DOMESTIC HOT WATER SYSTEM MODELING FOR THE DESIGN OF ENERGY EFFICIENT SYSTEMS

Prepared for

NREL
1617 Cole Boulevard
Golden, CO 80401-3393

Prepared by

NAHB Research Center, Inc.
400 Prince George's Boulevard
Upper Marlboro, MD 20774-8731

NAHB RESEARCH CENTER℠

America's Housing Technology and Information Resource

ACKNOWLEDGMENTS

This report was prepared by the NAHB Research Center, Inc., under contract to the client. The principal authors of this report were Joe Wiehagen and Jeannie Leggett Sikora. Technical support was provided by Randy Johnson and Dave Harrell, review was provided by Chris Fennell.

ABOUT THE NAHB RESEARCH CENTER

The NAHB Research Center, located in Upper Marlboro, Md., is known as America's Housing Technology and Information Resource. In its nearly 40 years of service to the home building industry, the Research Center has provided product research and building process improvements that have been widely adopted by home builders in the United States. Through testing and certification services, the Research Center seal is recognized throughout the world as a mark of product quality and an assurance of product performance.

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April 2, 2002

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EXECUTIVE SUMMARY

This report evaluates the use of demand water heating equipment in conjunction with various hot water piping configurations. These systems are being evaluated as an alternative to a standard tank with a tree delivery system used in most new homes today. Four different domestic hot water heating systems are evaluated for incremental performance changes. Specific performance issues, such as hot water delivery temperatures at the outlet, are used as a basis for understanding the adequacy of the system as well as comparing delivered outlet energy relative to the electric energy required to supply the outlet energy.

Using one-minute hot water flow data, variable interior air temperatures, and monthly variable cold water inlet temperatures, the performance of a hypothetical domestic hot water system is simulated. Both high and low hot water consumption profiles are considered. These profiles were developed through previous testing in U.S. homes supported by NREL. Maximum energy savings resulted from using a combination of a centrally located demand water heater with a parallel piping system supplying individual outlets. For the high consumption home, savings were 17 percent or 920 kWh annually; savings were 35 percent or 817 kWh for the low use home. Savings included an adjustment to the input electric energy if the delivery temperature falls below the set point and an adjustment to water heater system efficiency for higher than necessary delivery temperatures.

For the demand water heating equipment, hot water delivery temperatures show hot water temperature degradation at outlets during periods of high flow rates. This performance issue appears problematic in the high use home but not in the low use home. Performance gains such as higher than necessary delivered outlet temperatures are assumed to be an efficiency gain that results in a decrease of water heating energy.

Other performance issues such as demand heater response time or comfort issues are not evaluated here, but are suggested for further testing and evaluation of an optimal system design.

1 BACKGROUND

Domestic hot water systems typically are comprised of a hot water storage tank, a fuel source to heat water, hot water piping to outlet points, and a cold water feed to the storage tank. The efficiency of the complete system includes all losses in heating the water from the cold water inlet to the desired outlet temperature, including losses from the storage tank and losses from the piping system transporting the hot water to the outlet. Efficiency of the overall system depends on the type of water heating equipment, the length and size of piping installed, the set point of the water heater, and the quantity of hot water consumed. System efficiencies may range from less than 50 percent to about 85 percent. Significant changes from this basic approach to water heating, in order to increase system efficiency including water heating equipment, overall system design, and piping systems are limited. Efficiency gains in domestic hot water systems have been modest compared with the results that have been achieved in heating and air conditioning equipment and delivery.

Advanced technologies and methods to increase energy savings in domestic water heating systems, such as heat pump water heaters, manifold plumbing systems, instantaneous water heaters, and solar water heaters are available, yet underutilized. Prior to implementing any new water heating system design, including the use of new equipment, system performance modeling is useful in uncovering potential problems or suspected performance deficiencies. The purpose of this analysis of water heating system design focuses on instantaneous water heating equipment in conjunction with plumbing system designs to increase the water heating system efficiency while maintaining at least comparable performance to storage tank systems.

Research Center staff have developed a computer simulation model of a typical plumbing system that incorporates the use of demand (electric) water heaters. System performance is simulated using one-minute hot water flow rates based on data taken from actual homes. The evaluation includes using the model to change the location of the heater relative to the outlets and use of a parallel piping plumbing system to reduce piping losses and improve system performance. Use of a one-minute interval taken from actual data provides a realistic evaluation, allowing for detailed results that account for system performance issues that might otherwise go undetected in a more convenient, longer time-step analysis based on hourly averaged data.

