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Validation of a Hot Water Distribution Model Using Laboratory and Field Data

C. Backman and M. Hoeschele

Alliance for Residential Building Innovation

July 2013

Building America℠

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Definitions

AET	Applied Energy Technology
BEopt	Building Energy Optimization model
CPVC	Chlorinated polyvinyl chloride
DOE	U.S. Department of Energy
gpd	Gallons per day
gpm	Gallons per minute
LBNL	Lawrence Berkeley National Laboratory
MRT	Mean radiant temperature
NREL	National Renewable Energy Laboratory
PEX	Cross-linked polyethylene
TRNSYS	TRaNsient System Simulation program

Executive Summary

Characterizing the performance of hot water distribution systems is a critical step in developing best practice guidelines for the design and installation of high performance domestic hot water systems. Overall hot water system performance is dependent upon the complex interactions between the household occupants' behavior, plumbing configuration, climate, and water heater characteristics. Historically, building energy simulation models have simplified distribution system algorithms to accommodate the longer time steps used in most building performance models. The advent of more advanced distribution modeling tools, and ongoing improvements in the quality of input data driving these models, lead to better predictive capabilities.

This project validated the TRNSYS Type 604 pipe model against laboratory pipe heat loss test data and detailed field monitoring data from a prior National Renewable Energy Laboratory (NREL) research project. The Type 604 model is an advanced pipe model that accounts for pipe heat transfer effects (convective, radiant, and axial conduction) and pipe heat capacitance effects utilizing a nodal pipe network. The model provided very good comparisons with the two datasets. Using measured data and an as-built distribution model of the NREL Solar Row project, modeled hot water distribution losses were determined to be within 2% of the monitored data over the 4-month period when field data were available. Extending the validated model to a prototypical distribution system configuration in different climates suggests that for an electric storage water heater, distribution losses represent about 26%–27% of the annual water heater recovery load, with an associated energy use impact of 534–892 kWh/yr. Insulating the full distribution system with ¾ in. pipe insulation reduces the distribution loss by a projected 111–170 kWh/yr. Different usage quantities and patterns would affect these savings estimates.

Key lessons learned in this work suggest that the model is highly accurate, yet it is complex to configure and requires a short time step (on the order of 5–10 s) to accurately model real hot water draw events and the cooldown effects between draws. The short time step results in long simulation runtimes. This poses an issue for how best to integrate with mainstream building energy simulation models that typically operate on a 1-h time scale. While the work demonstrated the validity of the model's underlying capabilities, a remaining key question centers on how best to extend this work to the broader energy efficiency community.

Developing the inputs for the modeling and reviewing current research findings on typical hot water usage quantity and patterns highlight the need for better input data on usage and usage patterns that are sufficiently granular to assess regional variations in hot water distribution installation practices, seasonal variations in load for different climates, and usage variations associated with vintages of homes (running the gamut from new highly water-efficient homes, to old homes that have had no improvements in appliance and fixture water use efficiency).

The findings of this work are directed toward researchers focused on understanding distribution system performance and overall hot water system performance. Future efforts in this research area include collecting better input data to drive the models, completing a parametric study to evaluate distribution performance under varying conditions, and determining the best strategy in accurately modeling performance without adding excessive complexity and extending simulation runtimes.

Acknowledgements

We would like to acknowledge the support and contributions of Jeff Maguire (NREL), Greg Barker (Mountain Energy Partnership), Jim Lutz (Lawrence Berkeley National Laboratory), Jeff Thornton (Thermal Energy Simulation Specialists), and Carl Hiller (Applied Energy Technology). This project builds upon their prior efforts in both collecting valuable laboratory and field data and developing and demonstrating the available simulation models.

1 Introduction

1.1 Background and Motivation

The performance of residential hot water distribution systems is not well understood for several reasons, including:

- A lack of validated simulation tools to model system performance
- Limited field monitoring data that accurately represent the detailed, high-resolution hot water usage data needed to drive the models
- Proper characterization of hot water distribution layouts regionally and by house vintage
- The impact of occupant behaviors in regards to patterns and preferences.

All of these factors contribute to a generally poor understanding of hot water distribution system performance, since all of these factors strongly impact overall performance. Limited hard data currently exist in quantifying distribution losses, especially in terms of understanding how climate, plumbing practices (i.e., pipe layout and variations with house vintage and house design), hot water usage patterns, and user behavior affect overall losses. A variety of factors contribute to this poor understanding of distribution system performance, including the following:

- Detailed monitoring of water heater energy and water flows to use points is challenging and expensive, since remote temperature sensors and individual flow meters are ideally required to properly characterize performance. Few studies have been completed that accurately quantify single-family home distribution performance, limiting the data available for model validation efforts.
- Detailed water heating distribution system modeling tools have historically been limited in their modeling rigor. This, coupled with the uncertainty regarding key inputs, has left this area not well understood.
- For many homes and apartments, much of the distribution piping is largely hidden from view, making accurate descriptions difficult of how the pipe is routed and what the actual pipe lengths and diameters are. Without knowledge of the pipe layout and end use point locations, it is challenging to understand the system interactions.
- Hot water loads, usage patterns, and user behavior vary widely between similar sized households, as well as within a household on a day to day basis. These patterns can significantly affect distribution system performance in terms of heat loss and water waste. Addressing all of these issues is critical in developing a better understanding of distribution system performance.

Conventional building energy simulation models are typically run on hourly time steps to provide an appropriate balance between simulation time and modeling accuracy. An hourly time step does not provide sufficient resolution to capture the transient effects associated with hot water draw events, which are typically on the order of a few minutes in length (Lutz and Melody 2012). A robust simulation tool needs to accurately model the physical of the flow and heat transfer effects, simulate on a short time step to capture individual hot water events, and be driven by accurate input data defining all the key inputs (such as layout, use pattern, etc.).

The ongoing development of advanced simulation models, such as the HWSIM distribution system model (Springer et al. 2008) and recent TRNSYS modeling work completed by the University of Colorado at Boulder and NREL (Maguire et al. 2011), represent valuable steps in the process of developing the tools to improve quantification of hot water system performance, ultimately leading to the identification of cost-effective improvement options that will contribute to Building America's goal of 30%–50% energy savings.

Work is proceeding in many of the identified water heating gap areas, but additional effort is needed to generate higher quality input data and improve the simulation tools required to properly assess distribution system performance. Current activities include:

- Jim Lutz of Lawrence Berkeley National Laboratory (LBNL) has been working for several years on developing a database for archiving high resolution hot water use data from field monitoring studies.1 As more studies expand the database, the characterization of hot water usage nationally and regionally will improve.
- LBNL is also working on developing and demonstrating wireless temperature and flow measurement systems that will greatly enhance the ability to disaggregate hot water use and flow by fixture. LBNL is hoping to demonstrate this system in February 2013 and expand to a broader pilot project in the spring of 2013.
- The Advanced Residential Integrated Energy Solutions Building America team is starting a field effort to assess the impact of water heater and distribution system upgrades at three or more existing homes in central New York.
- Davis Energy Group has recently completed simulation enhancements to HWSIM (with a focus on integrating both gas storage and gas tankless water heater models with the distribution model), as part of a California Energy Commission Public Interest Energy Research sponsored advanced water heating project led by the Gas Technology Institute. LBNL has a follow-on Public Interest Energy Research project that will be completed in 2013 that develops a more comprehensive model that incorporates distribution system modeling with a wider range of water heater types.
- Davis Energy Group also has completed field documentation of installed distribution piping in 100 new California homes. Further similar studies of typical plumbing practice are needed to document regional variations in distribution system configuration.

The emergence of new water heaters over the past 5–10 years also could impact distribution system performance by affecting energy waste and water waste due to variations in outlet water temperature and system delivery characteristics. Although storage water heaters have historically claimed close to 100% of the U.S. market, the recent inroads of gas tankless water heaters have

[1] www.aceee.org/files/pdf/conferences/hwf/2010/3D_Jim_Lutz.pdf

been significant, with recent sales estimates at approximately 400,000 units/yr.[2] Tankless water heaters operate very differently than storage water heaters, since they heat water only when there is a hot water demand. Therefore, a "cold start" situation results in first cold, and then tepid water being delivered. This impacts hot water waiting times, and the associated water and energy waste while waiting for hot water to arrive at the use point.

1.2 Research Questions

The primary objective of this project was to build on prior work that ultimately leads to developing a better fundamental understanding of residential water heating system performance. Realizing that there are numerous modeling and data collection efforts underway that will ultimately feed into this goal, we see the current effort as a step in the process toward the development of the required tools needed for a comprehensive hot water design guide.

The primary research questions to be answered in this project are:

> ***How well can detailed distribution system models predict hot water delivery temperatures and distribution losses given available input validation data?***
>
> ***What model limitations are identified as part of this validation effort?***

Secondary questions related to the use of these modeling tools include:

> ***What new information have we learned on hot water usage quantity and patterns (e.g., climate impact, seasonal impacts), how do these revised assumptions affect advanced system savings projections, and what information is useful in improving modeling algorithms (BEopt, HWSIM, TRNSYS, etc.) and supporting standards activities (ASHRAE Standard Project Committee 118.2 and the U.S. Department of Energy's (DOE) Energy Factor test procedure update)?***
>
> ***What conclusions can we draw on customer behavioral hot water use (seven sites) as they change from conventional storage water heaters to gas tankless water heaters and other advanced system options (to the extent data are available)?***

The latter two research questions are peripheral to the primary research questions, yet are tightly linked to the goal of better understanding overall system performance, since hot water usage quantity and use patterns are critical factors affecting residential hot water system performance.

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[2] www.energystar.gov/ia/partners/prod_development/new_specs/downloads/water_heaters/Water_Heater_Market_Profile_2010.pdf

2 Methodology

2.1 TRNSYS Distribution Model Description

The TRNSYS 17 (TESS 2011) simulation program was used in this study to model distribution system performance despite Davis Energy Group's extensive development work over the years with the HWSIM simulation tool. Both models offer advantages and limitations, as summarized in Table 1. Given that TRNSYS is widely recognized as a mainstream building system simulation tool, the decision was made to focus the validation effort on using TRNSYS with the newly developed Type 604 "bi-directional node pipe model." This pipe model, described in full detail in Appendix A, is an enhanced version of the Type 709 model used in prior work (Maguire et al. 2011). The Type 604 dynamically models pipe exterior surface convective and radiant heat transfer effects based on fluid, pipe, and environmental properties, as opposed to Type 709's use of a fixed pipe outside heat transfer coefficient. In addition, the Type 709 model does not account for pipe heat capacitance effects, which influence the ability to accurately model hot water flows from a "cold start" condition and cooldown heat transfer effects.

Table 1. Comparison of TRNSYS Type 604 and HWSIM Model Capabilities

	TRNSYS Type 604	HWSIM
User-Specified Time Step	Yes	Yes
Able To Model Simultaneous Hot Water Draw Events	Yes	No overlapping draws allowed
Specification of Hot Water Loads	User-specified hot water thermal load (i.e., recovery load = use + distribution)	End use loads specified (distribution system impact determines recovery load)
Able To Model 365 Unique Days of Hot Water Draw Events	Yes	No, can model 7 days/month or 1 day/season)
Public Domain	No	Yes
Distinguish Between Volume Draws and Draws Requiring Minimum Temperature	Yes	Yes
Model Hourly Variations in Pipe Heat Loss Environments	Yes	Yes

The Type 604 model is configured for a user-defined piping layout (an example plumbing layout is shown in Figure 1) and is driven by a profile of hot water draws imposed on the water heater. The draw profile is included in the user-defined input file that specifies the end use fixture, draw start time, and flow rate. The configuration of the distribution system provides for "valves" at each branch point in the distribution system that serve to throttle hot water flows to each branch, as needed, under simultaneous hot water draw conditions. Each branch path ultimately ends up serving an individual hot water use point. For the plumbing layout shown in Figure 1, Table 2 summarizes the hot water end use points.

