other. Furthermore, colder weather in the Northeast compared to California may lead to different DHW consumption patterns by occupants—both in the amount of DHW used per person and the DHW comfort temperature.

A comprehensive literature review is included in Appendix A.

Advanced Residential Integrated Energy Solutions (ARIES) team partners New York State Energy Research and Development Authority (NYSERDA), CDH Energy Corp. (CDH), and the Syracuse Center of Excellence are implementing a project that includes laboratory tests and field measurements in 18 New York State homes to understand the energy costs and environmental impacts of both high-efficiency and conventional DHW systems. This Building America (BA) effort expands the scope of the field research component to include a characterization of DHW end uses and an assessment of DHW distribution retrofit approaches in a subset of these homes.

In the NYSERDA-funded effort, the team is monitoring eight water heating systems in a laboratory test setup at the Syracuse Center of Excellence. The team has also recruited 18 field test homes. Data will be collected on the water heating systems of the field test homes to understand detailed water heater performance as well as to quantify hot water use and energy use patterns. The plan calls for detailed field monitoring (to determine fuel input, equipment efficiency and energy balance) at two of the field sites, with overall hot water use (or volume flow rate) monitoring at the remaining 16 sites.

1.3 Relevance to Building America's Goals

This project seeks to quantify the energy losses and waste associated with hot water distribution systems in existing homes in the Northeast. Our goal is to quantify the energy associated with waste and losses due to distribution system piping size and layout. While The National Renewable Energy Laboratory (NREL) and other BA teams have quantified these losses in homes in Colorado (Magnusson 2009) and California (Hendron et al. 2009), we believe that no testing has been completed in existing northeastern homes.

Once losses are quantified, we will evaluate various options to mitigate these losses and quantify the impact of any improvements. The ultimate goal of this effort is to develop guideline documents that recommend retrofit approaches that can be implemented as part of the traditional water heater replacement, millions of which are completed every year in the United States.

This work will contribute to the eventual development of the following planned BA guidelines for existing homes:

- Replacing water heaters
- Reducing hot water tank and pipe losses.

1.4 Cost Effectiveness

For any water heating system improvements to be cost effective, they must fit into normal business practices. Water heater replacements are implemented by plumbers who normally replace the units on an emergency basis with little or no notice. In this market, it is important to have high efficiency water heaters available "on the truck" or at least at the distributor for each installation visit.

We seek to develop a standard set of modifications or improvements that can be implemented as part of a typical water heater installation. Integrating distribution system improvements with a water heater installation is a necessary condition to ensure the improvements can be cost-effectively implemented.

Klein (2005) reports that the incremental cost of installing demand recirculation pumps, insulation, and other changes in new construction are on the order of $500. Some more recent cost estimates are closer to $1,000. If costs for distribution retrofits in the Northeast are in the $500–$1,000 range and assuming 15% savings on annual hot water cost of $400/year, the simple payback would be approximately 8–16 years. Integrating this measure with a water heater replacement can potentially make it even more cost effective. Costs and savings will be measured for the retrofits to be conducted at two sites.

1.5 Tradeoffs and Other Benefits

Our goal is to quantify the energy savings and other impacts of various distribution system improvements. The ultimate goal is to gather sufficient performance data so that this measure can be compared and ranked relative to the other energy efficiency improvements normally implemented in a residence.

In addition to energy efficiency, distribution improvements can enhance homeowner convenience and comfort by speeding up the delivery of hot water to each end use. Homeowners are often frustrated by the amount of time they must wait for hot water to reach a sink or shower.

2 Experiment

2.1 Research Questions

This project seeks to answer the following research questions:

- What is the magnitude of hot water waste for existing homes in the Northeast, considering a variety of water heating systems (i.e., tankless and storage tank)?
- What constitutes a "typical" distribution system in the Northeast? How does it compare to systems in other regions of the United States?
- What improvements or remediation can be cost-effectively implemented in a DHW retrofit to reduce hot water waste and energy use, focusing on hot water system configurations commonly found in older single-family homes in the Northeast?

2.2 Technical Approach

The NYSERDA-funded field monitoring effort was expanded at five field test sites in order to collect more detailed data on the hot water distribution system by placing temperature sensors on hot water distribution lines and enhancing the data logger capabilities. These enhancements provided the means to assign hot water draw events to each fixture using a flow disaggregation method using temperature rise similar to that discussed by Barley et al. (2010) and Magnusson (2009). This flow disaggregation method allows flows to be characterized at the fixture level with a single flow meter installed on the DHW system. It avoids the installation of flow meters at each fixture in each home. Installation of multiple flow meters would have been costly and very disruptive for homeowners.

The limitations of this technique, as noted in the Results section of this report, include difficulty in classifying very brief events, very low flows, and simultaneous flows at multiple fixtures. Nevertheless, these unclassified events represented only a small portion (less than 10%) of total hot water used and so are not significant sources of DHW distribution energy waste. Ongoing work will include benchmarking a sample of events using this technique against known end-use draws to confirm this analysis.

The enhanced data logger was programmed to collect event-based data required for this disaggregation method. These five enhanced field test sites include three groups of homes (Table 1).

At Group 1 (two sites) no changes were made to the existing systems; these homes represent baseline performance to disaggregate water draws and estimate the magnitude of losses and water waste.

At Group 2 (one site) the water heating equipment was replaced with new, high performance equipment (e.g., a tankless system) in order to detect any changes in distribution system performance.

At Group 3 (two sites) a new, high performance water heater was installed and cost-effective distribution system improvements implemented.

Data collection began at the five sites in December 2012. At the Group 2 and Group 3 field test sites data were collected both before and after water heater installation. The retrofits at the Group 2 and Group 3 sites were implemented in March, April, and May 2013. This report includes post-retrofit data through June 2013.

Table 1. Five Field Test Sites With Detailed Monitoring

Group	Site	System Changes	Data Collection Start	Date of Retrofit
Group 3, Retrofit	Site 1 Cazenovia/ Ballina	Install HPWH and distribution improvements	Dec. 1, 2012	April 3, 2013 recirculation pump April 10, 2013 HPWH
Group 3, Retrofit	Site 2 Syracuse/ Gifford	Install condensing tank, distribution improvements	Dec. 15, 2012	May 20, 2013
Group 2, Tankless	Site 3 Manlius	Install tankless unit	Dec. 13, 2012	March 22, 2013
Group 1, Baseline	Site 4 Cazenovia/Burton	None	Dec. 26, 2012	–
Group 1, Baseline	Site 5 Syracuse/Hornady	None	Dec. 14, 2012	–

This report summarizes the data collected from the five sites.

2.3 Measurements and Data Logging Equipment

At the five BA test sites, a monitoring system was installed to measure:

- The energy content of the delivered hot water from the water heater
- The fuel and/or electric input into the water heater (post-retrofit only).

In addition we measured:

- Key temperatures in the trunks and branches leading to each fixture
- The environmental conditions (air temperature) near the water heater and piping (the relative humidity was measured where the system is an HPWH)
- Flue gas temperature for combustion appliances
- Runtime or status of each component (e.g., resistance elements, fans, pumps).

Figure 1 schematically shows the location of the instrumentation for a typical water heating system. All the monitored points are listed in Table 2. For each system, the cold inlet temperature (TC), hot outlet temperature (TH), and water flow (FW) were measured to determine delivered energy (QH) from the water heater. The low-mass type-T thermocouples (± 1°F) were attached to the outside of the copper pipe using thermally conductive paste. The surface-mounted sensors were well insulated to shield them from ambient conditions surrounding the pipe. On well-insulated copper pipes we found that the transient response of the sensor in detecting the internal fluid temperature was within a few seconds. The transient response of the temperature sensor on cross-linked polyethylene (PEX) piping was much slower because of the thermal resistance of the pipe wall. The high resolution flow meter provided 151 pulse/gal (accuracy is ± 2% of reading at flows under 0.6 gpm, ± 1.5% at higher flow rates). The accuracy was confirmed at each site with a measured volume test of approximately 1 gal.

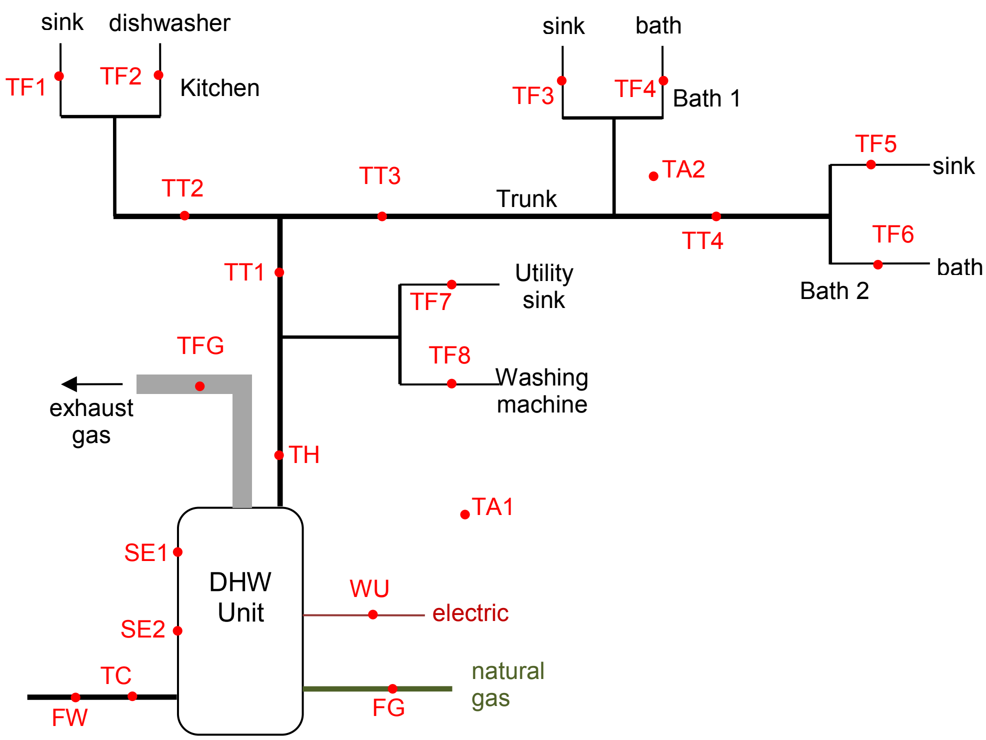

Figure 1. Schematic showing monitored points collected at a typical test site

Table 2. Data Points Monitored at Typical Site

Data Point	Description	Instrumentation	English Units
TC	Cold water inlet temperature	Type-T TC, 1/16 in. probe (± 1°F)	°F
TH	Hot water outlet temperature	Type-T TC, 1/16 in. probe (± 1°F)	°F
FW	Hot water flow rate	Omega FTB4605 ½ in. (151 ppg, ± 2% below 0.6 gpm)	Gal
TA1	Space temperature near unit	Type-T TC, 1/16 in. probe (± 1°F)	°F
TA2	Space temperature near piping	Type-T TC 1/16 in. probe (± 1°F)	°F
TTn	Trunk temperature – Location "n"	Type-T TC, 1/16 in. probe (± 1°F)	°F
TFn	Fixture temperature – Location "n"	Type-T TC, 1/16 in. probe (± 1°F)	°F
TFG	Flue gas temperature	Type-T TC, 1/16 in. probe (± 1°F)	°F
SEn	Status, elect element (if applicable)	Veris 300 current switch	Min
WU	Unit electric use (if applicable)	Wattnode WNB-3Y-208-P (± 1%)	Wh
FG	Unit gas use (if applicable)	Gas meter (0.25 CF/p)	CF

Total unit power use (WE) was measured for each new electric unit. New units with a resistance heating element such as electric tanks or an HPWH also had a status measurement to record the runtime of that component (SE1, SE2). Gas use (FG) was measured for the new gas units with a temperature-compensated gas meter (0.25 CF per pulse). Flue gas temperature (TFG) was measured for all gas-fired units with a type-T thermocouple. For conventional gas-fired tanks in Group 1, gas use was not directly measured but the flue gas sensor was used to infer unit runtime. Ambient air temperature around the water heater and in unconditioned areas with significant hot water piping runs was also measured (TA1, TA2, etc.). Relative humidity was measured at Site 1, which has an HPWH.

Low mass thermocouples were also installed on the outside of the trunk, branch, and fixture pipes (i.e., "twigs") to determine the path of hot water flow during each draw. Where practical, we installed a thermocouple on the dedicated line or twig to each point of hot water use or fixture (TF1, TF2, etc.). Temperature sensors were installed on trunk or branch lines to major areas (kitchen, bath, etc.) to help determine the path of hot water flow (TT1, TT2, etc.). In some cases it was not possible to measure the temperature of every location (e.g., second-floor showers), but we endeavored to measure enough points to provide meaningful results for each fixture. At several sites we installed wireless Campbell Scientific CR206X data loggers to record temperature measurements in areas that could not be reached with hard-wired sensors. Two CR206X loggers were installed in the two upstairs bathrooms at Site 1. At Site 4, CR206X loggers were installed in a remote basement and in an upstairs bathroom. Site 5 used a CR206X in the kitchen area. Data from these remote, wireless loggers were transferred back to the CR1000 at least every 5 seconds.

Each site had a Campbell Scientific CR1000 data logger installed to collect averaged or totalized data at 15-minute intervals. The data logger was programmed to sample each sensor at a 5-second scan rate. In addition, several key data points (FW, TC, TH, TTn and TFn) were recorded at 5-second intervals while a draw is occurring. This short time step data collection is initiated once any flow occurs (i.e., when one or more pulses are detected) and continues for at least five intervals (25 seconds) after the last flow pulse is detected. The CR1000 data loggers were connected to the wireless network in each home via a wireless bridge. The data loggers were programmed to send data to CDH servers each night. The 15-minute and short time step data were stored in separate databases.

Appendix B summarizes the specific instrumentation and data loggers used at each site. It also includes the site description and a survey that provides the location of each fixture and the effective pipe lengths and volume for each section of the distribution system. The new systems and equipment installed at the retrofitted sites are also described.

3 Analysis Approach

3.1 Typical Hot Water Draw Events

The data logger at each site was programmed to collect short time step data (i.e., 5-second intervals) for total flow rate and temperature during each hot water draw event. Temperature data at the water heater, trunk lines and fixtures were also logged for each interval. The result is that a small dataset was collected for each hot water draw event (e.g., the period starting with flow and ending with 25 seconds of no flow). Following are analyses of three hot water events at Site 1.

Figure 2 through Figure 4 show flow events and temperatures corresponding to the master bath shower (in this report when the term *shower* is used, it indicates either a shower or bathtub draw), master bath sink, and kitchen sink. For each figure the plot in the upper left shows the flow trace during the event (ending with five intervals at zero flow). The red line corresponds to the most common flow rate (in gpm) or “mode” during the event. The plot in the lower left shows the various temperatures during the event. Blue lines correspond to trunk temperatures (TT1, TT2…) while the green lines are the fixture temperatures (TF1, TF2,..). Each line is identified by a number. The plot at the upper right shows the temperature rise for each sensor compared to the beginning of the event (using the same colors). The red line on the upper right and lower left plots is the supply temperature from the unit (TS). The black line on these plots corresponds to the cold water inlet (TC). The trunk line with the highest temperature rise is indicated by blue text and the fixture temperature with the biggest rise is indicated with green text.

For Figure 2 the first shower of the day lasts for about 6 minutes (84 intervals) and the total draw is more than 8 gal. The temperature leaving the tank increases as expected and the inlet cold water temperature drops as cold water flows by the sensor. The trunk to the master bedroom increases by 40°F as expected. In this case, there is no temperature sensor for the shower fixture; only for the bathroom sink. So a trunk temperature rise with no change in fixture temperature indicates a shower. However, the sink temperature did see a small rise (< 4°F) that could have confounded the fixture prediction.

Figure 3 below shows a hot water draw event on the master bath sink following the shower event. The temperature leaving the tank (TH) and in the trunk to the master bathroom were already at 105°F due to the recent shower. The temperature at the fixture increases quickly once the hot water reaches that location. The temperature rise compared to the beginning of the event was 32°F. Even with the trunk temperature already warm, a temperature rise of 7°F was still apparent.

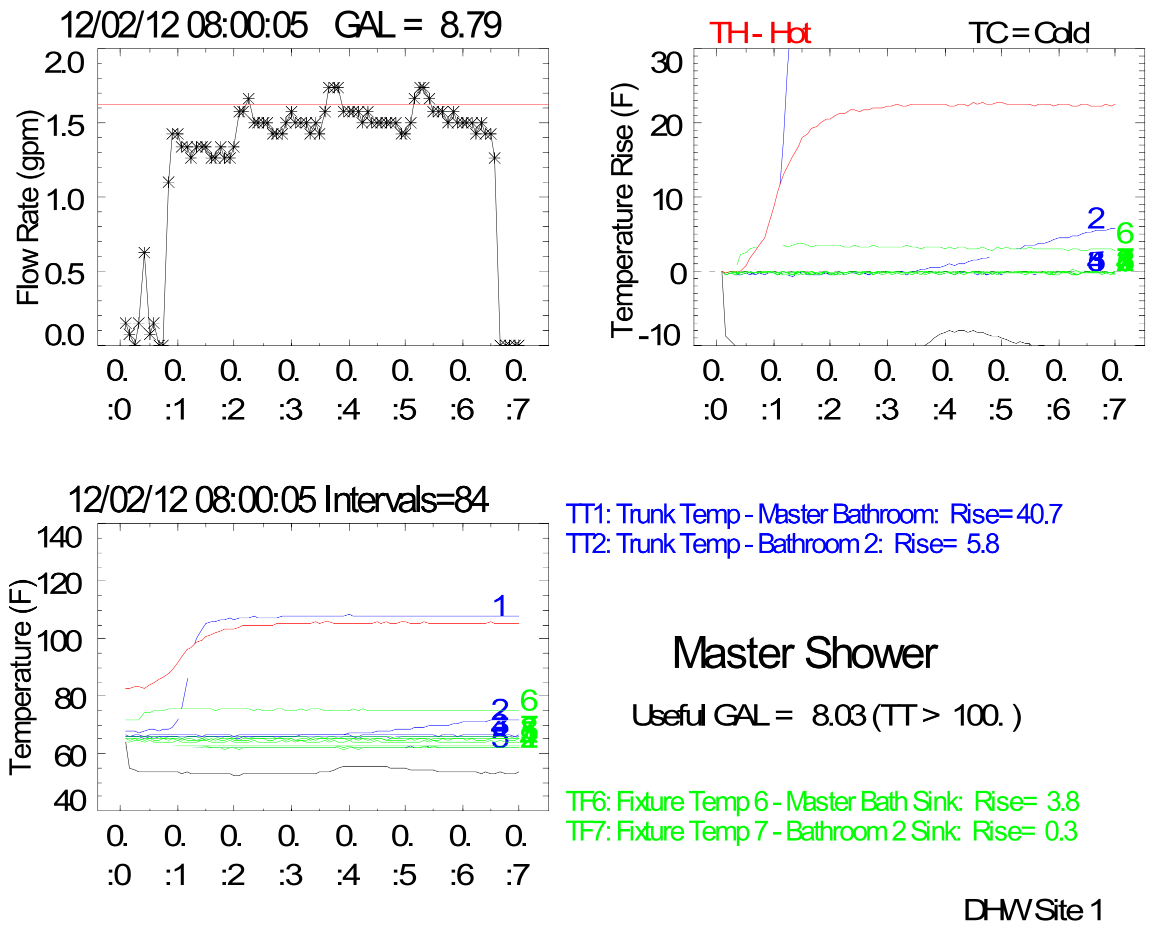

Figure 2. Hot water draw at master bath shower—December 2, 2012

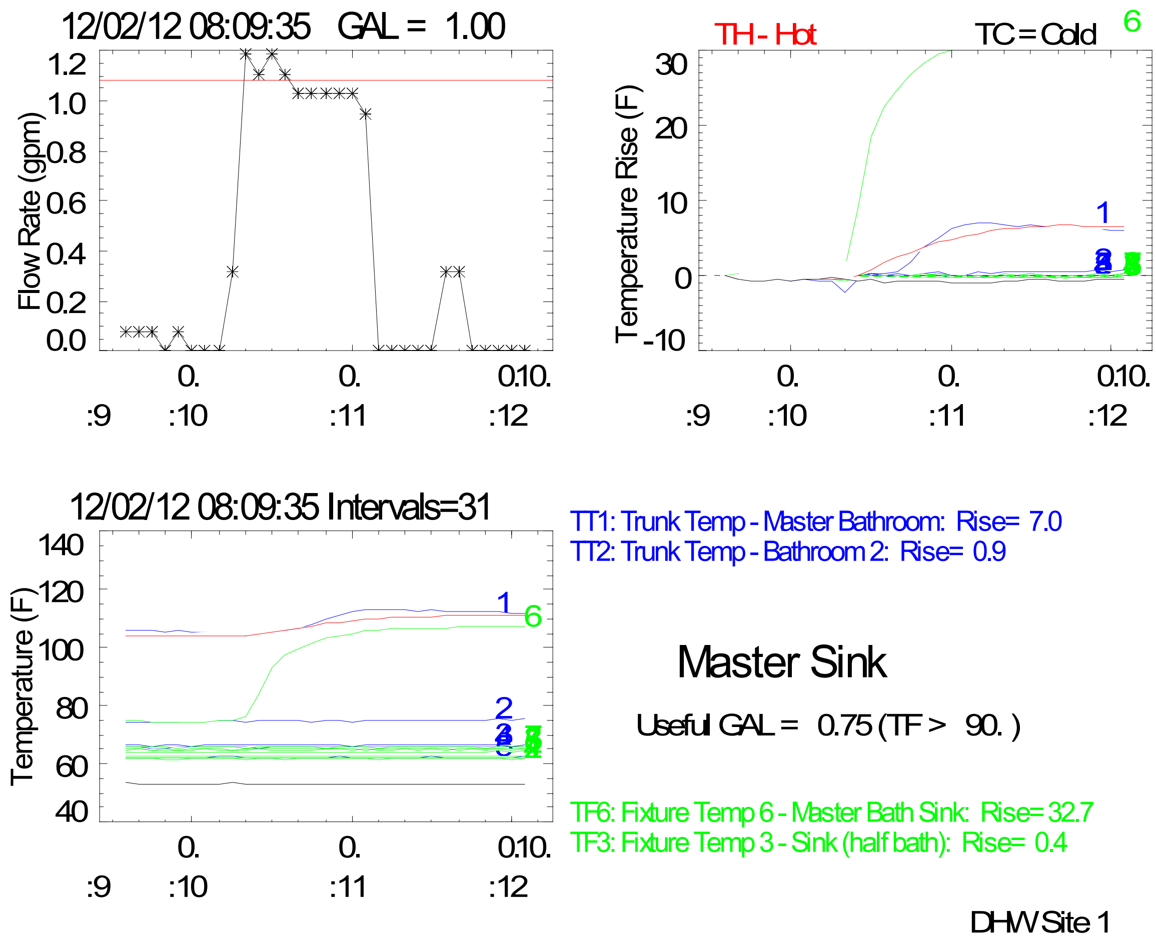

Figure 3. Hot water draw at master bath sink—December 2, 2012

Figure 4 shows the subsequent first hot water draw of the day in the kitchen. The trunk temperature to the kitchen increases by 21°F and the fixture temperature increases by only 5.5°F, indicating that hot water was heading for—but apparently never reached—the kitchen sink.

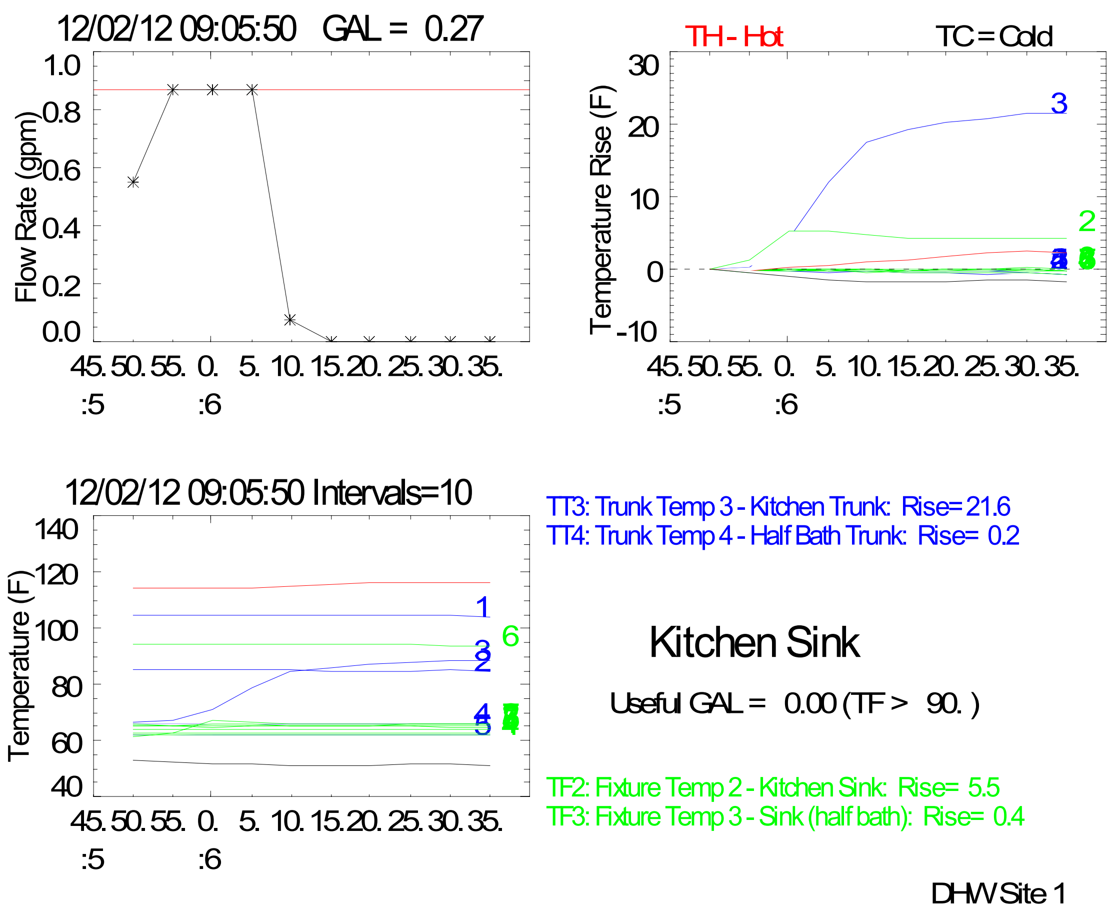

Figure 4. Hot water draw at kitchen sink—December 2, 2012

3.2 Classifying Draw Events

A classification procedure was developed to classify hot water events and assign them to an end use or fixture. The larger text in lower right side in the figures above indicates the end use assigned to these particular draws by the procedure.

Table 3 summarizes how the fixture and trunk temperatures associated with each fixture are used to assign hot water draws at Site 1. The temperature rise for any fixture ‘n’ is defined as

$$TFn_{rise} = TFn_{max} - TFn_0$$

Where TFn_0 is the temperature for the first interval of the event and TFn_{max} is the maximum value observed during the event. Most fixtures at Site 1 have a temperature associated with them except for the upstairs master bathroom shower. In this case a temperature rise on the master bath trunk temperature (TT1) with a total draw of more than 1.5 gal causes it to be associated with this fixture. Similarly, a temperature rise on the master bath sink must be coupled with a total draw of less than 1.5 gal to be associated with that fixture.

Table 3. Logic Table for Fixture and Trunk Temperatures (Site 1)

Fixture	Logical Test	Event Range Check
Dishwasher	$TF1_{rise}$ is highest and $TF1_{rise} > 2°F$	–
Kitchen Sink	$TF2_{rise}$ is highest and $TF2_{rise} > 2°F$	–
Half Bath Sink	$TF3_{rise}$ is highest and $TF3_{rise} > 2°F$	–
Wash Machine	$TF4_{rise}$ is highest and $TF4_{rise} > 2°F$	–
Utility Sink	$TF5_{rise}$ is highest and $TF5_{rise} > 2°F$	–
Master Sink	$TF6_{rise}$ is highest and $TF6_{rise} > 2°F$	< 1.5 gal
Master Shower	$TT1_{rise}$ is highest and $TT1_{rise} > 4°F$	> 1.5 gal
Bath 2 Sink	$TF7_{rise}$ is highest and $TF7_{rise} > 2°F$	–
Bath 2 Shower	$TF8_{rise}$ is highest and $TF8_{rise} > 2°F$	–

Once the draw has been associated with fixture, or "classified," we used the appropriate end use temperature sensor to estimate what portion of the water draw was "useful." Hot water is deemed useful for all intervals during a draw event where

$$TF > T_{threshold}$$

If the fixture is associated with a trunk temperature (such as for the master shower in Table 3), then the intervals deemed as useful have a slightly higher threshold of

$$TT > T_{threshold} + 10°F$$

We used 90°F for $T_{threshold}$ at all sites. The selection of this threshold level did not affect the classification process. However, the determination of the useful portion of each draw is expected to depend on the selected value. Therefore, a sensitivity analysis of threshold value is given in Section 4.3.

We developed similar criteria for Sites 2 through 5. Table 4 through Table 7 summarize the criteria that were applied at these sites.

Table 4. Logic Table for Fixture and Trunk Temperatures (Site 2)

Fixture	Logical Test	Event Range Check
Bath Sink	$TF1_{rise}$ is highest and $TF1_{rise} > 2°F$	–
Bath Shower	$TF2_{rise}$ is highest and $TF2_{rise} > 2°F$	–
Kitchen Sink	$TF3_{rise}$ is highest and $TF3_{rise} > 2°F$	–
Wash Machine	$TF4_{rise}$ is highest and $TF4_{rise} > 2°F$	–

Table 5. Logic Table for Fixture and Trunk Temperatures (Site 3)

Fixture	Logical Test	Event Range Check
Bath 1 Sink	$TF1_{rise}$ is highest and $TF1_{rise} > 2°F$	–
Bath 1 Shower	$TF2_{rise}$ is highest and $TF2_{rise} > 2°F$	–
Bath 2 Sink	$TF3_{rise}$ is highest and $TF3_{rise} > 2°F$	–
Bath 2 Shower	$TF4_{rise}$ is highest and $TF4_{rise} > 2°F$	–
Kitchen Sink	$TF5_{rise}$ is highest and $TF5_{rise} > 2°F$	–
Dishwasher	$TF6_{rise}$ is highest and $TF6_{rise} > 2°F$	–
Wash Machine	$TF7_{rise}$ is highest and $TF7_{rise} > 2°F$	–
Laundry Sink	$TF8_{rise}$ is highest and $TF8_{rise} > 2°F$	–

Table 6. Logic Table for Fixture and Trunk Temperatures (Site 4)

Fixture	Logical Test	Event Range Check
Master Sink	$TF1_{rise}$ is highest and $TF1_{rise} > 2°F$	–
Wash Machine	$TF2_{rise}$ is highest and $TF2_{rise} > 2°F$	–
Kitchen Sink	$TF3_{rise}$ is highest and $TF3_{rise} > 2°F$	–
Laundry Sink	$TF4_{rise}$ is highest and $TF4_{rise} > 2°F$	–
Master Shower	$TF5_{rise}$ is highest and $TF5_{rise} > 2°F$	–
Utility Sink	$TF6_{rise}$ is highest and $TF6_{rise} > 2°F$	–
Old Bath Sink	$TF7_{rise}$ is highest and $TF7_{rise} > 2°F$	–
Old Bath Shower	$TT1_{rise}$ is highest and $TT1_{rise} > 4°F$	> 4 gal

Table 7. Logic Table for Fixture and Trunk Temperatures (Site 5)

Fixture	Logical Test	Event Range Check
Lower Sink	$TF1_{rise}$ is highest and $TF1_{rise} > 2°F$	–
Lower Shower	$TF2_{rise}$ is highest and $TF2_{rise} > 2°F$	–
Wash Machine	$TF3_{rise}$ is highest and $TF3_{rise} > 2°F$	–
Laundry Sink	$TF4_{rise}$ is highest and $TF4_{rise} > 2°F$	–
Upper Sink	$TF5_{rise}$ is highest and $TF5_{rise} > 2°F$	–
Upper Shower	$TF6_{rise}$ is highest and $TF6_{rise} > 2°F$	–
Kitchen Sink	$TF7_{rise}$ is highest and $TF7_{rise} > 2°F$	–
Dishwasher	$TF8_{rise}$ is highest and $TF8_{rise} > 2°F$	–

3.3 Errors in Classifying Draw Events

The Results section that follows provides overall statistics on the success of the classification process. This subsection looks at some draws that were not properly identified.

Figure 5 shows a draw event in the master bath shower at Site 1 that could not be properly identified since the temperature rise on the master bath trunk was lower than the temperature rise on the bath 2 trunk. The master bath trunk was already up to temperature before the event began, so the rise was small. As is normally observed, the bath 2 trunk is slowly heated when there is flow to the master bath. In this case, the first part of the draw (at 0.9 gpm) was apparently a draw at the master bath sink. The shower began when the flow jumped to 1.3 gpm. So these two separate draws were classified as a single draw event.