2 SYSTEM EQUIPMENT AND DESIGNS EVALUATED

Two types of water heating equipment are evaluated, an electric storage tank and an electric demand water heater without storage. A combination of a storage tank with a demand heater is briefly considered on a performance, rather than energy savings, basis. Two types of plumbing distribution systems are considered; a 'tree' system where individual outlets are fed from a main supply or trunk, and a 'parallel' piping system where each outlet is fed from an individual line directly from a manifold.

Four water heating systems are evaluated, in progression, to determine incremental energy savings:

- A storage tank, located in the utility room fed into a tree distribution system,
- A demand heater located in the utility room fed into the same tree system,
- A demand heater located in a more central location in the house and fed into a tree system, and,
- A demand heater, centrally located, fed into a parallel piping system.

For each system design, two sets of annual hot water flow data are used to determine the delivered hot water energy at the outlets and the electric energy input required to supply the outlet energy. The data sets include variable interior air temperature that modify the system losses throughout the changing seasons as in a typical home. In addition, the incoming water temperature is modified to realistically reflect changes from month to month.

One minute hot-water use data is used: one set from a home that has higher than average water consumption; the other from a home that has lower than average hot water consumption. Each data set is applied to the same plumbing system and water heating equipment for comparative purposes.

The combination of the water heating equipment and plumbing system design provides a basis for considering efficiency gains available to typical domestic water heating systems. From this basis, addition of ancillary equipment such as desuperheaters, solar water heaters, or even waste-heat recovery equipment may be considered in future studies but is not part of this evaluation.

3 HOT WATER SYSTEM MODEL

Domestic hot water systems heat utility-supplied or well water for various home uses such as laundry, showering, or hand washing. The delivered product, heated water at a point of hot water use (outlet point), is supplied by piping and water heating equipment situated within the home. Electricity or fossil fuels are the most typical means for heating water. This analysis evaluates energy use only at the home. It ignores distribution losses from the point of generation.

To better understand the performance of demand water heater systems in various plumbing systems, Research Center staff developed an analytical computer model representing the various parts of a domestic hot water system. A system model is employed to theoretically determine if actual field trials of such system designs would prove beneficial and to determine any potential shortcomings of the system designs. The model is comprised of water heating equipment, hot water piping, and numerous outlet points. The hot water system is designed for a "typical" two story, single-family home based on an evaluation of housing features gathered by the NAHB Research Center's proprietary Annual Builder Practices Survey.[1] Appendix A shows the basic layout of the home and including possible design options.

Two types of water heating systems are analyzed: tank-type storage water heaters and non-storage demand water heaters. Additionally, the effect of location of the demand

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[1] The home design has been identified to have features most common or representative of homes

heater and the type of piping system connected to the heater on energy consumption is analyzed.

The hot water piping system is designed to be consistent with the requirements of various plumbing codes. Local jurisdiction requirements, which may vary widely, are not incorporated. However the piping layout is designed to be consistent with typical practice.[2] For example, although a plumbing system is allowed by code to use nominal 1/2-inch tubing to supply an outlet, in practice, nominal 3/4-inch tubing is used for at least portions of the plumbing system in most homes. The hot water piping system design incorporates both tree and parallel-piping (sometimes referred to as a manifold system) configurations for analysis.

Outlet points are assigned to be representative of new single family homes and are based on the typical home having 2-1/2 baths, a dishwasher, and a clothes washer.

The hot water flow to each outlet point is estimated based on actual annual residential hot water flow data measured during previous experiments.[3] Two sets of one-year data are analyzed, one set having a higher-than-average hot water use and one with a lower-than-average hot water use. The data sets define the total hot water flow for each minute time step; flow to specific outlet points is assigned based on the combination of findings of a literature review of residential domestic hot water use and reasonable estimates of the time of outlet use. (Refer to Appendix B for specific references.)

Using standard heat transfer equations, the simulation program calculates heat loss from the piping system, heat gain to the water from the heating equipment, and the electrical energy required to heat the water to a desired set point. The data used in the simulation includes the minute flow rate, indoor air temperature, and average cold water inlet temperature for the month period. The time step of the flow data was chosen to be one minute intervals (rather than hourly or daily intervals) in order to model both higher flow

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constructed throughout the U.S. It is not representative of any particular geographic location.

[2] Based on observations and discussions with plumbing professionals.