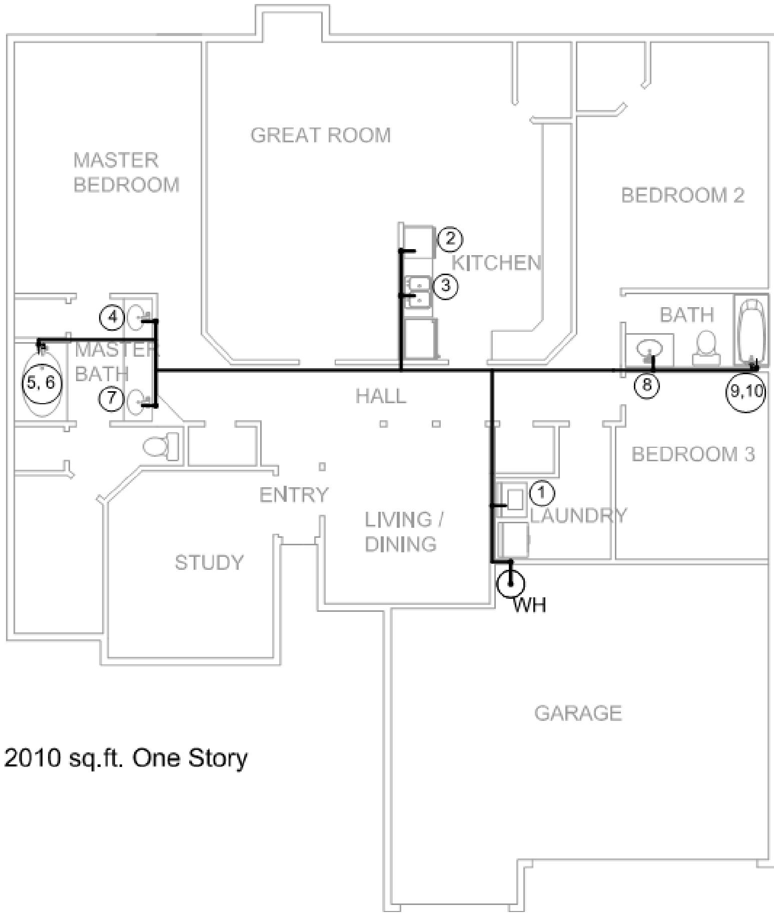

Figure 1. Sample distribution system layout

Table 2. TRNSYS Model Fixture Description

Use Point Identifier*	Fixture Location
1	Clothes Washer
2	Dishwasher
3	Kitchen Sink #1
4	Sink #2 (Master Bath)
5	Shower #1 (Master Bath)
6	Bathtub #1 (Master Bath)
7	Sink #3 (Master Bath)
8	Sink #4 (2nd Bath)
9	Shower #2 (2nd Bath)
10	Bathtub #2 (2nd Bath)

* As noted in Figure 1

In contrast to TRNSYS, HWSIM (Springer et al. 2008) first defines what the user wants at a fixture, including whether a minimum use temperature is needed before the use begins (e.g., shower), what the desired use temperature is, the volume of (mixed) water desired, and the flow rate. The sizing, configuration, and thermal characteristics of the distribution system impact how much water in the hot line needs to be "wasted" until satisfactory hot water arrives.[3]

TRNSYS reads the draw input file at each time step to drive the hot water demand. The cold water inlet temperature is included in the Typical Meteorological Year 3 weather file. If pipes are located in unconditioned space, such as the crawlspace, the environment temperature to which pipe heat loss occurs was derived from the hourly BEopt house model.

Each hot water draw event specifies the flow rate of hot or mixed-temperature water that is required to satisfy the draw. Sinks, showers, and baths are assumed to require a minimum "use" temperature before the water is used. In this study, a minimum usable hot water temperature of 105°F was assumed. If, at the beginning of the draw, the fixture outlet temperature is lower than that reference temperature, energy and "hot" water are wasted until the fixture outlet temperature rises above the minimum use temperature.

2.2 TRNSYS Model Validation

To validate the model, we followed a two-step effort. The first step involved utilizing high resolution laboratory data collected on a range of plumbing configurations under controlled conditions. Detailed data from laboratory testing completed by Carl Hiller of Applied Energy Technology (AET) were used to assess steady-state heat transfer, cold startup delivery characteristics, and post-draw cooldown effects. The second step in the validation process involved using high resolution distribution system field data collected at the National Renewable Energy Laboratory's (NREL) Solar Row research test house.

2.3 Distribution Model Pipe Heat Loss Validation

The first step in the validation process was to use AET laboratory test results (Hiller 2006) to validate the TRNSYS Type 604 pipe heat loss model during startup and steady-state flow conditions. The AET laboratory testing protocol involved running hot water through a serpentine pipe array and sensing water temperatures (with immersion probes) at the entrance and exit, as well as at regular intervals along the length of pipe. The testing was completed in an unconditioned warehouse, and often at night to improve the stability of environmental air and mean radiant temperatures (MRTs) during the duration of each test. MRT of the space was not directly measured, but was assumed to be equal to air temperature of the space (personal communication with Carl Hiller February 2010). Inlet water temperatures and flow rates were carefully controlled, with fluctuations in temperature of a few tenths of a degree Fahrenheit during the course of a single test.

A TRNSYS model was configured to model various piping configurations tested in the AET lab. Copper, cross-linked polyethylene (PEX), and chlorinated polyvinyl chloride (CPVC) pipe cases were all modeled with three different pipe diameters, insulated and uninsulated cases, and flow

[3] This behavioral concept of waiting for hot water is currently not well understood and potentially important. Clearly, showers can only begin when the water is hot. Sink uses are different and subject to both behavioral and climate influences. In mild climates, many users may rarely use hot water for sink washing, since cold water temperatures may provide adequate user comfort.

rates ranging from 0.5–4.0 gpm. Material properties assumed in the validation effort for the different pipe material types (as well as for pipe insulation) are summarized in Table 3. These parameters are inputs to the Type 604 model and directly affect the calculated heat loss. Surface emissivity, especially for copper pipe, is an important factor influencing uninsulated pipe radiant heat loss, especially under situations where the pipe surface temperatures are high and the surrounding environment MRT is low. Uninsulated copper pipe is particularly challenging to model, since the emissivity of copper is strongly dependent on the surface condition. New, shiny, polished copper can have an emissivity as low as 0.02, while fully oxidized copper can approach an emissivity of 0.78 (Kreith 1973).

Table 3. Pipe and Insulation Material Properties

Material	Assumed Surface Emissivity	Thermal Conductivity (Btu/h-ft-°F)	Specific Heat (Btu/lb-°F)	Material Density (lb/in.^{3})
PEX Pipe	0.91	0.20	0.48	0.032
Copper Pipe	0.40	232.0	0.092	0.320
CPVC Pipe	0.91	0.08	0.36	0.055
Pipe Insulation	0.91	0.03	0.31	0.0023

Table 4 shows the series of cases from the AET laboratory testing that were used in the initial model steady-state pipe heat loss validation. Three different pipe materials, three pipe diameters, and two insulation cases (uninsulated and ¾ in.) are included in the range of configurations simulated. The insulation conductivity value assumed was derived in prior modeling work where the HWSIM model was validated against AET laboratory data (Hoeschele and Weitzel 2012).

Table 4. Summary of AET Configurations and TRNSYS Inputs for Model Validation

Case	Tested Pipe Case	Nominal Hot Water Flow (gpm)	Total Pipe Length (ft)	Initial Pipe Surface Temp. (°F)	Average Entering Water Temp. (°F)	Average Environ-ment Temp. (°F)	Total Pipe Entrained Volume (gal)
1	PEX ⅜ in. uninsulated	1.0	159	53.5	134.9	56.1	0.79
2	PEX ⅜ in. insulated	1.0	159	55.6	136.5	55.8	0.79
3	PEX ½ in. uninsulated	1.0	124	52.6	136.1	54.7	1.14
4	PEX ½ in. insulated	1.0	124	49.6	115.8	53.0	1.14
5	PEX ¾ in. uninsulated	0.5	89	55.5	135.3	57.2	1.64
6	PEX ¾ in. insulated	0.5	89	54.0	137.2	58.6	1.64
7	PEX ¾ in. insulated	4.0	89	50.4	135.6	51.3	1.64
8	Copper ¾ in. uninsulated	1.0	91	60.7	135.8	62.3	2.30
9	Copper ¾ in. insulated	1.0	91	46.7	136.2	47.5	2.30
10	CPVC ¾ in. uninsulated	1.0	91	70.8	135.8	72.1	1.79
11	CPVC ¾ in. insulated	1.0	91	64.4	135.6	69.9	1.79

2.4 Whole-House Model Validation Effort

The second step in the validation process utilized detailed monitoring data from the Solar Row project (Barley et al. 2010) to validate "full system" performance. The Solar Row home, located in Boulder, Colorado, features a trunk-and-branch plumbing configuration composed of both ½-in. and ¾-in. uninsulated PEX piping, with piping located in both conditioned and unconditioned space. The "as-built" plumbing layout for the home defined exact pipe lengths, diameters, orientations, and locations. At the time of the Solar Row project evaluation, preliminary TRNSYS model validation work was undertaken using the older Type 709 pipe model. With the updated Type 604 pipe model, each distinct pipe element (defined by diameter, insulation level, orientation, and environment) would be modeled with a large number of individual nodes. Initial runs with the full "as built" Solar Row distribution system modeled resulted in very long run times with the 1000 nodes per segment approach, so a lower resolution 50 nodes per segment resolution was used for the evaluation presented here.

Monitoring data from the Solar Row test home from March to June 2008 was used to drive the model's hot water demand, as well as provide environment temperature and water heater outlet temperature input data. The dataset included 5-s interval temperature and flow data for each fixture as well as mains inlet water temperature and water heater outlet temperature. Ambient air temperatures for some pipe environments were monitored on a one minute interval.

2.5 Extending the Validated Model to Other Climates

The final step in the modeling process, after successful validation against the laboratory and field data, was to exercise the model in five different climates to assess the impacts of climate on distribution system performance. The plumbing configuration from the 2,010-ft^2 home, shown in Figure 1, was input using the Type 604 model. The three-bedroom home was modeled with a trunk-and-branch plumbing layout, which is fairly common for much of the country. The modeled layout consists of uninsulated copper pipes located in an unconditioned crawlspace. An electric water heater, located in semi-conditioned space was also modeled. Model runs were completed for five climates (Denver, Chicago, Houston, Phoenix, and Seattle), both with and without pipe insulation.

The model was fed 6-s interval hot water draw data based on loads generated by the Domestic Hot Water Event Schedule Generator (Hendron and Burch 2008). Previous analysis of this model suggests that a 6-s time step captures the realistic minimum duration of hot water draw events while saving some processing time, when compared to 1-s time step (Maguire et al. 2011). The discrete draw events are then processed to make a TRNSYS input file that lists draw volumes and fixture type indicators (see coding in Table 2) for every time step. A sample day of 6-s interval hot water use data is presented in Figure 2.

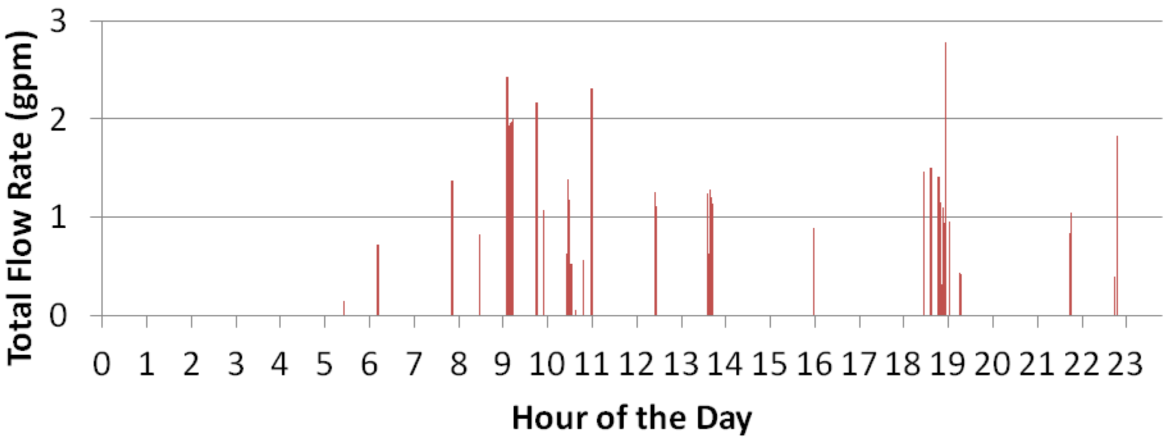

Figure 2. Sample 6-s interval hot water draw profile for one day

2.6 Impact of Load Patterns on Distribution System Performance

Distribution system performance is highly dependent on many factors, with a key variable being how the occupants consume hot water. The pattern of use, number of draws, and hot water volume consumed impact not only the energy losses during hot water draws, but more importantly, the losses and water waste that occur between draw events. This latter effect represents the bulk of distribution system inefficiencies, since hot water uses that require minimum use point temperatures (showers, many bath and kitchen sink uses) will require the purging of the entire distribution path if the entrained water is below the use temperature. Clustering of hot water draws tends to reduce energy use and water waste, since there is a greater likelihood that hot water in the lines will be adequate to satisfy the next hot water demand. In fact, in the extreme case of highly clustered household hot water use (e.g., all hot water consumed from 6:00 a.m. to 8:00 a.m. and 6:00 p.m. to 9:00 p.m.), the widely assumed benefits of pipe insulation in nonrecirculating distribution systems would be minimized, since insulation offers value primarily in extending the time that usable hot water remains in the pipe (typically from 10–15 min without insulation to 30–45 min with insulation).

This area of research relies on gathering high-resolution hot water usage data (< 5-s interval data during flow events) in an effort to develop a statistically valid characterization of hot water draw events in terms of timing, duration, end uses, and flow rate.[4] LBNL (Lutz and Melody 2012) has been working on developing and populating a hot water use database with data from high-resolution hot water end use field monitoring studies. The current status of the available data in the database will be reviewed to provide input on the state of knowledge in this area, and what additional information is needed to support future improved assessments of hot water distribution system performance.