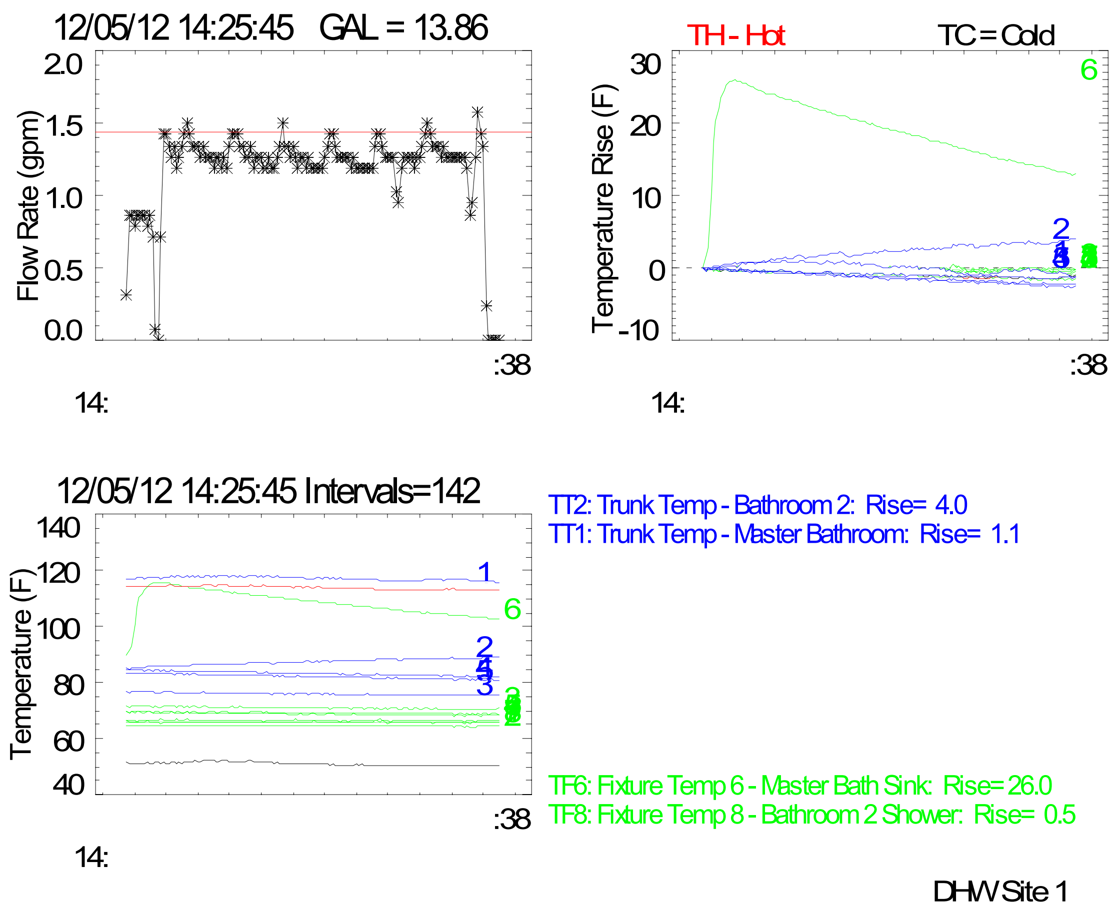

Figure 5. Hot water draw that was unclassified, Site 1, December 5, 2012

Similarly, the draw event shown in Figure 6 (also Site 1) was also two draws combined but it was misclassified as a bath 2 sink draw, but only the second portion corresponds to that fixture. The first part of the draw was due to the master bath shower. In this case the useful hot water draw was more than 3.8 gal while the total draw was more than 13 gal. The difference between the useful and the total water draw provides an indication, in this case, that there could be a classification error.

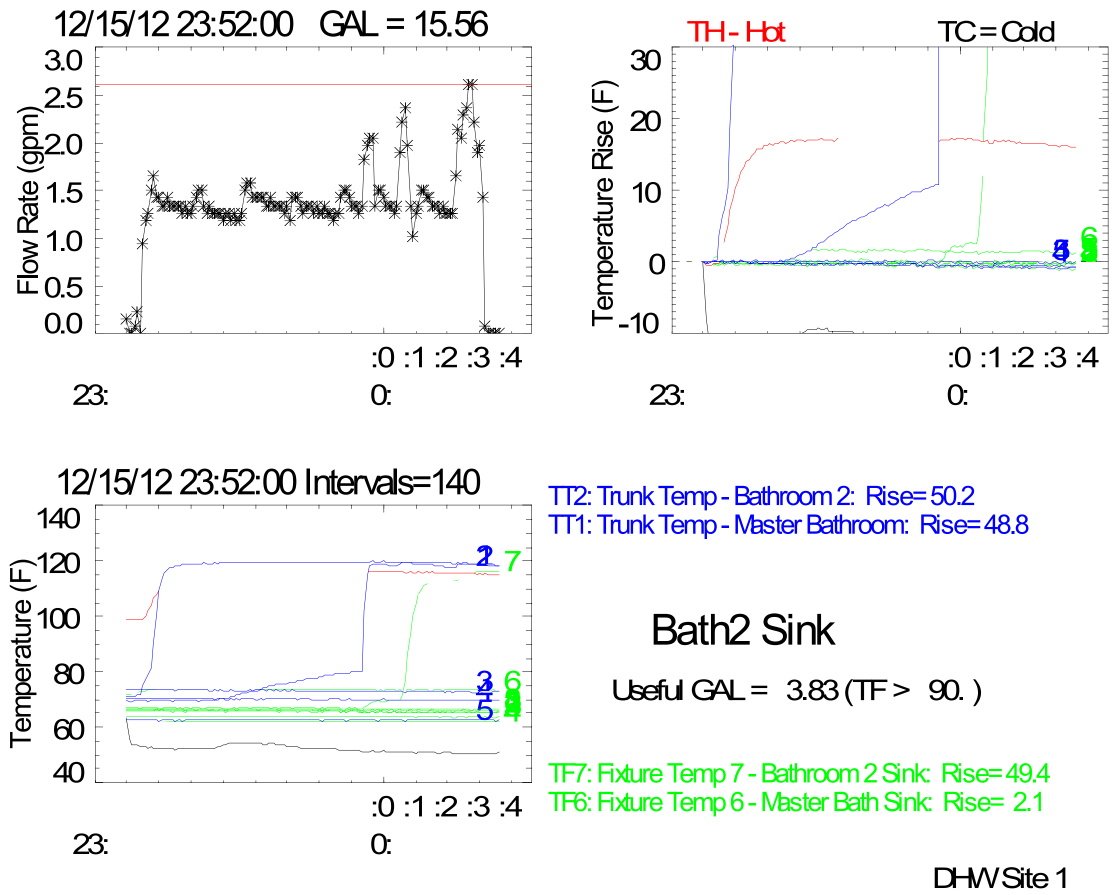

Figure 6. Hot water draw that was misclassified, Site 1, December 15, 2012

At Site 4 there are two hot water systems in the house (see Appendix B): (1) an old conventional gas-fired tank that serves the old bathroom; and (2) a new tankless water heater that serves an addition that includes most other fixtures in the home. Figure 7 shows that the draw for the old bath shower (on the old water heater, blue data) happens at the same time as the kitchen sink/dishwasher (on the tankless water heater, black data).

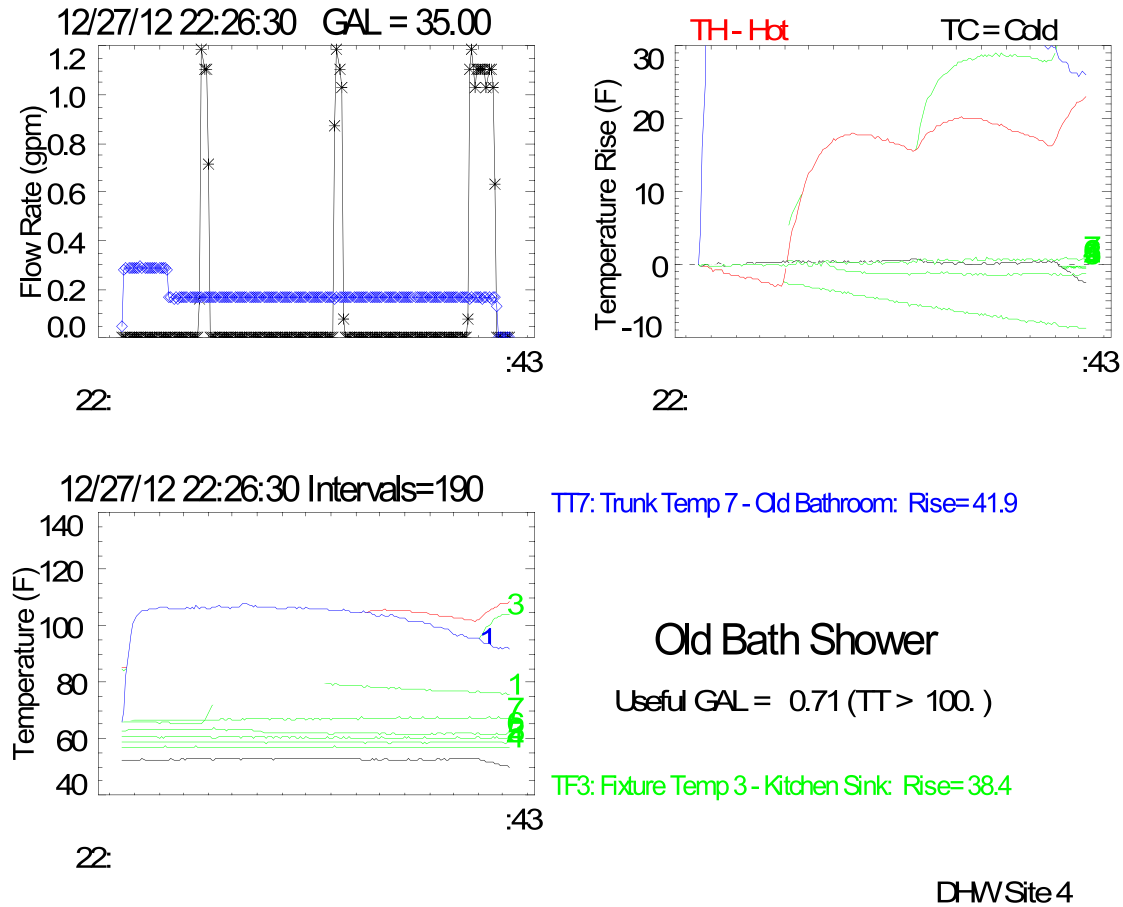

Figure 7. Hot water draw that was misclassified, Site 4, December 27, 2012

4 Pre-Retrofit or Baseline Results

4.1 Classifying Draw Events at Each Site

The classification procedures described in the previous section were applied to each site for the data collected in the pre-retrofit periods for Sites 1, 2, and 3 and for the entire period for Sites 4 and 5. The results of that process are shown for each site in the following tables and figures. The figures show the total hot water use verses the draw rate (or mode) for each event. This type of graph was used by Magnusson (2009) to qualitatively illustrate the characteristics of various draw types.

The results for Site 1 are shown in Table 8, Figure 8, and Figure 9. This home has two adults and two college-age students who returned for the college breaks (who mostly used bathroom 2). Fewer than half of the 8,534 events in the 123-day period could be assigned. However, these classified (or assigned) events accounted for 94% of the total water use. Numerous small events could not be assigned (these are shown as black "+" on the plots). The average unclassified event was less than 0.1 gal. Of the unclassified events, only 18 were more than 1 gal in the 123-day period. One of the biggest unclassified events is shown in the previous section in Figure 5. Overall, about 82% of the total classified water use was deemed to be useful, based on the 90°F threshold. As expected, the sinks result in the largest amount of hot water waste on a percentage basis.

Table 8. Summary of Results for Site 1, December 1, 2012 to April 2, 2013 (123 Days)

Site 1	Events per Day	Total Hot Water Use (gpd)	Useful Hot Water (gpd)	Wasted Hot Water (gpd)	Useful %
Dishwasher	1.5	2.7	2.4	0.3	90%
Kitchen Sink	17.0	9.1	5.7	3.3	63%
Half Bath Sink	2.1	0.7	0.1	0.5	21%
Washing Mach	0.7	9.1	8.3	0.8	91%
Utility Sink	0.3	0.9	0.5	0.4	53%
Master Sink	6.8	2.2	0.6	1.5	28%
Master Shower	1.5	17.8	17.0	0.8	95%
Bath 2 Sink	1.7	1.2	0.6	0.6	49%
Bath 2 Shower	0.7	8.4	7.7	0.8	91%
Unaccounted	36.8	3.4	–	3.4	0%
All Events	69.4	55.4	42.9	12.5	77%
Classified	33	52.0	42.9	9.1	82%
% Classified	47%	94%	100%	73%	
No. of Events	8,534				

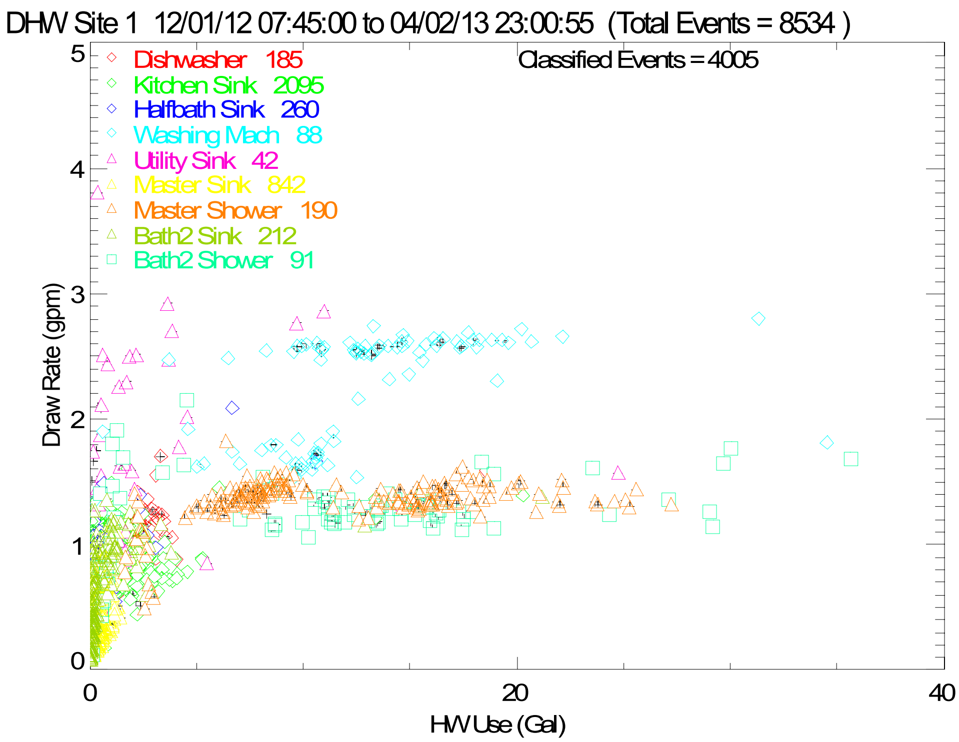

Figure 8. Summary of classified draw events, Site 1, December 1 to April 2: 0–40 gal

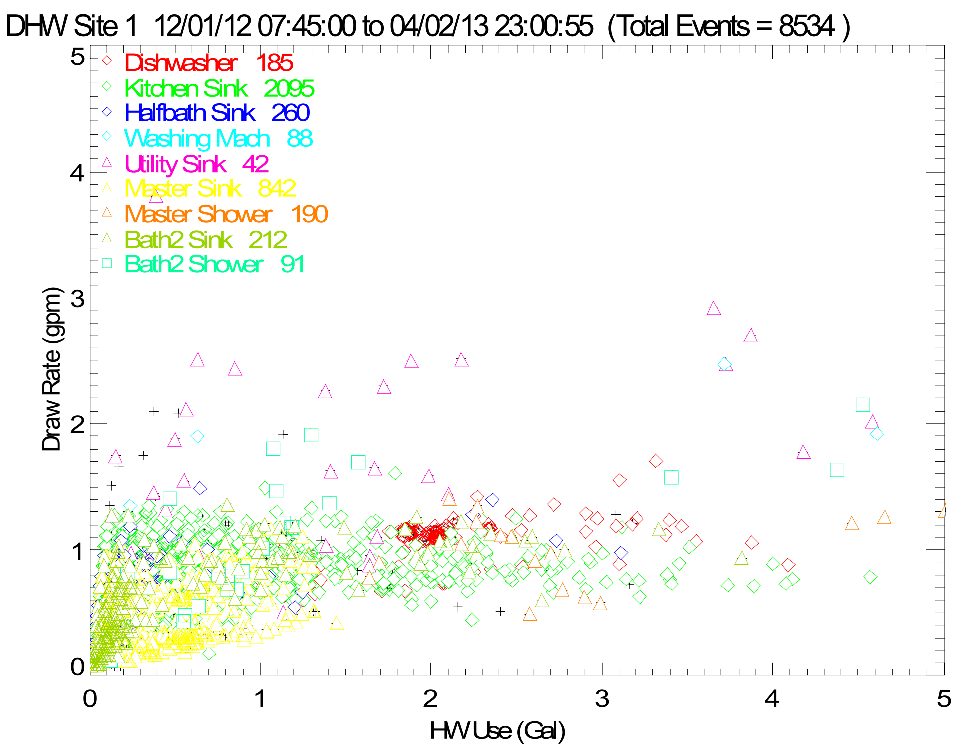

Figure 9. Summary of classified draw events, Site 1, December 1 to April 2: 0–5 gal

The results for Site 2 are shown in Table 9, Figure 10, and Figure 11. This home has two occupants. Fewer than half of the 4,648 events in the 157-day period could be assigned. However, these classified events accounted for 98% of the total water use. Numerous small events could not be assigned. The average unclassified event was approximately 0.05 gal. Only six of the unclassified events were more than 1 gal. Overall 87% of the total classified water use was deemed to be useful. One very large draw exceeding 164 gal and lasting more than 1 hour occurred when the occupants apparently left the bathtub running in December. Some of the bath shower draws were misclassified as bath sink draws because the temperature rise was slightly higher at the sink fixture (or because simultaneous draws occurred).

Table 9. Summary of Results for Site 2, December 14, 2012 to May 19, 2013 (157 Days)

Site 2	Events per Day	Total Hot Water Use (gpd)	Useful Hot Water (gpd)	Wasted Hot Water (gpd)	Useful %
Bath Sink	4.0	4.8	4.7	0.2	96%
Bath Shower	3.2	41.9	37.1	4.8	89%
Kitchen Sink	2.3	3.0	1.8	1.1	62%
Washing Mach	2.0	1.3	0.7	0.6	56%
Unaccounted	18.2	1.0	-	1.0	0%
All Events	29.6	52.0	44.3	7.7	85%
Classified	11.5	51.0	44.3	6.7	87%
% Classified	39%	98%	100%	86%	
No. of Events	4,648				

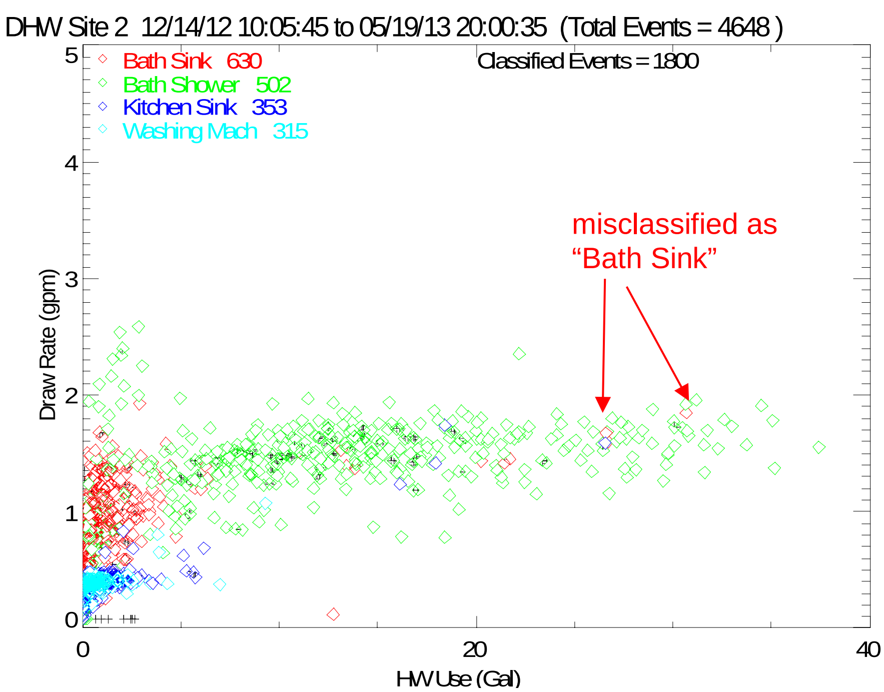

Figure 10. Summary of classified draw events, Site 2, December 14 to May 19: 0–40 gal

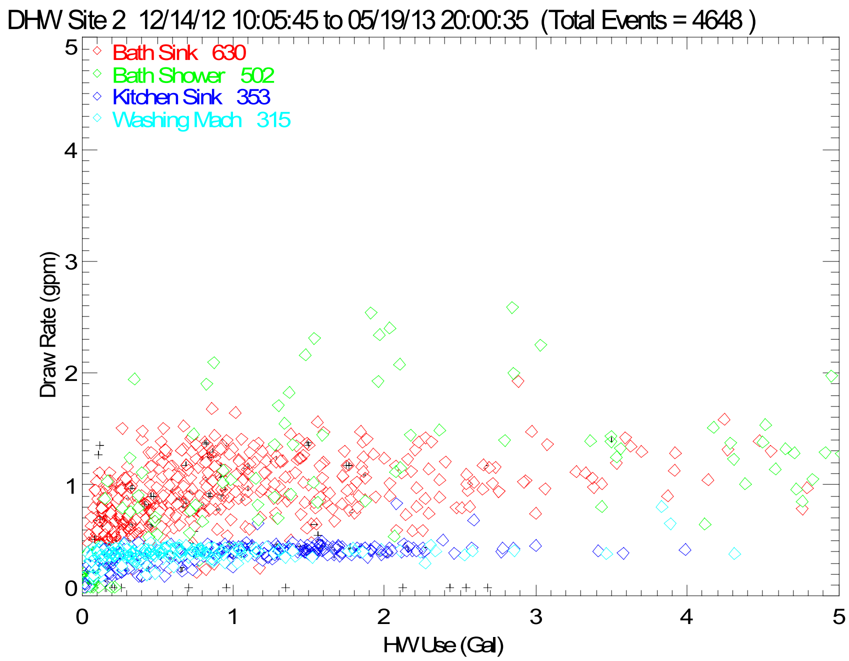

Figure 11. Summary of classified draw events, Site 2, December 14 to May 19: 0–5 gal

The results for Site 3 are shown in Table 10, Figure 12, and Figure 13. This home has two adult occupants. About half of the 2,909 events in the 98-day period could be assigned. However, these classified events accounted for 94% of the total hot water use. Numerous small events could not be assigned. The average unclassified event was about 0.1 gal. Only 17 of the unclassified events were more than 1 gal. Overall, 90% of the total classified water use was deemed to be useful.

Table 10. Summary of Results for Site 3, December 13, 2012 to March 22, 2013 (98 Days)

Site 3	Events per Day	Total Hot Water Use (gpd)	Useful Hot Water (gpd)	Wasted Hot Water (gpd)	Useful %
Bath 1 Sink	0.2	0.4	0.3	0.1	78%
Bath 1 Shower	1.4	18.2	17.1	1.0	94%
Bath 2 Sink	5.8	1.7	1.2	0.5	69%
Bath 2 Shower	0.1	1.7	1.7	0.0	98%
Kitchen Sink	5.8	4.8	3.8	1.0	80%
Dishwasher	1.7	2.0	1.7	0.3	86%
Washing Machine	0.7	3.4	3.2	0.2	94%
Laundry Sink	0.0	0.1	0.1	0.0	93%
Unaccounted	14.1	2.0	–	2.0	0%
All Events	29.6	34.3	29.2	5.1	85%
Classified	15.6	32.3	29.2	3.1	90%
% Classified	53%	94%	100%	60%	
No. of Events	2,909				

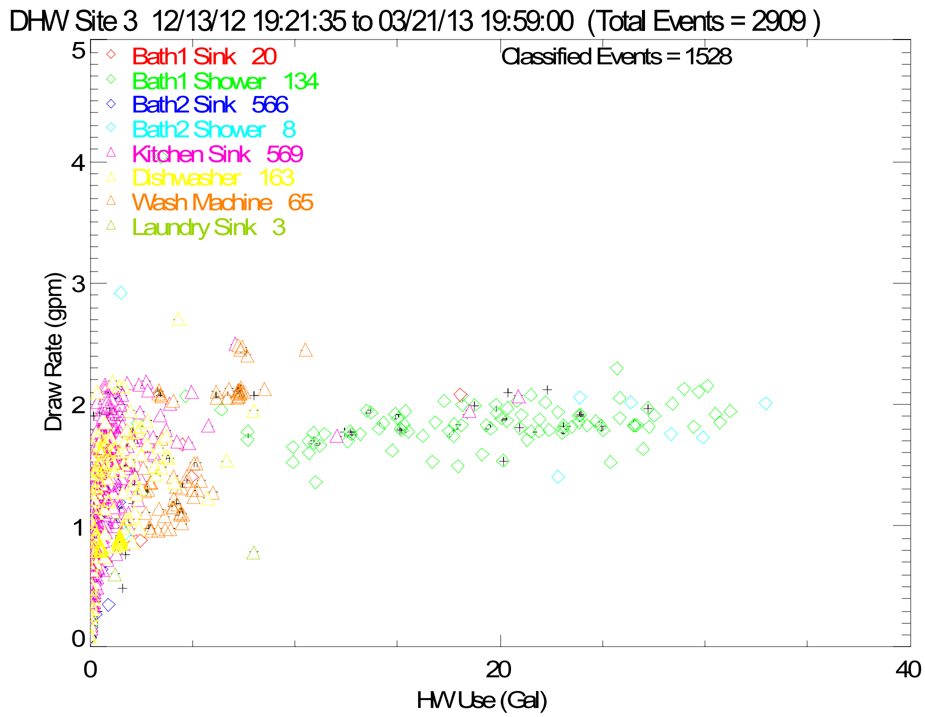

Figure 12. Summary of classified draw events, Site 3, December 13 to March 22: 0–40 gal

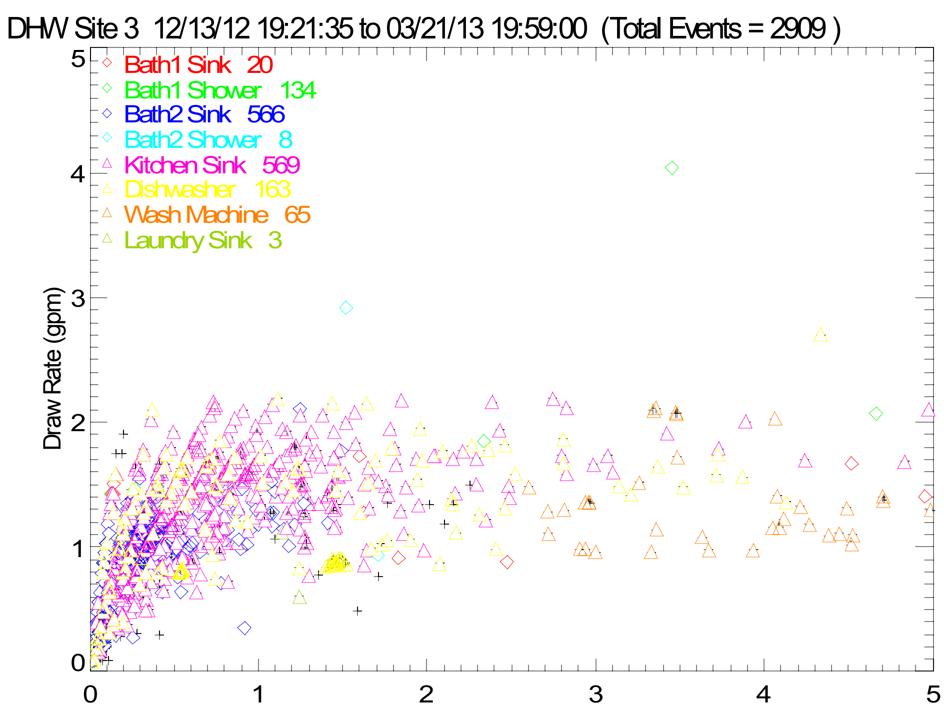

Figure 13. Summary of classified draw events, Site 3, December 13 to March 22: 0–5 gal

The results for Site 4 are shown in Table 11, Figure 14, and Figure 15. This home has two adults and three high school or college-age children. Only 17% of the 36,592 events in the 202-day period could be assigned. However, these classified events accounted for 88% of the total water use. Numerous small events could not be assigned. The average unclassified event was less than 0.1 gal. More than 200 of the unclassified events exceeded 1 gal. Overall, about 75% of the total classified water use was deemed to be useful. The placement of sensors on the PEX tubing may have provided a slower response than the sensors installed on copper piping at the other sites, resulting in a delay in sensing the time when the water temperature reached the assumed threshold of 90°F.

Table 11. Summary of Results for Site 4, December 10, 2012 to June 30, 2013 (202 Days)

Site 4	Events per Day	Total Hot Water Use (gpd)	Useful Hot Water (gpd)	Wasted Hot Water (gpd)	Useful %
Master Sink	6.8	6.4	2.5	3.8	40%
Washing Machine	1.1	1.8	0.2	1.5	14%
Kitchen Sink	15.8	19.4	12.5	7.0	64%
Laundry Sink	-	-	-	-	
Master Shower	2.7	39.4	34.9	4.5	89%
Utility Sink	0.0	0.1	-	0.1	0%
Old Bath Sink	2.9	3.5	1.8	1.7	51%
Old Bath Shower	1.4	31.8	25.2	6.6	79%
Unaccounted	150.3	13.3	-	13.3	0%
All Events	180.9	115.8	77.2	38.6	67%
Classified	30.6	102.4	77.2	25.2	75%
% Classified	17%	88%	100%	65%	
No. of Events	36,592				

The breakdown of hot water use over 7 months for Site 4 is shown in Figure 16. The monthly variation the "usefulness" of draws by end use is shown in Figure 17 for the same period. The hot water use did vary significantly across the period, with the highest value in March 2013 (when cold water inlet temperatures were lowest). The useful portion of the draws did not show as much variation, with the exception of the washing machine, which did show random monthly variations in "usefulness."