[3] Refer to the NAHB Research Center, Inc. report *Measured Performance of Five Residential Geothermal Systems*, prepared for Geothermal Heat Pump Consortium, National Renewable Energy Laboratory, and U.S. Department of Energy, November, 1999.

rate events, on the order of 5 gpm or more, and realistic flow duration events. A shorter time step permits a more accurate analysis of delivered outlet energy, piping losses, and the effect of short duration flow events.

The simulation analyzes hot water temperature at different points in the system. Simulation results are used to determine hot water system efficiency. This analysis determines the delivered hot water energy at the outlet and the estimated electrical energy input to supply the delivered load at the outlet. The delivered outlet energy and the required electrical energy input depend on the incoming water temperature, indoor air temperature, piping lengths, and flow rate.

4 MODEL COMPONENTS

The hot water system model used in the simulations is based on a plumbing system designed for a "typical" single-family home. The home design is based on an evaluation of housing designs gathered by the NAHB Research Center's Annual Builder Practices Survey. The selected design is a 2,094-square-foot, two-story home with a basement foundation. The 1,049-square-foot basement is unfinished[4] for the purposes of the plumbing system design. Components, such as storage heaters and piping, of the hot water system model are described in the following sections.

4.1 Plumbing System Design

The design of the plumbing system is based on the International Residential Code for One- and Two-Family Dwellings, Part VII, Plumbing.[5] Estimates of water flow in each pipe section and the minimum pressure available at the water service are used in the design procedure. The water flow load at each outlet is based on a water-supply fixture unit (w.s.f.u.) value as determined in the code for each type of outlet. Each pipe section is assigned a total w.s.f.u. which may then be converted to flow in units of gallons per

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[4] An unfinished basement may allow for additional bathing facilities but in which fixtures or finished living areas have not been completed.

[5] The *2000 International Residential Code for One- and Two-Family Dwellings*, published by International Code Council, Inc. Refer to Chapter 29 for specific sizing requirements.

minute, based on the load. For example, a typical full bath group which includes a tub/shower, sink, and water closet would have a w.s.f.u. of 2.7 for the cold water supply and 1.5 for the hot water supply. Piping that services a full bath group would be sized to supply the flow rates associated with the total w.s.f.u. If the distribution piping includes branches to other outlets, the w.s.f.u. for that pipe is equal to the sum of all the w.s.f.u. served by the piping. Additional tables specify the minimum pipe size for a given w.s.f.u. and are based on the minimum water pressure available.

Other requirements, such as minimum pipe sizes, pressure allowances for special valves, and maximum velocities may affect the plumbing system design. Other types of systems such as a manifold piping system have unique requirements. The minimum pipe size in a manifold system is 3/8-inch, unless a larger supply line is required by the manufacturer.

4.2 Piping System

Figures 1 and 2 show the piping layout for each of the systems used in the simulation program along with any options for placement of water heating equipment. Only the hot water supply lines are shown, but the cold water piping would be similar in dimension and length. For a tree system, where outlet points branch from main trunk lines, the piping is progressively smaller to a minimum of 1/2-inch inside diameter. The lengths of pipe are determined from what is considered an efficient layout for the house design with an unfinished basement. The parallel piping system consists of 1/2- or 3/8-inch diameter tubing with one pipe dedicated to each load.