Storage water heaters, whether electric or gas, reliably deliver hot water, with the exception being those rare occasions when the storage tank has been fully depleted by prior large hot water demands. Although the outlet temperature will fluctuate with the wide dead band associated with storage tank aquastats, the leaving water temperature will nearly always be of sufficient

[4] Data collected at 1-min or longer intervals will mischaracterize the flow rate and duration of the many short draw events that typically occur.

temperature (nominally 105°F) to satisfy end uses such as showering and sink use. The advent of gas tankless water heaters over the past 10 years, as well as the emergence of heat pump water heaters, may suggest a change in hot water usage as customers interface with products that provide different hot water delivery characteristics. This is likely most pronounced with tankless water heaters, as a “cold start” situation results in added time for the unit to generate hot water. A recent field study where existing gas storage water heaters were retrofitted with advanced gas water heaters (including eight gas tankless units) provides detailed monitoring data on observed hot water delivery characteristics and usage patterns (Hoeschele and Weitzel 2013).

3 Results

3.1 Model Validation With Laboratory Pipe Heat Loss Data

The monitored AET laboratory data for flow rate, inlet water temperature, pipe layout, and environmental conditions (see Table 4) were used as inputs to drive the TRNSYS model. Table 5 summarizes the comparison between monitored and simulated results for the following output parameters:

- Steady-state outlet water temperatures
- Elapsed time to achieve 105°F outlet
- The ratio of "unusable" hot water dumped (< 105°F) to the entrained pipe volume.

Table 5. Summary of Laboratory and Simulated Results

Case	Steady-State Pipe Outlet Temperature			Elapsed Time From Cold Start to 105°F Outlet			Ratio of Wasted Water to Entrained Pipe Volume	
	Lab (°F)	Model (°F)	Delta (°F)	Lab (s)	Model (s)	Delta (s)	Lab	Model
1 PEX ⅜ in. U	124.6	126.4	–1.77	89	88	1	1.38	1.36
2 PEX ⅜ in. I	133.8	133.7	0.16	66	64	2	1.50	1.46
3 PEX ½ in. U	126.4	128.1	–1.69	88	86	2	1.15	1.12
4 PEX ½ in. I	113.5	113.3	0.21	159	157	2	2.07	2.05
5 PEX ¾ in. U (0.5 gpm)	121.4	122.9	–1.55	296	286	10	1.40	1.35
6 PEX ¾ in. I (0.5 gpm)	132.4	132.3	0.10	286	296	–10	1.33	1.38
7 PEX ¾ in. I (4 gpm)	135.1	134.8	0.30	25	27	–2	1.10	1.19
8 Copper ¾ in. U	129.8	129.7	0.05	198	204	–6	1.28	1.32
9 Copper ¾ in. I	133.9	133.4	0.42	188	193	–5	1.21	1.24
10 CPVC ¾ in. U	129.3	129.8	–0.43	156	163	–7	1.11	1.16
11 CPVC ¾ in. I	n/a	n/a	n/a[5]	139	136	3	1.16	1.14

Note: "U" = uninsulated case, "I" = insulated case

In reviewing Table 5, keep in mind that the inlet hot water temperatures, flow rate, and environmental temperatures were not consistent for all test cases. On average, the model predicted steady-state outlet temperatures 0.4°F warmer than the monitored data, ranging from 0.05°–1.77°F different. The largest discrepancy was for the uninsulated PEX pipes that averaged 1.7°F warmer for the model when compared to the monitored data. The insulated PEX pipes had

[5] This test did not reach steady-state outlet temperature before the test was concluded.

an average steady-state temperature difference of 0.1°F, with no deviation greater than 0.21°F.[6] Modifications to the assumed uninsulated pipe emissivity yielded little improvement of steady-state temperature differences. (Note: Plastic pipe and pipe insulation surface emissivities are fairly well documented to be in the 0.91 range; however, bare copper pipe surface emissivity will change significantly as the pipe transitions from shiny new pipe to oxidized older pipe.)

The elapsed time for the pipe leaving water temperature to reach 105°F was also compared to the AET laboratory data. This metric for characterizing pipe heat transfer effects is important to accurately estimate hot water waste when draws occur after a long cooldown period. The elapsed time results for each configuration varied slightly between model and laboratory data, but in general the match was excellent with typical deviations from the laboratory result of < 3.5%. The largest percentage difference was observed in the insulated ¾-in. PEX case where the model projected a 2-s slower delivery time to achieve 105°F (27 versus 25 s). It is important to look at these results in context of the physical flow phenomenon that is occurring in the laboratory and may not be fully captured in the model. The final parameter in Table 5 is the ratio of hot water dumped (before 105°F outlet is achieved) divided by the pipe volume. This flow characteristic is a function of pipe material, flow rate, and temperatures, and varies from slightly more than 1.0 to values exceeding 2.0. Intuitively one might expect the hot water waste would be no greater than the entrained pipe volume, but both the laboratory data and the model indicate pipe heat capacitance and flow effects that increase the waste term based on flow rate, hot inlet temperatures, and environment conditions.[7]

Figure 3 below compares the insulated and uninsulated ⅜-in. PEX simulation results to laboratory data using 1000 nodes for the full length of pipe. From a cold start, the insulated cases show an earlier rise in outlet temperature than the corresponding uninsulated case, as less heat is lost in transit. For the insulated case, although the temperatures are virtually equal at steady state (~3 minutes elapsed), the initial impulse of warm water (at about 0.6 min) is observed earlier in the model than in the laboratory. This transition to a steady-state condition appears to be the most complex aspect in trying to achieve consistent validation. Interestingly in the uninsulated case, where pipe surface heat transfer effects are more critical, the model appears to be converging to a 0°F temperature difference at 1.75 min elapsed, but then slowly drifts away and stabilizes at an ~2°F differential at 3 min. This pattern of convergence and then separation is interesting and potentially suggests changing conditions in the laboratory or pipe flow effects whose impacts may be accentuated in narrow ⅜-in. diameter piping.

[6] All things being equal, one would expect a better match with insulated pipe versus uninsulated pipe, since uninsulated pipe will be much more influenced by surface convective and radiant effects, which are challenging to control for in all but the most controlled laboratory environments.
[7] This effect is discussed in detail in the Hiller (AET) ASHRAE papers.

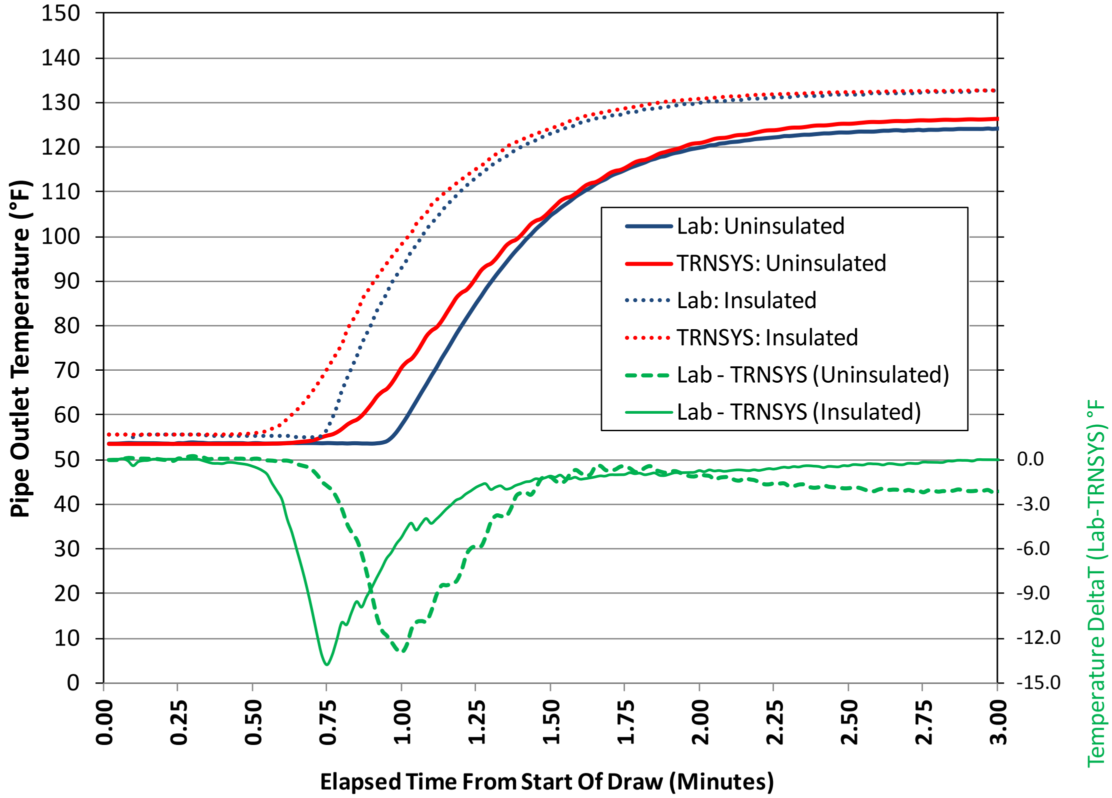

Figure 3. Comparison of laboratory and TRNSYS model results for ⅜-in. PEX from a cold start

3.2 Model Validation With Solar Row Field Data

With the successful validation comparison to the AET laboratory data, the Type 604 pipe model was next incorporated into the Solar Row as-bulit whole house distribution model. The original Type 709 Solar Row TRNSYS model developed by Greg Barker was converted to the Type 604 using a noding resolution of 50 nodes per pipe segment.[8] Collected data from the Solar Row project[9] included detailed monitoring data of delivered hot water temperature at end use points and recording of environment temperatures at some of the areas where hot water piping was run.

One aspect of the simulation was tested with the field data by comparing the volume of water wasted before the master shower outlet temperature reached 105°F. The ratio of wasted hot water divided by entrained pipe volume was plotted in Figure 4, as a function of time between master shower draws. Based on the graph it can be seen that the volume of wasted water, as a ratio of total entrained pipe volume, is reduced if the fixture was used within 1 h.

[8] The reported simulation results were completed using 50 nodes per pipe segment, since the original 1000 nodes required upward of 12 h of simulation time per month. Reducing the number of nodes shortened the run time to < 1 h while only increasing the May monthly deviation between model and data by 0.02%.

[9] www.nrel.gov/docs/fy10osti/48385.pdf

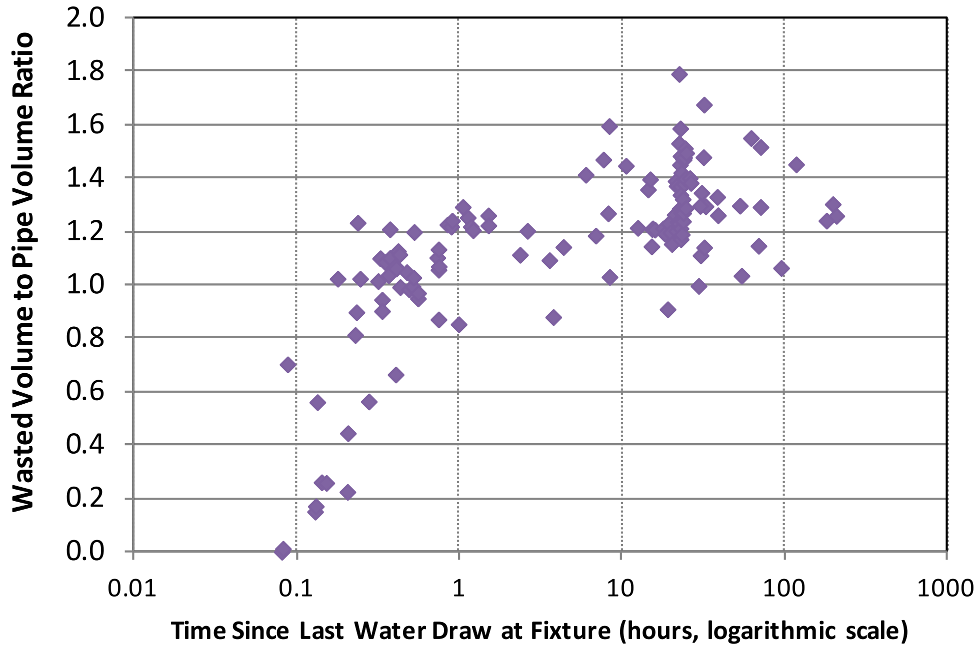

Figure 4. Wasted water ratio as a function of time between draws (field data)

The amount of water wasted to reach 105°F at the fixture is ~35% of the entrained water volume when showers are taken within 10 min of each other, compared to 130% when showers are taken more than 60 min apart. These findings are generally consistent with the AET laboratory results. For the Solar Row piping configuration, consecutive master bathroom showers would potentially[10] save 0.8 gal of hot water relative to "cold start" showers whereby entrained water would have cooled below a minimum comfort temperature. The data from Figure 4 are binned and presented in Figure 5 with average bin values shown above each bar. At time intervals between draws greater than 60 min, the ratio approaches the results observed in the AET laboratory testing, as shown in Table 5.