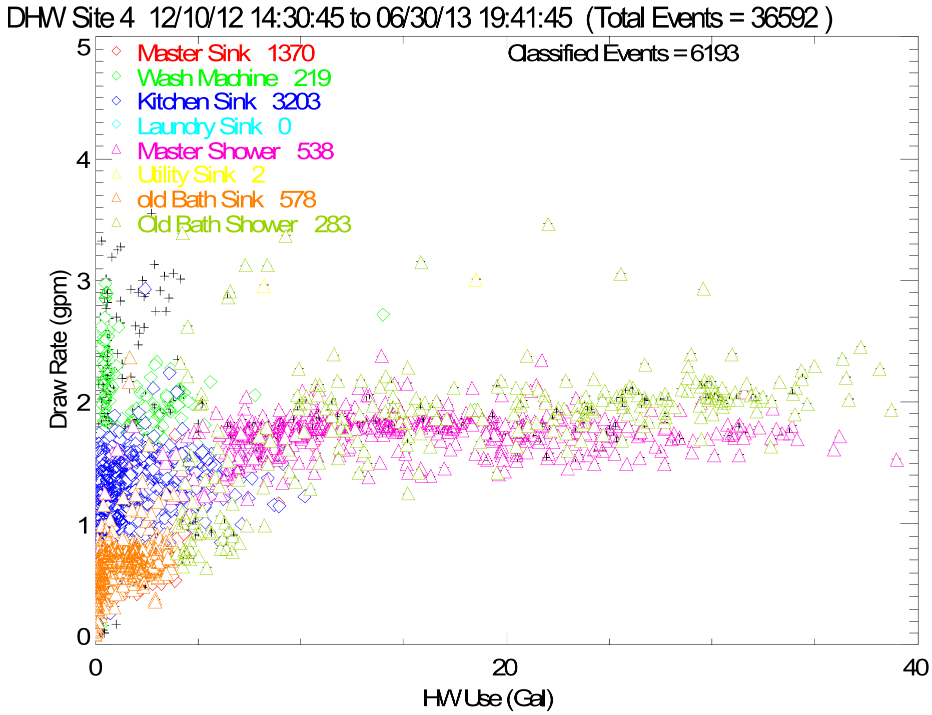

Figure 14. Summary of classified draw events, Site 4, December 26–30, 2012: 0–40 gal

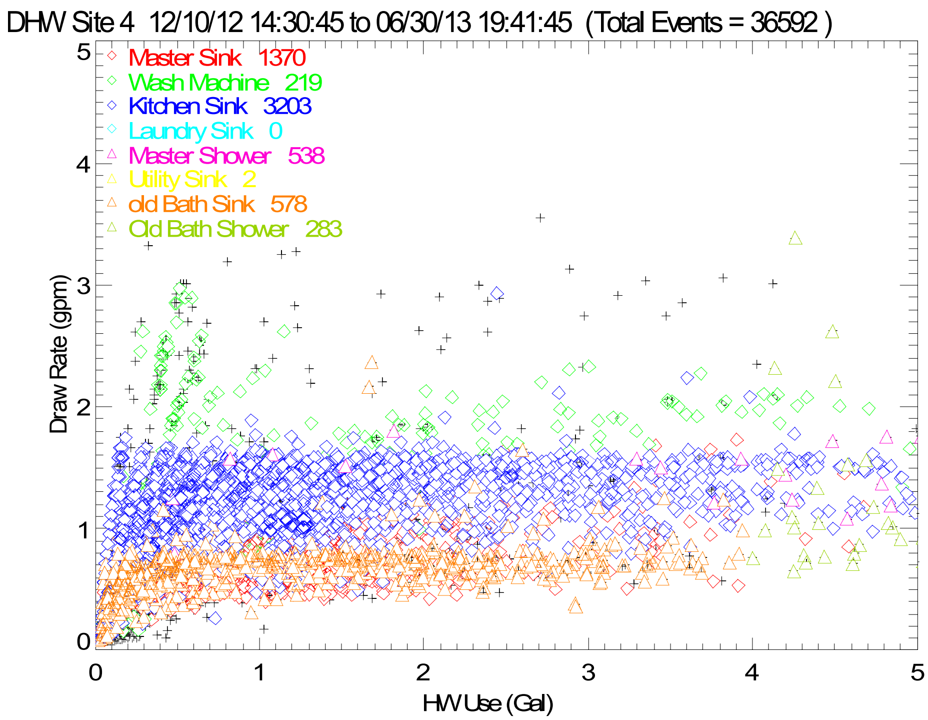

Figure 15. Summary of classified draw events, Site 4, December 26–30, 2012: 0–5 gal

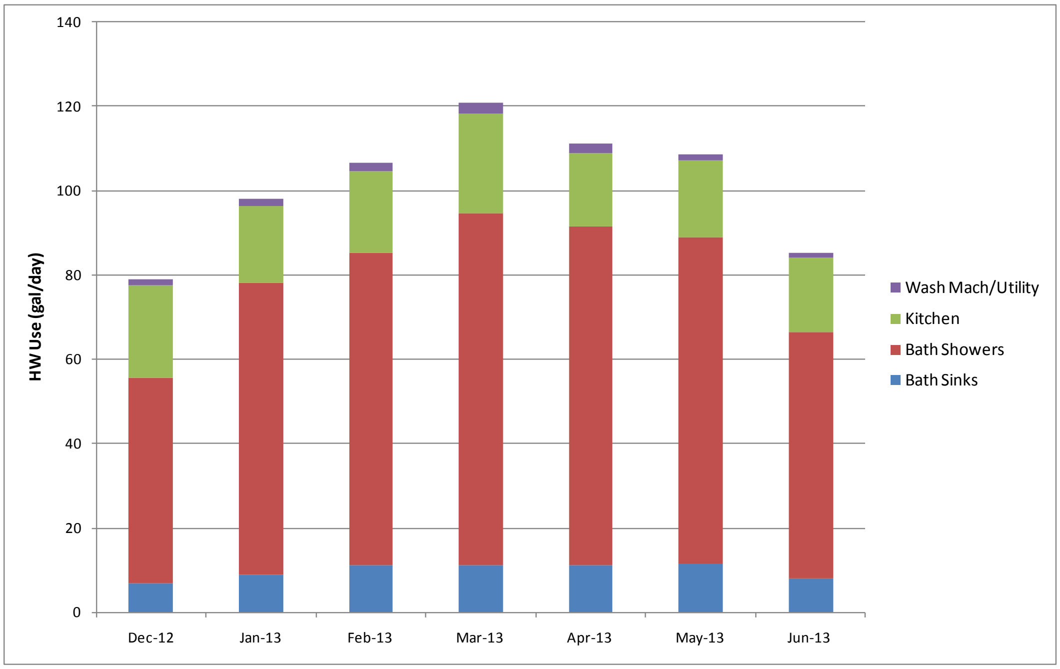

Figure 16. Monthly breakdown of hot water use (Site 4)

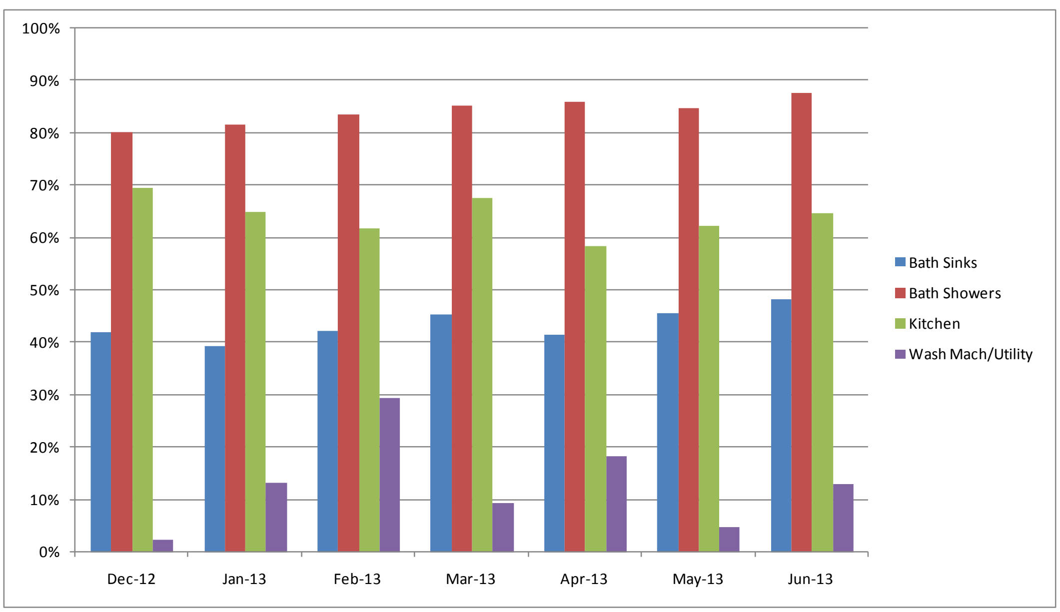

Figure 17. Monthly variation of "usefulness" by end use (Site 4)

The results for Site 5 are shown in Table 12, Figure 18, and Figure 19. This home has two adults. Slightly more than a half of the 5,191 events in the 198-day period could be assigned. However, these classified events accounted for 98% of the total water use. Numerous small events could not be assigned. The average unclassified event was less than 0.1 gal. Only three of the unclassified events were more than 1 gal. Overall, 91% of the total classified water use was deemed to be useful.

Table 12. Summary of Results for Site 5, December 14, 2012 to June 30, 2013 (198 Days)

Site 5	Events per Day	Total Hot Water Use (gpd)	Useful Hot Water (gpd)	Wasted Hot Water (gpd)	Useful %
Lower Sink	1.0	1.3	1.0	0.3	79%
Lower Shower	0.4	4.0	3.7	0.4	91%
Washing Machine	0.5	3.5	3.3	0.1	97%
Laundry Sink	0.1	0.4	0.3	0.0	94%
Upper Sink	3.0	7.5	6.6	1.0	87%
Upper Shower	1.9	20.9	19.7	1.2	94%
Kitchen Sink	4.2	2.1	1.4	0.7	66%
Dishwasher	3.9	5.3	4.9	0.4	93%
Unaccounted	11.2	0.8	-	0.8	0%
All Events	26.2	45.7	41.0	4.7	90%
Classified	15.0	44.9	41.0	4.0	91%
% Classified	57%	98%	100%	84%	–
No. of Events	5,191				

The breakdown of hot water use over 7 months for Site 5 is shown in Figure 20. The monthly variation the "usefulness" of draws by end use is shown in Figure 21 for the same period. Neither hot water use nor the useful portion of the draws showed a significant amount of variation.

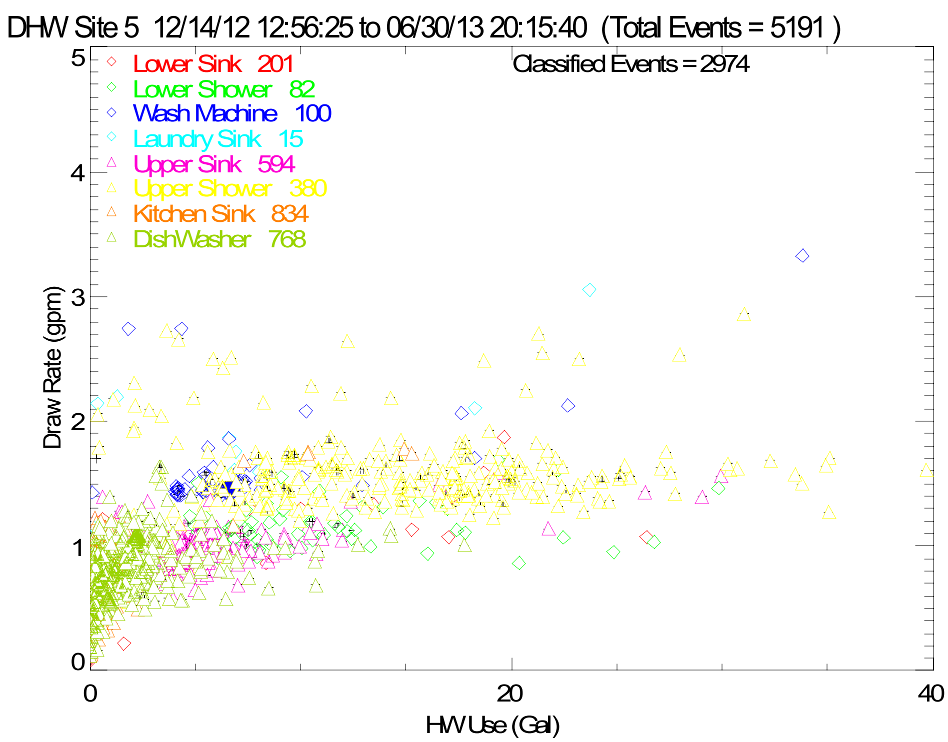

Figure 18. Summary of classified draw events, Site 5, December 14 to June 30: 0–40 gal

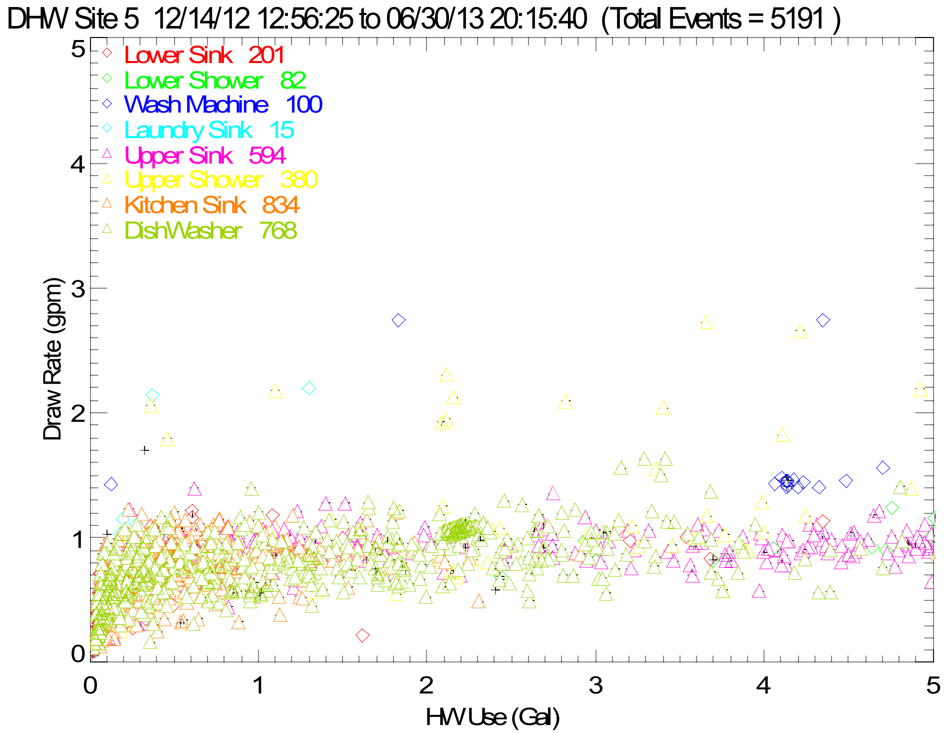

Figure 19. Summary of classified draw events, Site 5, December 14 to June 30: 0–5 gal

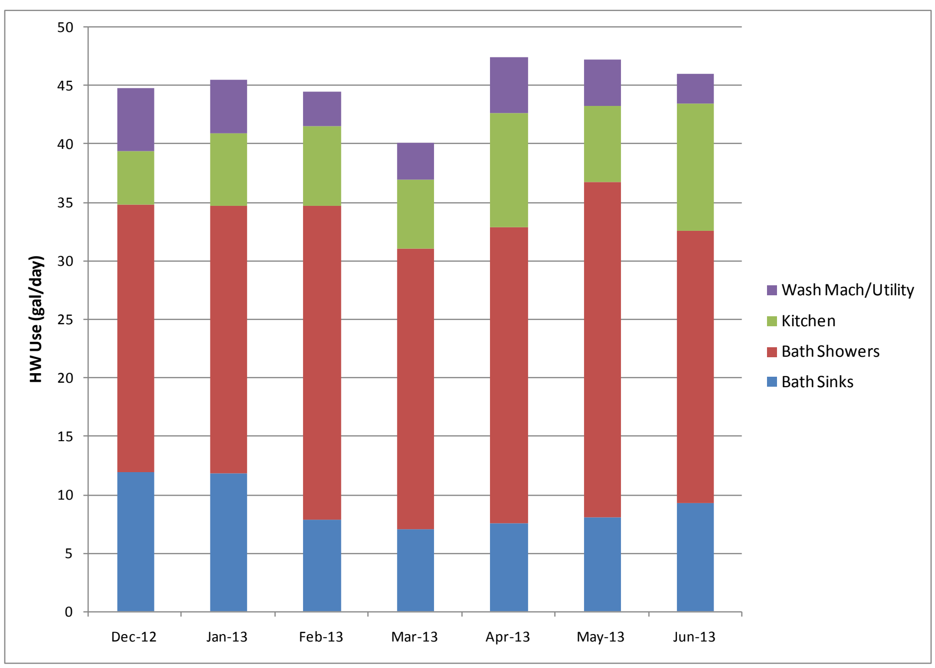

Figure 20. Monthly breakdown of hot water use (Site 5)

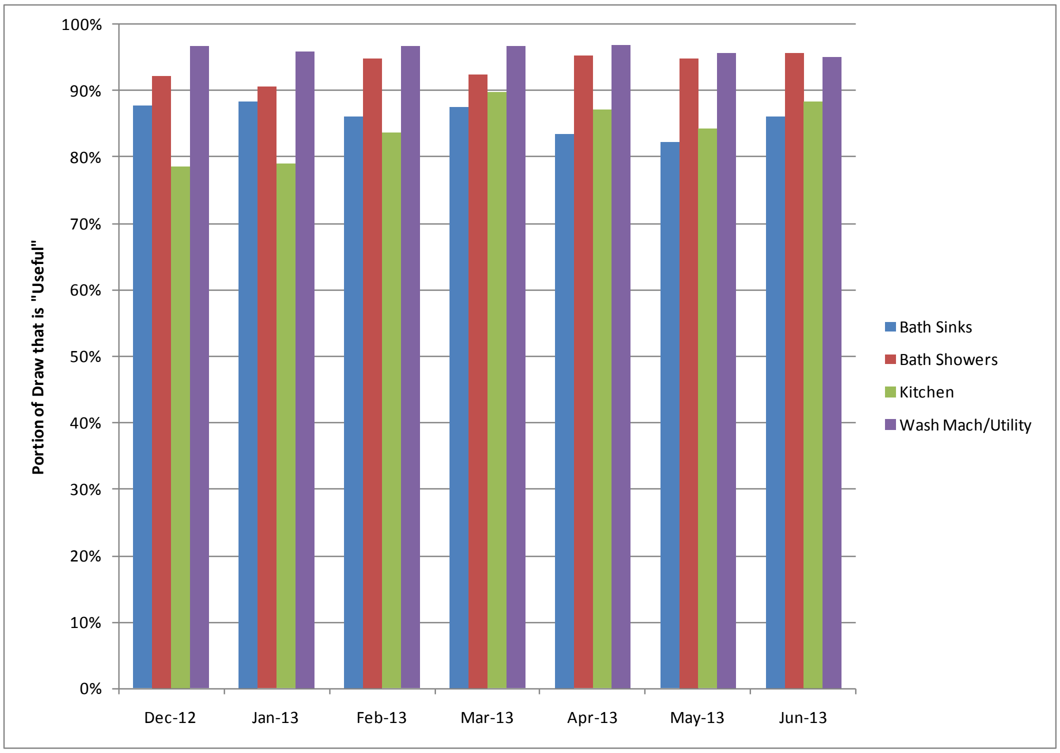

Figure 21. Monthly variation of "usefulness" by end use (Site 5)

4.2 Summary of Cross-Site Performance

Figure 22 and Figure 23 compare the breakdown of hot water use in the five homes. As expected, showers (and baths) account for the largest portion of hot water use in all the houses. The kitchen sink and dishwater are the next largest end uses in three of the five houses.

Total daily hot water use ranged between 40 and 60 gal at three of the houses. At Site 2 the usage was a little more than 30 gpd. At Site 4, the two adults and three teenage children used more than 100 gpd.

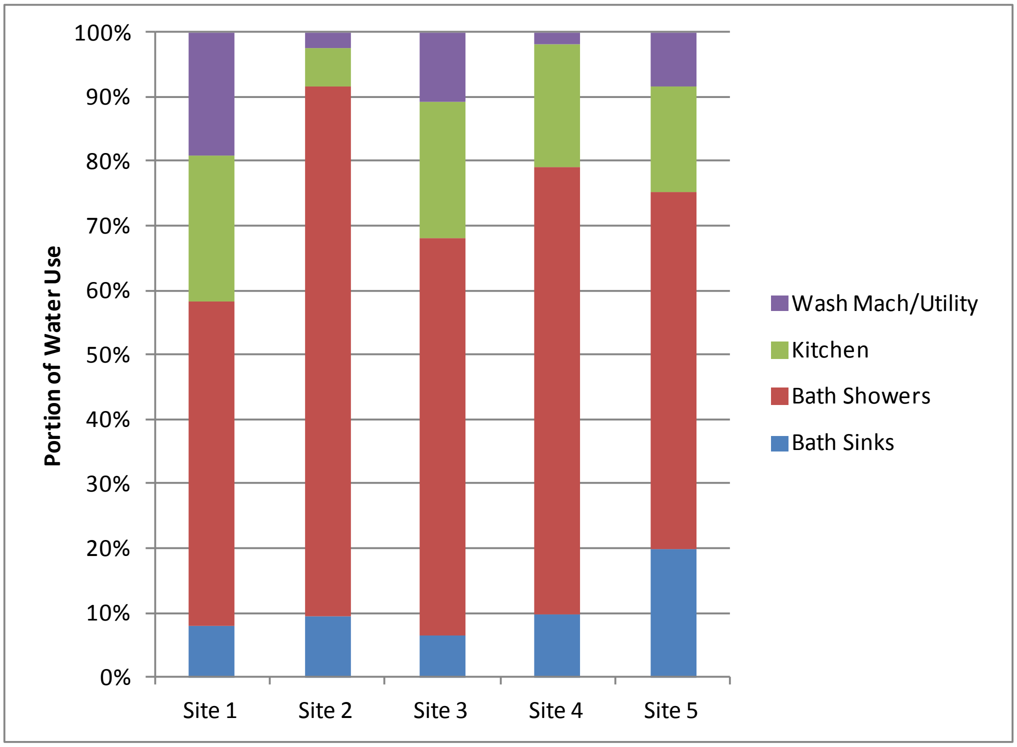

Figure 22. Breakdown of hot water use by end use

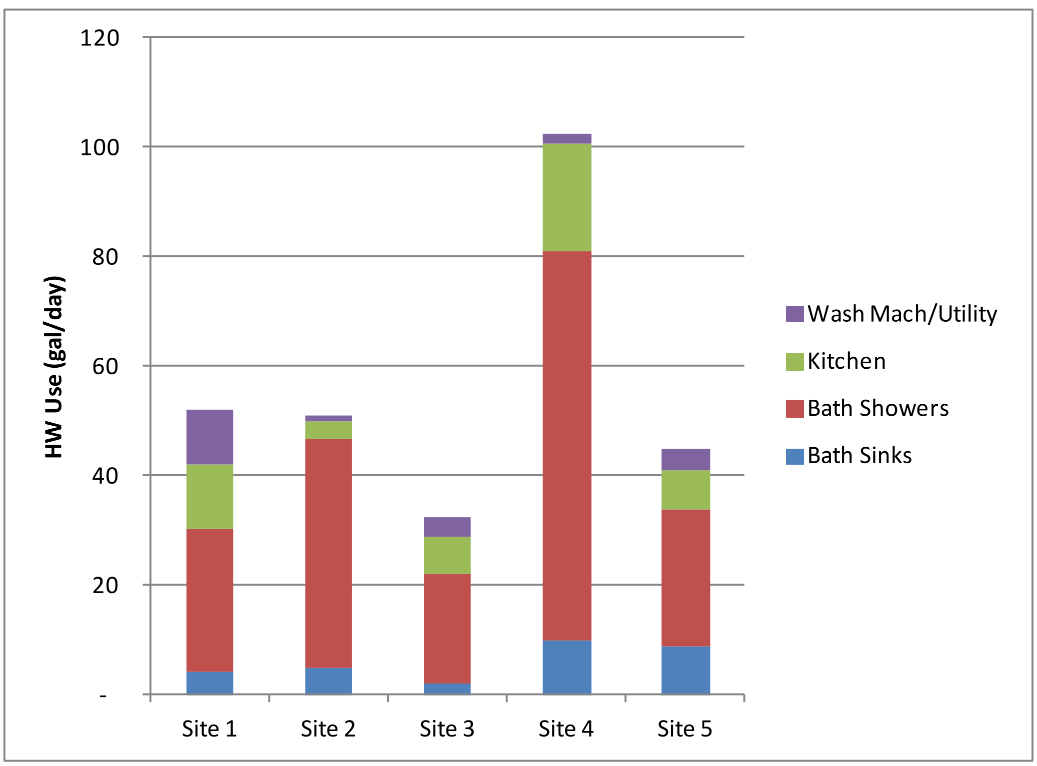

Figure 23. Breakdown of daily hot water use by end use

All the classified draws were also evaluated to determine the portion of the water use that was useful. Water at the fixture above a threshold temperature of 90°F was deemed to be useful. Figure 24 shows the percentage of draws associated with each major end use category that were deemed useful. Showers (and tubs) typically have highest percentage of useful hot water, with three sites exceeding 90% and two sites exceeding 80%. Washing machine draws also have a high useful percentage. Bathroom sinks have a lower useful draw percentage, as would be expected.

Some notable exceptions to the overall trends included:

- Site 2 has a high useful percentage for the bathroom sink since it is very close to the water heater.
- The Site 4 washing machine had a lower useful percentage.

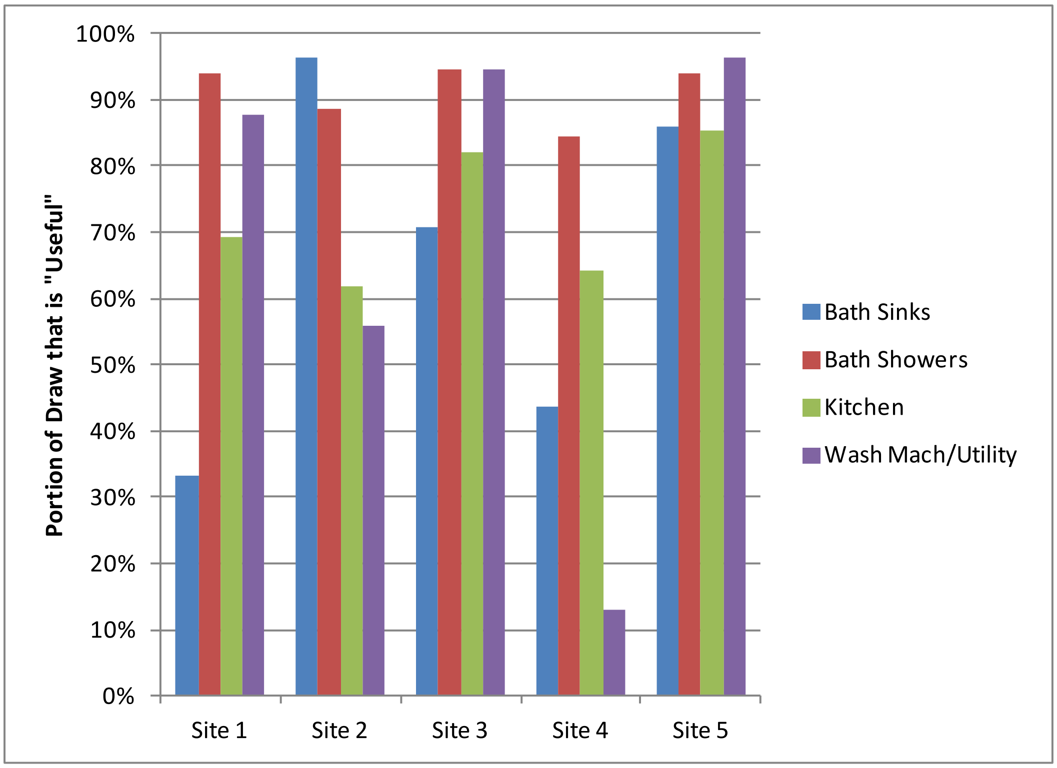

Figure 24. Portion of hot water deemed as useful from each end use

Table 13 summarizes the statistics for the portion of hot water use events that were able to be classified and assigned to a fixture at the five sites. Generally, about half of the events (42%) could be assigned, though 95% of the hot water use could be accounted for. The unclassified (or unassigned) draws were typically on the order of 0.1 gal. Only a small portion of unclassified draws were more than 1 gal.

Table 13. Summary of Classification Statistics for Five Sites

	Site 1	Site 2	Site 3	Site 4	Site 5
Classified Events	47%	39%	53%	17%	57%
Classified Use	94%	98%	94%	88%	98%

4.3 Assessing the Impact of Threshold Level

The threshold level of 90°F for determining the useful portion of each draw was a somewhat arbitrary value. While this definition of might be appropriate for sinks, some argue that a higher value (say 105°F) might be more appropriate for showers and other end uses.

The plots and tables below assess the impact of using a different threshold of 80°F and 100°F at each site. Table 14 and Figure 25 show the results for Site 1. Generally the sinks and dishwasher show the most sensitivity to threshold level. Table 15 and Figure 26 show the results for Site 2. In this case the kitchen sink and washing machine are most sensitive to the threshold level. Table 16 and Figure 27 show the results for Site 3. Again bathroom sinks, the kitchen sink, and the dishwasher are the most sensitive. Table 17 and Figure 28 show the results for Site 4. The slow response of the surface-mounted sensor on PEX piping at this site means that the threshold has a big impact on the determination of “usefulness.” The fixtures in the old bathroom seem to rarely reach 100°F since that water heater has lower setting. Finally the results for Site 5 are shown in Table 18 and Figure 29. At this site the kitchen sink showed the most sensitivity to threshold level.

Table 14. Impact of Threshold Temperature on Determining “Usefulness” (Site 1)

Useful Portion	Threshold Temperature		
	80°F	90°F	100°F
Dishwasher	98%	90%	75%
Kitchen Sink	74%	63%	48%
Half Bath Sink	31%	21%	16%
Washing Machine	93%	91%	89%
Utility Sink	57%	53%	48%
Master Sink	50%	28%	13%
Master Shower	97%	95%	78%
Bath 2 Sink	67%	49%	39%
Bath 2 Shower	93%	91%	89%
	88%	82%	71%

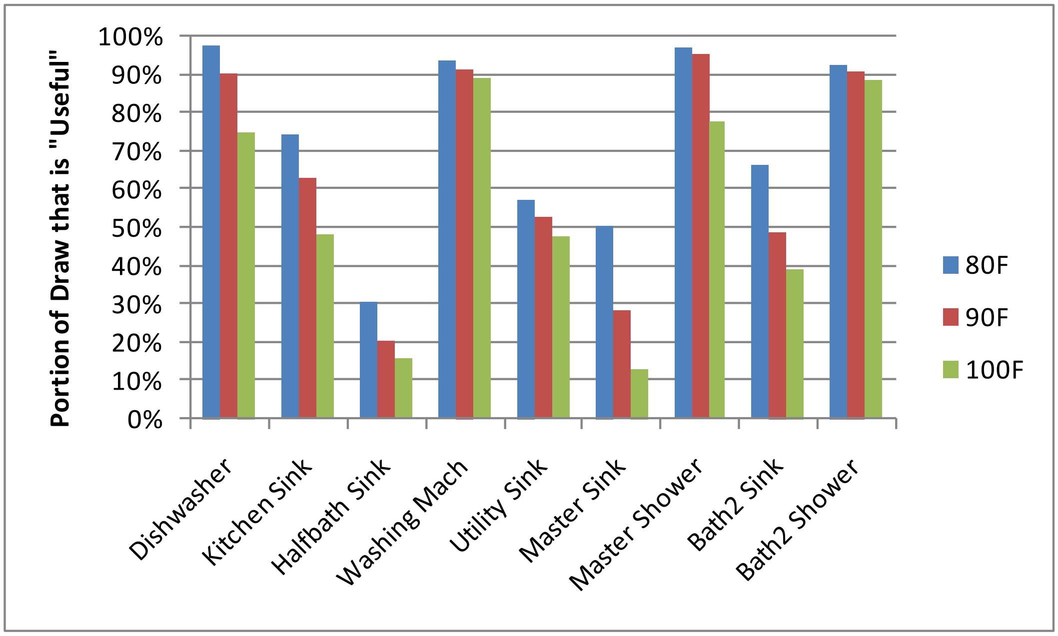

Figure 25. Impact of threshold temperature on "usefulness" at each fixture (Site 1)

Table 15. Impact of Threshold Temperature on Determining "Usefulness" (Site 2)

Useful Portion	Threshold Temperature		
	80°F	90°F	100°F
Bath Sink	98%	96%	88%
Bath Shower	90%	89%	87%
Kitchen Sink	71%	62%	48%
Washing Machine	66%	56%	40%
	89%	87%	84%

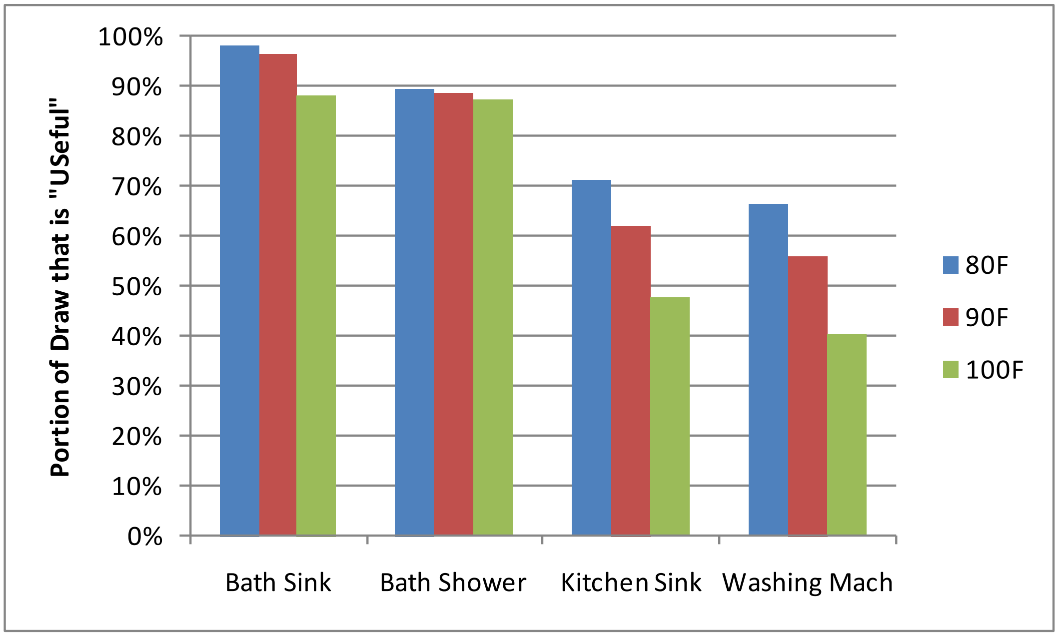

Figure 26. Impact of threshold temperature on "usefulness" at each fixture (Site 2)

Table 16. Impact of Threshold Temperature on Determining "Usefulness" (Site 3)

Useful Portion	Threshold Temperature		
	80°F	90°F	100°F
Bath 1 Sink	82%	78%	59%
Bath 1 Shower	96%	94%	89%
Bath 2 Sink	78%	69%	52%
Bath 2 Shower	99%	98%	97%
Kitchen Sink	84%	80%	72%
Dishwasher	97%	86%	67%
Washing Machine	96%	94%	93%
Laundry Sink	96%	93%	91%
	93%	90%	83%