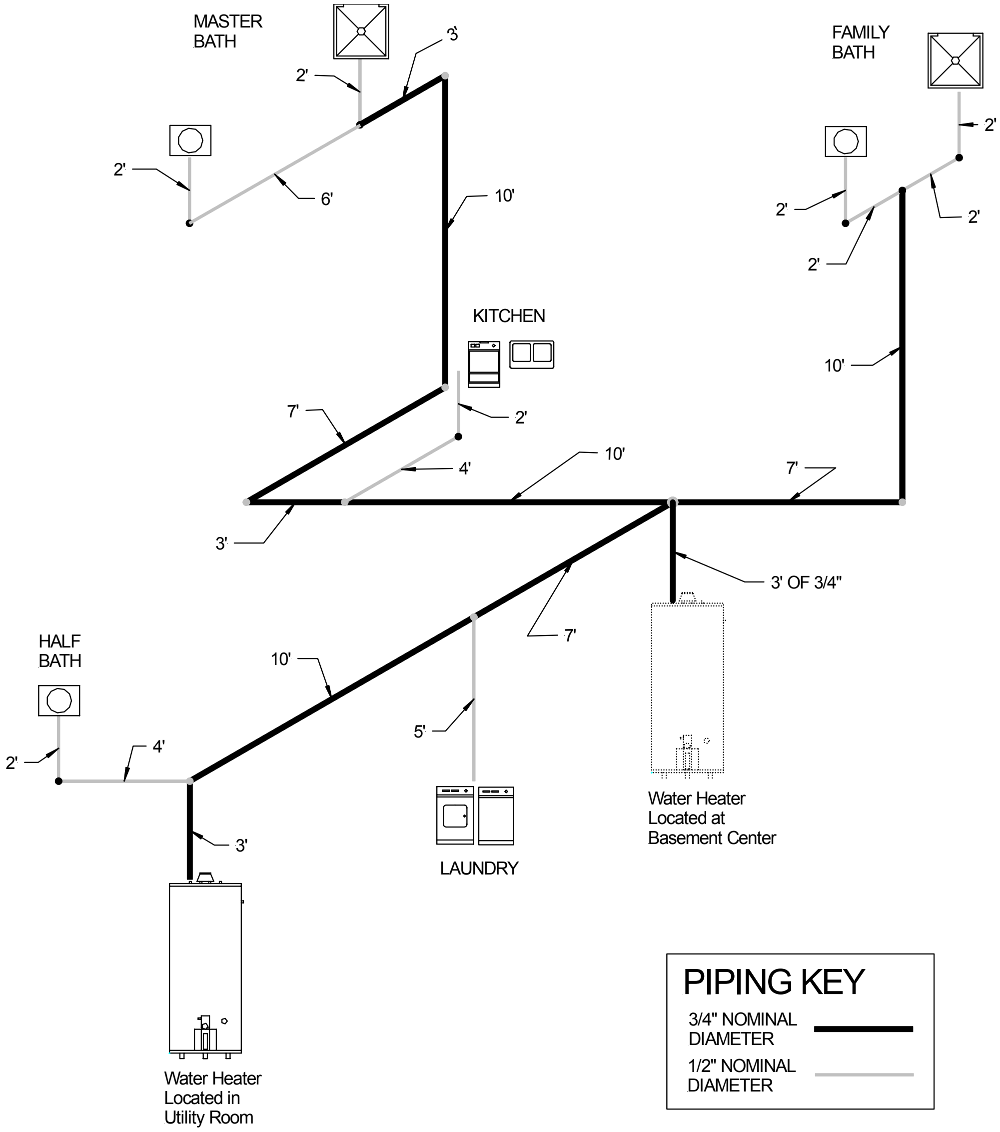

Figure 1: Tree Plumbing System Layout as Simulated

For the base case, a tree plumbing system layout is used and the water heating tank is located in the utility room area at one end of the house. This location is chosen since the basement may be finished at some future point. The utility room is located at the farthest point from the master bath and therefore represents the most extensive piping layout possible for the home. This is a typical scenario because the location of water heating equipment is usually based on convenience and aesthetics rather than an optimized layout to reduce pipe length, unless required by a local jurisdiction or water authority. In subsequent simulations, water heating equipment is relocated to a more central point in the basement to evaluate the impact of piping length on system losses. The use of demand heaters enables a more flexible water heater placement since demand units are significantly smaller than storage water heater units.