[10] Depends upon user behavior

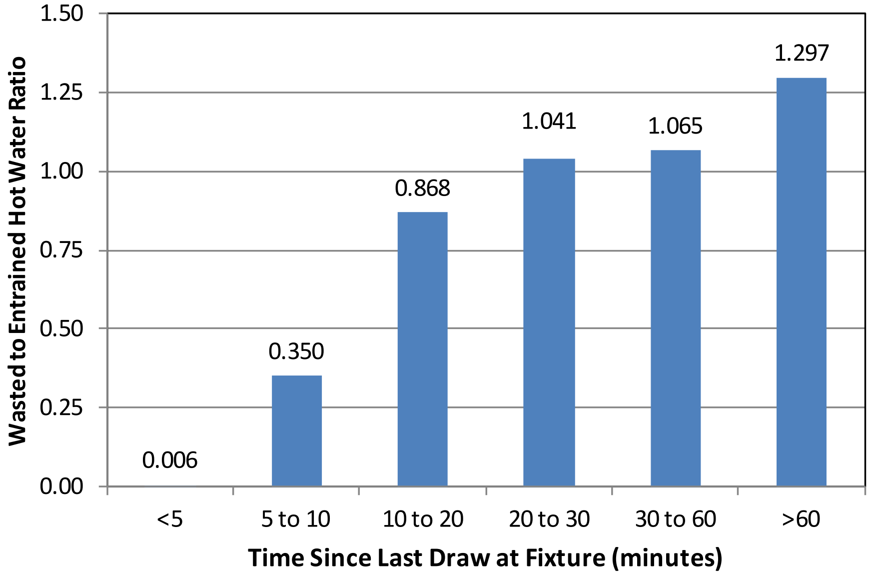

Figure 5. Binned wasted water ratio as a function of time between draws (field data)

A second comparison was made to compare monitored and modeled pipe cooldown rates between hot water draw events. As shown in Figure 6, the model initially decays slower than the monitored data suggest, resulting in negligibly warmer temperatures then indicated by the monitored data. At about minute 20 (~15 min after the draw ends), the temperature profiles cross and the modeled temperature falls slightly below the monitored data. This pattern of changing decay rates over time was consistently observed throughout the dataset. In general, the match is very good with minimal impact on the delivered water temperature. Figure 7 shows the decay characteristics for a series of kitchen sink draws.

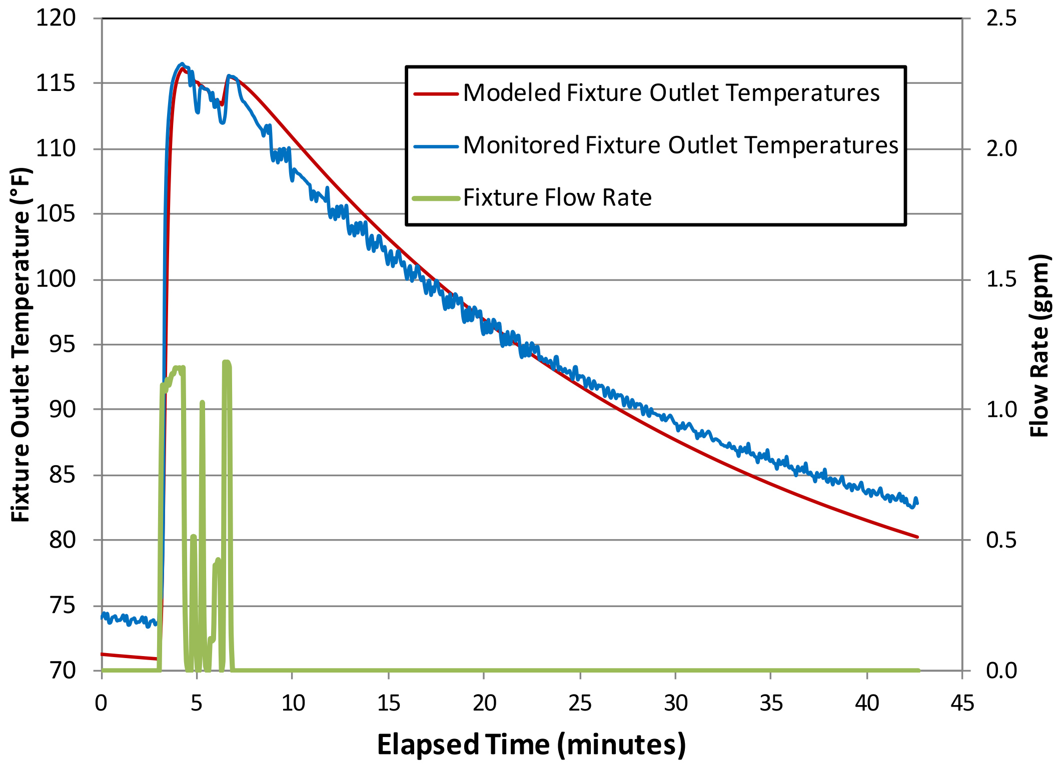

Figure 6. Comparison of simulated and actual pipe thermal decay over time

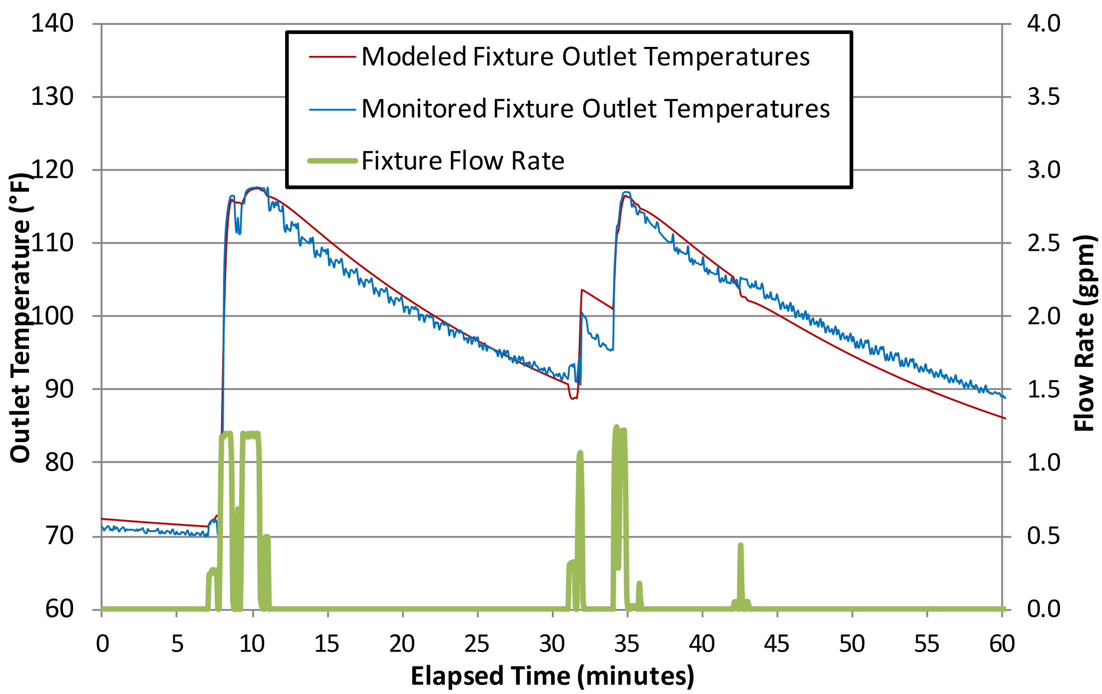

Figure 7. Comparison of simulated and actual pipe thermal decay with sequential draws

Given the favorable comparison with individual draws against the Solar Row data, the TRNSYS model was then used to predict Solar Row system performance over the March to June period where hot water draw data, cold water inlet temperatures, and environment temperatures were available to drive the model. Distribution losses were calculated and summed monthly. The monthly distribution losses shown in Table 6 were found to be within 2% of the monitored losses for each of the four months, which is a surprisingly consistent result. Over the four months, the total distribution losses ranged from 16%–19% of the energy delivered from the water heater.

Table 6. Comparison of Observed and Modeled Pipe Heat Losses

Month	Average Hot Water Use (gpd)	Simulated (Siml) Pipe Losses (kBtu/month)	Observed (Obs) Pipe Losses (kBtu/month)	% Difference (Obs-Siml)/ Observed)	Pipe Losses as % of Total Energy Delivered
March	14	41.9	42.0	0.2%	–17%
April	28	76.2	75.5	–0.8%	–16%
May	22	61.5	60.5	–1.7%	–17%
June	22	61.4	60.3	–1.7%	–19%

3.3 Distribution System Performance in Different Climates

The final step in the development and validation of the TRNSYS Type 604 model was to exercise the validated model on a prototypical distribution system layout in various climates. The goals of this effort were to document distribution system performance in different climates and assess the energy impact of insulating the entire distribution system.

Table 7 shows annual energy use and losses for a typical 0.91 energy factor storage electric water heater. Water heater tank losses, recovery load, distribution losses, and useful delivered energy are reported, as well as daily average hot water usage (gpd) and hot water waste. Hot water waste is the energy that is dumped at a non-appliance use point that is of insufficient thermal quality (i.e., 105°F). Projected annual electric water heater energy consumption among the five locations varies by 64% from the warmest climate (Phoenix) to the coldest climate (Chicago). The major factor impacting this large variation is the cold water inlet temperature, which influences both the heating energy input as well as the required mixing ratio of hot and cold water to achieve the expected 105ºF minimum thermal condition (for showers). Distribution pipe losses during draws (row E in the Table) vary with climate to a lesser degree, but represent a greater percentage of total water heater recovery load in the mildest climates (range from 16%–23% of total recovery load). The fraction of energy wasted due to temperature decay between draw events was found to be higher in the colder climates. The combined "pipe + waste" distribution losses were found to be a consistent 26%–27% of the total recovery load, although the associated energy ranged from 534 kWh/yr in Phoenix to 892 kWh/yr in Chicago. Wasted water heat loss, associated with the time between draws, pipe location, and heat loss environment temperatures, were found to be four times greater in cold climates versus the hot Phoenix climate. These findings are specific to the simulation inputs, with results being sensitive to usage pattern, overall hot water load, user behaviors, and plumbing configuration.

Table 7. Modeled Results by Climate Zone

	Denver	Chicago	Houston	Phoenix	Seattle
A. Water Heater Energy Input (kWh/yr)	3,698	3,793	2,600	2,307	3,666
B. Water Heater Tank Losses (kWh/yr)	377	376	362	359	383
C. Water Heater Recovery Load (kWh/yr)	3,322	3,417	2,238	1,948	3,283
D. Wasted Water Losses (kWh/yr)	324	344	124	85	313
E. Distribution Pipe Losses (kWh/yr) †	537	548	468	449	541
F. Useful Energy to Use Points (kWh/yr)	2,461	2,526	1,646	1,414	2,429
Annual Efficiency (“F”/“A”)	67%	67%	63%	61%	66%
G. Hot Water Use (gpd)	60.1	60.3	56.6	54.5	60.1
H. Wasted Hot Water (gpd)	13.1	13.3	11.5	11.2	13.2
% Wasted Water Volume (“H”/“G”)	22%	22%	20%	21%	22%
Losses as a Percentage of Water Heater Recovery Load					
% Wasted Energy (“D”/“C”)	10%	10%	6%	4%	10%
% Pipe Loss (“E”/“C”)	16%	16%	21%	23%	16%
% Total Distribution Loss ((“D+E”)/“C”)	26%	26%	26%	27%	26%
% Useful (“F”/“C”)	74%	74%	74%	73%	74%

† During hot water flow events

The model was then run for each climate with ¾-in. insulation on all pipes to evaluate the energy and water savings impact of pipe insulation. The estimated energy and water savings are presented in Table 8. Insulation energy savings ranged from 19%–21% of the total distribution losses reported in Table 7 (sum of rows D and E), with total savings of 111–170 kWh/yr, or 4%–5% of annual water heater energy use.[11] Wasted water savings, reflecting the reduction in water dumped at the beginning of a draw, demonstrated a similar 18%–20% annual reduction, with the remaining 1%–2% water savings associated with hotter delivery temperatures. Results are sensitive to distribution system configuration, and most importantly to occupant behaviors in terms of hot water usage and load pattern.

[11] In the recent California Title 24 Standards update, evaluations were completed to assess the cost effectiveness of pipe insulation. Modeled performance and life cycle cost calculations resulted in a new requirement for piping ¾ in. and larger to be insulated. See section 4.1 at the link below: www.energy.ca.gov/title24/2013standards/prerulemaking/documents/current/Reports/Residential/Water_Heating/2013_CASE_R_SEMPRA_Single_Family_DHW_%20Sept_2011.pdf

Table 8. Modeled Climate Zone Insulation Savings Results

	Denver	Chicago	Houston	Phoenix	Seattle
	Savings (% Savings)	Savings (% Savings)	Savings (% Savings)	Savings (% Savings)	Savings (% Savings)
Distribution kWh/yr Savings (Wasted +Pipe)	166 kWh/yr (19%)	170 (19%)	122 (21%)	111 (21%)	164 (19%)
Water Savings (gal/yr)	287 gal/yr (1%)	282 (1%)	389 (2%)	452 (2%)	293 (1%)
Wasted Water Savings (gal/yr)	858 gal/yr (18%)	854 (18%)	842 (20%)	846 (20%)	855 (18%)

3.4 Summary of Latest Findings on Hot Water Usage and Impact of Gas Tankless Water Heaters on Use Patterns

Hot water usage patterns have a significant influence on hot water distribution system performance, since the timing and draw characteristics vary. Understanding in this area has improved in the past few years, as several larger datasets of high resolution usage data have been added to the LBNL database. More work is needed to provide better regional resolution, as well as impacts of vintage[12] on usage. The recently completed study (Lutz and Melody 2012) documents the current findings and develops three representative usage patterns to characterize low, medium, and high usage households represented in the database. The database contains information from 12 studies representing a total of 159 monitored homes and 33,500 days of collected data. A vast majority of the studies represents older homes (pre-2000 vintage), which raises the question of how representative the data are for newer homes, which would be expected to have a higher level of water efficiency. Average household hot water usage over all samples was found to be 54.5 gpd with an average median water heater outlet temperature of 122.7°F.