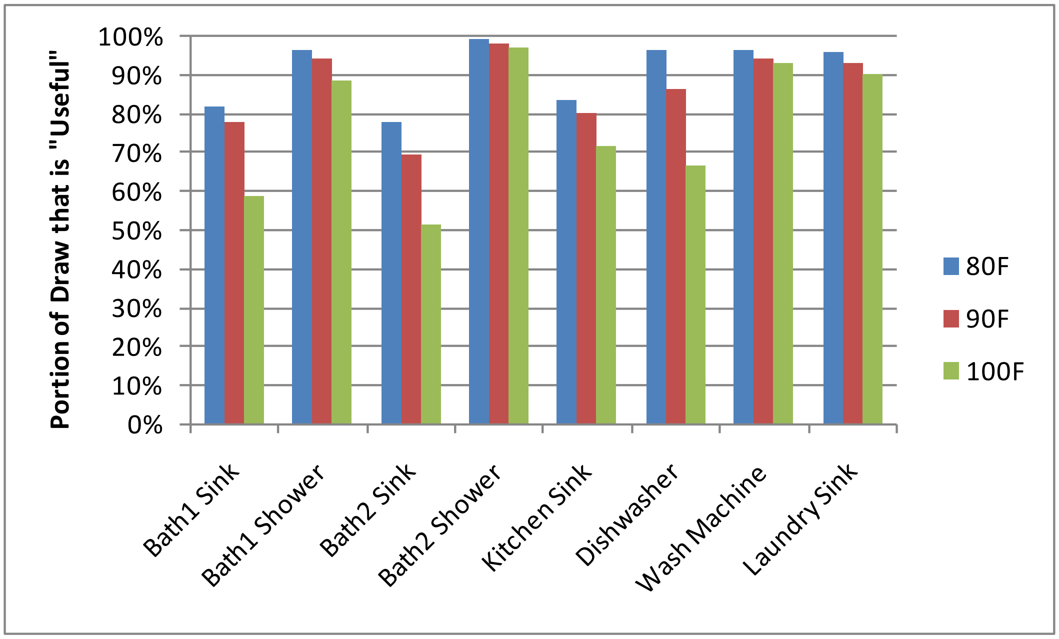

Figure 27. Impact of threshold temperature on "usefulness" at each fixture (Site 3)

Table 17. Impact of Threshold Temperature on Determining "Usefulness" (Site 4)

Useful Portion	Threshold Temperature		
	80°F	90°F	100°F
Master Sink	57%	40%	21%
Washing Machine	38%	14%	6%
Kitchen Sink	80%	64%	39%
Laundry Sink	–	–	–
Master Shower	93%	89%	82%
Utility Sink	0%	0%	0%
Old Bath Sink	62%	51%	27%
Old Bath Shower	86%	79%	31%
	84%	75%	51%

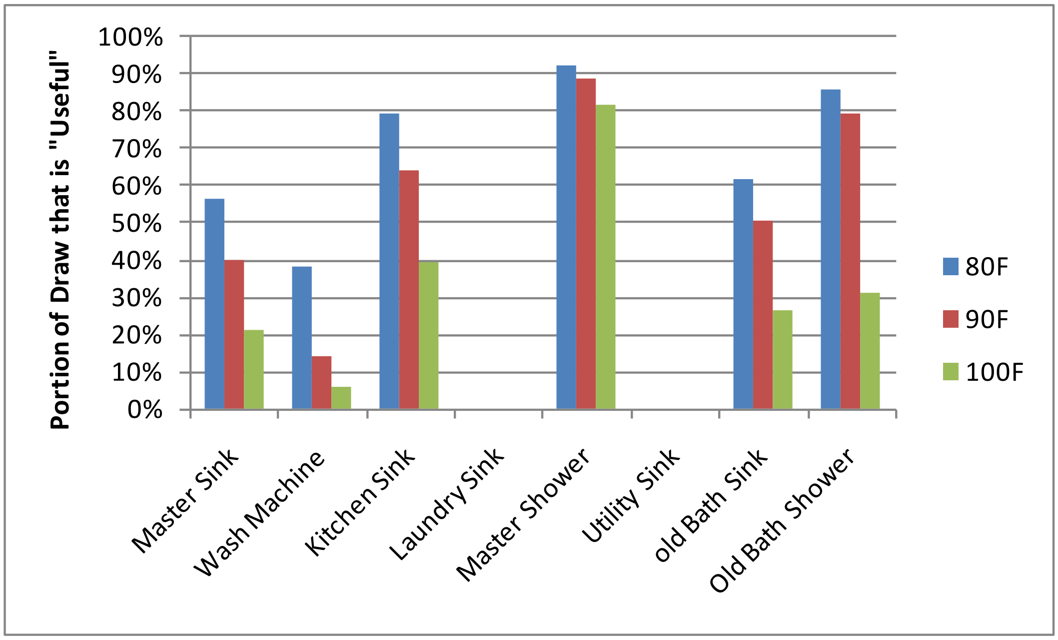

Figure 28. Impact of threshold temperature on "usefulness" at each fixture (Site 4)

Table 18. Impact of Threshold Temperature on Determining "Usefulness" (Site 5)

Useful Portion	Threshold Temperature		
	80°F	90°F	100°F
Lower Sink	81%	79%	75%
Lower Shower	93%	91%	89%
Washing Machine	98%	97%	95%
Laundry Sink	94%	94%	94%
Upper Sink	90%	87%	85%
Upper Shower	96%	94%	90%
Kitchen Sink	77%	66%	54%
Dishwasher	96%	93%	88%
	94%	91%	87%

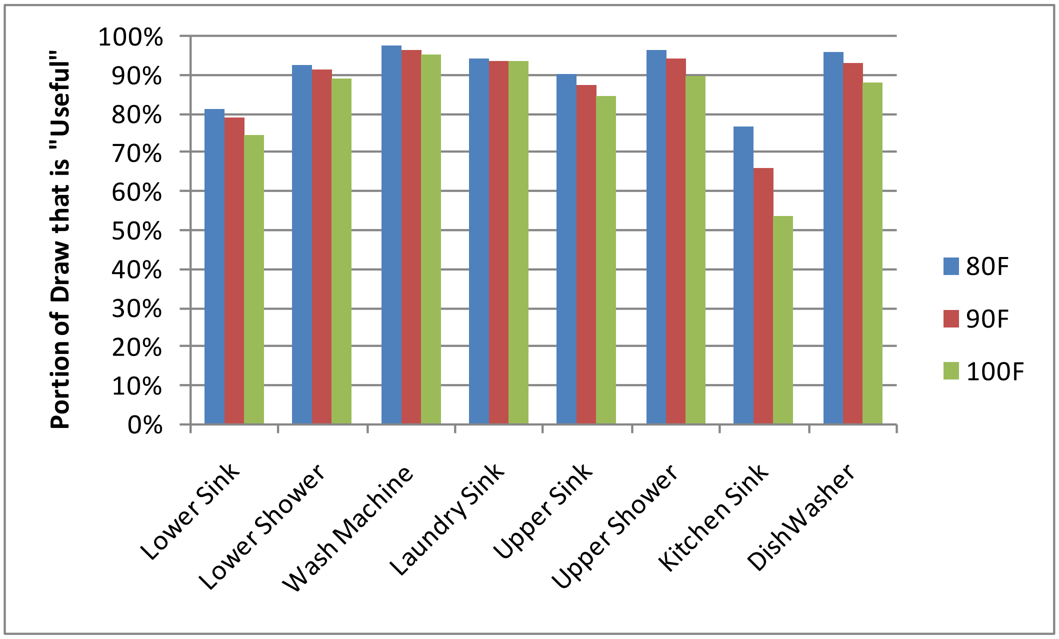

Figure 29. Impact of threshold temperature on "usefulness" at each fixture (Site 5)

4.4 Propagation of Measurement Errors to the Determination of "Usefulness"

The sensitivity analysis also provided the means to propagate the measurement uncertainty associated with the temperature sensors and flow meters and determine its impact on the prediction of usefulness.

Table 19 uses the results of the sensitivity analysis to estimate the uncertainty in the determination of "usefulness" for each site. The measurement errors for flow and temperature are propagated using the estimated sensor errors. The probable error in the determination of "usefulness" is estimated to be ± 2% for Sites 1, 2, 3, and 5 with copper piping and ± 5 % at Site 4 where PEX piping was used.

Table 19. Propagation of Measurement Errors to Error in Determination of "Usefulness"

	Estimated Error in Threshold Temperature (± °F)[a]	Slope: Usefulness % per °F (%/ °F)[b]	Error From Temperature (± %)[c]	Error From Flow (± %)[d]	Combined Probable Error (± %)[e]
Site 1	2	0.6	1.2	1.6	2.0
Site 2	2	0.2	0.4	1.7	1.8
Site 3	2	0.3	0.6	1.8	1.9
Site 4	5	0.9	4.5	1.5	4.7
Site 5	2	0.3	0.6	1.8	1.9

[a] Estimated error in determining threshold temperature includes a static error of ± 1°F as well as an additional estimated transient response error of ± 1°F for copper pipes and ± 4°F for PEX piping.
[b] Slope is taken from difference between 80°F and 90°F thresholds in Tables 25 to 29 above.
[c] Temperature error is product of (a) and (b)
[d] Flow error is ± 2% of average usefulness
[e] Probable error is square root of sum of squares of (c) and (d)

5 Impact of Retrofits

5.1 Impact of Tankless Retrofit at Site 3 (Group 2)

At Site 3 a tankless water heater (Rinnai RL75i) was installed to replace the conventional gas-fired tank on March 22, 2013. The system cost $2,420 to install (see Appendix B). The impact of this change on this household with two people is shown in the plots below. Figure 30 shows data for the pre-retrofit period with the conventional gas-fired tank as black, while data with the tankless unit (after March 22) are shown as red. Total water use changed only slightly; however, the number of hot water draws was reduced by more than 50% with the tankless unit. The minimum activation flow threshold of 0.4 gpm for the tankless unit (as well as the startup delay) apparently caused the occupants to change their hot water use behavior (i.e., they learned to stop making small draws when they wanted to get hot water).

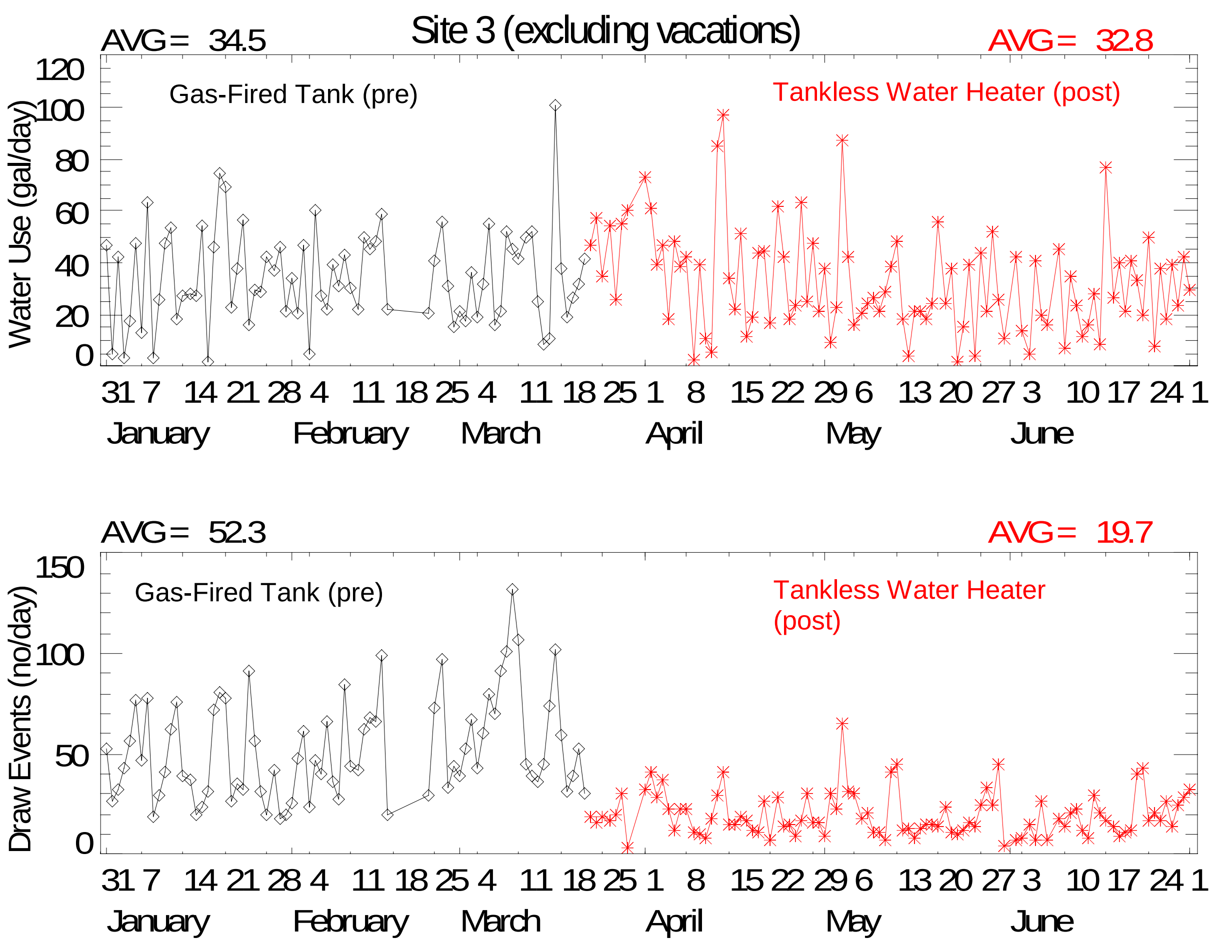

Figure 30. Comparing pre- and post-retrofit periods (Site 3)

Figure 31 and Table 20 shows how the useful percentage of hot water use for each month changed across the monitoring period. The overall percentage of useful hot water use decreased from 90%–91% with the conventional tank to 84%–86% with the tankless unit. This reduction in useful delivered hot water is mostly due to the startup delay of the tankless unit (i.e., a time delay for burner activation) which results in less hot water being delivered to the faucet. The largest drops were associated with the kitchen, bath sinks, and laundry end uses. The impact of the retrofit on total water use is summarized in Table 21. The sinks showed the expected reduction in the number of draw events. Other changes were related to known differences in water use between the pre- and post-retrofit periods, such as guests in the "bath 2 shower" in the pre-retrofit period. The homeowners also purchased a new energy-efficient washing machine on May 2, 2013. This had a significant impact on the washing machine water use in the post-retrofit period.

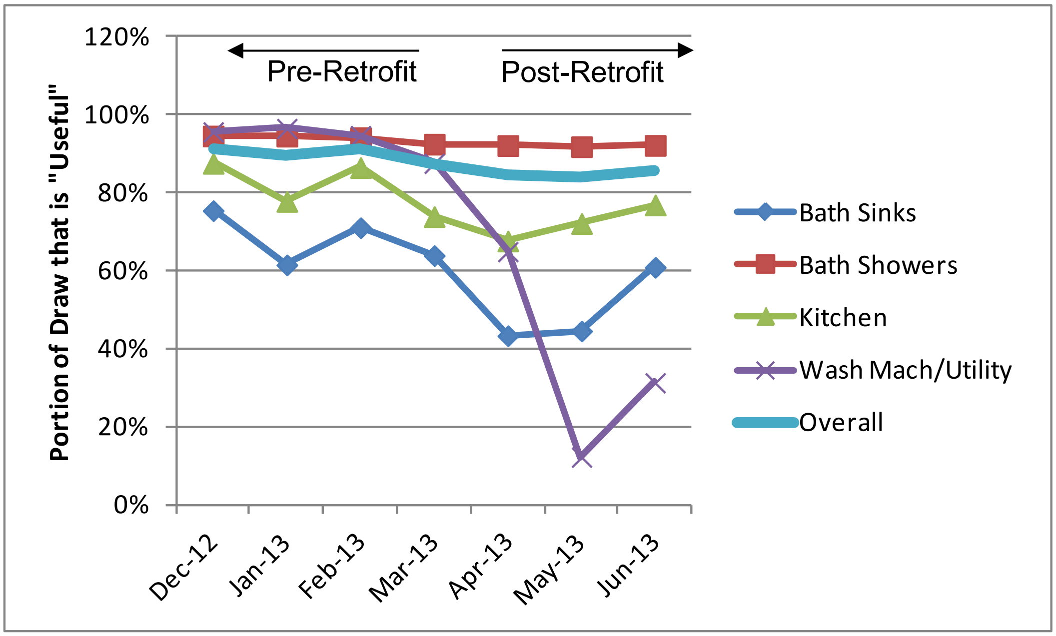

Figure 31. Plot showing variation of useful water draw percentage across period (Site 3)

Table 20. Variation of Useful Water Draw Percentage Across Period (Site 3)

	Pre-Retrofit				Post-Retrofit			Total
	Dec. 2012	Jan. 2013	Feb. 2013	Mar. 2013	Apr. 2013	May 2013	June 2013	
Bath Sinks	75%	62%	71%	64%	43%	45%	61%	62%
Bath Showers	95%	95%	94%	93%	92%	92%	92%	93%
Kitchen	88%	78%	87%	74%	68%	72%	77%	77%
Washing Machine/Utility	96%	97%	95%	88%	65%	12%	31%	83%
Overall	91%	90%	91%	87%	84%	84%	86%	87%

Table 21. Impact of Retrofit on Events and Hot Water Use
(Pre-Retrofit = Tank; Post-Retrofit = Tankless)

	Events per Day				Total Hot Water Use (gpd)			
	Portion of Water Use	Pre-Retrofit	Post-Retrofit	Notes	Portion of Water Use	Pre-Retrofit	Post-Retrofit	Notes
Bath 1 Sink	1%	0.2	0.6		2%	0.4	0.6	
Bath 1 Shower	56%	1.4	1.2		70%	18.2	20.9	
Bath 2 Sink	5%	5.8	1.4	Fewer small events	2%	1.7	0.6	
Bath 2 Shower	5%	0.1	0.0		1%	1.7	0.2	Fewer guests
Kitchen Sink	15%	5.8	4.7	Fewer small events	15%	4.8	4.5	
Dishwasher	6%	1.7	0.8		5%	2.0	1.5	
Washing Machine	11%	0.7	0.6		5%	3.4	1.3	New washing machine
Laundry Sink	0%	0.0	0.0		0%	0.1	0.1	
Unclassified	–	14.1	6.5	Fewer small events	–	2.0	1.5	
Total	–	29.6	15.8			34.3	31.2	

The plots below compare typical draw events for three different scenarios before and after the water heater and washing machine were replaced:

- Original water heater and original washing machine (Figure 32)
- New tankless water heater and original washing machine (Figure 33)
- New tankless water heater and new energy efficient washing machine (Figure 34).

Table 22 summarizes the performance under these three scenarios.

Figure 32 shows the expected performance with the conventional water heater and the original washing machine (see Section 1.9 for a full description of these plots). The washing machine had a draw exceeding 4 gal and most of the draw (3.81 gal) was deemed useful (i.e., hotter than 90°F).

Figure 33 shows what changed when the tankless water heater was installed. The water draw was 1–2 gpm yet the tankless burner apparently cycled on and off even though the flow rate was well above the 0.28 gpm cutout flow. It is interesting to note that the washing machine's control valve modulated the hot water flow in an attempt to maintain a desired water temperature. The period of the oscillations was about 90 seconds. Overall, percentage of useful hot water dropped by a nearly factor of two (to 49%).

Figure 34 shows the energy-efficient washing machine with the tankless water heater. The new washing machine attempts to make several small hot water draws that apparently do not last long enough to result in significant burner operation; therefore, no hot water is delivered to the appliance. The tankless burner fires only briefly after the second draw and as a result delivers no water hotter than 90°F to the appliance during the total 1.2-gal draw event.

Table 22. Comparing Water Draws for Different Water Heaters and Washing Machines

Water Heater	Washing Machine	Total Draw (gal)	Useful Draw (gal)	Useful Percentage
Old (Tank)	Old	4.05	3.81	94%
Tankless	High Efficiency	5.22	2.58	49%
Tankless	High Efficiency	1.24	0	0%

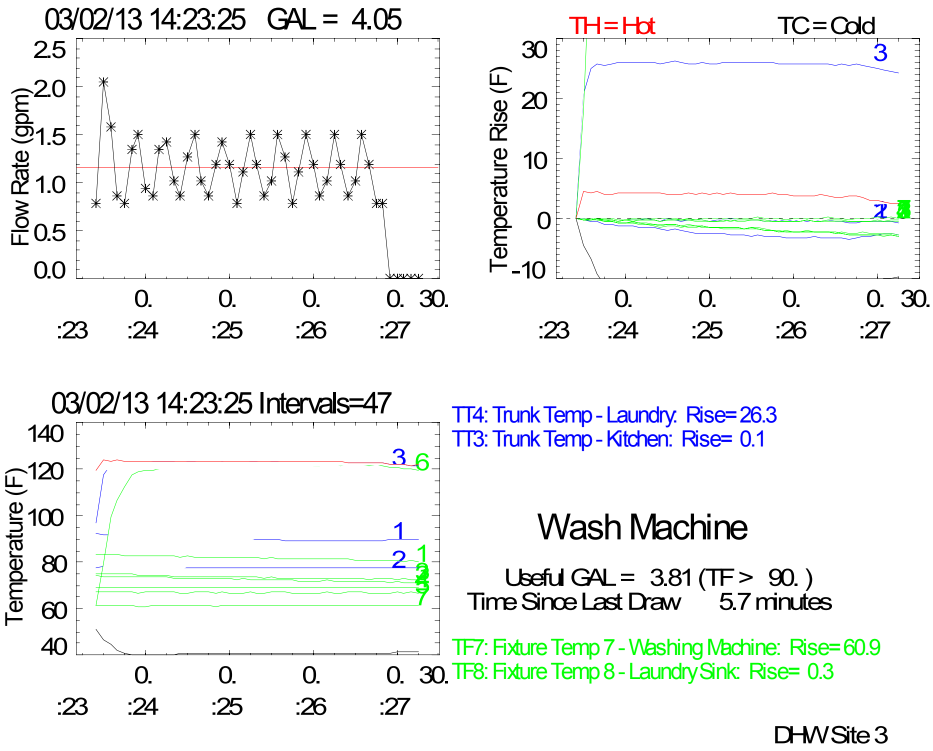

Figure 32. Typical water draw—conventional tank and old washing machine

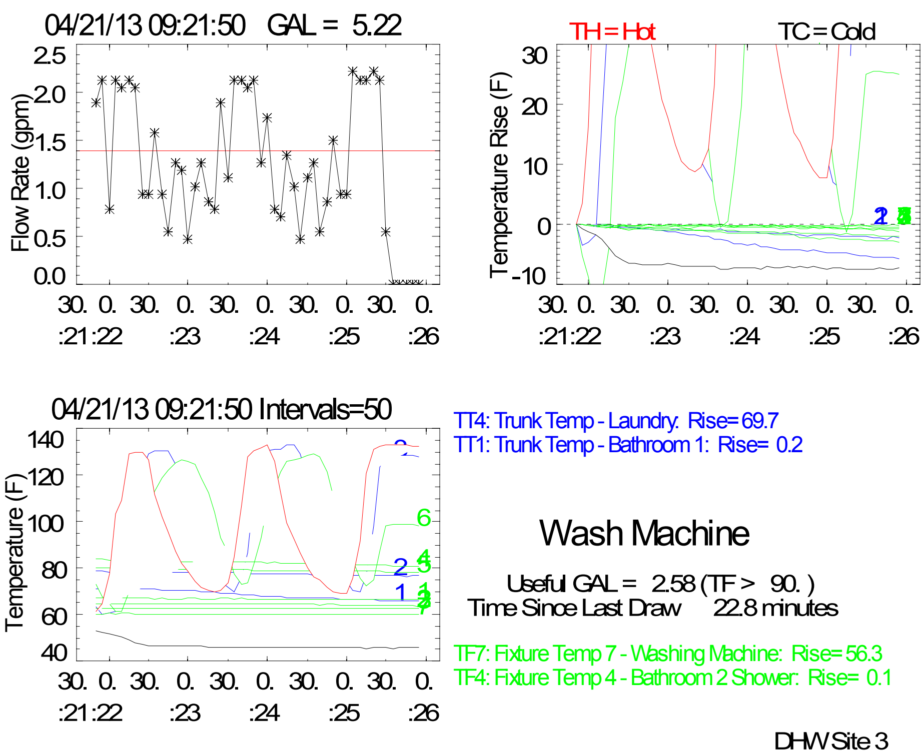

Figure 33. Typical water draw—tankless and old washing machine

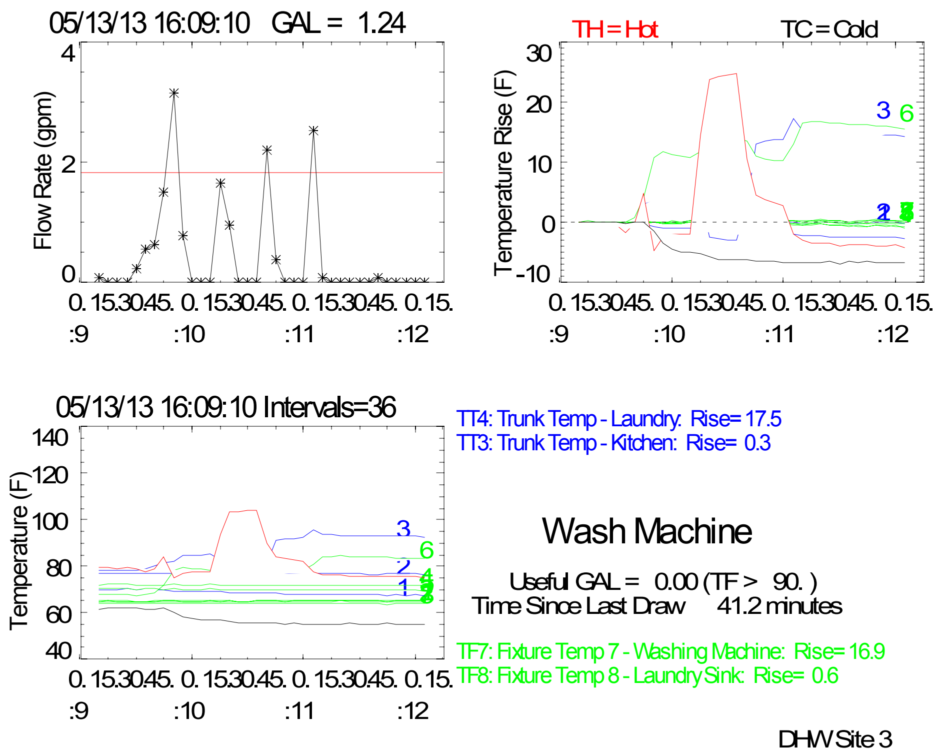

Figure 34. Typical water draw—tankless and new efficient washing machine

The performance of the two water heaters during a typical kitchen draw are compared in Figure 35 and Figure 36. The overall impacts are summarized in Table 23. With the conventional water heater tank, hot water is provided immediately and the delay in hot water reaching the fixture is the primary reason that the useful percentage is 68%. With the tankless water heater unit it takes about 40 seconds for the water exiting the unit to reach full temperature. Then it takes another few seconds for the hot water at the sink faucet to reach 90°F. The net effect is that the portion of the hot water draw deemed useful is much lower (31%), even though the draw is slightly larger.

Table 23. Comparing Kitchen Water Draws With Different Water Heaters

Water Heater	Total Draw (gal)	Useful Draw (gal)	Useful Percentage
Old (Tank)	0.96	0.65	68%
Tankless	1.34	0.42	31%

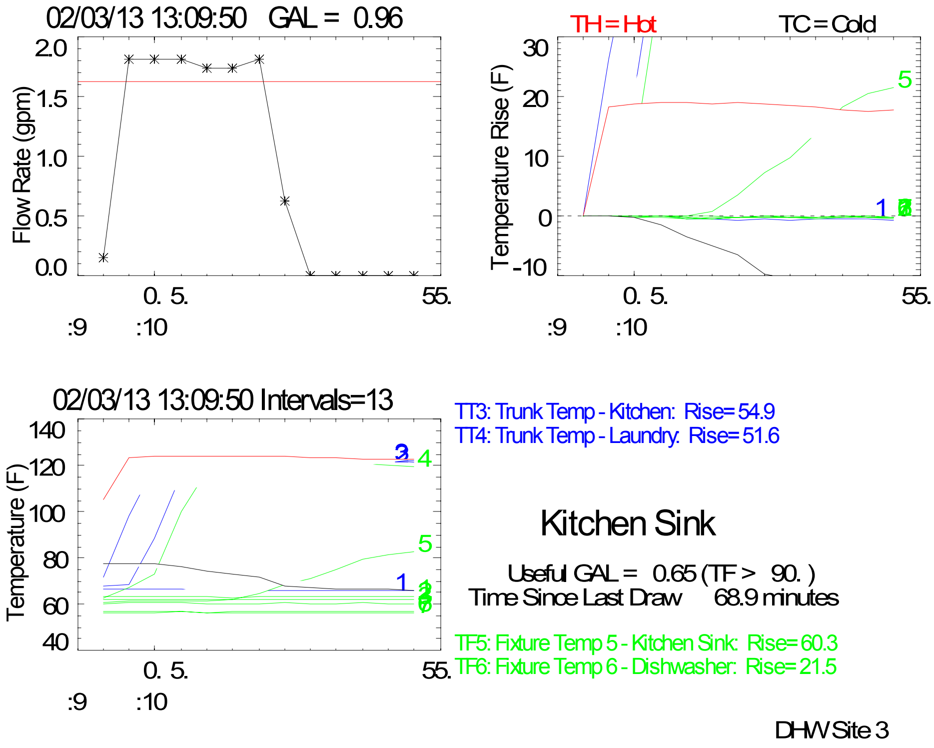

Figure 35. Typical kitchen sink water draw—conventional tank

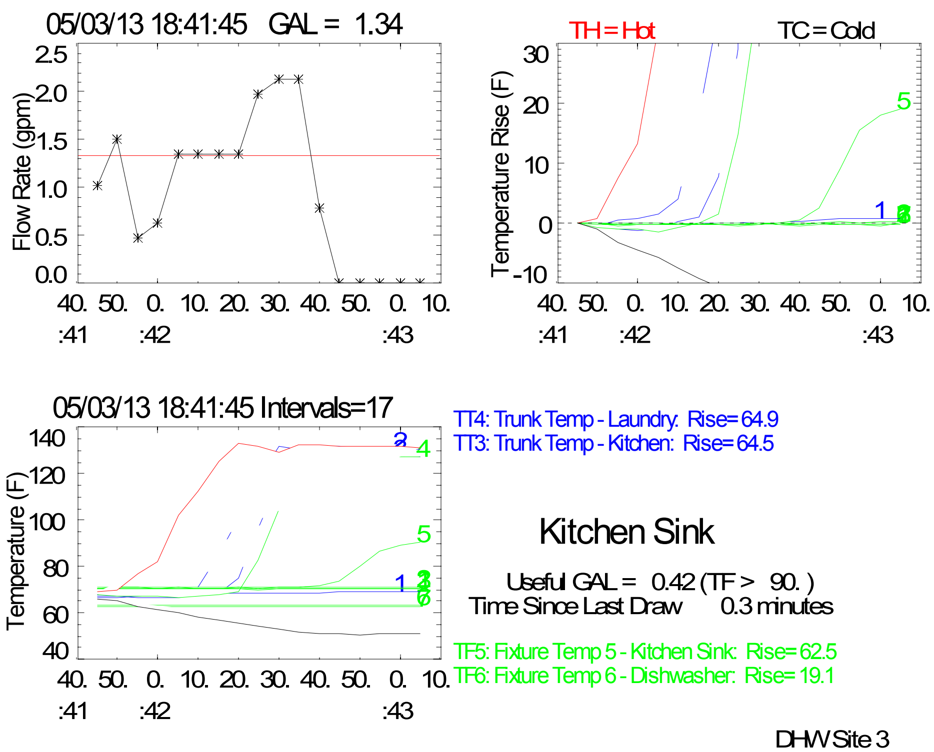

Figure 36. Typical kitchen sink water draw—tankless

5.2 Impact of Distribution Retrofit at Site 1 (Group 3)

At Site 1 an HPWH was installed in April to replace the indirect hot water tank on the oil-fired boiler. The monitoring was updated to measure the power use of the unit as well as the status of the two electric resistance elements in the HPWH tank (see Appendix B). In addition, the installation of the new tank shortened the ¾-in. hot water distribution line by 177 in. (which reduced the wait time by 15 seconds for a 1.5-gpm hot water draw).

On April 10 the distribution system was further modified to include a Bell & Gossett ecorcirc pump. This recirculation pump includes a built-in time clock to initiate operation as well as a built-in temperature sensor to stop operation once return water at the pump has warmed to the desired set point (the setting was 85°F). The pump was installed near the tank and pulls water from supply lines at two remote locations: kitchen sink and half bath sink. One-half-in. PEX was used for the recirculation line. All total these improvements cost $2,276 to implement. The recirculation pump and distribution system improvements were estimated to be $475 of the total costs.