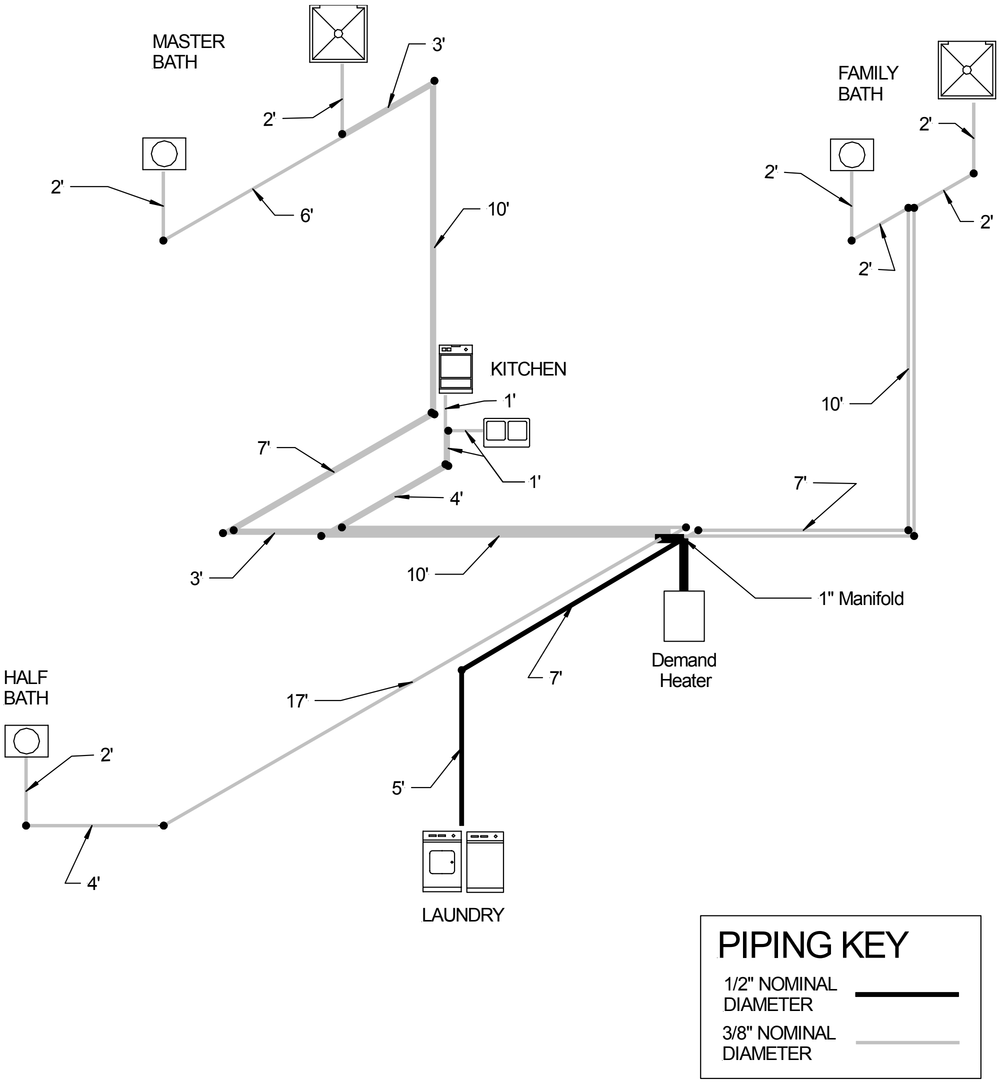

Figure 2: Parallel Piping System Layout as Simulated

4.3 Outlet Points

Simulations are performed with the water heater located in the utility room or in a central location and with seven hot water outlets as identified in Table 1.

Table 1: Hot Water Outlets in the Tree Piping System Design

Hot Water Outlet Point	Representative Fixtures	Location and Distance from Water Heater	
		Heater in Utility Room	Heater Centrally Located
1. Half Bath	Sink	Basement, 9'	Basement, 19'
2. Laundry Group	Washer, Utility Sink	Basement, 18'	Basement, 12'
3. Kitchen Group	Sink, Dishwasher	First Floor, 36'	First Floor, 16'
4. Family Bath, Shower	Shower/Tub Unit	Second Floor, 40.5'	Second Floor, 20.5'
5. Family Bath, Sink	Sink Unit	Second Floor, 40.5'	Second Floor, 20.5'
6. Master Bath, Shower	Shower/Tub Unit	Second Floor, 54.5'	Second Floor, 34.5'
7. Master Bath, Sink	Sink Unit	Second Floor, 60.5'	Second Floor, 40.5'

Since hot water use is sporadic throughout the day, the flows are assigned to each outlet based on the time of day and to groups of outlets (e.g., laundry group) based on percentage of flow the group receives. The assignment of flows is not intended to precisely account for the water flow at each fixture, but to distribute flows through different lengths of pipe throughout the day (to model piping heat losses) and to represent a typical hot water use distribution in the home. The flows are assigned as follows. Between 7:30 p.m. and 8:30 a.m., all the flow is assigned to the second floor fixtures. The shower outlets are assigned 75 percent of the flow and the sink outlets are assigned the remaining 25 percent. During the rest of the day, between 8:30 a.m. and 7:30 p.m., all flow is assigned to the basement and first floor outlets. The half bath receives five percent, the laundry group 23.75 percent, and the kitchen group, 71.25 percent of any flow event that occurs during the period.

In other simulations, the piping design is changed to a parallel piping type system where each outlet has a dedicated hot water supply pipe (typically 3/8-inch nominal diameter tubing). This system is designed with the heater centrally located and all piping lengths similar to that in the last column of Table 1. Refer to Figure 2 for the piping layout description. With the parallel piping system, a second kitchen outlet is added to separate the dishwasher from the kitchen sink, providing eight rather than seven outlets, since these outlets would be separated in a parallel piping system.