Table 9 was developed using a statistical cluster analysis technique. Typical usage ranged from 29 gpd in the low use category to 98 gpd in the high use category. The number of draws correspondingly ranged from 45–86/day, although it should be noted that what is represented in the field data as a hot water draw may well be due to very short unintentional hot water demands that may, for example, be initiated with a single lever faucet.

The usage data provide for a better understanding of usage patterns and draw characteristics. The summary data suggests lower usage, lower flow rates, and many more hot water draws than assumed in the current DOE service hot water Energy Factor test procedure. This has implications for both water heater performance, as well as distribution system performance. Jim

[12] Vintage influences appliance, showerhead, and fixture hot water use, although older homes will often have a mix of low and high water use appliances, showerheads, and fixtures.

Lutz is leading efforts within the ASHRAE Standard Project Committee 118.2 to provide input on revisions to the test procedure, which will better reflect real world operating conditions.

Table 9. Summary of Hot Water Database Median Usage Characteristics

	Usage (gpd)	Number of Draws/Day	Average Flow Rate (gpm)	Draw Duration (s)	Time Since Prior Draw (s)
Low Use	29.38	45.22	1.21	20	180
Medium Use	60.52	66.48	1.21	24	120
High Use	98.04	86.37	1.16	60	172

In addition to improving our understanding of hot water use and usage patterns as a key input for simulation models, it is important to keep in mind that emerging water heating technologies may also influence the consumption of hot water. A technology that has gained significant market share over the past 10 years is the gas tankless water heater. This technology has several performance attributes that may influence hot water usage: minimum flow rates to activate firing, cold start time delays before hot water is generated, and the ability to deliver limitless hot water (up to a maximum flow rate). A recently completed California field study (Hoeschele and Weitzel 2013) provides a before and after comparison of hot water usage in seven households that were converted from conventional gas storage water heaters to gas tankless units. Since that work is peripheral to the main research focus of this study, a detail summary is presented in Appendix B rather than in the body of the report. A brief summary of the key findings from that study follow:

- On average, 7.2% of total volume of tankless hot water flow was found to be at a temperature < 105°F versus 1.2% for the storage water heater cases. This result suggests that all things being equal, tankless water heaters will waste more water and increase hot water times in comparison to a traditional storage water heater.
- Overall, for the seven sites, hot water recovery loads increased by an average of 8%. Although one site in particular appeared to change its usage as evidenced by longer showers and greater usage with the tankless water heater, this dataset does not suggest that all tankless users will consume more hot water than with a storage water heater. This finding is consistent with prior field study research (Schoenbauer et al. 2012).
- Small draws[13], especially when starting with a “cold” tankless unit, are more difficult to effectively satisfy, since there will be an increased time delay in delivering the hot water to the use point. The field data suggest that on average there is a 23% reduction in hot water draw events in the households that converted to tankless units.

This emerging research on hot water usage patterns and the impact of gas tankless water heater on usage provides new information on the expected loads and patterns of hot water consumption. Clearly more field data and better data granularity would support the development of improved inputs for driving the detailed hot water distribution simulation models.

[13] Which may include low flow rate draws that are below the unit’s minimum firing rate.

4 Conclusions

This research effort focused on extending the state of the art in demonstrating the accuracy and usability of advanced hot water distribution system simulation models.

The primary research questions addressed include:

- **How well can detailed distribution system models predict hot water delivery temperatures and distribution losses given available input validation data?**

  The TRNSYS Type 604 pipe heat loss model was validated against both detailed laboratory and field monitoring data. The model aligned well with the laboratory dataset, providing a good match in terms of heat loss (as reflected in steady-state use point delivery temperature), time required to meet a specified end use delivery temperature, and estimation of water waste from a cold start. The latter characteristic is especially important in characterizing the waste implications of a distribution system as many end uses, such as showers, require a minimum use temperature before the event can occur. In comparison to four months of detailed field monitoring data from the Solar Row research site, the TRNSYS model of the as-built distribution system demonstrated no more than 1.7% monthly deviation in pipe heat losses as compared to the monitoring data.

  Modeling results evaluating a prototypical distribution system configuration in different climates suggests that for an electric storage water heater distribution losses represent about 26%–27% of the annual water heater recovery load, with an associated energy use impact of 534–892 kWh/yr. Insulating the full distribution system with ¾ in. pipe insulation would reduce the distribution loss by 111–170 kWh/yr. Different usage quantities and patterns would affect these savings estimates.

- **What model limitations are identified as part of this validation effort?**

  Although the model was found to match well with both datasets, it is fairly time consuming to configure, and also requires a short (< 10 s) time step to adequately represent hot water draw events. This short time step results in lengthy simulation run times and raises the question of how best to integrate a detailed distribution system model within the context of overall building energy simulation models, or whether it is even necessary. As researchers gain a better understanding of the many factors affecting distribution system performance, a better determination can be made on whether the effort is warranted in developing a detailed distribution system model.

Secondary questions related to the use of these modeling tools include:

- **What new information have we learned on hot water usage quantity and patterns (e.g. climate impact, seasonal impacts), how do these revised assumptions affect advanced system savings projections, and what information is useful in improving modeling algorithms (BEopt, HWSIM, TRNSYS, etc.) and supporting standards**

activities (ASHRAE Standard Project Committee 118.2 and DOE's Energy Factor test procedure update)?

Hot water loads identified in various research studies and aggregated in the LBNL hot water database suggest that hot water loads both in terms of gallons per day and Btu of recovery load are considerably lower than assumed in DOE's water heater test procedure. The implications of this are significant not only in terms of influencing the DOE test procedure revision, but also in comparing alternative water heating technologies. Lower loads, more draws per day, and a greater seasonality in hot water usage have performance implications for a range of water heating system types.

- **What conclusions can we draw on customer behavioral hot water use (seven sites) as they change from conventional storage water heaters to gas tankless water heaters and other advanced system options (to the extent data are available)?**

  A controlled field test in California monitored the changes in hot water usage and usage pattern at seven households that experienced conversions from gas storage water heaters to tankless water heater. At all seven sites, households were found to uniformly change usage patterns by reducing the number of daily hot water draws (23% on average) and corresponding increases in the average draw volume. Small, low flow rate draws were seen to become less frequent in all households as users adjusted to the different hot water delivery characteristics of the tankless unit water heater. In terms of whether households offset the higher observed efficiency of the tankless unit by consuming more hot water, only one of seven sites showed a clear increase in the length of typical larger volume shower draws. This limited sample of test sites suggest that further study is warranted to better support or dispute the hypothesis that hot water usage with a tankless unit is significantly higher than with a conventional storage water heater.

4.1 Next Steps

A key recommendation for further research activities would center on refining the inputs needed to drive the detailed distribution models and completing more detailed modeling to assess the sensitivity of the results to changes in the input assumptions. This information would be useful in evaluating whether there is sufficient value in developing a methodology to simplify the integration of the detailed TRNSYS model into mainstream simulation applications.

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Appendix A: TRNSYS Documentation for Type 604, TESS (2011)

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TYPE 604: BI-DIRECTIONAL NODED PIPE

General Description

Type604 models a liquid filled pipe that can accommodate flow in either direction. Unlike the standard Type 31 pipe model in TRNSYS, Type604 can also consider the effects of the pipe and insulation mass. Type31 treats the pipe and insulation as massless, asking the user only to provide a value of the loss coefficient. The model calculates the heat loss coefficient based on the fluid properties, the pipe properties, the insulation properties, convection (forced and natural) and radiation from the outer surface to the environment. The model assumes that the pipe can be characterized by a series of inter-connected, fully-mixed, fluid nodes. This mimics a plug-flow model when the number of nodes is high. The model does not allow for flow in both directions at the same time step. Figure 1 shows cutaway and end views of the pipe modeled by Type604.

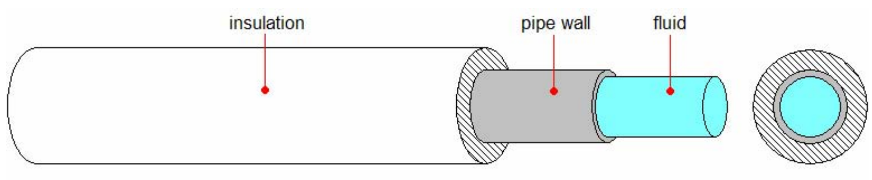

Figure 1: Cutaway and End Views of the Type604 Pipe

Nomenclature

$n_{FluidNodes}$	[-]	The number of fluid nodes along the length of the pipe
$n_{Pipe/InsNodes}$	[-]	The number of pipe or insulation nodes along the length of the pipe.
$h_{outside}$	[kJ/h.m^2.K]	The total heat transfer coefficient off the outside of the pipe (pipe wall or insulation jacket)
$h_{outside,conv}$	[kJ/h.m^2.K]	The convection heat transfer coefficient off the outside of the pipe (pipe wall or insulation jacket)
$h_{outside,rad}$	[kJ/h.m^2.K]	The radiation heat transfer coefficient off the outside of the pipe (pipe wall or insulation jacket)
$h_{outside,conv,natural}$	[kJ/h.m^2.K]	The contribution of natural convection to the outside convection coefficient.
h_{inside}	[kJ/h.m^2.K]	The convection heat transfer coefficient from the inside wall of the pipe.
$\mathrm{Re}_{outside}$	[-]	The Reynold's number for the outside of the pipe
ρ_{air}	[kg/m^3]	The density of air
V_{wind}	[m/s]	The velocity of air movement across the outside of the pipe
$d_{outside,insul}$	[m]	The outside diameter of the insulation jacket.
$d_{inside,pipe}$	[m]	The inside diameter of the pipe
$d_{inside,insul}$	[m]	The inside diameter of the insulation jacket (also the outside diameter of the pipe)
$d_{outside,pipe}$	[m]	The outside diameter of the pipe (also the inside diameter of the insulation jacket)
μ_{air}	[kg/m.s]	The viscosity of air
μ_{fluid}	[kg/m.s]	The viscosity of the fluid
Nu_{forced}	[-]	The Nusselt number for forced convection from the outside of the pipe
Nu_{inside}	[-]	The Nusselt number for flow on the inside of the pipe

Re	[-]	The Reynolds number
Re_{inside}	[-]	The Reynolds number for flow on the inside of the pipe
Pr	[-]	The Prandtl number
Pr_{inside}	[-]	The Prandtl number for flow on the inside of the pipe
$h_{ouside,conv,forced}$	[kJ/h.m^2.K]	The contribution of forced convection to the outside convection coefficient.
k_{air}	[kJ/h.m.K]	The thermal conductivity of air
k_{fluid}	[kJ/h.m.K]	The thermal conductivity of fluid
k_{pipe}	[kJ/h.m.K]	The thermal conductivity of the pipe material
k_{insul}	[kJ/h.m.K]	The thermal conductivity of the insulation material
Ra	[-]	The Rayliegh number
β_{air}	[1/K]	The inverse of the film temperature (air temperature at the outside of the pipe)
T_{surf}	[°C]	The surface temperature of the insulation jacket
$T_{pipe,surf}$	[°C]	The surface temperature of the pipe
T_{env}	[°C]	The environment temperature in which the pipe is immersed.
α_{air}	[m^2/s]	The thermal diffusivity of air
$Nu_{natural,horiz}$	[-]	The Nusselt number due to natural convection from a horizontally oriented pipe
$Nu_{natural,vert}$	[-]	The Nusselt number due to natural convection from a vertically oriented pipe
Gr	[-]	The Grashof number
L_{pipe}	[m]	The length of the pipe
L_{fnode}	[m]	The length of a fluid node
L_{pnode}	[m]	The length of a pipe node
L_{inode}	[m]	The length of an insulation node
$Nu_{natural}$	[-]	The Nusselt number due to natural convection
m	[kg]	The mass of a node
Cp	[kJ/kg.K]	The specific heat of a node material
$\dot{Q}_{in}$	[kJ/h]	Energy transferred into a node
$\dot{Q}_{out}$	[kJ/h]	Energy transferred out of a node
$\dot{m}_{fluid,left}$	[kg/h]	The mass flow rate of fluid entering a fluid node from the left hand side
$\dot{m}_{fluid,right}$	[kg/h]	The mass flow rate of fluid entering a fluid node from the right hand side
$\dot{m}_{fluid}$	[kg/h]	The actual mass flow rate entering a fluid node (the maximum of the left and right flows)
Cp_{fluid}	[kJ/kg.K]	The specific heat of fluid
$T_{fluid,n}$	[°C]	The temperature of a fluid node
$T_{fluid,n-1}$	[°C]	The temperature of the adjacent fluid node to the left
$T_{fluid,n+1}$	[°C]	The temperature of the adjacent fluid node to the right
$T_{pipe,n}$	[°C]	The temperature of a pipe node
$T_{pipe,n-1}$	[°C]	The temperature of the adjacent pipe node to the left

$T_{pipe,n+1}$	[°C]	The temperature of the adjacent pipe node to the right
$T_{insul,n}$	[°C]	The temperature of an insulation node
$T_{insul,n-1}$	[°C]	The temperature of the adjacent insulation node to the left
$T_{insul,n+1}$	[°C]	The temperature of the adjacent insulation node to the right
A_{xs}	[m^2]	The cross sectional area of a fluid node
A_{pipe}	[m^2]	The cross sectional area of an annular pipe node
A_{insul}	[m^2]	The cross sectional area of an annular insulation node.
R_{fluid}	[kJ.K.m^2/kJ]	The radial thermal resistance of the fluid.
R_{wall}	[kJ.K.m^2/kJ]	The thermal resistance of the pipe wall
R_{pipe}	[kJ.K.m^2/kJ]	The radial thermal resistance of the pipe material
R_{insul}	[kJ.K.m^2/kJ]	The radial thermal resistance of the insulation material
$R_{contact}$	[kJ/h.m2.K]	The thermal contact resistance between the pipe wall and insulation
$T_{pipe,m}$	[C]	The temperature of a pipe node
$T_{insul,m}$	[C]	The temperature of an insulation node
SA_{inside}	[m^2]	The surface area of the inside of a pipe node.
$r_{pipe,inside}$	[m]	The inside radius of the pipe
$r_{pipe,outside}$	[m]	The outside radius of the pipe
$r_{insul,inside}$	[m]	The inside radius of the insulation jacket
$r_{insul,outside}$	[m]	The outside radius of the insulation jacket.