The pump was scheduled operate at times when hot water use was considered probable (6:30 to 8:30 a.m., 11:30 a.m. to 12:30 p.m., and 4:30 p.m. to 6:30 p.m. each day). Monitored points were added to measure the pump runtime and the return water temperature. The recirculation pump is allowed to operate for up to 5 hours each day, though the actual runtime is typically in the range of 2–5 minutes/day (average of 3 minutes/day) because of the pump's internal set point threshold. Figure 37 includes 15-minute data to show how the trunk temperatures (TT3 to Kitchen, TT4 to the half bath) vary with pump operation. The fixture line temperatures are also shown (TF1 – Dishwasher, TF2 – Kitchen Sink, TF3 – Half Bath Sink). On this day the pump ran for about one minute to prime the lines. Subsequent shorter pump cycles were required to hold the return temperature (TR) near 85°F.

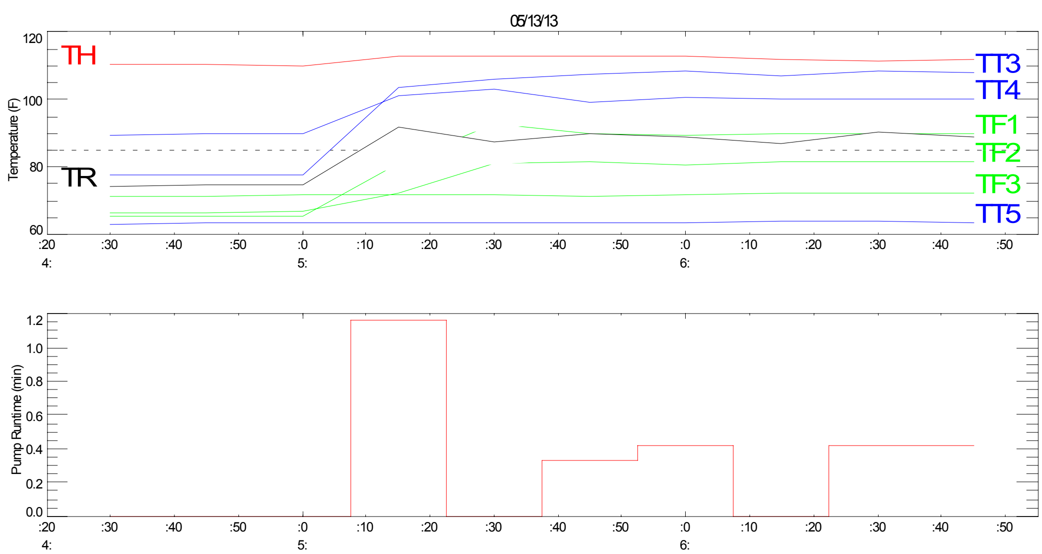

Figure 37. Trunk and fixture temperatures during recirculation pump operation (Site 1 EST)

Installing the recirculation pump and making the other distribution improvements increased the portion of useful hot water delivered to the end uses. Table 24 and Figure 38 show how the useful portion of hot water use varied across the monitoring period. The overall useful portion was 78%–84% before the changes and increased to be 90%–92% after the retrofit. The largest improvement was in the kitchen end uses.

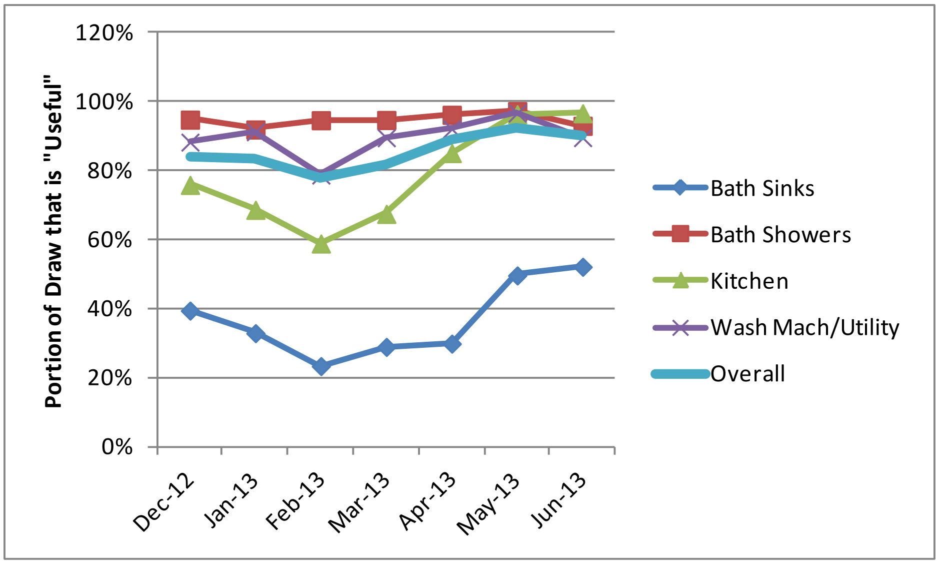

Figure 38. Plot showing variation of useful water draw percentage across period (Site 1)

Table 24. Variation of Useful Water Draw Percentage Across the Period (Site 1)

	Pre-Retrofit					Post-Retrofit		
	Dec. 2012	Jan. 2013	Feb. 2013	Mar. 2013	Apr. 2013	May 2013	June 2013	Total
Bath Sinks	40%	33%	23%	29%	30%	50%	52%	38%
Bath Showers	95%	92%	95%	95%	96%	97%	93%	95%
Kitchen	76%	69%	59%	68%	85%	96%	97%	77%
Washing Machine/ Utility	88%	91%	79%	90%	92%	97%	90%	90%
Overall	**84%**	**83%**	**78%**	**82%**	**89%**	**92%**	**90%**	**86%**

Table 25 compares the pre- and post-retrofit performance by specific fixture. The overall water use and number of events were not significantly impacted by the retrofit, with the exception of the kitchen sink, which did show a significant drop in hot water use. Other changes at the fixture level were attributable to occupancy differences in the two periods. Some improvement in the portion of useful hot water was noted for the kitchen sink (from 63%–97%) with less improvement noted for the half bath sink (21%–30%), utility sink (53%–66%), and dishwasher (90%–98%).

Modest improvements were also noted for the master bath sink (28%–35%) and the bath 2 sink (49%–66%), which were not enhanced by the recirculation pumps directly. However, the reduction in piping length (177 in.) with the new water heater location and the modest hot water priming of the first 30–40 in. of the piping near the tank both contributed to the improvement.

Table 25. Impact of Retrofit on Events and Total Hot Water Use at Site 1 (Pre-Retrofit; Post-Retrofit)

	Events per Day			Total Hot Water Use (gpd)			Useful Portion		
	Pre-Retrofit	Post-Retrofit	Notes	Pre-Retrofit	Post-Retrofit	Notes	Pre-Retrofit	Post-Retrofit	Notes
Dishwasher	1.5	1.3		2.7	2.4		90%	98%	
Kitchen Sink	17.0	13.0		9.1	5.6		63%	97%	Recirc pump
Half Bath Sink	2.1	3.0		0.7	1.0		21%	30%	Recirc pump
Washing Machine	0.7	1.1		9.1	12.7		91%	94%	
Utility Sink	0.3	0.4		0.9	0.4		53%	66%	Recirc pump
Master Sink	6.8	4.2		2.2	1.2		28%	35%	Shorter run
Master Shower	1.5	1.4		17.8	13.3		95%	97%	
Bath 2 Sink	1.7	1.3		1.2	1.6		49%	66%	Shorter run
Bath 2 Shower	0.7	0.8		8.4	9.9		91%	93%	
Unclassified	36.8	44.9		3.4	7.5		–	–	
	69.4	71.3		55.4	55.6		82%	91%	

5.3 Impact of Distribution Retrofit at Site 2 (Group 3)

At Site 2 a new AO Smith Vertex (GDHE-50) condensing storage tank water heater was installed (very close to the location of the original water heater) on May 21, 2013. At the same time a Taco SmartPlus recirculation pump was installed on the supply line with the sensor downstream of the pump. A ½-in. PEX return line was added from the supply line under the kitchen sink back to the cold water inlet to the water heater. The water heater and all improvements were installed by a city-licensed plumber for $5,170. The recirculation pump and return line were estimated to be $988 of the total installation.

The pump was set in the "Smart/Learn Mode," where it runs based on the pattern established over the last 7 days of operation. In this Smart Mode, the pump runs in the Pulse Mode (running for 2.5 minutes out of every 10 minutes) for a 2-hour window centered around each draw observed/recorded 7 days ago.

The measured runtime for the pump was about 200 minutes/day (about 14% of the time). The "Smart/Learn Mode" reduced the runtime by only a modest amount compared to the "Pulse Mode," which would have run the pump 25% of the time 24 hours/day. In contrast, the timer-controlled pump at Site 1 runs the pump only about 3 minutes/day in the 5-hour window when operation is enabled.

Water use at this site was highly variable across the monitoring period as shown in Figure 39, implying that the number of occupants in the house frequently changed. This confounded some of the pre- and post-retrofit comparisons below.

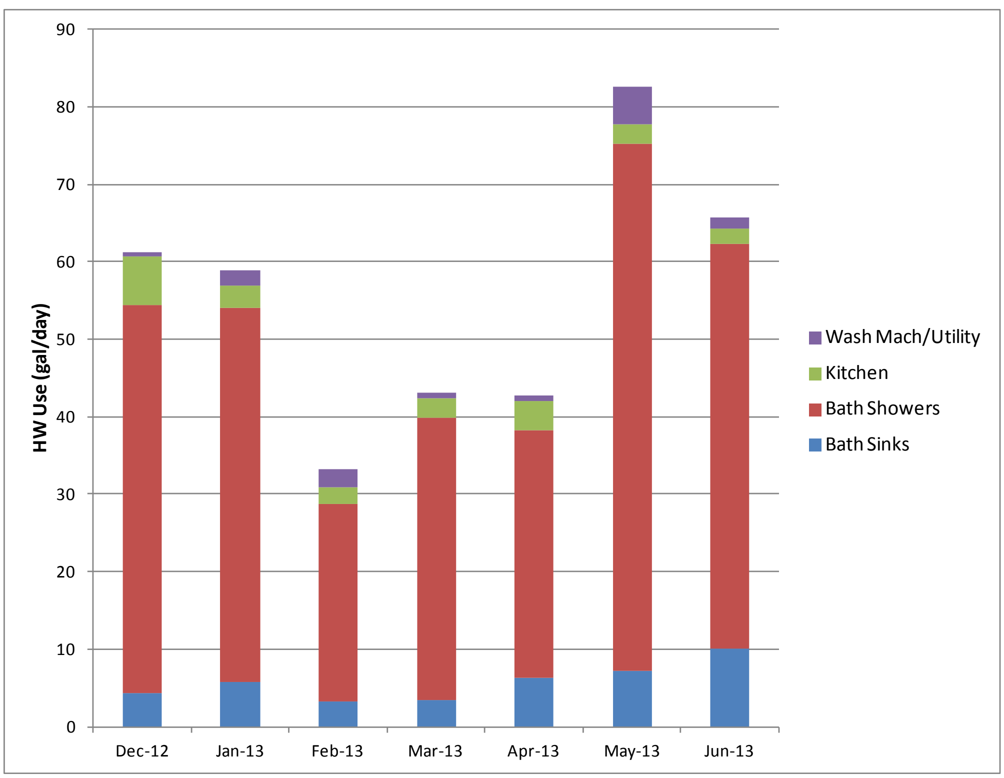

Figure 39. Plot showing variation of water use across monitoring period (Site 2)

The substantial runtime of the recirculation pump greatly increased thermal losses from the system and lowered the effective daily water heating efficiency[1] to 0.40–0.70, depending on hot water use (see Figure 40). Based on laboratory data for this same water heater unit, the expected daily water heating efficiency for this system is about 0.85 at 64 gpd (see Henderson et al. 2013).

Figure 41 shows the measured delivered thermal output supplied by the unit versus the measured natural gas input. The data show some scatter since the occupants frequently used water late at night (and gas consumption for recovery occurs on the next day). However the data show that the standby losses for the system are approximately 20 MBtu/day (i.e., the fuel input with no water use).

Laboratory measurements for the same unit indicated that standby losses for the tank alone were 6.9 MBtu/day. From this difference we can infer that operation of the recirculation pump increases daily gas use by about 14 MBtu/day. Assuming a marginal unit efficiency of 0.85–0.90 for the system, the added thermal losses are about 15–16 MBtu/day.

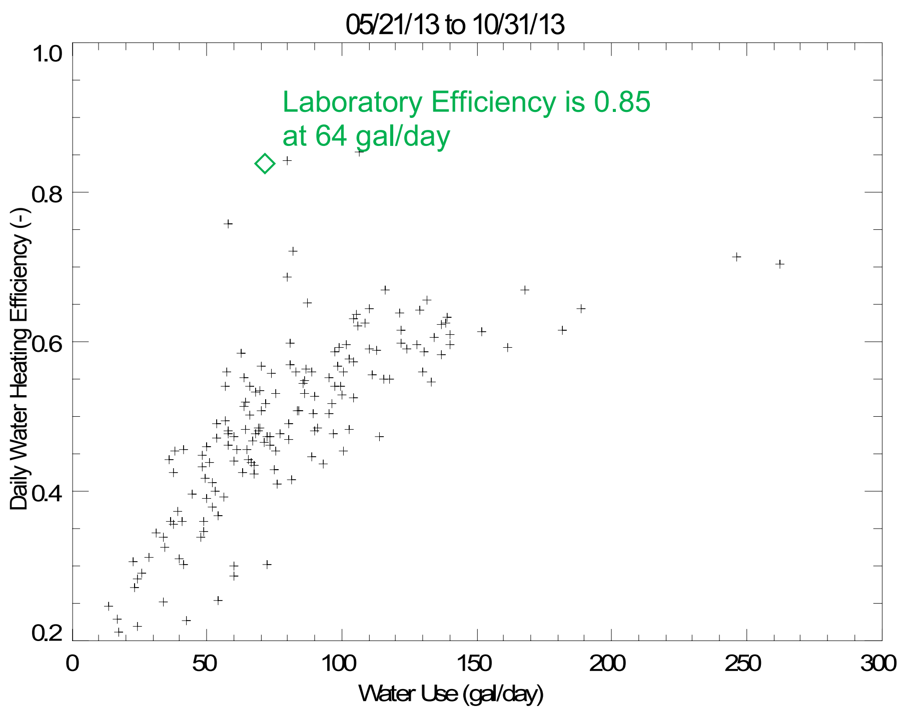

Figure 40. Daily system efficiency as a function of hot water use (Site 2)

[1] Daily water heating efficiency is integrated thermal energy supplied by the unit divided by the fuel energy input over the day. The recirculation pump operation did not affect this value (since it did not induce any makeup water flow).

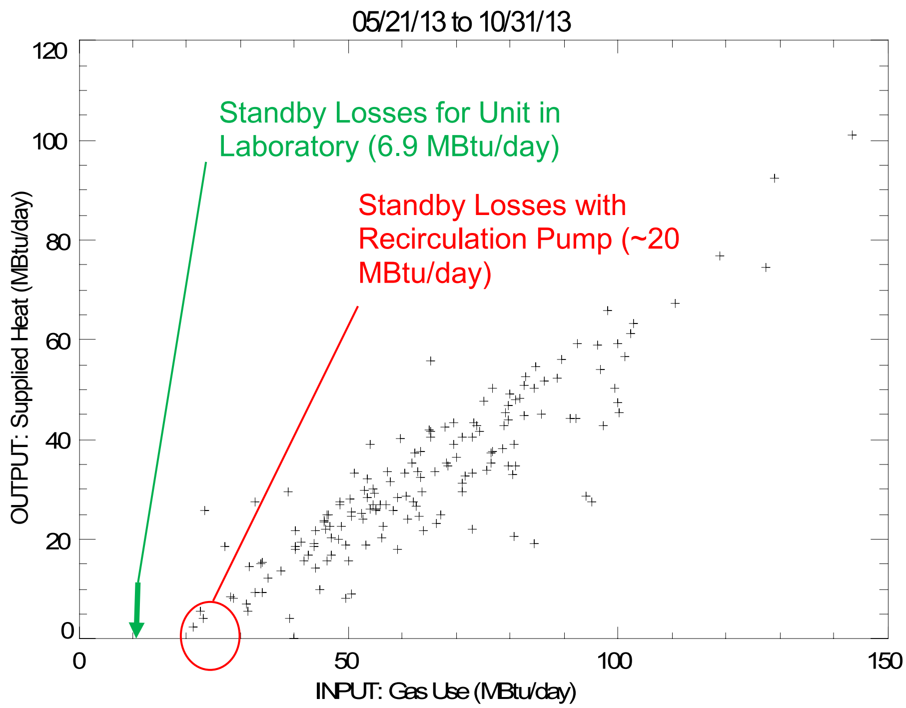

Figure 41. Plot showing thermal input versus thermal output (Site 2)

In spite of the high thermal losses, installing the recirculation pump appeared to have very little impact on hot water distribution performance at this site. The portion of useful hot water delivered to the end uses was not noticeably different in the pre- and post-retrofit periods. Table 26 and Figure 42 show how the useful portion of hot water use varied across the monitoring period. No positive change was apparent.

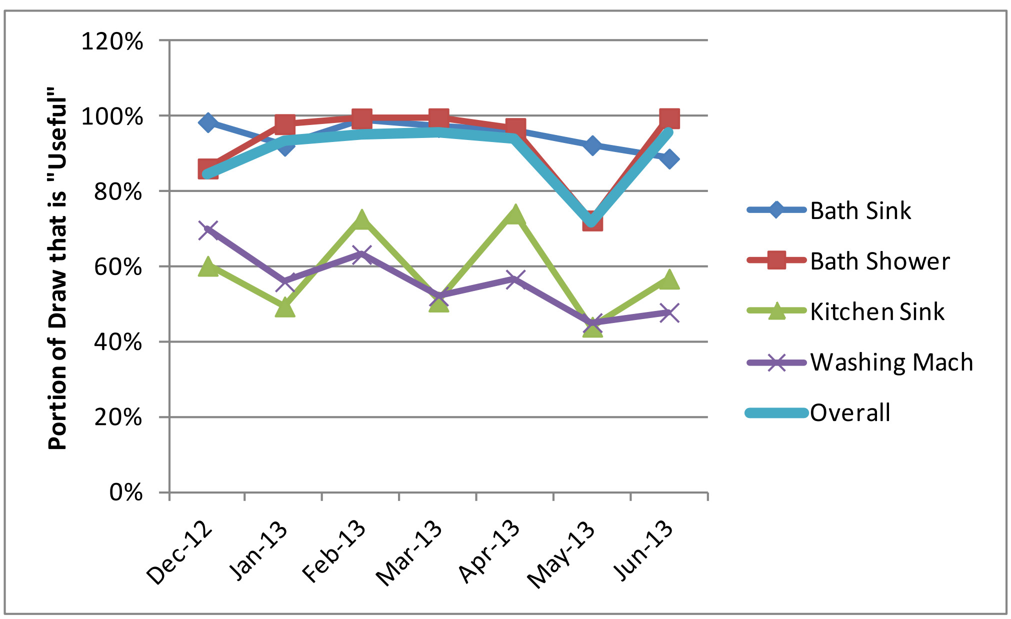

Figure 42. Plot showing variation of useful water draw percentage across period (Site 2)

Table 26. Variation of Useful Water Draw Percentage Across Period (Site 2)

	Pre-Retrofit						Post-Retrofit	
	Dec. 2012	Jan. 2013	Feb. 2013	Mar. 2013	Apr. 2013	May 2013	June 2013	Total
Bath Sink	99%	92%	99%	97%	96%	92%	89%	93%
Bath Shower	86%	98%	100%	100%	97%	72%	100%	91%
Kitchen Sink	60%	49%	73%	51%	74%	44%	57%	59%
Washing Machine	70%	56%	63%	52%	57%	45%	48%	52%
Overall	**84%**	**94%**	**95%**	**96%**	**94%**	**72%**	**96%**	**88%**

Table 27 compares the pre- and post-retrofit performance by specific fixture. The overall water use and number of events were not significantly impacted by the distribution retrofit.

Table 27. Impact of Retrofit on Events and Total Hot Water Use (Site 2) (Pre-Retrofit; Post-Retrofit)

Events per Day			Total HW Use (gpd)		Useful Portion	
	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit
Bath Sink	4.0	4.0	4.8	9.9	96%	88%
Bath Shower	3.2	3.3	41.9	54.8	89%	99%
Kitchen Sink	2.3	1.6	3.0	2.6	62%	59%
Washing Machine	2.0	2.5	1.3	4.0	56%	48%
Unclassified	18.2	7.6	1.0	0.7	–	–
	29.6	19.0	52.0	72.0	87%	93%

6 Conclusions

Surface-mounted temperature sensors were installed on trunk lines as well as branch lines to each hot water fixture in five existing houses to both disaggregate hot water use and assess the portion of each hot water draw that was deemed useful (i.e., exceeded 90°F). Data were collected during hot water draws at 5-second intervals in order to track temperature changes and understand the flow variations during the draw. In some cases wireless data loggers were used to reach fixture piping located in remote locations in the house.

At two of the houses no changes were made (Group 1, Sites 4 and 5). At three of houses, changes were made to the hot water systems after a few months of data collection:

- Group 2. At Site 3, a tankless water heater was installed to assess the impact on distribution performance.
- Group 3. At Sites 1 and 2, new water heaters were installed and recirculation pumps were added to improve hot water distribution performance.

6.1 Disaggregation and Useful Hot Water Delivery

Simple rules about temperature level and temperature rise were developed and automated to disaggregate hot water loads, or to assign each hot water draw to a given fixture based on the temperature measurements on the trunk and fixture piping. Using this approach we were able to classify only 17%–57% of the hot water draw events in each of the five homes. However, the process was able to classify 88%–98% of the total water use in these homes. The house with the lowest level of classification (Site 4) had an average of 180 draws and used 115 gpd—most of these draws were of very short duration. The house with the highest level of classification (Site 5) averaged about 26 draws and used 46 gpd.

The temperature data were also used to assess the portion of each hot water draw that was deemed “useful”; i.e., exceeded a certain temperature threshold at the fixture or trunk location. We used a threshold of 90°F at the fixture and 100°F at trunk lines leading to the fixture to gauge “usefulness.” We also evaluated the impact of using higher and lower temperature thresholds to gauge “usefulness.”

By this method, amount of hot water that could be deemed as useful ranged from 75% ± 5% at Site 4 to 91% ± 2% at Site 5. The average for the five houses before retrofit was 85%. The probable error in the determination of “usefulness” was estimated to be ± 2% for Sites 1, 2, 3, and 5 with copper piping and ± 5% at Site 4 with PEX piping. The fixtures with the lowest fraction of useful hot water were typically kitchen and bathroom sinks.

6.2 Retrofit Impacts

At Site 3 a tankless water heater was installed after 3 months of monitoring with a conventional water heater. The occupants changed their hot water use behavior after the tankless unit was installed. The number of hot water draw events per day was cut in half. Most of this change occurred at sinks, where small duration events were eliminated.

Overall hot water use showed no perceptible change after the tankless unit was installed. The overall percentage of useful hot water use decreased from 90%–91% with the conventional tank to 84%–86% with the tankless unit. This reduction in useful delivered hot water was mostly due to the 40-second startup delay of the tankless unit, which resulted in less hot water being delivered to the faucet. The largest reduction in usefulness was associated with the kitchen, bath sinks, and laundry end uses.

The homeowners at Site 3 also purchased a high efficiency washing machine about 5 weeks after the tankless water heater was installed. When the tankless unit was working with the original washing machine it behaved in an unexpected way: cycling the burner on and off even though the hot water flow remained well above the minimum cutout flow of 0.26 gpm. The result was that a limited amount of hot water was delivered to the appliance. When the new high efficiency washer was used, the pulsed water demand profile of the appliance resulted in almost no hot water being delivered to the device.

At Site 1 a new HPWH was installed in a new location that shortened the ¾-in. hot water supply line by 177 in. In addition, a Bell & Gossett ecocirc recirculation pump with time-clock controls and an internal temperature sensor was added along with a return line pulling water from two remote locations (kitchen sink and half bath). The pump was enabled to operate for three key periods totaling 5 hours each day. On average the pump operated only about 3 minutes each day to prime the hot water lines. The pump installation cost about $478.

The overall useful portion of delivered hot water was 82% before the changes. The useful portion increased to 91% after the retrofit. The largest improvement was in the kitchen end uses, where typical waits for hot water had previously been very long. Modest improvements were also noted at other fixtures (not served by the pump) due to the shorter hot water supply line (i.e., 28%–35% for the master sink and 49%–66% for the bath 2 sink).

Site 2 had a new condensing water heater tank installed along with a Taco SmartPlus recirculation pump. The pump installation cost $988. The pump was set to operate in the smart mode, where it anticipates when to operate the pump based on the previous 7-day operating pattern. This pump was observed to operate about 200 minutes/day or about 14% of the time. This excessive runtime on the pump resulted in significant thermal losses. The water heater, which in the laboratory had standby gas use of 6.9 MBtu/day for the tank alone, operated with standby losses of 20 MBtu/day with the recirculation pump operating in the field.

The recirculation pump had no perceptible impact on the useful portion of delivered hot water. The large variations in hot water use across the pre- and post-retrofit periods (due to changes in occupancy) may have partially obscured the impact of adding the recirculation pump.

6.3 Addressing the Research Questions

The following answers to the research questions were determined from this field research project:

QUESTION: What is the magnitude of hot water waste for existing homes in the Northeast, considering a variety of water heating systems (i.e., tankless and storage tank)?

Overall average hot water waste was found to be in the range of 9%–25% at the five houses. Houses with new additions (Sites 1 and 4) tended to result in longer piping runs that resulted in more hot water waste. Smaller homes with their original, compact floor plans intact had less hot water waste.

What constitutes a "typical" distribution system in the Northeast? How does it compare to systems in other regions of the United States?

Houses in this study were all older homes with water heaters and piping located in basements (with some piping in crawlspaces). All homes were either two-story or raised ranch. Many had been substantially retrofitted or had new additions added. No piping was in the slab. In some cases very old steel piping was still hidden in the walls. Most exposed piping in the basement was converted (or was originally installed) copper or PEX.

What improvements or remediation can be cost-effectively implemented in a DHW retrofit to reduce hot water waste and energy use, focusing on hot water system configurations commonly found in older single-family homes in the Northeast?

At one house (Site 1) placement of an indirect water heater tank near the space heating boiler resulted in a long hot water piping supply run. Installation of a new HPWH closer to the center of the hot water piping arrangement resulted in a 177-in. reduction in the ¾-in. hot water supply trunk. At this same site, adding a ½-in. PEX recirculation line and pump to the remotely located kitchen fixtures had a significant impact on the portion of hot water delivery that was deemed useful.

Other houses (Site 2) with centrally located plumbing did not seem benefit from a recirculation pump, especially when the pump controls led to excessive pump runtime. As with commercial installations, controls that operate the pump only a few minutes per day have the best impact on hot water delivery performance.

6.4 Lessons and Recommendations

Adding a recirculation pump and return line was demonstrated to increase the "usefulness" and reduce hot water wait times at the expected fixtures in a recently remodeled home with long piping runs. However, at a smaller home with a more centralized floor plan, no change in "usefulness" was observed. At both these homes, no detectable change in hot water use or energy use was observed. Clear evidence of greater system standby losses were linked to prolonged recirculation pump operation at the smaller home. The $478–$988 investment for this recirculation system improved home owner satisfaction at least in one case but did not provide any clear evidence of energy cost savings in the first few months of system operation.

Based on this study we make the following recommendations:

- Monitoring should continue at these test sites for at least 12 months to confirm the initial findings, specifically to further assess if hot water use is reduced with increased "usefulness."
- Further research is required to understand the situations and house configurations where recirculation pumps may provide the energy savings and/or improved occupant satisfaction with hot water delivery.

References

Barley, C.D.; Hendron, R; Magnusson, L. (2010). "Field Test of a DHW Distribution System: Temperature and Flow Analyses." Presented at ACEEE May 2010 Hot Water Forum. Golden, CO: National Renewable Energy Laboratory, NREL/PR-550-48385.

Chinery, G.T. (2006). "Policy Recommendations for the HERS Community To Consider Regarding HERS Scoring Credit Due to Enhanced Effective Energy Factors of Water Heaters Resulting From Volumetric Hot Water Savings Due to Conservation Devices/Strategies." Presented at meeting of EPA ENERGY STAR® for Homes, December.

Henderson, H.; Bogucz, E.A.; Wade, J.; Straile, C. (2013). *Evaluating Domestic Water Heater Performance for NY Homes*. Albany, NY: NYSERDA. http://cloud.cdhenergy.com/dhw_coe/documents/reports/Laboratory_Test_Results-Report_1_Nov2013.pdf

Hendron, R.; Burch, J.; Hoeschele, M.; Ranier, L. (2009). "Potential for Energy Savings through Residential Hot Water Distribution Improvements." Proceedings of the 3rd Annual International Conference on Energy Sustainability. Paper ES2009-90307. San Francisco, CA.

Klein, G. (2005). "Hot-Water Distribution Systems – Part III." *Plumbing Systems & Design*, May/June.

Klein, G. (2006). "Saving Water and Energy in Residential Hot Water Distribution Systems." Slides from California Energy Commission at DOE website.

Lutz, J. (2005). "Estimating Energy and Water Losses in Residential Hot Water Distribution Systems." Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-57199.

Magnusson, L. (2009). "Methods and Results for Measuring Hot Water Use at the Fixture." Golden, CO: National Renewable Energy Laboratory. Presented at ACEEE June 2009 Hot Water Forum.

RECS (2005). Residential Energy Consumption Survey. Table 13. www.eia.doe.gov/emeu/recs/.

Appendix A: Literature Review

A1 Review of the Literature

A1.1 Identification and Bounding of the Problem

Gary Klein a wrote a three-part series of articles on hot water distribution systems for *Plumbing Systems & Design* magazine from the American Society of Plumbing Engineers in 2005 (Klein 2005a, 2005b, 2005c). This series of articles provides a very good explanation of the concept and problem of hot water waste. In Part I he points out that the issue of long wait times for hot water to arrive at your fixture is tied to newer homes (built since 1970) that have been built based on newer plumbing codes. He points out that in newer homes:

- Piping increased from ½ in. to ¾ in.
- Piping layouts moved from radial arrangement to trunk-branch.
- More fixtures in the house are farther away from the water heater.

He makes the case that these factors have increased wait times for hot water by a factor of 18 compared to old houses. He also lays out a thought exercise demonstrating that hot water waste is probably on the order of 10%–30% (or 5–20 gpd). Hot water waste is related to the actual wait time for hot water as well as the behavior of occupants in response to that time delay (which often makes the hot water waste even worse).

Part II discusses what people want and expect from their water heater and distribution system: namely safety and convenience. The safety concerns include the water not being too hot (to cause scalding) or too cold (so harmful bacteria can grow). Consumers also value the convenience of being able to adjust temperature and flow and expect an unlimited or continuous supply of hot water.

The article also describes a manifold/homerun system architecture—with ½-in. or ⅜-in. piping running from a central point to each fixture—as a partial solution to reducing water waste. He points out that the reduction in water waste can be about 50%, but there can be usage patterns that can often result in more waste.

Part III talks about the concept of recirculation loops and compares them to other less practical options (such as heat tracing). He describes that recirculation pumps can run continuously, can run based on a timer, or be based on the recirculation return water temperature. He points out that demand control of the pump has a much lower energy cost. He points out that demand can be sensed using buttons at the sink, occupancy sensors, or flow switches (but he provides no discussion as to which demand control option is better).

A1.2 Products on the Market to Reduce Water Waste and Distribution Losses

Hot water recirculation pumps are widely used in commercial and multifamily buildings. However, there have historically been fewer products for single-family homes. Some residential products are now available where the pump sits under the sink and pumps cooled water from the hot water lines into the cold water line or, alternatively, back toward the water heater.

The Metlund D'MAND hot water pump from Advanced Conservation Technology, Inc. (www.gothotwater.com) is one of the most prominent options for residential recirculation pumps (Acker and Klein 2006; Acker 2009). The most common retrofit application is with the pump mounted under the bathroom sink at the location farthest from the water heater. The pump moves cooled water from the hot water piping into the cold water piping at this fixture. Pump operation is operator-initiated by an occupancy sensor, a remote control, or button near the sink. The pump turns off when the temperature at the pump increases by 6°F.

Manufacturers such as Taco (www.taco-hvac.com) offer traditional commercial-style recirculation pumps that can be controlled by either a temperature sensor (aquastat) on the return line and/or a timer that operates the pump only at high demand times. The timer and control functions are integrated into the pump body. Taco also appears to have licensed the D'MAND pump technology from Advanced Conservation Technologies, Inc. as one of its available product options.

In addition Taco has recently introduced its SmartPlus system that senses usage by measuring the system supply temperature and then "learns" the 7-day draw pattern and keeps applying it to subsequent 7-day periods. It also has the ability to detect vacations and stop operation after a few days. It can be installed near the water heater and does not require sensors at fixture locations. It does require that a return line be added to the system.

The Grundfos Comfort System has a timer initiated pump and a thermal valve that mounts under the farthest sink (http://us.grundfos.com/products/find-product/comfort-pumps-up-10.html). This pressure boost pump is intended to mount on the outlet of the water heater. The thermal valve mounts under the sink between the hot and cold water lines. When the valve is cool, a bimetallic element opens and allows flow from the hot to cold side. The valve starts to close at 93°F and is fully closed at 103°F. The pump is activated to provide a pressure boost by the on-board timer. The pump (apparently) goes off when the pressure increases as the thermal valve closes. The system has the advantage of not requiring the pump to be located under a bathroom sink; instead the pump is installed at the water heater (where 120 VAC power is more likely to be available). Some users report that the valve must be replaced every few months, though the price of these valves is relatively modest.

Similarly Bell & Gossett produces recirculation pumps (ecocirc) that use electronically commutated motors (ECMs) so that pumping power is very low. It includes options for timer and aquastat control and is designed to be installed in a dedicated return line. The autocirc model also includes built-in timers and thermostats to control pump operation. It is designed to mount under the fixture that is farthest from the water heater.

All these systems appear to be marketed to consumers based on convenience and comfort of instant hot water at the fixture instead of energy savings. Only the D'MAND system offers occupant-initiated pump operation, which is expected to have the lowest energy impact. No residential products appear to offer the control method of using a flow switch on the makeup water line – the approach that is often used in large multifamily buildings. However the Taco SmartPlus system does appear to use the supply temperature as a low cost surrogate for sensing demand (at least after the fact). Table 28 summarizes the key features of these different systems.

Table 28. Summary of Residential Recirculation Products on the Market

Manufacturer/ Trade Name(s)	Pump Installation Location	Control Activation and Shutoff	Other
ACT, Inc. Metlund D'MAND	Under sink or in return line	Occupant initiated, off on temperature rise	
Taco Plumb n' Plug	Near water heater, return line	Timer and/or aquastat	
Taco SmartPlus	Near water heater, return or supply line	Supply line sensor, "learns" 7-day pattern	
Bell & Gossett ecocirc	Near water heater, return line	Timer	ECM 10 Watts
Bell & Gossett autocirc	Under sink	Timer and thermostat	ECM 14 Watts
Grundfos Comfort System	Near water heater, supply line	Timer	Thermal valve under fixture

A1.3 Laboratory Measurements of Piping Losses and Flow Patterns

Klein (2006a) also discusses the results of Hiller (2005) that was funded by the California Energy Commission (CEC). Several types of hot water piping (copper, PEX, and PEX-Aluminum-PEX) at several sizes (½ in. and ¾ in.) were tested in a laboratory setup to measure heat loss and temperature reductions with different flow rates. The impact of insulation was also evaluated. The tests revealed some expected and unexpected results. One unexpected finding was that slip flow – with less dense hot water slipping over the top of the cold water – occurred at low flow rates. The slip flow profile doubled the volume of water required before a full profile of hot water could reach a fixture, compared to simple plug flow.

A1.4 Field Measurements of Distribution Losses and Baseline Usage/Characteristics

Hiller (2005) also surveyed about 28 California homes to understand common installation practices for hot water distribution systems. He found that the length and volume of under slab piping was much greater than expected and greater than that of above ground piping. Hot water piping is normally run in the same trenches as the drainage pipes for each fixture which usually runs parallel and perpendicular to structure. This is rarely the shortest distance between fixtures. Straight runs between fixtures under the slab would have substantially reduced the piping length. Minimal insulation was installed in tract built homes, but in custom built homes the majority of the hot water piping was insulated. However, the insulation was poorly installed with elbows completely lacking insulation. The under slab piping environment was found to be very moist to wet with standing water in most cases. He also noted that the hot and cold piping were typically bundled together.

The Davis Energy Group (Hoeschele and Chitwood 2006) also surveyed 60 production built homes in California to gather information about the hot water distribution systems. This effort was part of a larger effort with LBNL that was funded by the CEC (Lutz 2008). The survey gathered extensive information including site and water heater characteristics, developed sketches and tabulations of piping systems, points of use and fixture type, and under slab soil and pipe environment characteristics. The recirculation system and control method was also noted when applicable. The survey revealed that new homes were growing in size and the number of hot water end use points was increasing.

The American Water and Wastewater Association Research Foundation sponsored the Residential End Uses of Water Study (REUWS) in the late 1990s (Mayer et al. 1999). This study collected very detailed water end use data from 1200 single-family homes in 12 North American locations from 1996 to 1998. The REUWS installed a flow meter on the main water meter and collected data at 10 second intervals. The study used flow trace analysis software to assign the individual draws to the appropriate end use or fixture (hot or cold). The REUWS database contains the total volume of water used, duration of each draw, and the peak and mode (i.e., most commonly recorded) flow rates for the draw. The database includes nearly 2 million draw events.

Lutz (2005) estimated the amount of wasted hot water in North American homes using the data from the REUWS database. Lutz estimated the water and energy waste for three types of water draw events:

- Hot water that runs down the drain before it can be used (e.g., shower)
- Hot water that cools down in the distribution system after a draw (e.g., short sink draws),
- Hot water that cools down and must be reheated (e.g., dishwasher).

Lutz developed methods to analyze data from the REUWS database to estimate the amount of waste associated with each type of loss. For instance, he analyzed nearly 49,000 shower hot water events and estimated that the average volume of hot water wasted at the beginning of each shower draw was 3.48 gal, or about 20% of the average shower. Similarly he estimated the waste associated with sink draw events. Short draws often do not allow useful heat to even reach the fixture. Losses at the dishwasher do not include water losses, but equate to additional energy that is required to reheat the water. All total these losses were estimated be 10.7 gpd or about 20% of 52.6 gpd used in an average home.

Lutz et al. (2008) gathered together and used 1-minute interval data available from multiple field studies to develop an hourly profile for hot water use. This effort was intended to develop an improved water use profile for the CEC in order to support the efforts to update the Title 24 energy efficiency standards. They developed an end use profile that was close to the ASHRAE 90.2 profile, with slightly less morning use. The profile is shown below in Figure 43.

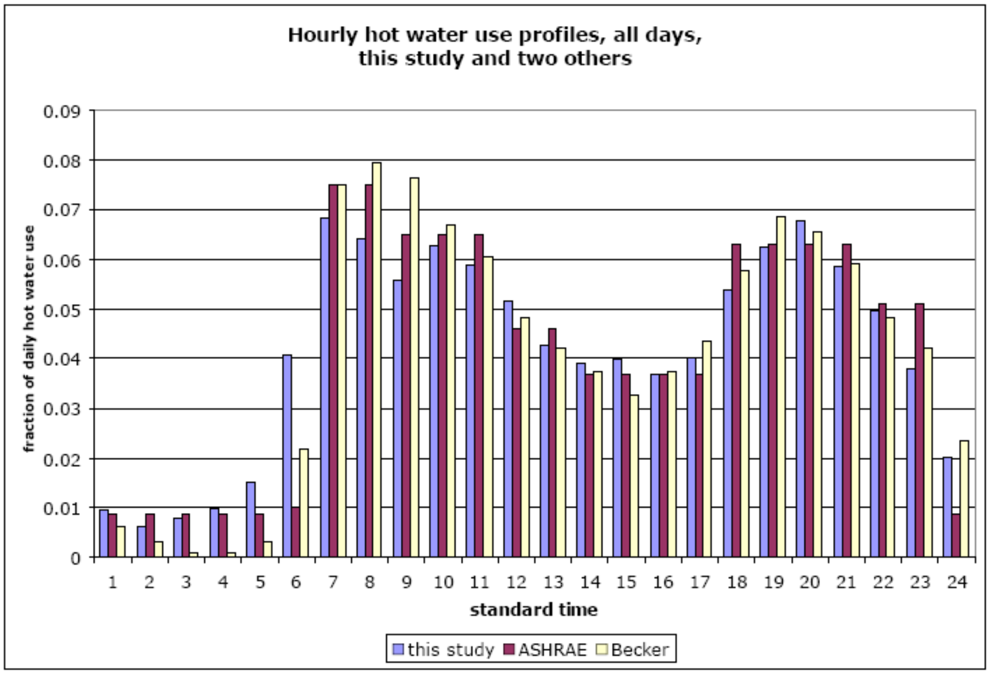

Figure 43. Comparing various hot water use profiles from Lutz et al. (2008). Blue bars are the results from Lutz et al.; red bars are from ASHRAE 90.2; yellows bars are from Becker (1990)

Hoeschele et al. (2009) recently worked with the Gas Technology Institute (GTI) to field test several higher efficiency gas water heaters at 18 single-family homes in California. Each home was monitored with the original system for 4 months and then retrofit with a more efficient gas water heater. A range of water heaters were installed, including ENERGY STAR units (EF = 0.67–0.70), non-condensing tankless, condensing tankless, and high efficiency condensing storage units. The field testing gathered fuel, energy, and water use data at 15-minute intervals to assess efficiency and energy use. These data were used to evaluate technical and economic performance of the various higher efficiency options. Detailed data, down to a 4-second resolution, were also collected on each water draw to understand the water consumption pattern and draw details.

A1.5 Analysis Techniques to Indirectly Measure Hot Water Use at Fixtures

As mentioned above, the REUWS measurements (Mayer et al. 1999) determined water use at each end use or fixture using direct measurements at the main meter combined with a flow trace analysis method. They used the Aquacraft Trace Wizard software, which is a commercially available software tool that uses flow trace data collected from a main meter to allocate each draw to a fixture or end use (www.aquacraft.com). The approach has been widely used to disaggregate residential water uses in hundreds of homes. A recent study of California houses is representative of the use of this method (DeOreo et al. 2011).

NREL monitored several homes in detail, installing a flow meter on each end use. This field testing was presented by Magnusson (2009) and then Barley et al. (2010) at the ACEEE Hot Water Forum. The Aquacraft Flow Trace method of assigning flows to each fixture was also implemented and compared to the actual measurements. In addition, the method of using a temperature probe attached the pipe near each fixture to detect the direction of flow was also implemented at the sites. This temperature method was first described by Weihl and Kempton (1985). Data at these sites were collected at 1-second intervals.

Figure 44 compares the actual flow measurements at each fixture to the predicted values from the Aquacraft software. While the Aquacraft results are fairly good, some errors were apparent.

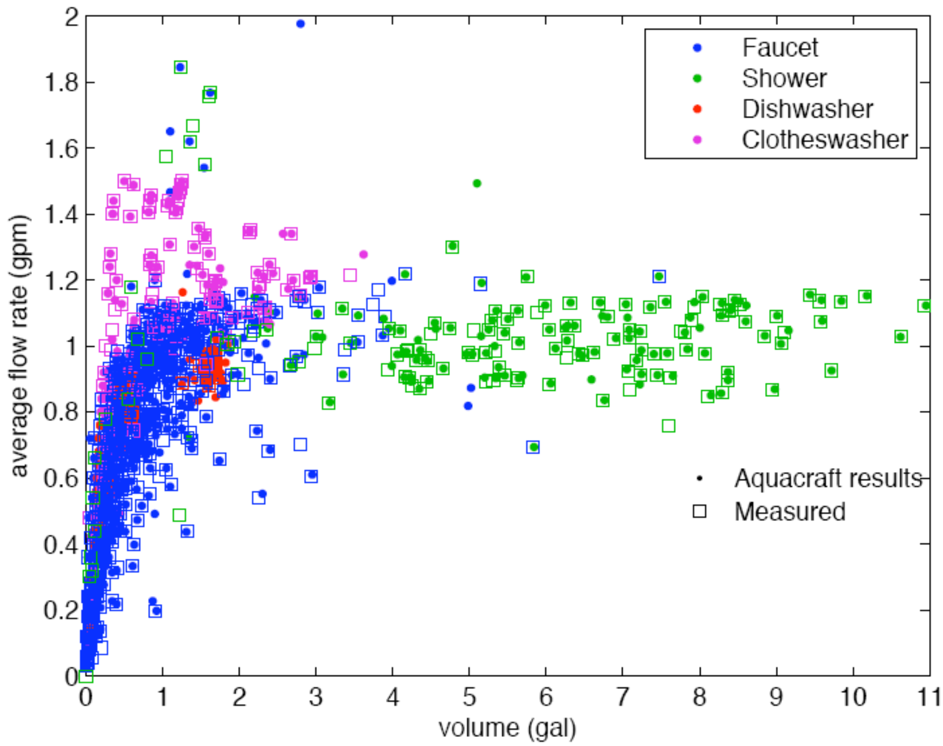

Figure 44. Plot from Magusson (2009) comparing direct measurements of hot water flow events (square) to Aquacraft results; Aquacraft method was good but did have some error.

Barley et al. (2010) analyzed the errors of the flow trace and temperature methods of flow disaggregation and demonstrated that the errors of the two methods were similar. He noted that the temperature method might therefore be preferable because it provides the additional information of temperatures at the fixture. The temperature data can be used to further determine time delays and water waste associated with each fixture.

Researchers at the University of Washington (Larson et al. 2010) have developed a less-obtrusive measurement technique to disaggregate water draws and assign then to specific fixtures using a pressure signature method. Total water use is measured at the main meter. A pressure transducer (usually installed on a hose barb) measures the pressure response in the frequency domain. A draw at each fixture produces a unique signature that can be used to assign measured water use to that end use. Possibilities for distinguishing simultaneous draws at multiple end uses also exist.

A1.6 Field Measurements of Distribution System Improvements

One of the first studies of demand recirculation systems was a field test of five Palo Alto, California homes by Ally et al. (2002). These homes had new water heaters installed along with the D'MAND hot water pumps from Metlund (www.gothotwater.com). The pumps were mounted under the bathroom sink to pump cooled down water from the hot water piping to the cold water piping at this fixture. Pump operation is initiated by an occupancy sensor, remote control, or button under the sink. The pump turns off when the temperature at the pump increases by 6°F.

The homes had Btu meters and water flow meters installed that were manually read by the homeowners. The study had problems with reliable data collection but was able to estimate hot water savings in the range of 11%–30% in the winter months, and typically about one third of that amount in the summer months. Energy savings were probably less than this amount since this water still cools down and is ultimately consumed as cold water (their energy data were inconclusive).

Barley et al. (2010) retrofitted a highly instrumented house in Boulder, Colorado with recirculation pumps at three fixtures that returned water back to the tank. The pumps were activated by occupancy sensors and shut off based on a temperature rise at the pump. This house had a solar hot water system with an electric auxiliary tank. Operating the recirculation pumping system reduced hot use by 14%, but did not result in electric energy savings. They reported that the unexpected results may have been caused by interactions with the solar system.

Building Science Corporation (2005) also measured hot water wait times at some of its test homes in California with and without a continuous recirculation pump operating. This testing demonstrated that continuous pump operation resulted in significant water savings in these larger homes, where wait times for hot water had been significant. While energy use was not measured in these short-term tests, Building Science Corporation acknowledged that the energy impact of continuous pump operation would be significant.

A1.7 Modeling to Simulate Distribution System Performance, Losses and Improvements

Davis Energy Group (Springer et al. 2008; DEG 2007) developed the HWSIM software to simulate the performance of a hot water distribution system. The software was originally developed in 1990 as part of a CEC project to develop a comprehensive methodology for evaluating Title 24 Residential Energy Efficiency Standards. In 2004 the model was upgraded to consider hourly variations in environmental temperatures across a representative week in each month. Inlet water temperatures can be specified for each month. The model can consider various types of draws from any fixture or end use point. The draw can be specified several different ways (a specified hot water flow and duration; a hot water flow to maintain a temperature set point at the end use, etc.). Hundreds of draws can be defined and managed to build up a typical use profile. The amount of "useful" hot water delivered can be defined by setting a minimum acceptable delivery temperature.

The thermal model uses a finite difference method at short time intervals to predict temperatures within the distribution system piping. The piping system is discretized into nodes or volume elements that are on the order of 0.01 gal. Water-to-pipe heat transfer is assumed to be turbulent. Pipe-to-air heat transfer assumes still air surrounds the pipe. The software includes libraries of geometry property data for commonly used pipe and insulation materials. The hot water outlet temperature performance characteristics from the water heater can also be defined as can recirculation loop geometry, flow, and controls. The software can simulate a larger number of draws across the year.

The model calculates key performance metric on an annual and monthly basis such as delivered energy, distribution efficiency, wasted or unusable hot water, etc. The HWSIM has been verified by comparing its predictions to the measured laboratory data on piping heat loss collected by Hiller (2005).

NREL (Maguire et al. 2011) has also developed models in TRNSYS to simulate the thermal performance of a hot water distribution system. They developed this model to provide the following features that are not available with the current version of HWSIM:

- To allow for an entire year of multiple unique water draw events, entering water temperatures, and different environmental temperatures
- To simulate the detailed performance of the conventional and solar water heaters using the component libraries in TRNSYS
- To allow for the eventual integration of hot water distribution and building environmental conditions into a common model.

The transient model is very similar to HWSIM from a thermal point of view, but constructing the model in the TRNSYS environment provides flexibility that is not available in the HWSIM software, with its well-developed user interface.

Hendron et al. (2009) used the HWSIM model to predict the annual energy savings of various water heating distribution improvements. They looked at various insulation and recirculation pump control options in two different climates (Tampa and St. Louis).

NREL (Hendron et al. 2010) has developed a spreadsheet tool to generate a set of cold and hot water draws at each fixture over the course of a year. The draw events of both cold and hot water flow – starting at a certain time with flow and duration at each fixture – are stochastically generated to represent the defined characteristics of a household. The number of draw events and daily water use ranges can vary for each day. The number of events is on the order of 20–50/day. The tool is intended to generate the hot draw input schedules for hot water distribution system simulation tools such as those described above.

A2 Lessons for This Project

As part of the ARIES Project, we retrofitted two existing hot water systems while measuring performance both before and after the system change. The retrofits included distribution system improvements to reduce hot water waste due to distribution system losses. Based on this literature review we draw the following lessons relevant to this field testing effort:

- There are two recirculation systems that seem most appropriate for the retrofit sites: (1) the Metlund D'MAND pump that incorporates occupancy controls to activate the pump; and (2) the Taco SmartPlus system that senses a weekly demand pattern and then brings the pump on in response to that "learned" 7-day schedule.

- Lutz (2005) and Barley et al. (2010) point out that disaggregation of hot water end uses using temperature is the most accurate method. The ARIES project used this approach to disaggregate draws and assign them to the various end uses. Temperatures were used to determine the time delay for hot water to reach a fixture.
- Lutz (2005) demonstrated how the plot of water flow rate versus total water use for each draw is useful for classifying types of hot water draws. This analysis approach was used to evaluate the data collected in this project.
- To make the field data collected from these sites useful to other researchers that may want to simulate the performance of these systems in the future, we documented each home and collected characteristic data in a similar format that was used by the Davis Energy Group for its 60 home California study (Hoeschele and Chitwood 2006). We also collected ambient temperature data in locations where key piping runs are located.

A3 References

A3.1 Trade Press Articles

Acker, L. and G. Klein 2006. *Benefits of Demand Controlled Pumping*. Home Energy Magazine. September/October. Pp. 18.

Klein, G. 2005a. *Hot-Water Distribution Systems – Part I. Plumbing Systems & Design*. American Society of Plumbing Engineers. January/February.

Klein, G. 2005b. *Hot-Water Distribution Systems – Part II. Plumbing Systems & Design*. American Society of Plumbing Engineers. March/April.

Klein, G. 2005c. *Hot-Water Distribution Systems – Part III. Plumbing Systems & Design.* American Society of Plumbing Engineers. May/June.

Klein, G. 2006a. Hot Water Distribution Research. Plumbing Systems & Design. American Society of Plumbing Engineers. September/October.

A3.2 Product Literature

Bell & Gossett. http://completewatersystems.com/2011/01/new-bell-gossett-autocirc-pump-provides-instant-hot-water-to-any-faucet/

D'MAND pump. www.gothotwater.com

Grundfos Comfort System
http://us.grundfos.com/products/find-product/comfort-pumps-up-10.html

Taco Pump Instant Hot Water Options
http://www.taco-hvac.com/products.html?current_category=360

A3.3 Presentations, Papers, Reports

Ally, M.R., J.J. Tomlinson, B.T. Ward. 2002. *Water and Energy Savings using Demand Hot Water Recirculating Systems in Residential Homes: A Case Study of Five Homes in Palo Alto, California.* Oak Ridge National Laboratory. ORNL/TM-2002/245. September.

Acker, L. 2009. *Smart Controls.* Presented at ACEEE Hot Water Forum, Berkeley, CA. Session 7A.

Becker, B.R. and K.E. Stogsdill, 1990. "*Development of Hot Water Use Data Base*." ASHRAE Transactions, Vol. 96, Part 2, pp. 422-427. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

Barley, C.D., R Hendron, L. Magnusson. 2010. "*Field test of a DHW distribution system: temperature and flow analyses*." Presented at ACEEE May 2010 Hot Water Forum. NREL/PR, 550-48385.

Building Science Corp. 2005. Wait and Waste Testing of D.R. Horton Beta Home

Davis Energy Group. 2007. HWSIM Hot Water Distribution Model Validation Report. Subcontract# 6803947 with LBNL. APPENDIX M of CEC-500-2005-007-APA.

DeOreo, W. et. al. 2011 CALIFORNIA SINGLE-FAMILY WATER USE EFFICIENCY STUDY. July. Available at http://www.aquacraft.com/sites/default/files/pub/DeOreo-%282011%29-California-Single-Family-Water-Use-Efficiency-Study.pdf

Hendron, R. and J. Burch. 2007. *Development of Standardized Domestic Hot Water Event Schedules for Residential Buildings*. Presented at Energy Sustainability 2007 Long Beach, California. Jun 27–30. Conference Paper NREL/CP-550-40874.

Hendron, R., J. Burch, M. Hoeschele, L. Ranier. 2009. *"Potential for Energy Savings through Residential Hot Water Distribution Improvements*." Proceedings of the 3rd Annual International Conference on Energy Sustainability. Paper ES2009-90307. San Francisco, CA.

Hendron, R., J. Burch, and G. Barker. 2010. *Tool for Generating Realistic Residential Hot Water Event Schedules.* Presented at SimBuild 2010 New York, New York. August 15–19. Conference Paper NREL/CP-550-47685.

Hiller, C. 2005. *Hot Water Distribution System Research* – Phase I Final Report, California Energy Commission Report No. CEC-500-2005-161, May 2005.

Hoeschele, M. and Chitwood, R. 2006. Field Survey Report*: Documentation of Hot Water Distribution Systems in Sixty New California Production Homes*, Davis Energy Group, Inc. and Chitwood Energy Management, Davis.

Hoeschele, M. , E. Weitzel, J. McNeil, and D. Kosar. 2011. *California Field Performance of Advanced Residential Gas Water Heating Technologies*. Davis Energy Group, Inc. December 2.

Krigger, J. and Dorsi, C. 2009. *Residential Energy: Cost Savings and Comfort for Existing Buildings. 5th Edition*. Helena, MT: Saturn Resource Management Inc.; pp. 220.

Larson, E. J. Froehlich, T. Campbell, C. Haggerty, L. Atlas, J. Fogarty and S. Patel. 2010. *Disaggregated water sensing from a single, pressure-based sensor: An extended analysis of HydroSense using staged experiments.* Pervasive and Mobile Computing. August.

Lutz, J. 2005. "*Estimating Energy and Water Losses in Residential Hot Water Distribution Systems*." Lawrence Berkeley National Laboratory. Paper LBNL-57199. Also ASHRAE Transactions 111 (2).

Lutz, J. 2008. *WATER HEATERS AND HOT WATER DISTRIBUTION SYSTEMS.* Appendix Prepared by Lawrence Berkeley National Laboratory for the California Energy Commission, CEC-500-2005-007-APA. May. [this 473 page document includes several sub-reports from a large CEC project]

Lutz, J., G. Ghatikar, E. Edelson, S. Meyers. 2008. Hot Water Draw Patterns: Findings from Field Studies, APPENDIX H of CEC-500-2005-007-APA.

Magnusson, L. 2009. "*Methods and results for measuring hot water use at the fixture*." National Renewable Energy Lab. Presented at ACEEE June 2009 Hot Water Forum. 4B.

Maguire, J. M. Krarti, and X. Fang. 2011. *An Analysis Model for Domestic Hot Water Distribution Systems.* Presented at the 5th International Conference on Energy Sustainability and Fuel Cells Washington, D. C. August 7-10. Preprint NREL/CP-5500-51674.

Mayer, P.W., W.B. DeOreo, E. Opitz, J. Kiefer, W. Davis, B. Dziegiefewski and J. Nelson. 1999. *Residential End Uses of Water*. Report 99-41861. American Water Works Association Research Foundation.

RECS 2005, Residential Energy Consumption Survey. Table 13. www.eia.doe.gov/emeu/recs/.

Springer, D., L. Ranier, M. Hoeschele and R. Scott. 2008. HWSIM: *Development and Validation of a Residential Hot Water Distribution System Model*. ACEEE Summer Study, pp. 1-267 to 1-277. Asilomar, CA. August.

Weihl, J.S. and Kempton, W. (1985). "Residential Hot Water Energy Analysis: Instruments and Algorithms." Energy and Buildings, Vol. 8, pp. 197-204.

A3.4 Literature and Articles Not Directly Cited

Chinery, G.T. 2006. Policy recommendations for the HERS Community to consider regarding HERS scoring credit due to enhanced effective energy factors of water heaters resulting from volumetric hot water savings due to conservation devices/strategies. Presented at meeting of EPA ENERGY STAR® for Homes. December.

Klein, G. 2006b. *Saving Water and Energy in Residential Hot Water Distribution Systems*. Slides from California Energy Commission at DOE website.

Klein, G. 2006c. "*Saving Water and Energy in Residential Hot Water Distribution Systems*." Slides from California Energy Commission at DOE website.

Klein, G. 2008a. *Structured Plumbing Offers Real Benefits*. World Plumbing Review. Issue 1, pp. 38-40.

Klein, G. 2008b. Design "Green" Hot Water Distribution Systems. PM Engineer. July.

Klein, G. and J. McCabe. 2010. THE FUTURE OF HOT WATER AND SOLAR THERMAL. SOLAR 2010 Conference Proceedings. American Solar Energy Society.

Klein, G. 2011. *Green Code and Hot Water System*. Presented at ACEEE May 2011 Hot Water Forum. Berkeley, CA. 8B.

Appendix B: Site Descriptions

Site #1 - Cazenovia, Ballina Rd - Group 3 (New WH and Distribution System)

Site 1 is a four-bedroom 2,800-ft^2 house with an oil boiler. Hot water was originally provided by an indirect tank and oil fired boiler. The house dates to the late 1800s but was remodeled in 2000 with new plumbing. The household has two full-time residents and three college-age adults who live there periodically. The relatively wet basement has a mix of original rubble foundation, new basement, old crawlspace, and new crawlspace. The proposed retrofit included installation of an HPWH and the addition of a recirculation pump and return line.

Below is a list of events for Site 1:

- 11/15/12 – Data logger, thermocouples, switch closure CTs, and RH installed
- 11/27/12 – Flow meter installed
- 11/28/12 – Flow meter wired to data logger
- 03/12/13 – Install HPWH - includes 1 new status (SRP) and 1 new temperature (TR)
- 03/13/12 – 4th heating zone added to home (SZ4 added)
- 04/03/13 – Install Recirculation Pump and Return line
- 04/10/13 – Switch over to HPWH and Recirculation Pump
- 06/12/13 – Added Dehumidifier Status and "Kill-A-Watt" style power meter for DH.

The new water heater and recirculation pump were purchased by CDH. The HPWH was purchased on sale at Lowe's and the recirculation pump was purchased at a local plumbing supply shop. The plumbing contractor billed $900 (12 hours at $75/h) for labor and $78 for materials for the total install. We estimated that the HPWH installation accounts for 75% and the recirculation pump and return piping account for 25% of the total labor (see Table 29, Figure 45, Table 30, and Figure 46 through Figure 56).

Table 29. Cost Breakdown of Water Heater Install and Distribution Retrofit (Site 1)

	Equipment Costs	Contractor Costs			
Item		Labor (hrs)	Material	Installation	Total Cost
Heat Pump Water Heater	$ 1,078.92	9	$ 46.80	$ 675.00	$ 1,800.72
Recirculation Pump / Plumbing	$ 219.00	3	$ 31.20	$ 225.00	$ 475.20
	$ 1,297.92	12	$ 78.00	$ 900.00	$ 2,275.92

Notes: CDH purchased the equipment directly. The Contractor provided material and labor at $75/hr labor. We estimated the labor and material breakdown associated with each item

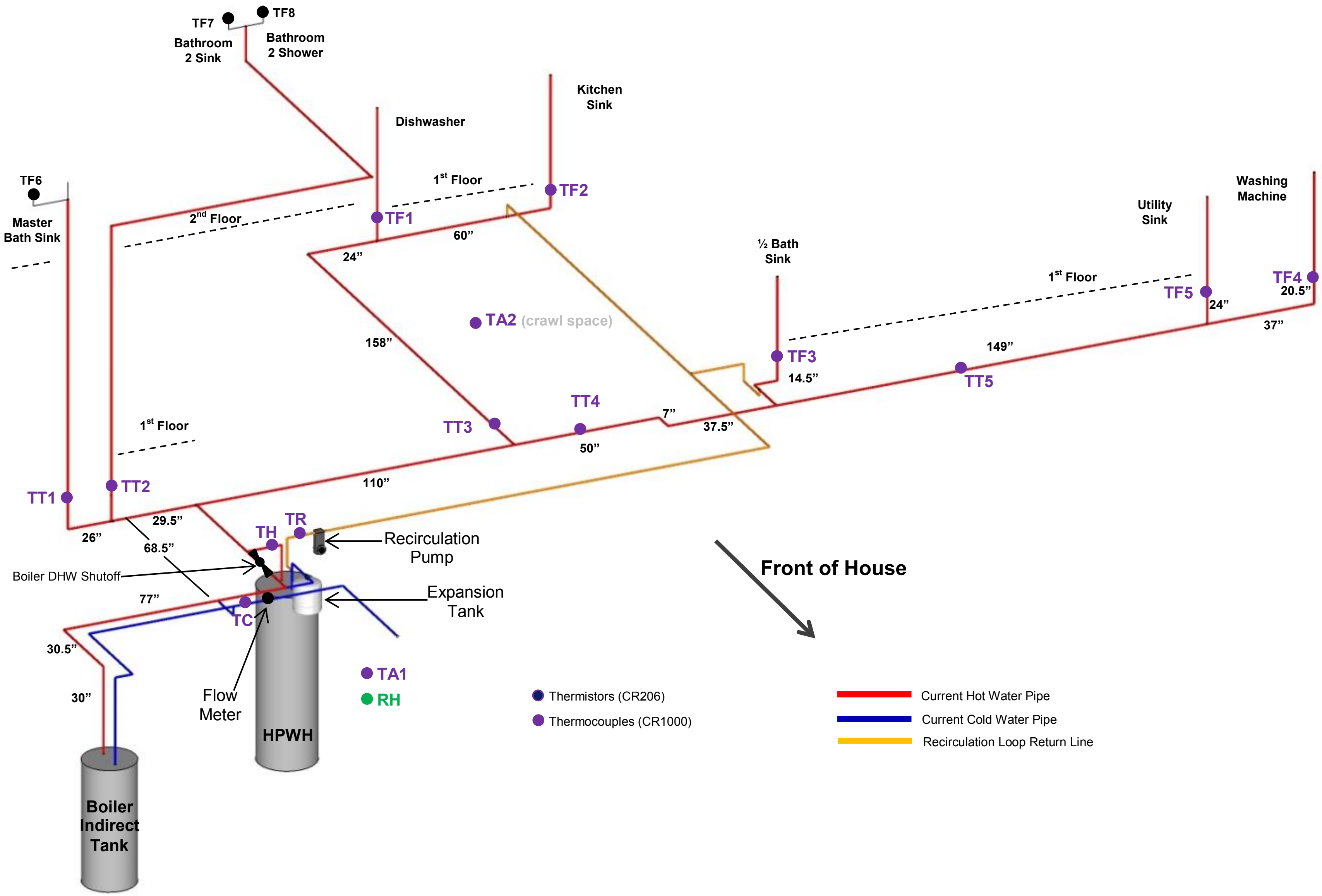

Figure 45. Site 1 pipe layout, pipe length, and sensor location

Table 30. Site 1 Data Point List and Descriptions

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
CR1000	A01	Analog	TH	Hot Water Outlet Temp	°F	Watlow type-T 1/16"	
CR1000	A02	Analog	TC	Inlet Water Temp	°F	Watlow type-T 1/16"	
CR1000	A03	Analog	TA1	Space Temp near Unit	°F	Watlow type-T 1/16"	
CR1000	A04	Analog	TA2	Space Temp (crawl space)	°F	Watlow type-T 1/16"	
CR1000	A05	Analog	TT1	Trunk Temp - Master Bathroom	°F	Watlow type-T 1/16"	
CR1000	A06	Analog	TT2	Trunk Temp - Bathroom 2	°F	Watlow type-T 1/16"	
CR1000	A07	Analog	TF1	Fixture Temp 1 - Dishwasher	°F	Watlow type-T 1/16"	
CR1000	A08	Analog	TF2	Fixture Temp 2 - Kitchen Sink	°F	Watlow type-T 1/16"	
CR1000	A09	Analog	TF3	Fixture Temp 3 - Sink (half bath)	°F	Watlow type-T 1/16"	
CR1000	A10	Analog	TF4	Fixture Temp 4 - Washing Machine	°F	Watlow type-T 1/16"	
CR1000	A11	Analog	TF5	Fixture Temp 5 - Utility Sink	°F	Watlow type-T 1/16"	
CR1000	A12	Analog	TT3	Trunk Temp 3 - Kitchen Trunk	°F	Watlow type-T 1/16"	
CR1000	A13	Analog	TT4	Trunk Temp 4 - Half Bath Trunk	°F	Watlow type-T 1/16"	
CR1000	A14	Analog	TT5	Trunk Temp 5 - Laundry Room Trunk	°F	Watlow type-T 1/16"	
CR1000	A15	Analog	TR	Recirc Temp	°F	Watlow type-T 1/16"	Installed 4/3/13
CR1000	A16	Analog	RH	Relative Humidity	%	Vaisala HMD60	
CR1000	C1	SDM		signal to SDM-SW8A			
CR1000	C2	SDM		signal to SDM-SW8A			
CR1000	C3	SDM		signal to SDM-SW8A			
CR1000	C4	Status	SDH	Status Dehumidifier	minutes	Veris 800	Installed 6/11/13
CR1000	C5	Status	SRP	Status Recirc Pump	minutes	Veris 300	Installed 4/10/13
CR1000	C6	Status	SE1	Element Status 1	minutes	Veris 300	Installed 4/10/13
CR1000	C7	Status	SE2	Element Status 2	minutes	Veris 300	Installed 4/10/13
CR1000	C8	Pulse	WE	DHW Total Power	kWh	Wattnode Pulse	Installed 4/10/13
CR1000	P1	Pulse	FW	Hot Water Use	gal	Omega FTB4605 1/2"	
CR1000	P2	Pulse	FC	Condensate Flow	gal	tipping bucket	not installed