Detailed Description

This routine models the heat loss from a pipe to the surroundings using a network of insulation, pipe, and fully-mixed fluid nodes. The user is asked to specify the various physical characteristics of the pipe, insulation, and liquid. Specifically: size (length, inner, and outer diameter of the pipe, and outer diameter of the insulation), density, thermal conductivity, and specific heat as well as the fluid viscosity is also required. The user is also asked to specify the number of axial fluid nodes and the number of axial pipe/insulation nodes. While the pipe material and insulation material are treated separately, have separate energy balances and separate temperatures, the length of the pipe nodes and the insulation nodes are identical. The model does not include radial nodes in the fluid, pipe wall, or insulation and the number of axial fluid nodes must be an integer multiple of the number of pipe/insulation nodes so that the end boundaries of fluid nodes coincide with the end boundaries of the pipe and insulation nodes. Figure 2 shows the configuration of the axial fluid nodes above and the of the axial pipe and insulation nodes below. In the diagram, there are two fluid nodes for each pipe node, satisfying the requirement shown in equation 604.1

$$\frac{n_{FluidNodes}}{n_{Pipe/InsNodes}} \geq 1 \text{, and must be an integer} \qquad \text{(Eq. 604.1)}$$

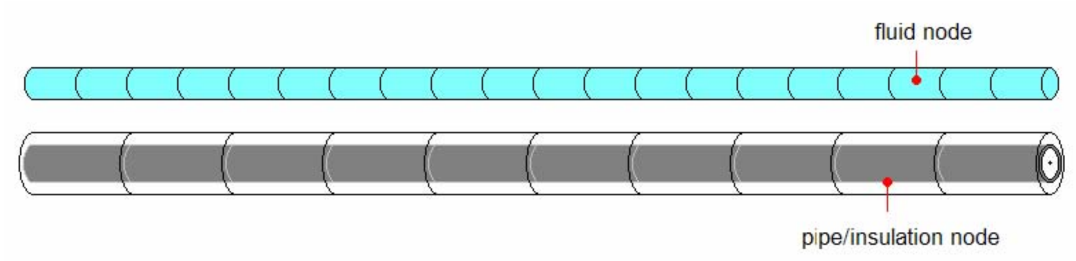

Figure 2: Pipe Axial Noding Scheme

The outside of the pipe insulation jacket is subject to both convection and radiation heat exchange with a single environmental temperature. In order to determine the radiation losses, Type604 calls the TESS Library long wave radiation exchange routine, which calculates the radiation heat transfer coefficient between two surfaces at known temperatures (the surface temperature of the insulation node and the environment temperature in this case) based on a user-supplied surface emissivity. Type604 assumes that both the insulation surface and the environment to which it radiates have the same emissivity. The total convection coefficient for the insulation jacket is determined as:

$$h_{outside} = h_{outside,conv} + h_{outside,rad} \quad \text{(Eq. 604.2)}$$

The user has two options when it comes to determining the convective heat loss coefficient ($h_{outside,conv}$); the value may be calculated internally or provided by the user. If the user sets the convection mode parameter to 1, the model will calculate the convection coefficient based on correlations for either a horizontal pipe or a vertical pipe. The orientation of the pipe is again set by the user as a parameter to the model. The Reynolds number for forced convection on the outside of the pipe is given by

$$\mathrm{Re}_{outside} = \frac{\rho_{air} V_{wind} d_{outside,insul}}{\mu_{air}} \quad \text{(Eq. 604.3)}$$

The Nusselt number for forced flow is:

$$Nu_{forced} = 0.3 + \frac{\left(0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}\right)}{\left[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}}{282000}\right)^{5/8}\right]^{4/5} \quad \text{(Eq. 604.4)}$$

In which the Prandtl number (Pr) is a function of air pressure and a film temperature, which in this case is the average of the insulation surface temperature and the surrounding air temperature. In turn, the forced convection heat transfer coefficient is given by an algorithm proposed by Churchill and Bernstein [1]

$$h_{ouside,conv,forced} = \frac{3.6\,Nu_{forced}\,k_{air}}{d_{outside,insul}} \quad \text{(Eq. 604.5)}$$

The 3.6 multiplier in the above equation is used simply to convert the units of the forced convection heat transfer coefficient to TRNSYS units of $kJ/h.m^2.K$ from $W/m^2.K$.

Natural convection for a horizontally oriented pipe is calculated using a second algorithm proposed by Churchill and Bernstein [2] by first obtaining the Rayleigh number:

$$Ra = \frac{9.81\,\beta_{air}\left|T_{surf} - T_{env}\right| d^3_{outside,insul}}{\alpha_{air}\;\mu_{air}} \quad \text{(Eq. 604.6)}$$

The Nusselt number for natural convection is

$$Nu_{natural,horiz} = \left[0.6 + \frac{\left(0.387\,Ra^{1/6}\right)}{\left[1+\left(\frac{0.559}{\Pr}\right)^{9/16}\right]^{8/27}}\right]^2 \quad \text{(Eq. 604.7)}$$

For a vertically oriented pipe, an algorithm from Lefevre and Ede [3] is used. The Rayleigh number is

$$Ra = \frac{9.81\,\beta_{air}\left|T_{surf} - T_{env}\right| L^3_{pipe}}{\alpha_{air}\;\mu_{air}} \quad \text{(Eq. 604.8)}$$

The Grashof number is

$$Gr = \frac{Ra}{\Pr} \quad \text{(Eq. 604.9)}$$

And the Nusselt number is

$$Nu_{natural,vert} = \frac{4}{3}\left[\frac{7\,Gr\Pr^2}{5\left(20+21\Pr\right)}\right]^{1/4} + \frac{4\left(272+315\Pr\right)L_{pipe}}{35\,d_{outside,ins}\left(64+63\Pr\right)} \quad \text{(Eq. 604.10)}$$

The natural convection heat transfer coefficient is then.

$$h_{ouside,conv,natural} = \frac{3.6\,Nu_{natural}\;k_{air}}{d_{outside,insul}} \quad \text{(Eq. 604.11)}$$

Where $Nu_{natural}$ is either $Nu_{natural,horiz}$ or $Nu_{natural,vert}$.

Fluid Node Energy Balance

Type604 performs an energy balance on each fluid node, annular pipe node, and annular insulation node in the pipe. The basic form of the energy balance for any given node is:

$$mCp\frac{dT}{dt} = \dot{Q}_{in} - \dot{Q}_{out} \quad \text{(Eq. 604.12)}$$

If the user wishes to neglect the thermal capacitance of either the pipe wall or the insulation jacket, it suffices to set the specific heat or the density of either the pipe wall material or the insulation material to 0. In this case, the energy balance for a given node of that material becomes:

$$0 = \dot{Q}_{in} - \dot{Q}_{out} \quad \text{(Eq. 604.13)}$$

For a fluid node, there are three basic terms in the energy balance. Energy transferred into and out of the node because of fluid flow, energy transferred due to axial conduction between fluid nodes, and energy transferred between the fluid and the pipe wall. Energy transfer due to flow takes the form:

$$\dot{Q}_{in,left} = \dot{m}_{fluid,left}\, Cp_{fluid}\left(T_{fluid,n} - T_{fluid,n-1}\right) \quad \text{(Eq. 604.14)}$$

$$\dot{Q}_{out,left} = \dot{m}_{fluid,left}\, Cp_{fluid}\left(T_{fluid,n+1} - T_{fluid,n}\right) \quad \text{(Eq. 604.15)}$$

$$\dot{Q}_{in,right} = \dot{m}_{fluid,right}\, Cp_{fluid}\left(T_{fluid,n} - T_{fluid,n+1}\right) \quad \text{(Eq. 604.16)}$$

$$\dot{Q}_{out,right} = \dot{m}_{fluid,right}\, Cp_{fluid}\left(T_{fluid,n-1} - T_{fluid,n}\right) \quad \text{(Eq. 604.17)}$$

These four equations indicate that flow can enter the pipe from the “left” end or from the “right” end. Flow cannot enter from both ends at the same time. If the user specified mass flow rates into both the “left” and “right” ends, the larger of the two flows will dominate and the smaller of the two will be ignored. The actual (dominant) flow rate is referred to as m_{fluid}.

Energy flow due to axial conduction takes the form:

$$\dot{Q}_{in} = \frac{k_{fluid}\, A_{xs}}{L_{node}}\left(T_{fluid,n} - T_{fluid,n-1}\right) \quad \text{(Eq. 604.18)}$$

$$\dot{Q}_{out} = \frac{k_{fluid}\, A_{xs}}{L_{node}}\left(T_{fluid,n+1} - T_{fluid,n}\right) \quad \text{(Eq. 604.19)}$$

In which L is the distance between two nodes; since all nodes are equal length, L is also the length of a node. Energy flow between the fluid and the wall depends on whether or not fluid is flowing in the pipe. The Reynolds number is calculated as

$$\boxed{\mathrm{Re}_{inside} = \frac{4\dot{m}_{fluid}}{\pi\, d_{inside,pipe}\, \mu_{fluid}}}$$ (Eq. 604.22)

$$\mathrm{Pr}_{inside} = \frac{Cp_{fluid}\, \mu_{fluid}}{k_{fluid}}$$ (Eq. 604.23)

Nusselt is then calculated as

$$Nu_{inside} = \left(3.66^3 + 1.61^3\, \mathrm{Re}_{inside}\, \mathrm{Pr}_{inside} \frac{d_{inside,pipe}}{L_{pipe}}\right)^{1/3}$$ For Re < 2300 and $\frac{L_{pipe}}{d_{inside,pipe}} \leq 0.0425\, \mathrm{Re}_{inside}\, \mathrm{Pr}_{inside}$ (Eq. 604.24)

$$Nu_{inside} = 4.364$$ For Re < 2300 and $\frac{L_{pipe}}{d_{inside,pipe}} > 0.0425\, \mathrm{Re}_{inside}\, \mathrm{Pr}_{inside}$ (Eq. 604.25)

$$Nu_{inside} = 0.0214\left(\mathrm{Re}_{inside}^{0.8} - 100\right)\mathrm{Pr}_{inside}^{0.4}$$ For Re > 2300 and $\mathrm{Pr}_{inside} \leq 1.5$ (Eq. 604.26)

$$Nu_{inside} = 0.012\left(\mathrm{Re}_{inside}^{0.87} - 280\right)\mathrm{Pr}_{inside}^{0.4}$$ For Re > 2300 and $\mathrm{Pr}_{inside} > 1.5$ (Eq. 604.27)

The inside convection coefficient follows as

$$h_{inside} = \frac{Nu_{inside}\, k_{fluid}}{d_{inside,pipe}}$$ (Eq. 604.28)

The general form of the energy transferred between the fluid node and the pipe wall node can finally be written as

$$\dot{Q} = \frac{1}{R_{fluid} + R_{wall}}\left(T_{pipe,m} - T_{fluid,n}\right)$$ (Eq. 604.29)

where

$$R_{fluid} = \frac{1}{h_{inside}\, SA_{inside}}$$ (Eq. 604.30)

$$R_{wall} = \frac{\ln\left(\frac{r_{pipe,inside} + \frac{r_{pipe,outside} - r_{pipe,inside}}{2}}{r_{pipe,inside}}\right)}{2\pi L_{fnode} k_{pipe}} \qquad \text{(Eq. 604.31)}$$

It is important to recall that a single pipe node may transfer energy with more than one fluid node.