Retrofit Points

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
CR206-1	A01	Analog	TF6	Fixture Temp 6 - Master Bath Sink	°F	Minco Thermistor	

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
CR206-2	A01	Analog	TF7	Fixture Temp 7 - Bathroom 2 Sink	°F	Minco Thermistor	
CR206-2	A02	Analog	TF8	Fixture Temp 8 - Bathroom 2 Shower	°F	Minco Thermistor	

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
SDM-SW8A	IN 1	Status	SC	DHW Pump Status	minutes	Veris 300	
SDM-SW8A	IN 2	BAD					
SDM-SW8A	IN 3	Status	SB	Boiler Status	minutes	Veris 300	
SDM-SW8A	IN 4	Status	SZ1	Status Zone 1	minutes	Veris 300	
SDM-SW8A	IN 5	Status	SZ2	Status Zone 2	minutes	Veris 300	
SDM-SW8A	IN 6	BAD					
SDM-SW8A	IN 7	Status	SZ3	Status Zone 3	minutes	Veris 300	
SDM-SW8A	IN 8	Status	SZ4	Status Zone 4	minutes	Veris 300	Installed 3/13/13

Site Photos

Figure 46. GeoSprings HPWH

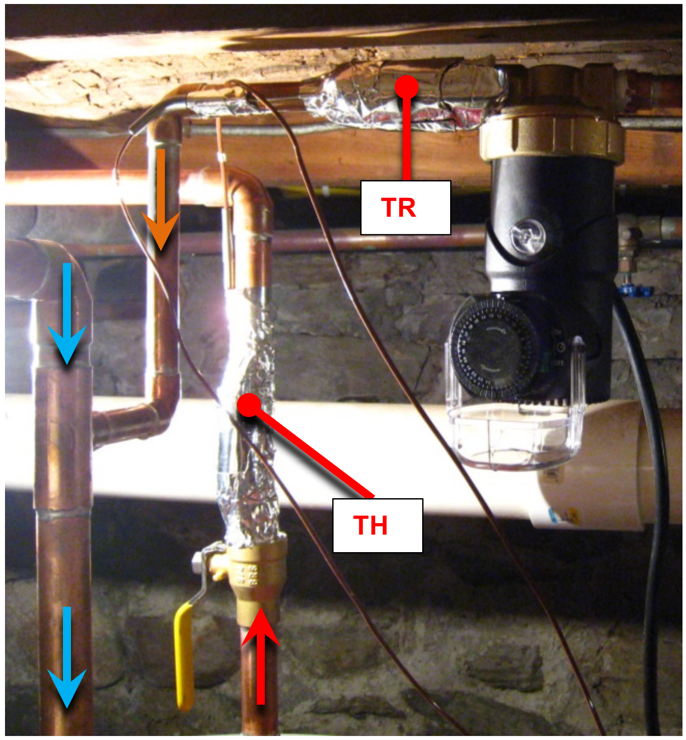

Figure 47. Bell & Gossett ecocirc recirculation pump installed on the return line to the domestic cold water inlet

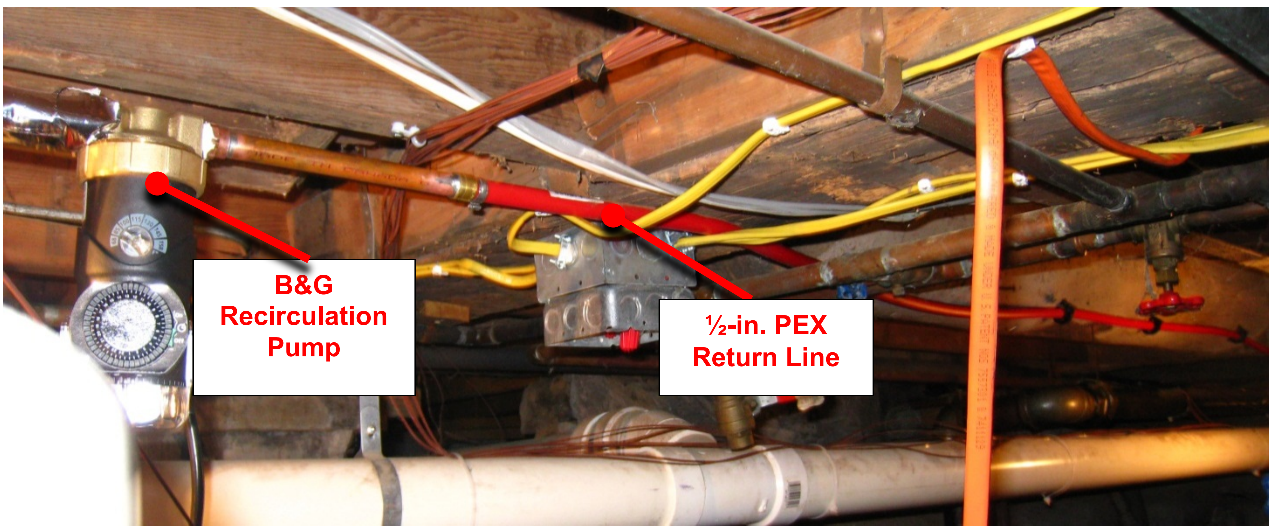

Figure 48. ½ in. PEX was used for the recirculation return line with ½-in. copper used from the recirculation pump to the cold water tie-in

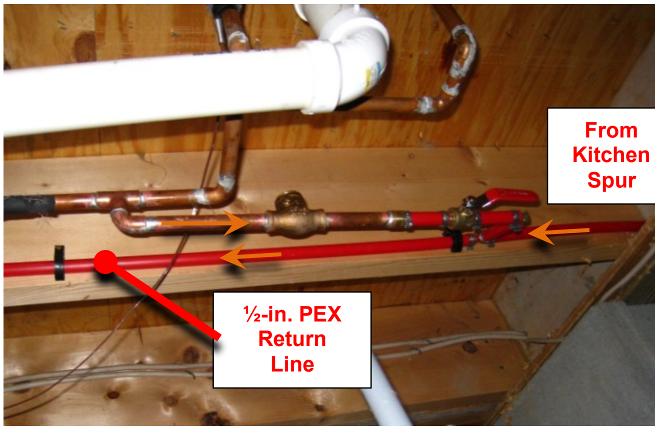

Figure 49. Return line from kitchen spur and half-bath sink with ball valve and check valve visible. This ball valve is almost completely closed allowing more recirculation from the kitchen spur than the main trunk.

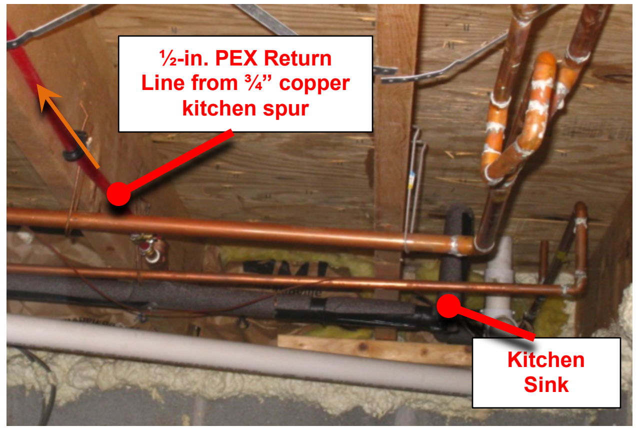

Figure 50. Kitchen piping in crawl space with return line and kitchen sink branch visible. Ball valve at this location is fully open allowing for full recirculation when the pump is on.

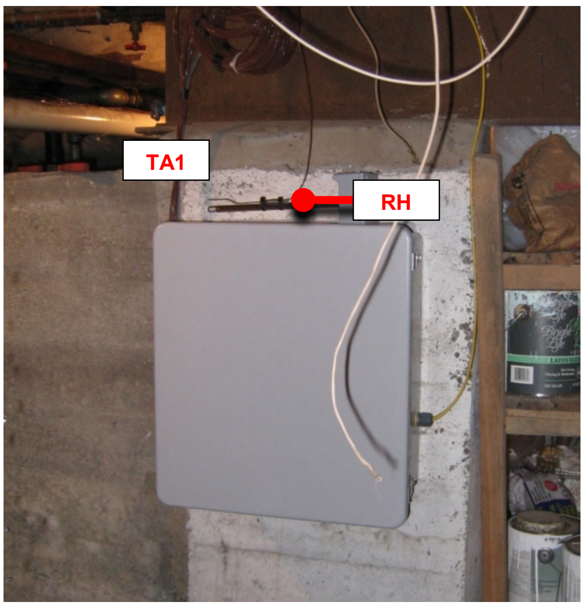

Figure 51. Data logger enclosure with space temperature and relative humidity sensors installed on top

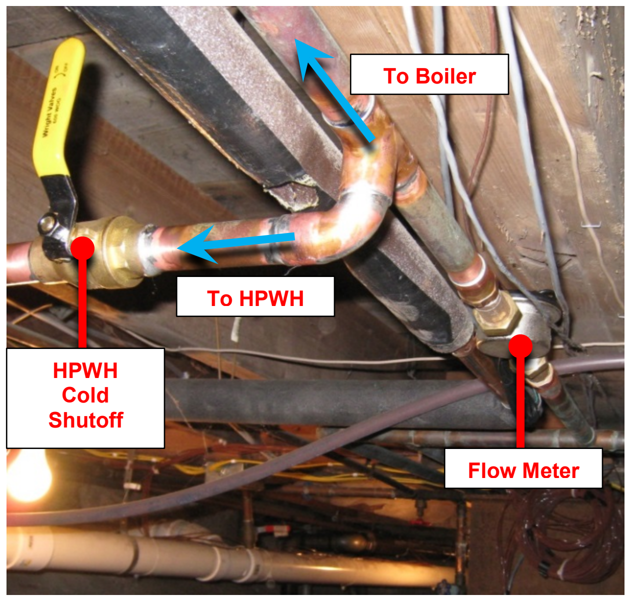

Figure 52. Cold water piping with flow meter and separate HPWH and boiler branches visible

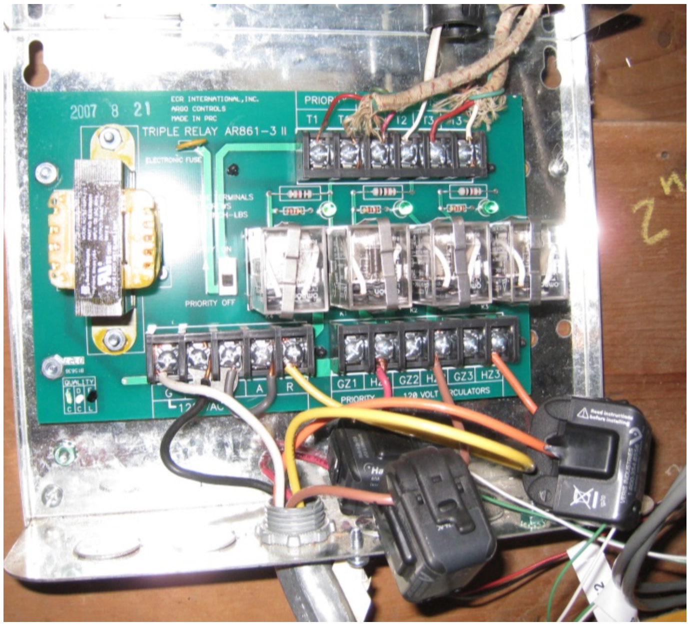

Figure 53. Boiler control board showing current switches measuring boiler zone statuses

Figure 54. Dehumidifier in newer basement section with status and power being measured.

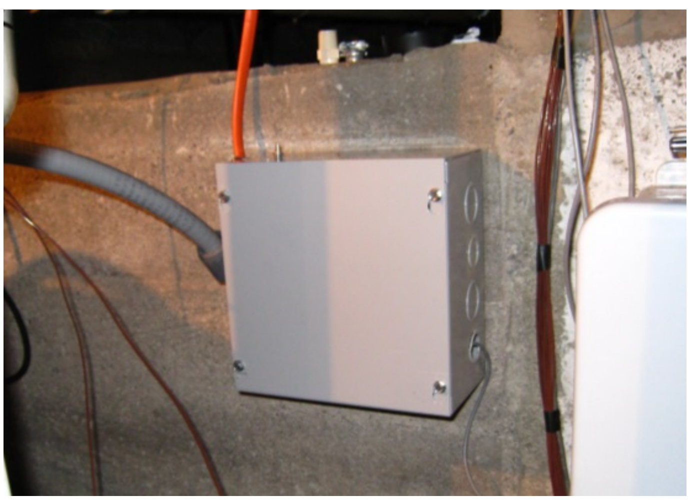

Figure 55. HPWH power is measured inside this enclosure. Inside are the CTs and power transducer.

Figure 56. Typical surface mount thermocouple installation. Thermal paste, thermocouple, foam insulation tape, and cable ties if necessary.

Site #2—Syracuse, Gifford St Group 3 (New Water Heater and Distribution System)

Site 2 is a 1½-story home with 3 bedrooms, 1 bathroom, and a full basement. According to the Onondaga County Department of Real Property, this house was built in 1920 and has 940 ft^2. There are three ful- time occupants. This home originally had a standard 40-gal natural gas storage water heater from Bradford White (Model No.: MI403S6FBN4). The majority of the hot water plumbing is copper with the exception of one section in the basement that feeds the kitchen sink and clothes washer that is steel. All cold piping was originally steel. All steel plumbing was replaced with copper when on site for retrofit install of new water heater and recirculation pump with return line. An A.O. Smith Vertex GDHE 50 high efficiency condensing gas storage water heater and a Taco SmartPlus recirculation pump were installed on 5/21/2013.

Below is a list of events for Site 2:

- 12/12/12 – Data logger and thermocouples installed
- 12/14/12 – Flow meter installed and wired to data logger
- 05/20/13 – Added QU calculation to program
- 05/21/13 – Installed new water heater, recirculation pump, SDHW, SRP, TR, FG, and TAO

Table 31. Cost Breakdown of Water Heater Install and Distribution Retrofit (Site 2)

	Equipment Costs	Contractor Costs			
Retrofit Item		**Labor (hrs)**	**Material**	**Installation**	**Total Cost**
HE Gas Condensing Storage Water Heater	$ 2,106.00	5	$ 433.50	$ 511.25	$ 3,050.75
New Cold Water		4	$ 722.50	$ 409.00	$ 1,131.50
Recirculation Pump and Plumbing	$ 392.00	3	$ 289.00	$ 306.75	$ 987.75
Total:	$ 2,498.00	12	$ 1,445.00	$ 1,227.00	$ 5,170.00

Notes: Total plumber costs were $4,778. CDH purchased pump directly. Water heater cost estimated by CDH. Total labor hours based on observed field time. Allocation of labor and material to each item estimated by CDH

The city-licensed plumbing contractor provided a not-to-exceed quote of $4,778 with a material and labor costs breakdown. CDH purchased the recirculation pump at a local plumbing supply shop. The contractor was observed to be on site for a total of 12 hours and we assumed the new water heater installation accounts for 5 hours of this time. We allocated 4 hours to the new cold water piping and 3 hours to installing the recirculation pump. The AO Smith GDHE-50 water heater was estimated to be $2,106 with sales tax (retail price). This left $1,445 for miscellaneous materials, which we allocated across the three items.

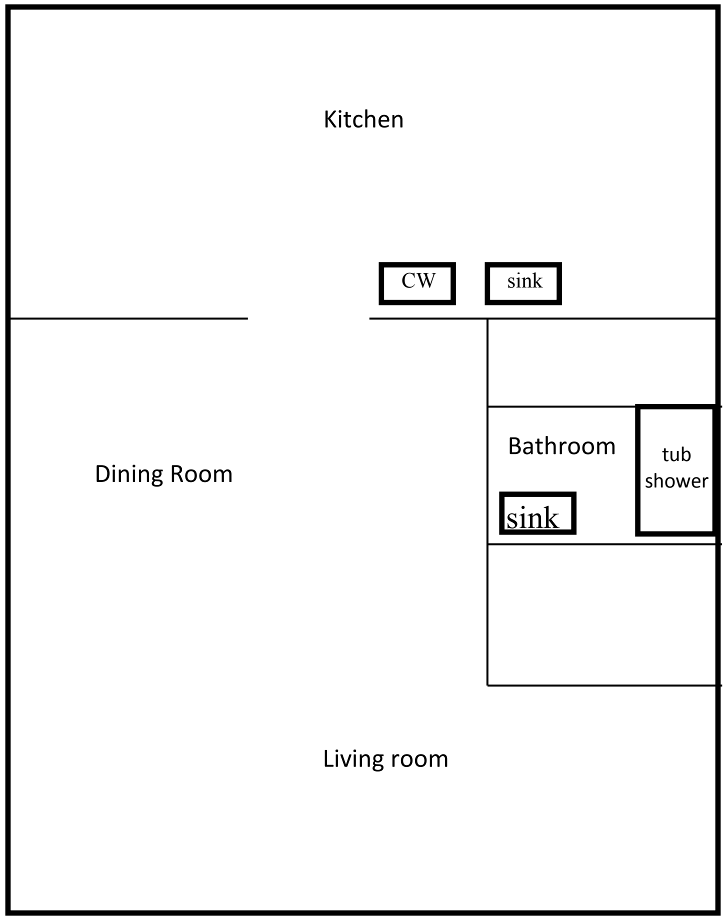

Figure 57. Site 2 floor plan

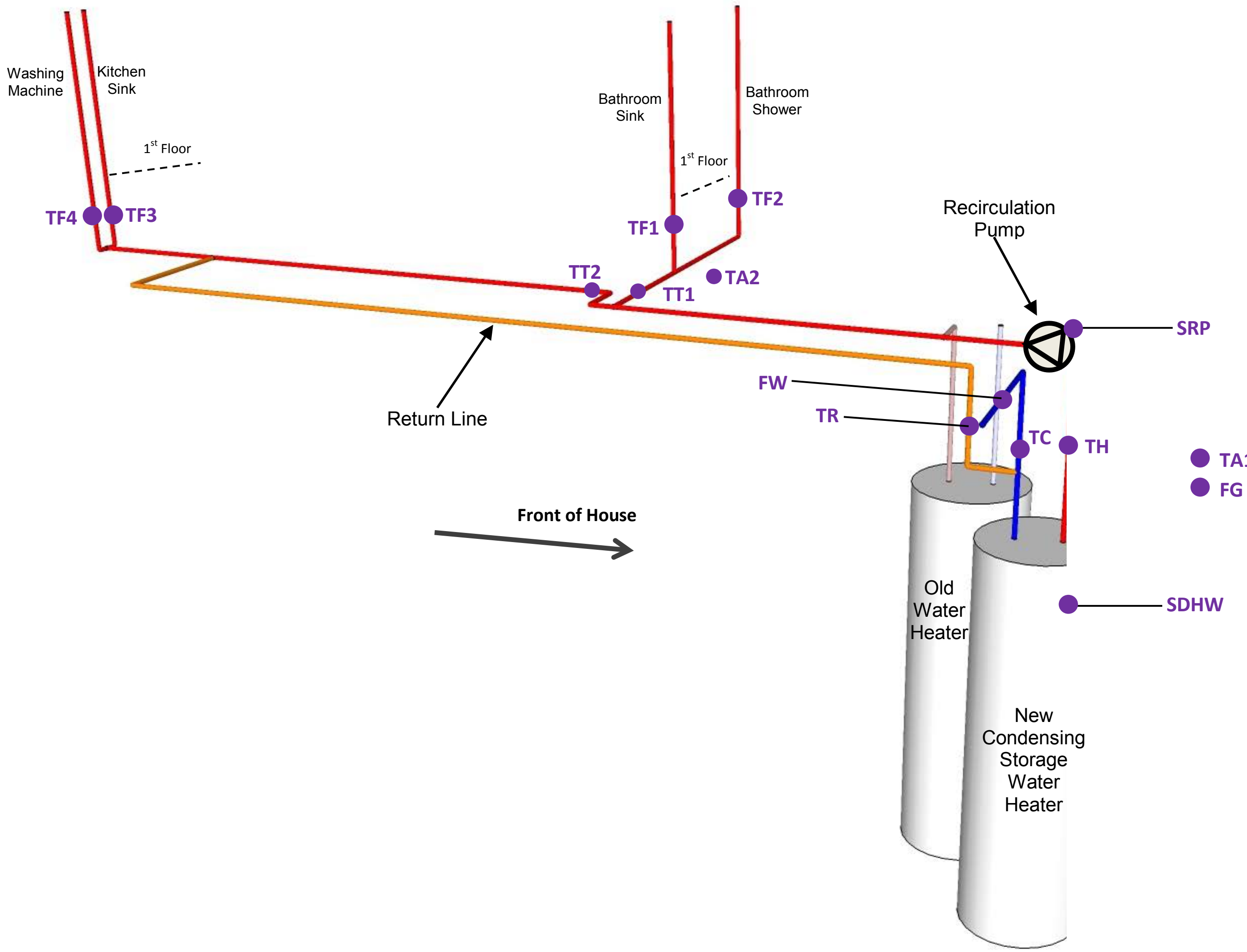

Figure 58. Site 2 pipe layout and sensor location

Table 32. Site 2 Data Point List and Descriptions

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
CR1000	A01	Analog	TH	Hot Water Outlet Temp	°F	Watlow type-T 1/16"	
CR1000	A02	Analog	TC	Inlet Water Temp	°F	Watlow type-T 1/16"	
CR1000	A03	Analog	TFG	Temp Flue Gas	°F	Watlow type-T 1/16"	Removed during retrofit 5/21/13
CR1000	A04	Analog	TA1	Space Temp near Unit	°F	Watlow type-T 1/16"	
CR1000	A05	Analog	TA2	Space Temp near Piping	°F	Watlow type-T 1/16"	
CR1000	A06	Analog	TT1	Trunk Temp - Bathroom	°F	Watlow type-T 1/16"	
CR1000	A07	Analog	TT2	Trunk Temp - Kitchen	°F	Watlow type-T 1/16"	
CR1000	A08	Analog	TF1	Fixture Temp 1 - Bathroom Sink	°F	Watlow type-T 1/16"	
CR1000	A09	Analog	TF2	Fixture Temp 2 - Bathroom Shower	°F	Watlow type-T 1/16"	
CR1000	A10	Analog	TF3	Fixture Temp 3 - Kitchen Sink	°F	Watlow type-T 1/16"	
CR1000	A11	Analog	TF4	Fixture Temp 4 - Washing Machine	°F	Watlow type-T 1/16"	
CR1000	A12	Analog	TR	Recirc Temp	°F	Watlow type-T 1/16"	Installed during retrofit 5/21/13
CR1000	C1	Status	SRP	Status Recirc Pump	minutes	Veris 300	Installed during retrofit 5/21/13
CR1000	C2	Status	SDHW	DHW Status	minutes	Veris 300	Installed during retrofit 5/21/13
CR1000	P1	Pulse	FW	Hot Water Use	gal	Omega FTB4605 1/2"	
CR1000	P2	Pulse	FG	Unit Gas Use	cf	Domestic Meter Pulser	Installed during retrofit 5/21/13
						Retrofit Points	

Site Photos

Figure 59. Original standard gas storage water heater

Figure 60. New condensing gas storage water heater installed during retrofit.

Figure 61. IMAC gas meter with pulser to measure gas use.

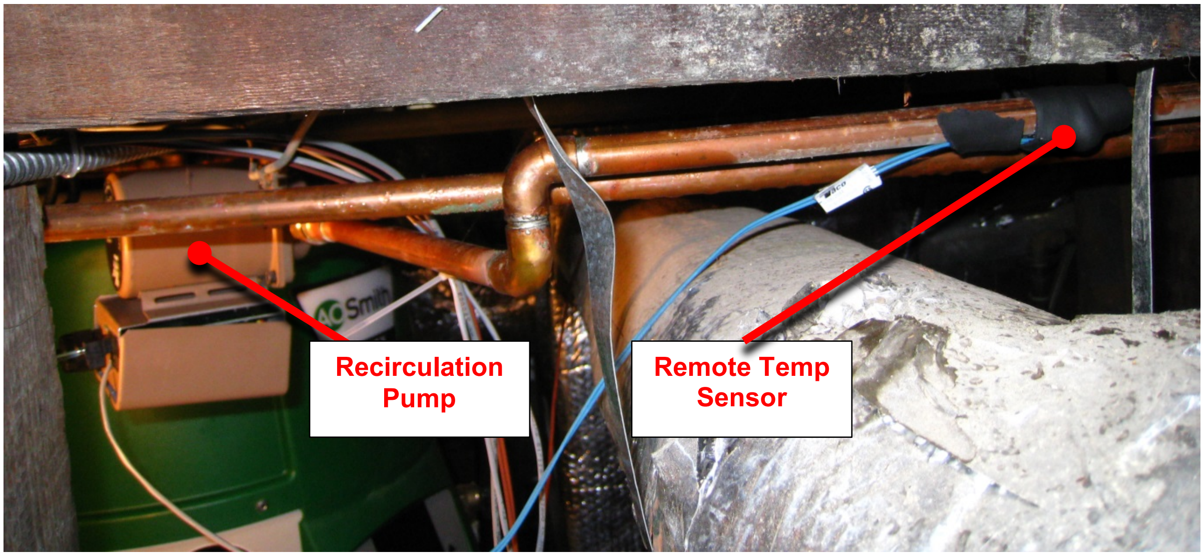

Figure 62. Taco SmartPlus recirculation pump installed on hot water supply with remote temperature sensor

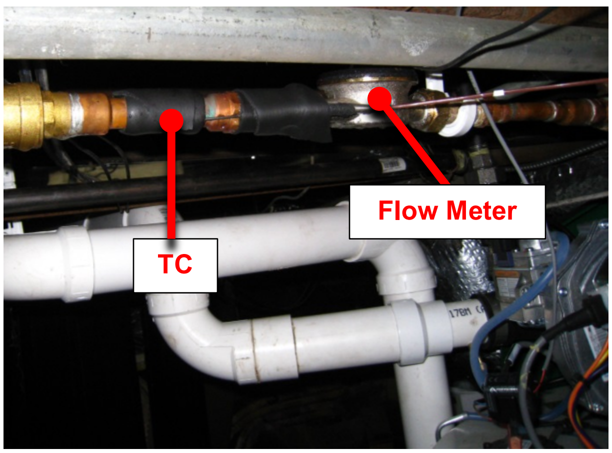

Figure 63. Flow meter and cold water temperature after retrofit

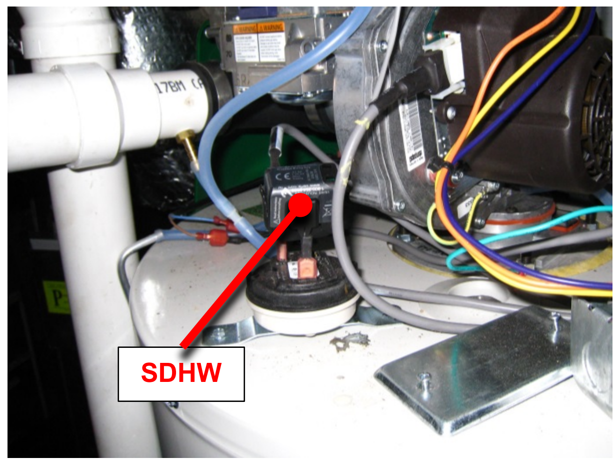

Figure 64. Current switch used to measure water heater status

Site #3 - Manlius, Brickyard Falls Rd - Group 2 (New Tankless)

Site 3 is a raised ranch with three bedrooms and two baths. This house was built in 1976 and has remained unchanged since built. Hot water was originally provided by a Bradford White 40-gal natural gas storage water heater. The kitchen and two baths are on the second level. The laundry/utility room is on the first level. All plumbing is copper with ¾-in. to ½-in. transitions. All but the bathroom 2 sink fixture branches are accessible. A Rinnai non-condensing tankless water heater was installed on March 22, 2013. Distribution changes were required to relocate the water heater and provide direct-vent capability. The changes can be seen in the pipe schematic figure below.

Below is a list of events for Site 3:

- 11/27/12 – Flow meter installed

- 12/12/12 – Data logger and Wi-Fi bridge setup and installed
- 12/13/12 – Thermocouples installed and wired (except for bathroom 2 TCs) and flow
- 12/18/12 – Changed program to expand range of thermocouple for flue gas temperature
- 12/21/12 – Installed Bathroom 2 shower thermocouple around 6:00 p.m.
- 03/22/13 – New tankless water heater installed
- 04/13/13 – QU calculation added to program

Table 33. Cost Breakdown of Water Heater Installation (Site 3)

	Contractor Costs				
Item	Equipment	Labor (hrs)	Material	Installation	Total Cost
Tankless Water Heater	$ 1,220	13	$ 200	$ 1,000	$ 2,420

The tankless water heater was provided and installed by the contractor for fixed price of $2,420. We allocated $1,220 to the equipment and $200 to other miscellaneous materials. The hours were inferred based on the $75/h rate charged by this contractor at other sites. The installation was completed in 1 day by two plumbers.