Pipe Node Energy Balance

The annular pipe nodes transfer energy axially with adjacent pipe nodes, with the fluid, and with the annular insulation nodes that surround them. Terms for the energy transfer with the fluid have already been discussed in the previous section. The terms for axial conduction between nodes take a form similar to that of the axial conduction between adjacent fluid nodes:

$$\dot{Q}_{out} = \frac{k_{pipe} A_{pipe}}{L_{pnode}} \left(T_{pipe,n} - T_{pipe,n-1}\right) \qquad \text{(Eq. 604.32)}$$

$$\dot{Q}_{out} = \frac{k_{pipe} A_{pipe}}{L_{pnode}} \left(T_{pipe,n+1} - T_{pipe,n}\right) \qquad \text{(Eq. 604.33)}$$

Where the annular area (A_{pipe}) is given by:

$$A_{pipe} = \frac{\pi}{4}\left(d^2_{outside,pipe} - d^2_{inside,pipe}\right) \qquad \text{(Eq. 604.34)}$$

The energy transferred between the pipe node and the insulation node can be written as

$$\dot{Q} = \frac{1}{R_{pipe} + R_{contact} + R_{insul}} \left(T_{pipe,n} - T_{insul,n}\right) \qquad \text{(Eq. 604.35)}$$

$R_{contact}$ is a user-defined parameter that accounts for the contact resistance between the pipe wall and the insulation. The other two terms (R_{pipe}, and R_{insul}) are given by:

$$R_{pipe} = \frac{\ln\left(\frac{r_{pipe,outside}}{r_{pipe,inside} + \frac{r_{pipe,outside} - r_{pipe,inside}}{2}}\right)}{2\pi L_{pnode} k_{pipe}} \qquad \text{(Eq. 604.36)}$$

$$R_{insul} = \frac{\ln\left(\dfrac{r_{pipe,outside} + \dfrac{r_{insul,outside} - r_{insul,inside}}{2}}{r_{pipe,outside}}\right)}{2\pi L_{inode} k_{insul}} \quad \text{(Eq. 604.37)}$$

If the user has set the thickness of the insulation layer to 0, the R_{insul} and $R_{contact}$ terms in equation 604.35 do not apply and pipe outer wall is subject to external convection in much the same manner as was discussed for the outside of the insulation jacket earlier in this document. The outside convection coefficient $h_{outside}$ is determined using equations 604.2 through 604.11 and is applied to the following equation:

$$\dot{Q}_{surface,pipe} = h_{outside}\, SA\left(T_{pipe,surf} - T_{env}\right) \quad \text{(Eq. 604.38)}$$

SA in this case is the outside surface area of the pipe node.

Insulation Node Energy Balance

The annular insulation nodes transfer energy axially with adjacent insulation nodes, with the pipe material, and with the environment. Terms for energy transfer with the pipe have already been discussed in the previous section. The terms for axial conduction between nodes take a form similar to that of the axial conduction between adjacent nodes:

$$\dot{Q}_{in} = \frac{k_{insul} A_{insul}}{L_{inode}}\left(T_{insul,n} - T_{insul,n-1}\right) \quad \text{(Eq. 604.39)}$$

$$\dot{Q}_{out} = \frac{k_{insul} A_{insul}}{L_{inode}}\left(T_{insul,n+1} - T_{insul,n}\right) \quad \text{(Eq. 604.40)}$$

Where the annular area (A_{insul}) is given by:

$$A_{insul} = \frac{\pi}{4}\left(d^2_{outside,insul} - d^2_{inside,insul}\right) \quad \text{(Eq. 604.41)}$$

The energy transferred between the insulation node and the environment is written as:

$$\dot{Q}_{surface,pipe} = h_{outside}\, SA\left(T_{pipe,surf} - T_{env}\right) \quad \text{(Eq. 604.42)}$$

In which $h_{outside}$ is the result of equation 604.11 and SA is the surface area of the insulation node.

References

[1] Churchill and Bernstein, Journal of Heat Transfer, no. 99 pg. 300, 1977

[2] Churchill and Bernstein, "Correlating Equations for Laminar and Turbulent Free Convection from a Horizontal Cylinder," International Journal of Heat and Mass Transfer, no. 18, pg 1049, 1975

Appendix B: Observed Impact of Gas Tankless Water Heater on Hot Water Use Patterns

A 12-month detailed field monitoring project (Hoeschele and Weitzel 2013) was recently completed where 18 homes (17 with existing gas storage water heaters) were initially monitored and then replaced with advanced gas water heaters (eight[14] of which were gas tankless units). Monitoring included energy use, hot water flow, and water heater inlet and outlet temperature sensors. A key project finding that has implications for distribution system performance was that observed hot water loads were lower than expected (15.6 gal/person-day). Average household usage totaled 56.4 gpd, with a corresponding recovery load of 27,200 Btu/day.[15] The lower Btu recovery load reflects the milder inlet water temperatures common to most of California.

The pre- and post-retrofit monitoring protocol employed in the monitoring project provided an opportunity to observe how household usage behaviors may change with a conversion to a tankless unit. An immersion thermocouple located at the water heater outlet provides an assessment of the "quality" of hot water exiting the unit over the 12+ month monitoring period. For storage water heaters, one would expect that virtually all water would be "hot" (we define 105°F as the minimum cutoff for defining an adequate hot water condition), with the likely exception being a few cases where high simultaneous loads fully deplete the storage tank. Figure 8 plots the percentage of the total hot water volume leaving the water heater that was > 105°F.[16] As one would expect, the storage water heaters with tank "set points" (average water heater leaving temperature) > 120°F demonstrated very little hot water volume below the 105°F quality threshold. In most cases < 1% of the volume did not meet the minimum temperature criteria. The two storage water heaters with set points of ≤ 115°F did demonstrate a fairly significant (~10%) of volume below 105°F. The tankless water data generally exhibited lower average outlet water temperatures (in most case < 120°) than the storage water heaters. The lower water temperatures appear to affect the percentage of flow < 105°F, probably because the firing control algorithms may throttle the initial firing rate if the set point is lower. On average, 7.2% of total volume of tankless flow was found to be at a temperature < 105°F versus 1.2% for the storage water heater cases. The one monitored tankless unit with a high set point (~150°F)[17] demonstrated a lower percentage of low-quality output (2.5%), although the volume of substandard hot water was still roughly double that of the storage water heaters in general. The data suggest that all things being equal, tankless water heaters will waste more water and increase hot water times in comparison to a traditional storage water heater. This would appear to be clearly evident for hot water uses such as a shower where the minimum acceptable temperature is important in defining the use, but may not necessarily be the case for other sink draws where individual behavior dictates if 105°F water is desired, or if lukewarm or even cold water is acceptable.

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[14] One of the eight tankless retrofits involved replacing a non-condensing tankless unit with a condensing tankless unit.

[15] The Energy Factor rating test assumes a daily load of 64.3 gal with a recovery load of 41,050 Btu/day.

[16] 36 data points are plotted since there was pre- and post-retrofit monitoring completed at each site. One of the sites had an existing tankless unit install during "pre" monitoring, resulting in nine tankless data points.

[17] This high set point was used by the homeowner to address the effect of significant lengths of underslab piping.

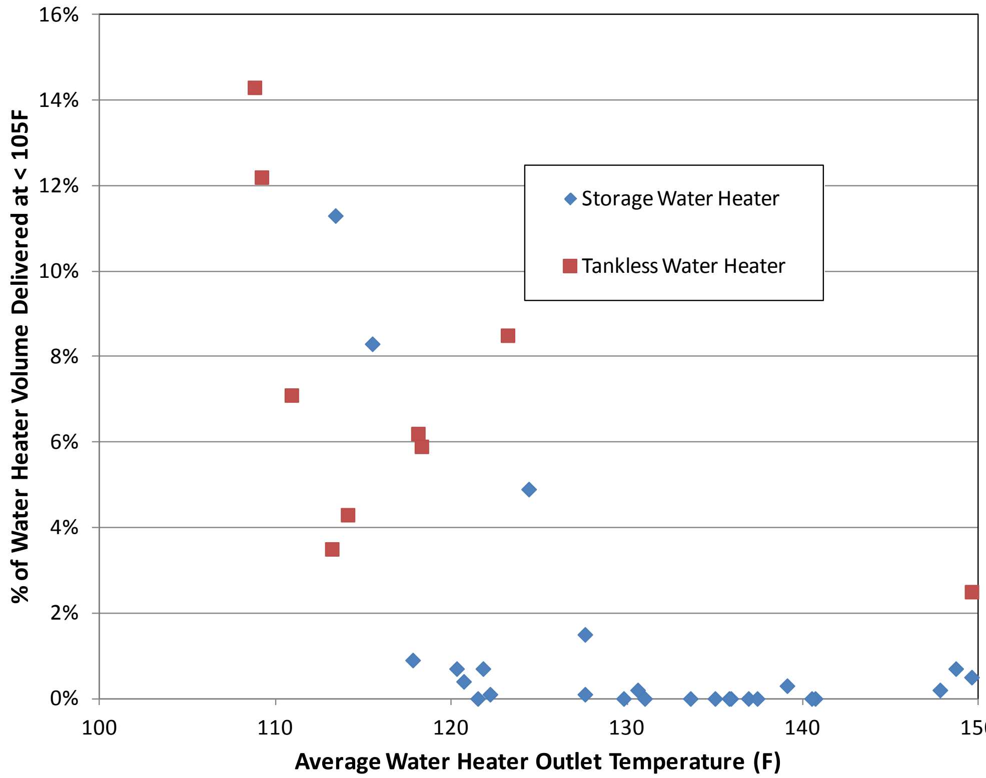

Figure 8. Percentage of water heater delivered volume at a temperature > 105°F

The prior data suggest a greater fraction of hot water flow from a tankless water heater will be < 105°F than for a gas storage water heater. A related effect is whether there is a general change in usage pattern that results from transitioning to a tankless water heater. Small draws, especially when starting with a "cold" tankless unit, are more difficult to effectively satisfy, since there will be an increased time delay in delivering the hot water to the use point. How individuals in the household respond to this delay can affect consumption. Another potential factor is the minimum hot water flow rate that is needed to trigger firing in the tankless unit.[18] Low flow rate hot water uses (e.g., shaving at a bathroom sink) may require the users to increase the flow rate, or the users may just change their use behaviors as they learn the delivery characteristics of the unit. Figure 9 and Figure 10 represent small (< 0.5 gal) hot water draw use as a fraction of total hot water usage both pre- and post-retrofit. Each site, denoted by a text descriptor for location[19] and a number (e.g., SD1), demonstrates a post-retrofit reduction in the fraction of small volume draws as a percentage of all hot water draws (Figure 9). In some households the effect is more pronounced than in others. On average, excluding site PG5 T,[20] the percentage of "< 0.5 gal" draws is reduced from 59% in the "pre" data, to 48% in the "post" dataset. In terms of the hot water volume associated with the small draws (Figure 10), on average, the data show a reduction from 10% of total hot water use down to 6.3% with the tankless unit. The variation among

[18] Most tankless units fire at a flow rate of around 0.5 gpm.
[19] "SD" = San Diego area, "LA" = Los Angeles area, and "PG" = Northern California Pacific Gas and Electric sites.
[20] This site had a tankless water heater in the "pre" period, and was retrofitted with a condensing tankless unit.

individual sites is significant and speaks to differences in use behaviors among the different households.

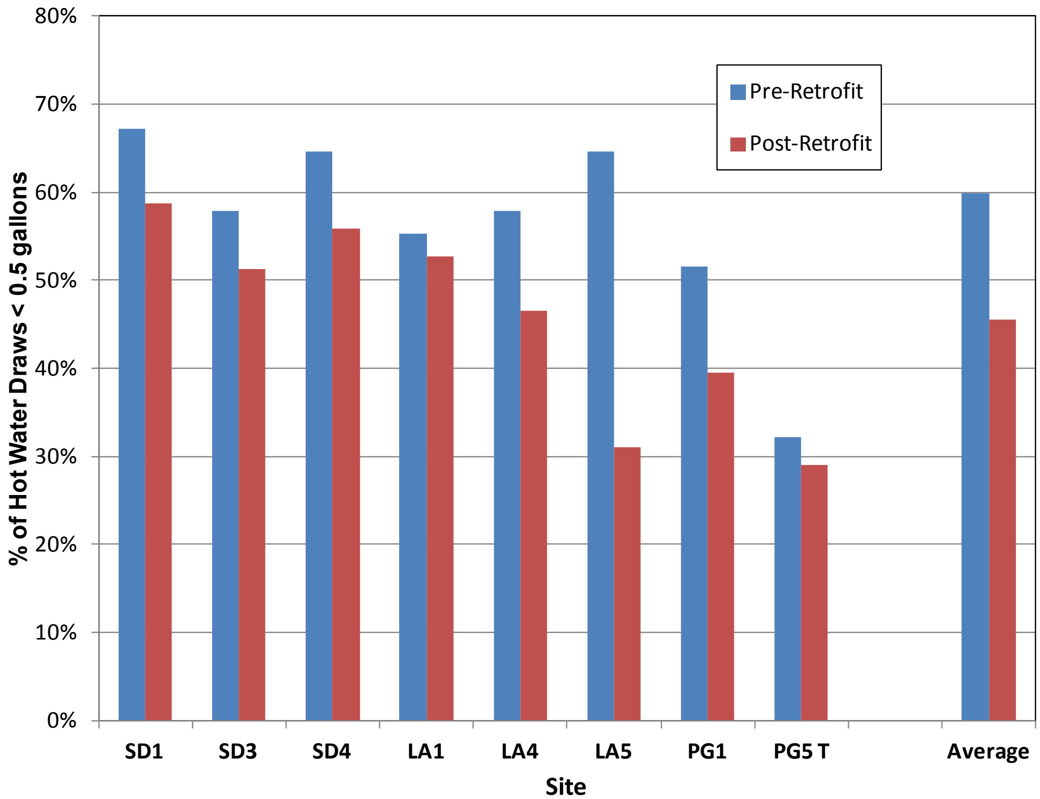

Figure 9. Percentage of all hot water draws < 0.5 gallons (pre- and post-tankless retrofit)