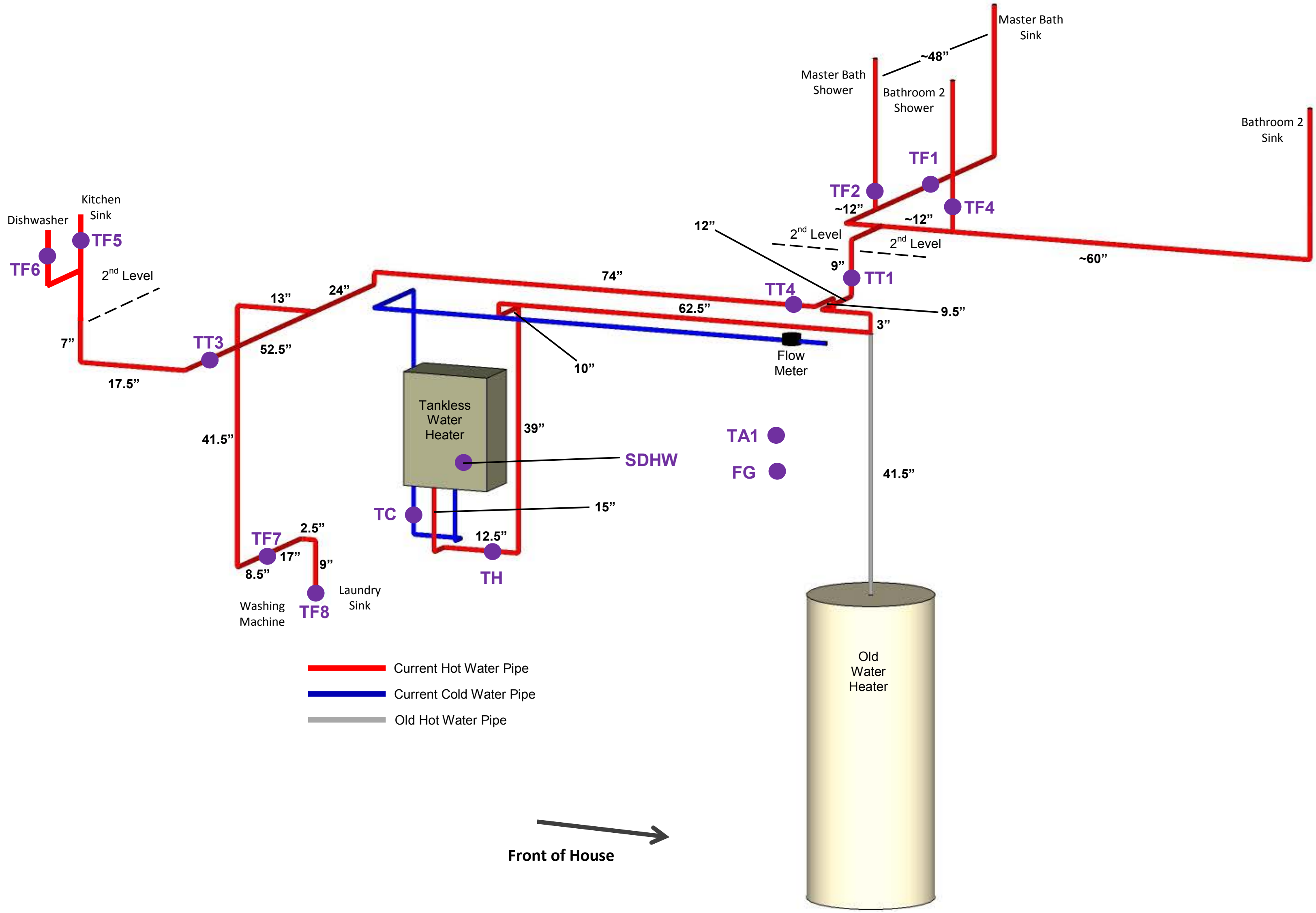

Figure 65. Site 3 pipe layout and sensor location

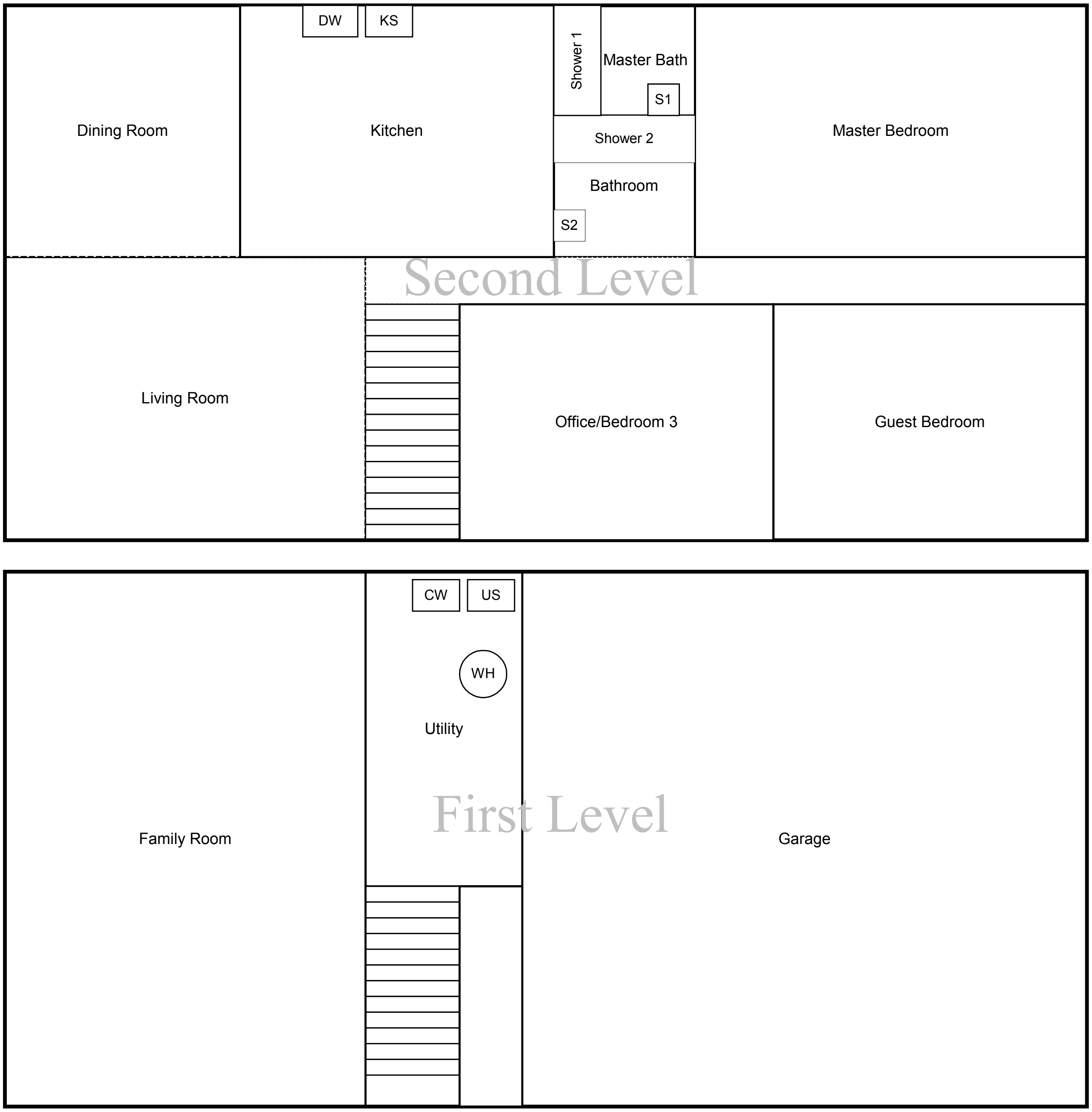

Figure 66. Site 3 floor plan

Table 34. Site 3 Data Point List and Descriptions

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
CR1000	A01	Analog	TH	Hot Water Outlet Temp	°F	Watlow type-T 1/16"	
CR1000	A02	Analog	TC	Inlet Water Temp	°F	Watlow type-T 1/16"	
CR1000	A03	Analog	TFG	Temp Flue Gas	°F	Watlow type-T 1/16"	Removed during retrofit 3/22/13
CR1000	A04	Analog	TA1	Space Temp near Unit	°F	Watlow type-T 1/16"	
CR1000	A05	Analog	TT1	Trunk Temp - Bathrooms	°F	Watlow type-T 1/16"	
CR1000	A06	Analog	OPEN				
CR1000	A07	Analog	TT3	Trunk Temp - Kitchen	°F	Watlow type-T 1/16"	
CR1000	A08	Analog	TT4	Trunk Temp - Laundry	°F	Watlow type-T 1/16"	
CR1000	A09	Analog	TF1	Fixture Temp 1 - Master Bath Sink	°F	Watlow type-T 1/16"	
CR1000	A10	Analog	TF2	Fixture Temp 2 - Master Bath Shower	°F	Watlow type-T 1/16"	
CR1000	A11	Analog	OPEN				
CR1000	A12	Analog	TF4	Fixture Temp 4 - Bathroom 2 Shower	°F	Watlow type-T 1/16"	
CR1000	A13	Analog	TF5	Fixture Temp 5 - Kitchen Sink	°F	Watlow type-T 1/16"	
CR1000	A14	Analog	TF6	Fixture Temp 6 - Dishwasher	°F	Watlow type-T 1/16"	
CR1000	A15	Analog	TF7	Fixture Temp 7 - Washing Machine	°F	Watlow type-T 1/16"	
CR1000	A16	Analog	TF8	Fixture Temp 8 - Laundry Sink	°F	Watlow type-T 1/16"	
CR1000	C8	Status	SDHW	DHW Status	minutes	Veris 300	Installed during retrofit 3/22/13
CR1000	P1	Pulse	FW	Hot Water Use	gal	Omega FTB4605 1/2"	
CR1000	P2	Pulse	FG	Unit Gas Use	cf	Domestic Meter Pulser	Installed during retrofit 3/22/13
						Retrofit Points	

Site Photos

Figure 67. Original storage water heater location

Figure 68. New tankless water heater from retrofit

Figure 69. IMAC gas meter with pulser

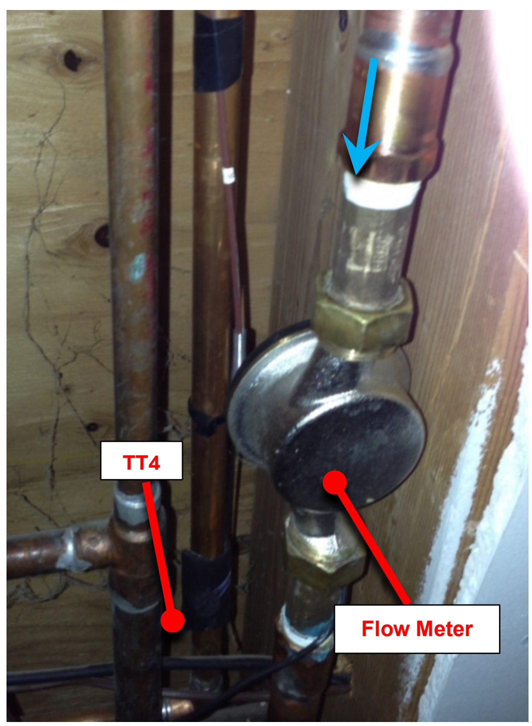

Figure 70. Flow meter and laundry trunk

temperature.

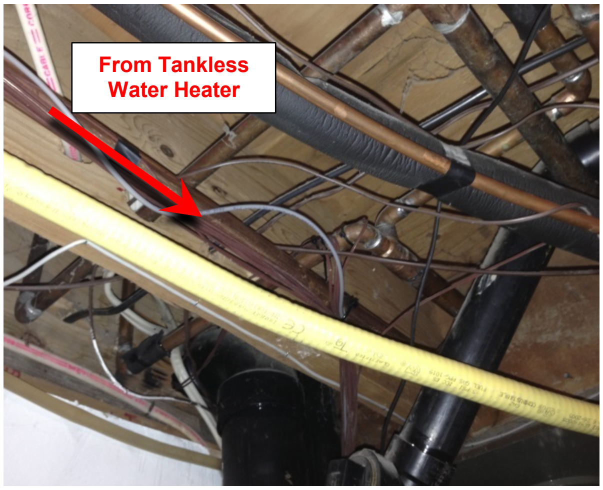

Figure 71. Showing direction of hot water flow from tankless water heater

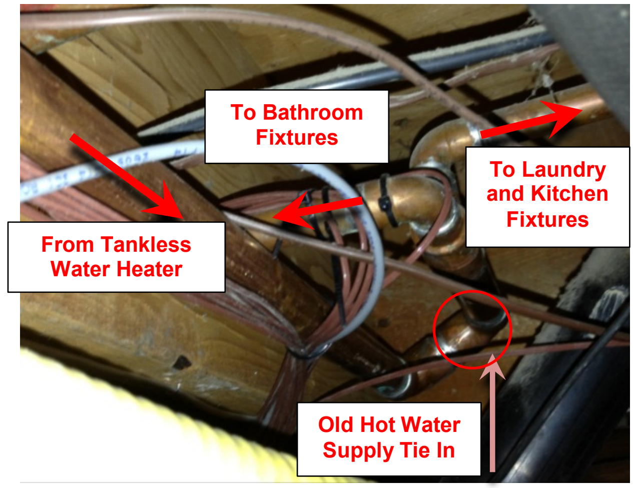

Figure 72. Shows direction of hot water flow after retrofit. The old hot water supply tied into the pipe at the elbow circled in red and was a vertical drop to the old water heater.

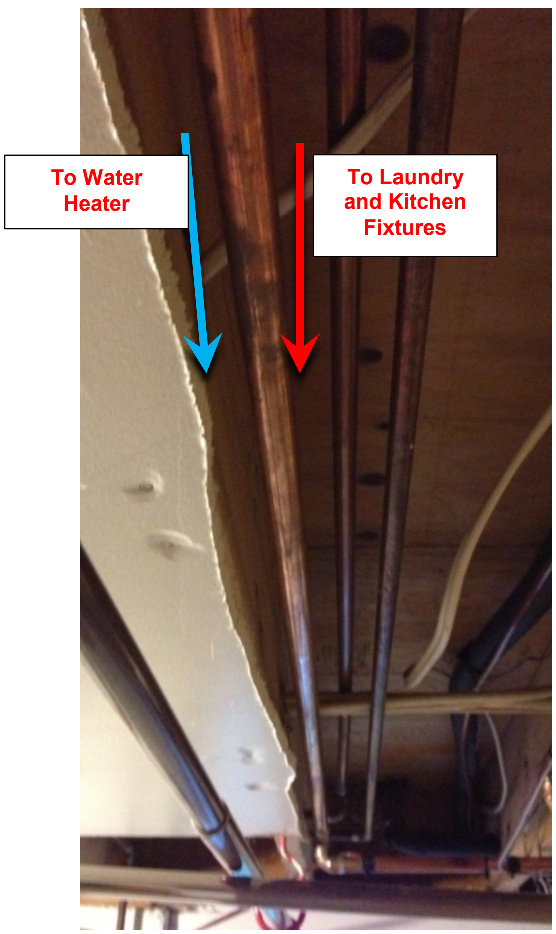

Figure 73. Shows lengthened cold water supply piping

Site #4 – Cazenovia, Burton St - Group 1 (Baseline)

Site 4 was built in 1860 and extensively renovated in 2010. A Rinnai tankless water heater and manifold water distribution with PEX plumbing was installed during the renovation. The old standard gas water heater was kept to provide hot water to a full bathroom on the second floor and a half bathroom on the first floor. All piping is copper. The Rinnai tankless water heater provides hot water for the master bathroom on the second floor, kitchen, and laundry room.

No changes were made to this DHW system.

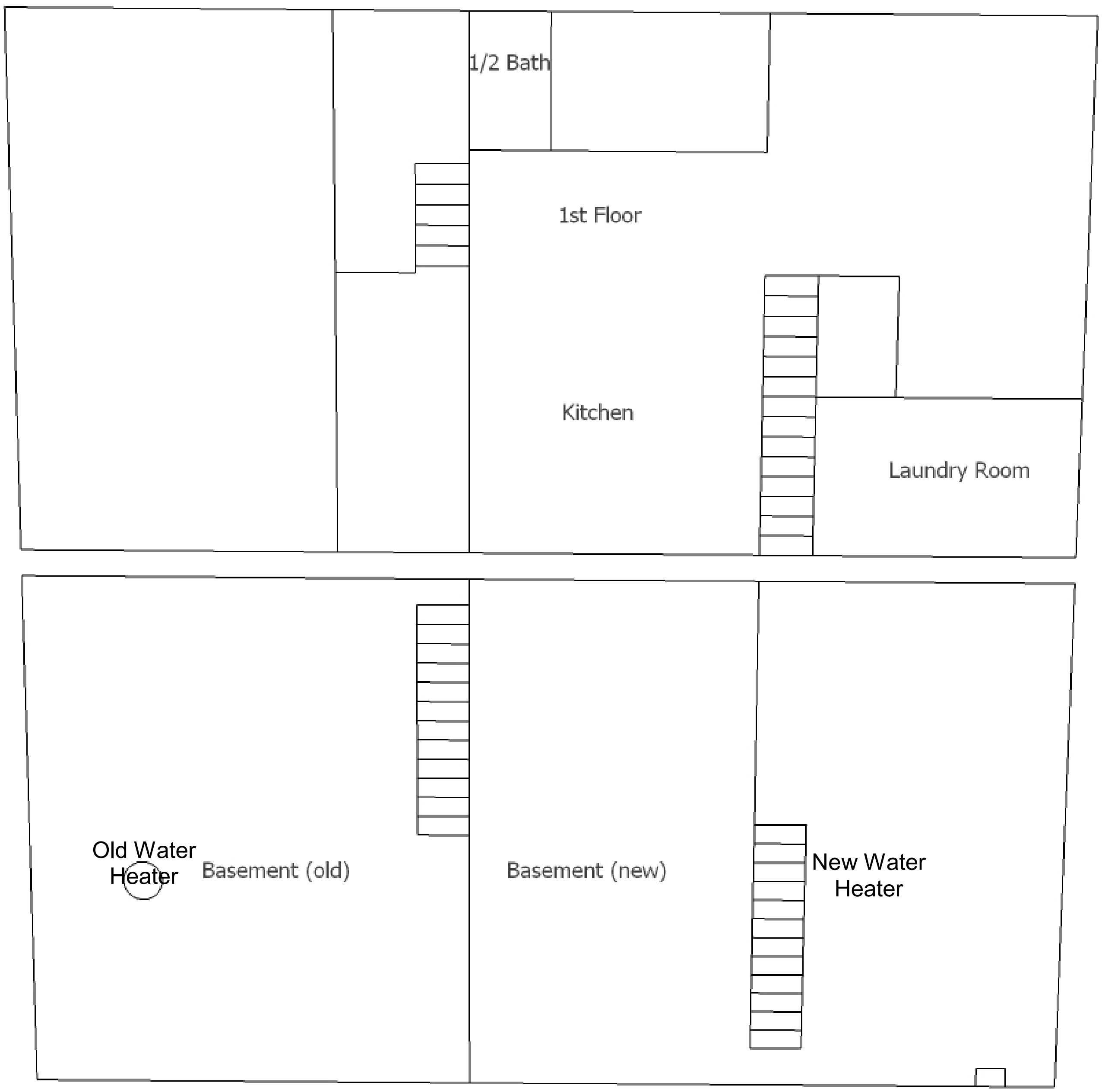

Figure 74. Site 4 floor plan

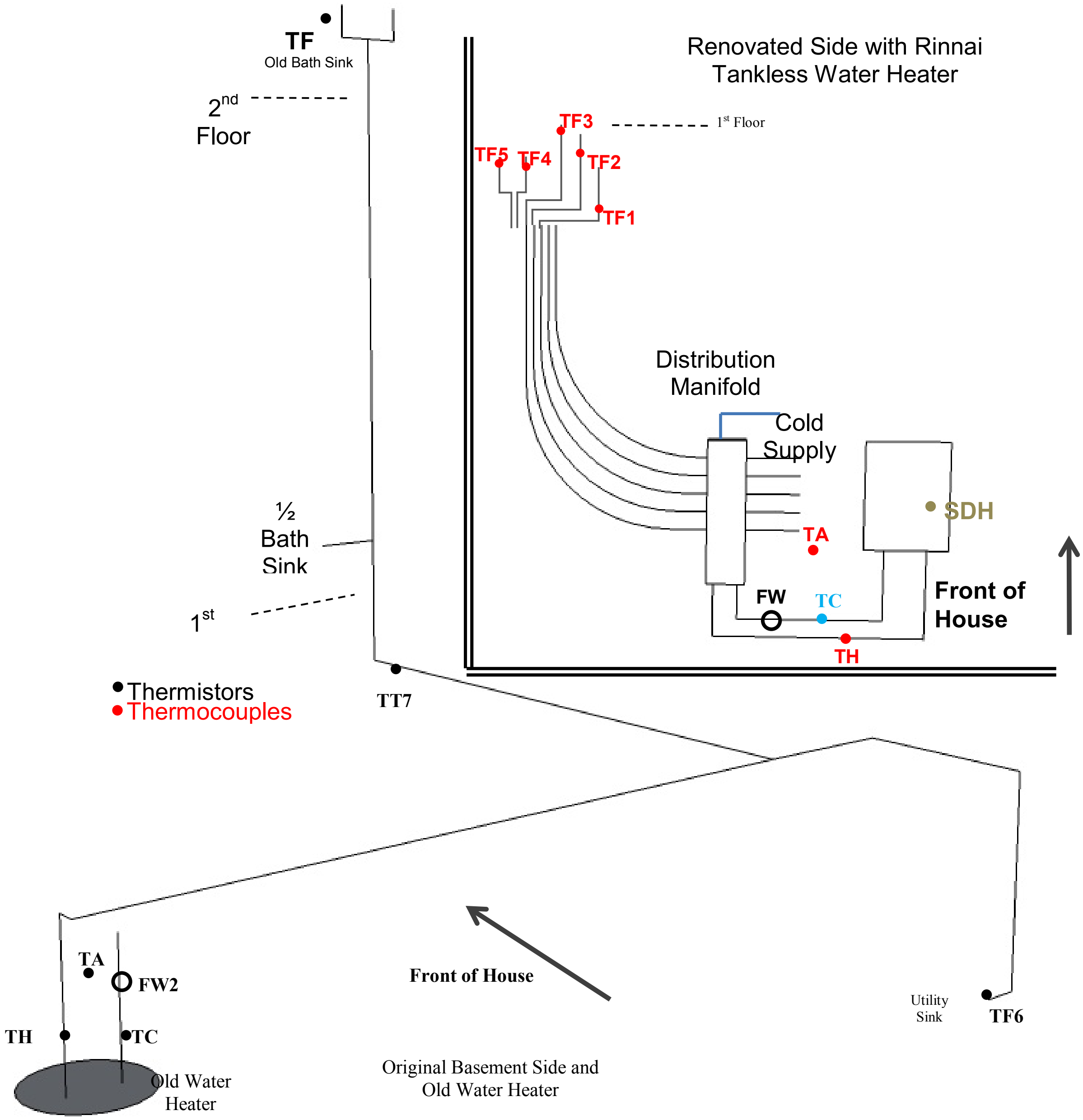

Figure 75. Site 4 Pipe Layout

Table 35. Site 4 Data Point List and Descriptions

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
CR1000	A01	Analog	TH	Tankless Hot Water Outlet Temp	°F	Watlow type-T 1/16"	
CR1000	A02	Analog	TC	Tankless Inlet Water Temp	°F	Watlow type-T 1/16"	
CR1000	A03	Analog	TFG	Tankless Flue Gas Temp	°F	Watlow type-T 1/16"	
CR1000	A04	Analog	TA	Space Temp near Tankless	°F	Watlow type-T 1/16"	
CR1000	A05	Analog	TF1	Fixture Temp 1 - Master Bath Sink	°F	Watlow type-T 1/16"	
CR1000	A06	Analog	TF2	Fixture Temp 2 - Clothes Washer	°F	Watlow type-T 1/16"	
CR1000	A07	Analog	TF3	Fixture Temp 3 - Kitchen Sink	°F	Watlow type-T 1/16"	
CR1000	A08	Analog	TF4	Fixture Temp 4 - Laundry Sink	°F	Watlow type-T 1/16"	
CR1000	A09	Analog	TF5	Fixture Temp 5 - Master Bath Shower	°F	Watlow type-T 1/16"	
CR1000	C8	Pulse	SDHW	Tankless Status	min	Veris CT	
CR1000	P1	Pulse	FW	Tankless Hot Water Use	gal	Omega FTB4605 1/2"	151.4 pulse/gal mult. = 0.00660502

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
CR206-1	A01	Analog	TH2	Old Heater Hot Water Outlet Temp	°F	Minco Thermistor	
CR206-1	A02	Analog	TC2	Old Heater Inlet Water Temp	°F	Minco Thermistor	
CR206-1	A03	Analog	TF6	Fixture Temp 6 - Utility Sink	°F	Minco Thermistor	
CR206-1	A04	Analog	TA2	Space Temp near Old Heater	°F	Minco Thermistor	
CR206-1	A05	Analog	TT7	Trunk Temp 7 - Old Bathroom	°F	Minco Thermistor	
CR206-1	P-SW	Pulse	FW2	Old Heater Hot Water Use	gal	Omega FTB4605 1/2"	151.4 pulse/gal mult. = 0.00660502

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
CR206-2	A01	Analog	TF7	Fixture Temp 7 - Old Bathroom Sink	°F	Minco Thermistor	

Site #5 – Syracuse, Hornady Dr - Group 1 (Baseline)

Site 5 is a split level home with three bedrooms and two baths and is occupied by two adults with a baby due in June 2013. According to the Onondaga County Department of Real Property this house was originally built in 1989 and has 1,640 ft^2. Hot water is provided by a 40 gal General Electric SmartWater natural gas storage water heater (Model No.: PG40S09AVJ00) with a manufacturing date of December 2006. There is a bathroom on the top level, a bathroom on the middle level and a laundry room on the lowest level. All plumbing is copper with all but the kitchen fixtures reachable from the lowest level.

No changes were made to this DHW system.

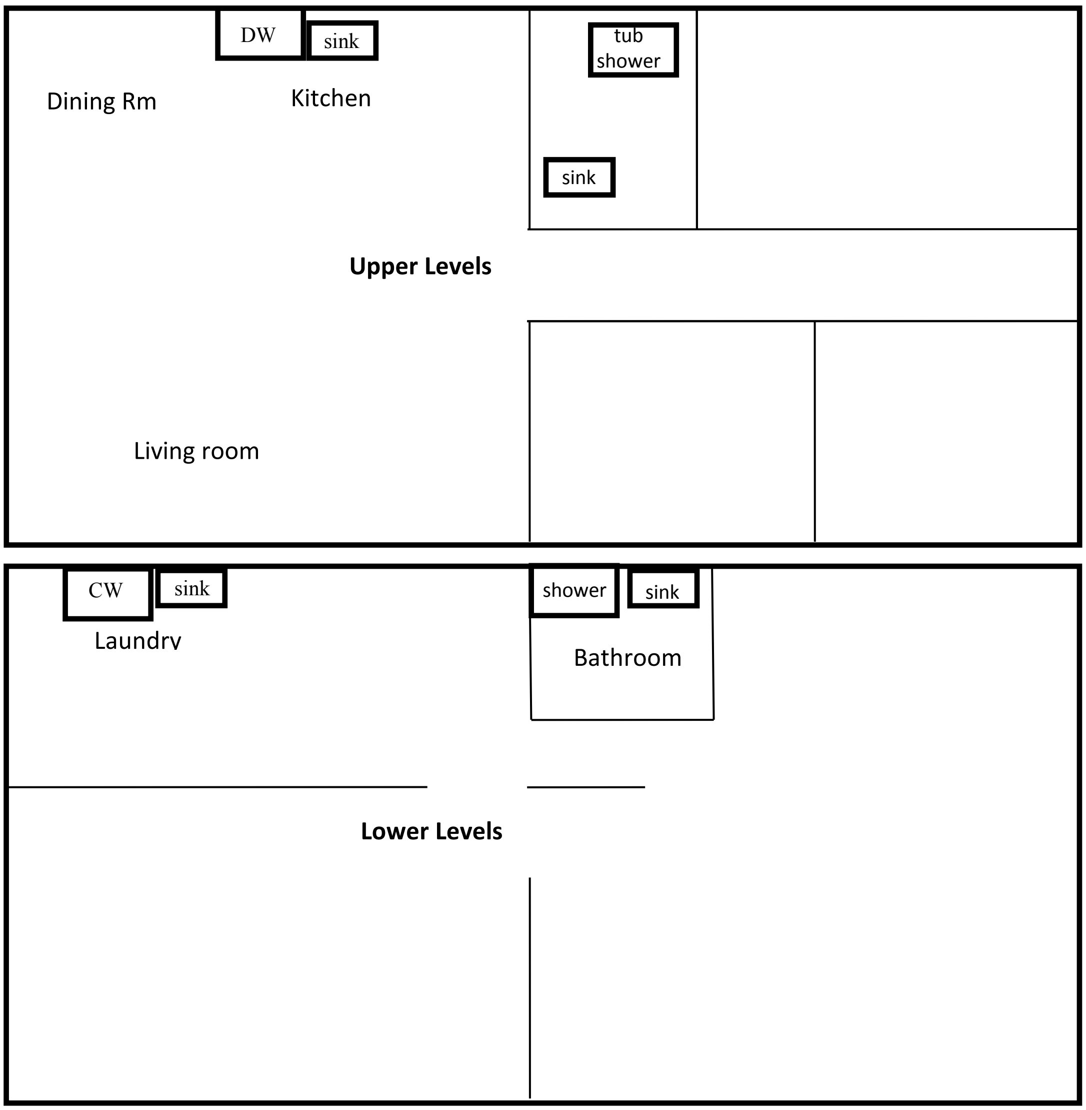

Figure 76. Site 5 Floor Plan

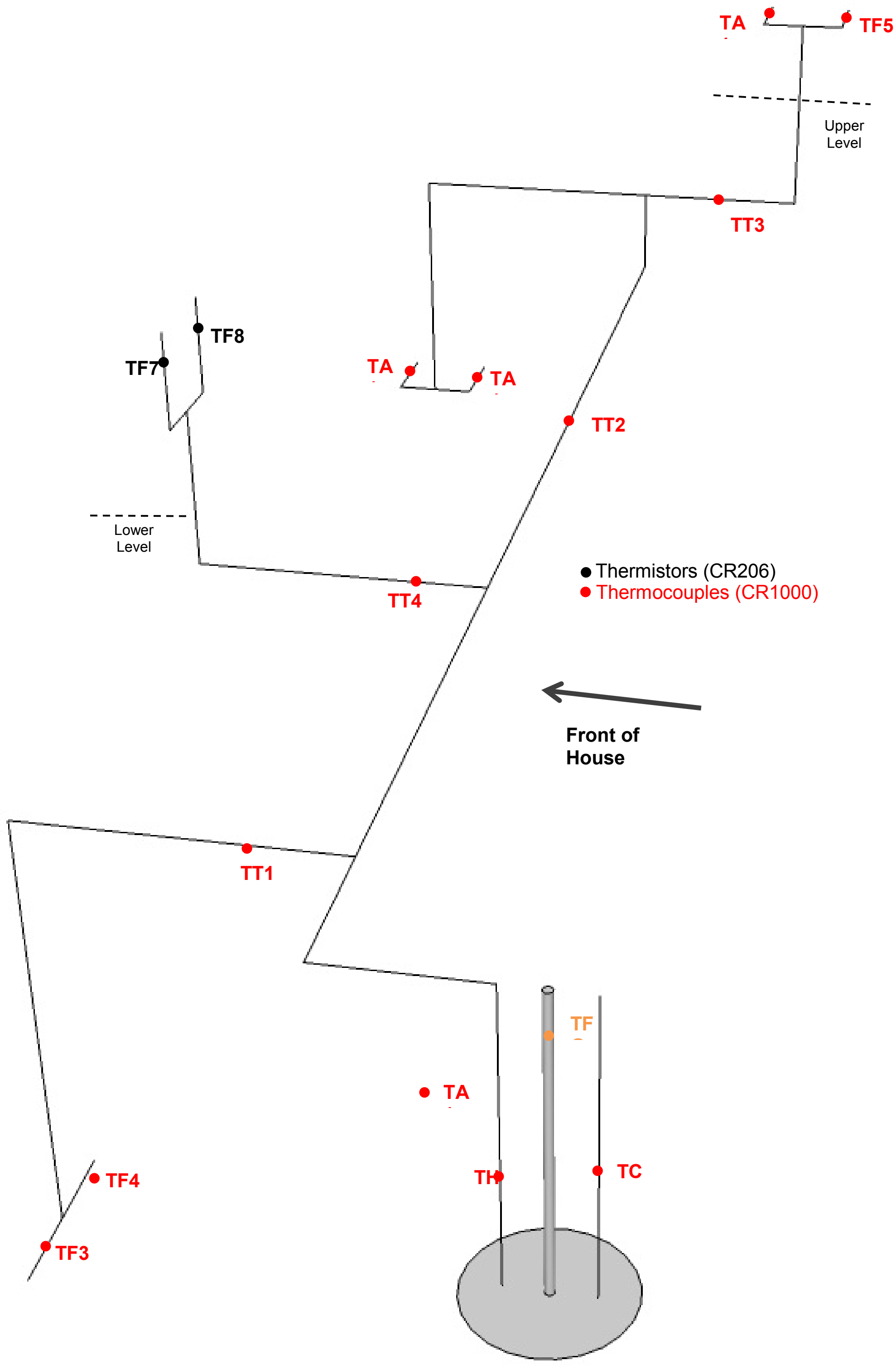

Figure 77. Site 5 Pipe Layout and Sensor Location

Table 36. Site 5 Data Point List and Descriptions

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
CR1000	A01	Analog	TH	Hot Water Outlet Temp	°F	Watlow type-T 1/16"	
CR1000	A02	Analog	TC	Inlet Water Temp	°F	Watlow type-T 1/16"	
CR1000	A03	Analog	TFG	Temp Flue Gas	°F	Watlow type-T 1/16"	
CR1000	A04	Analog	TA1	Space Temp near Unit	°F	Watlow type-T 1/16"	
CR1000	A05	Analog	TA2	Space Temp near Piping	°F	Watlow type-T 1/16"	
CR1000	A06	Analog	TT1	Trunk Temp - Laundry	°F	Watlow type-T 1/16"	Washing Machine
CR1000	A07	Analog	TT2	Trunk Temp - Bathroom	°F	Watlow type-T 1/16"	Bathrooms
CR1000	A08	Analog	TT3	Trunk Temp - Upper Bath	°F	Watlow type-T 1/16"	Upper Bath
CR1000	A09	Analog	TT4	Trunk Temp - Kitchen	°F	Watlow type-T 1/16"	Kitchen
CR1000	A10	Analog	TF1	Fixture Temp 1	°F	Watlow type-T 1/16"	Lower Bathroom Sink
CR1000	A11	Analog	TF2	Fixture Temp 2	°F	Watlow type-T 1/16"	Lower Bathroom Shower
CR1000	A12	Analog	TF3	Fixture Temp 3	°F	Watlow type-T 1/16"	Washing Machine
CR1000	A13	Analog	TF4	Fixture Temp 4	°F	Watlow type-T 1/16"	Laundry Sink
CR1000	A14	Analog	TF5	Fixture Temp 5	°F	Watlow type-T 1/16"	Upper Bathroom Sink
CR1000	A15	Analog	TF6	Fixture Temp 6	°F	Watlow type-T 1/16"	Upper Bathroom Shower
CR1000	P1	Pulse	FW	Hot Water Use	gal	Omega FTB4605 1/2"	151.4 pulse/gal mult. = 0.00660502

Logger	Channel	Type	Name	Description	Eng Units	Sensor	Notes
CR206	A01	Analog	TF7	Fixture Temp 7	°F	Minco Thermistor	Kitchen Sink
CR206	A02	Analog	TF8	Fixture Temp 8	°F	Minco Thermistor	Dishwasher

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