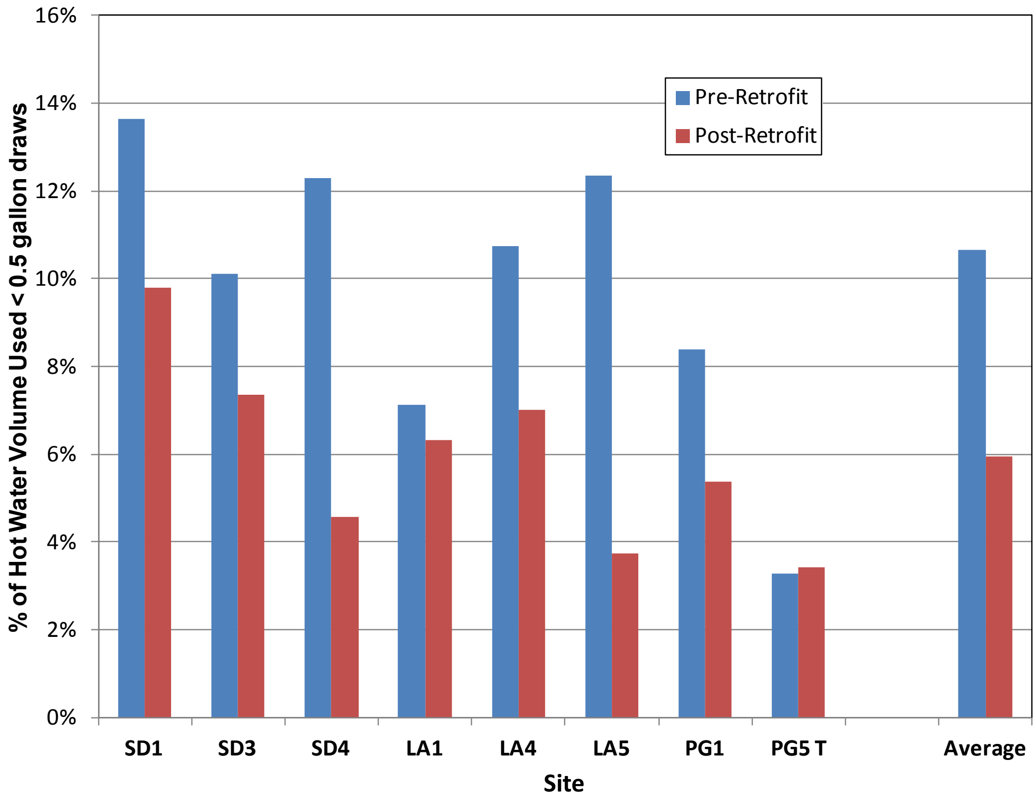

Figure 10. Percentage of all hot water volume < 0.5 gal (pre- and post-tankless retrofit)

Figure 11 and Figure 12 present similar plots for large volume draws, which are defined as > 5 gal. Most of these draws will likely be shower events, although tub uses and extended kitchen sink dishwashing may also be included. Figure 11 demonstrates that as the number of small draws decrease with the tankless conversion, the average percentage of larger volume draws increased from 6.8% of all draws with storage water heaters to 10% with tankless. Figure 12 plots the volume associated with these large draws for each of the sites. With the storage water heaters, the large volume draws represent an average of 53% of all hot water consumed, which increases to 62% for the tankless units.

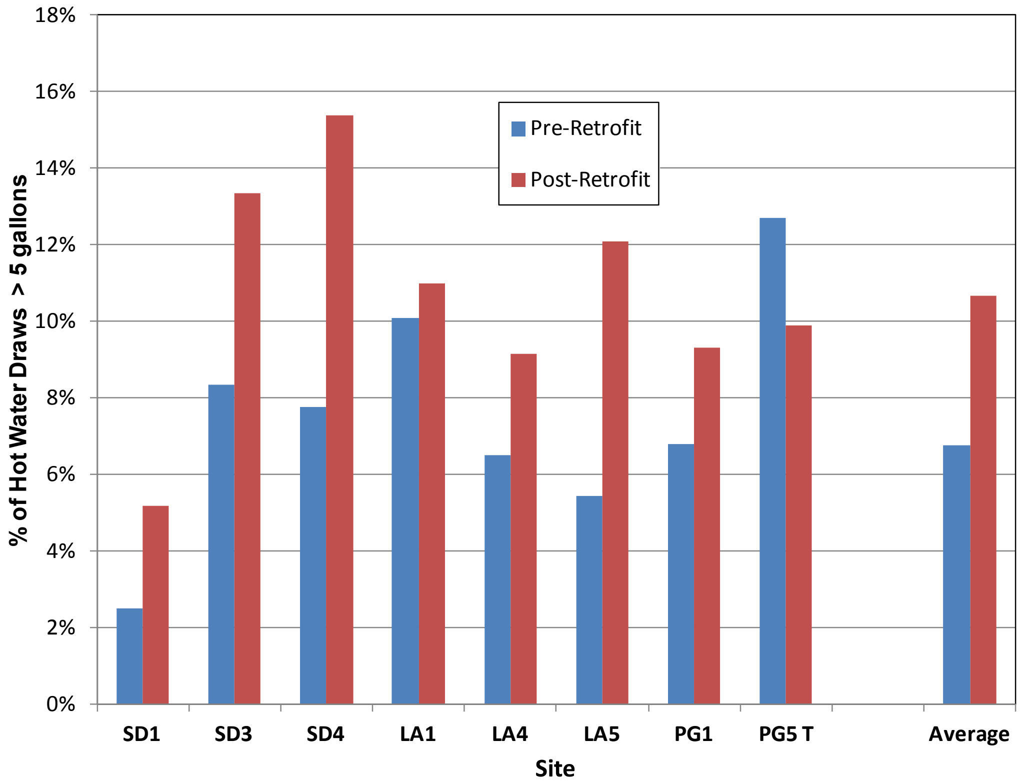

Figure 11. Percentage of all hot water draws > 5 gal (pre- and post-tankless retrofit)

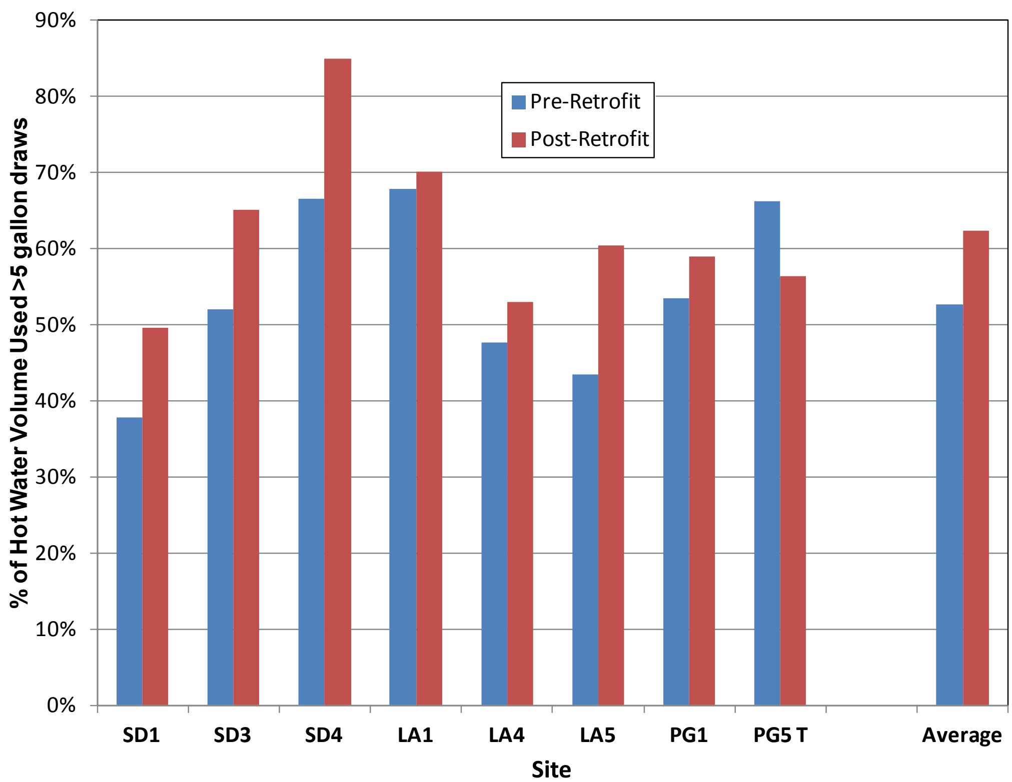

Figure 12. Percentage of all hot water volume > 5 gal (pre- and post-tankless retrofit)

In summary, as users moved from gas storage water heaters to gas tankless units, their observed usage changed significantly. Smaller volume draws, many of which are difficult to satisfy due to either flow rate or startup time delays, were found to be significantly reduced, with an overall 23% reduction in daily hot water draws as households switched to the tankless unit. Countering this reduction was an increase in average hot water draw volume size from 1.40–2.09 gal. In terms of water heater recovery load, Table 10 shows that in aggregate, the average recovery load during the pre- and post- periods was 8% higher with the tankless unit. While two sites (SD1 and SD4) appear to have significantly increased hot water consumption, the remaining five sites show small changes in average daily recovery load. A final review of larger volume draws representative of shower events (Figure 13) suggests that with the exception of site SD4, none of the sites indicated a significant change in shower length that would explain increased usage. While SD4 may represent a household that did take advantage of the tankless "endless hot water" marketing claims, it appears that most of the households did not increase consumption, although usage patterns were clearly affected.

Table 10. Monitored Pre- and Post-Retrofit Daily Recovery Loads by Site

Site	Recovery Load (Btu/day)		% Difference Post Versus Pre	Comments
	Pre-Retrofit	Post-Retrofit		
PG1	22,600	22,200	–2%	
LA1	29,200	28,100	–4%	
LA4	8,900	9,800	+10%	
LA5	31,600	31,000	–2%	Data through April 9, 2011
SD1	17,500	23,800	+36%	
SD3	9,400	10,200	+9%	Includes some buffer tank heating
SD4	11,400	16,200	+42%	
Average	18,700	20,200	+8%	

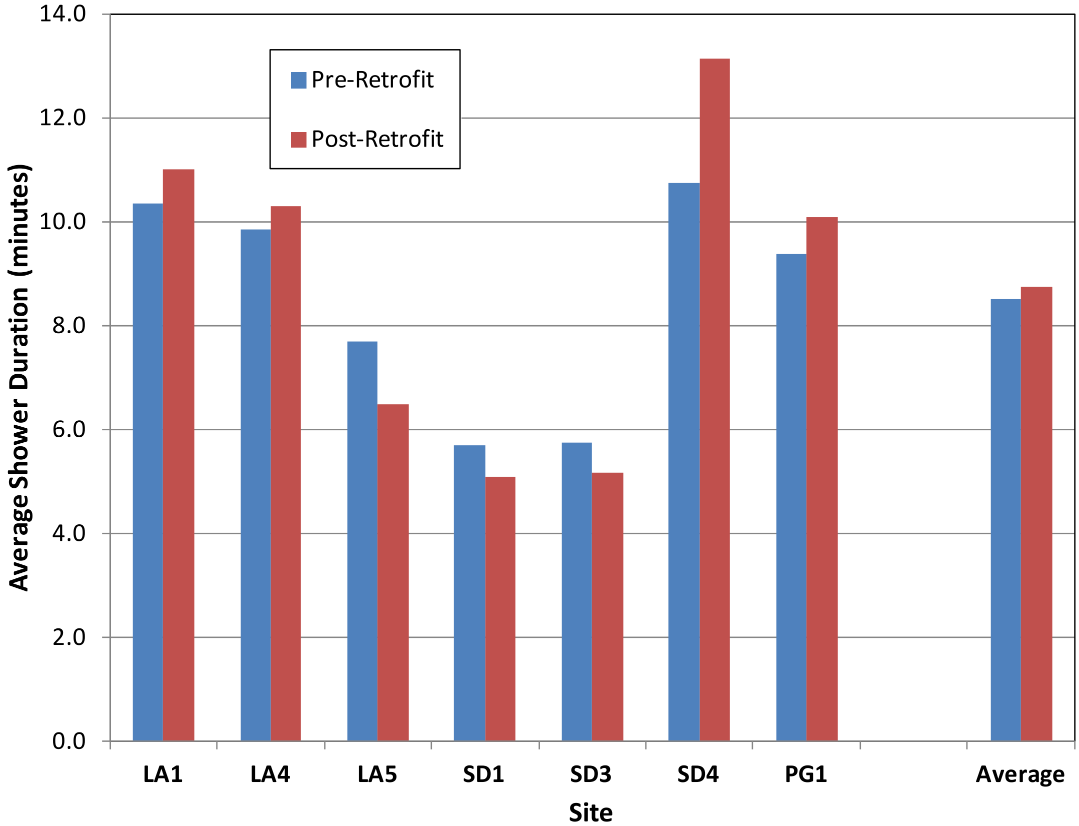

Figure 13. Average shower draw duration (pre- and post-tankless retrofit).

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