4.4 Hot Water Heating Equipment

The base case analysis includes a hot water storage tank with a copper tree-type distribution system. A tank size of 65 gallons was selected to be a midpoint between commercially-available large and small tanks to avoid penalizing one system over another based on water usage. Also, if a very large tank is used in the analysis, large stand-by losses may skew the results in favor of a demand heater, especially if the added capacity is underutilized.

The heat loss coefficient for the storage tank is assumed to be 0.1429 Btu/hr•ft^2•°F (R-7) and is determined from a brief telephone survey of water heater manufacturers regarding insulation values. The demand heater is assumed to have no loss associated with storage capacity. The hot water tank is assumed to have dual 4.5 kW heating elements operating in a primary-secondary fashion. Only one element may be activated at any time.

The delivery temperature for all simulation runs is set at 130°F. Common household water temperature settings range from about 120 to 140°F. Use of a midpoint provides a balance between performance for the high use home (delivery temperature can more easily be maintained during long hot water draws at higher delivery temperatures) and avoiding excessive standby losses (which are directly proportional to the set point in the low use home.

The demand heater used in the simulation is based on current technology where the input (electric) energy is capable of being finely regulated to accurately control delivered hot water temperature. The size of the unit is limited to 28 kW, a representative size for the largest available residential units. Also, increasing the capacity beyond 28 kW may be less realistic in terms of electrical services in most homes. A 28 kW unit draws about 117 amps at 240 volts.

4.5 Flow Data and Simulation Time Increment

Hot water system performance simulations require inputs of flow data from actual or contrived data. Several studies have disaggregated hot water usage in homes.[6] According to these studies, showers account for the largest single proportion of hot water use, between 40 and 45 percent. Other uses such as clothes washing account for about 12 percent and dishwashing between 5 and 10 percent. There is a wide variation in the distribution of household hot water use and an artificial division of the hot water flow to a particular outlet is less important in this analysis than is the energy delivered to the outlet, which is a function of piping losses. Piping losses, in turn, are a function of the assumed flow rate, length of draw, and pipe length—variables that must be assigned values for any simulation.

Of a more critical nature than distribution of hot water use is the individual time-step for flow events. A one-minute time-step is chosen to most accurately model piping heat loss, outlet hot water energy, and outlet delivery temperature. Although a larger time-step would be more convenient, hourly or daily time increments do not provide enough precision to analyze the desired parameters. Hourly (or daily) simulations overestimate piping heat loss and cannot simulate short duration water draws. In addition, the use of hourly simulations results in erroneous delivery temperatures at the outlet when an average flow over an hour is considered.

Since a main purpose of the simulation is to understand the impact of piping losses relative to water heater location, a smaller time increment (that more accurately simulates piping loss) is of great value. Likewise for modeling demand water heating equipment, the delivery temperature at an outlet is directly related to the flow rate, which is more accurate when averaged over a smaller time step. For these reasons, a one-minute time step is selected.

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[6] Refer to Appendix B for a previous Research Center report on hot water use for particular references related to hot water energy consumption and end uses.

5 DATA SET PARAMETERS FOR HOT WATER USE FOR TWO REPRESENTATIVE HOMES

In previous work supported by NREL and others, one-minute water heater flow data was recorded over a year for five homes near Cleveland, Ohio. This data reflects various levels of household hot water use, from a high range of 60 to 85 gallons per day to a low range of 20 to 40 gallons per day. The two extreme cases were chosen for simulation — one data set from the highest volumetric use home and the other from the lowest volumetric use home — to provide a range of savings that can be expected. If it is found that savings apply to only one of the water use profiles, the plumbing system design may need to be modified or at least recommended for a certain type of housing. Both data sets are applied to the same simulated plumbing system.

The data sets contain indoor air temperature, the minute average hot water flow, the inlet water temperature, and the water heater outlet temperature, among other data points. Of direct use in the simulation program is the minute flow data and the indoor air temperature. The flow data is applied directly to the water heating equipment and divided among specific outlets based on the time of day as described in Section 4.5. The indoor air temperature is used in calculations of piping losses. Piping losses are directly proportional to the temperature difference between the hot water in the pipe and the ambient air. Cold water and hot water temperatures from the data set are not used directly, in part because thermal lag effects of the sensors may have caused erroneous temperatures. However, the cold water inlet temperature is averaged on a monthly basis and then set as the inlet water temperature for each month of simulation. Hot water outlet temperature is a function of water heater set point and piping losses. Figure 3 shows the average monthly inlet water temperature for the year for the low and high use homes.

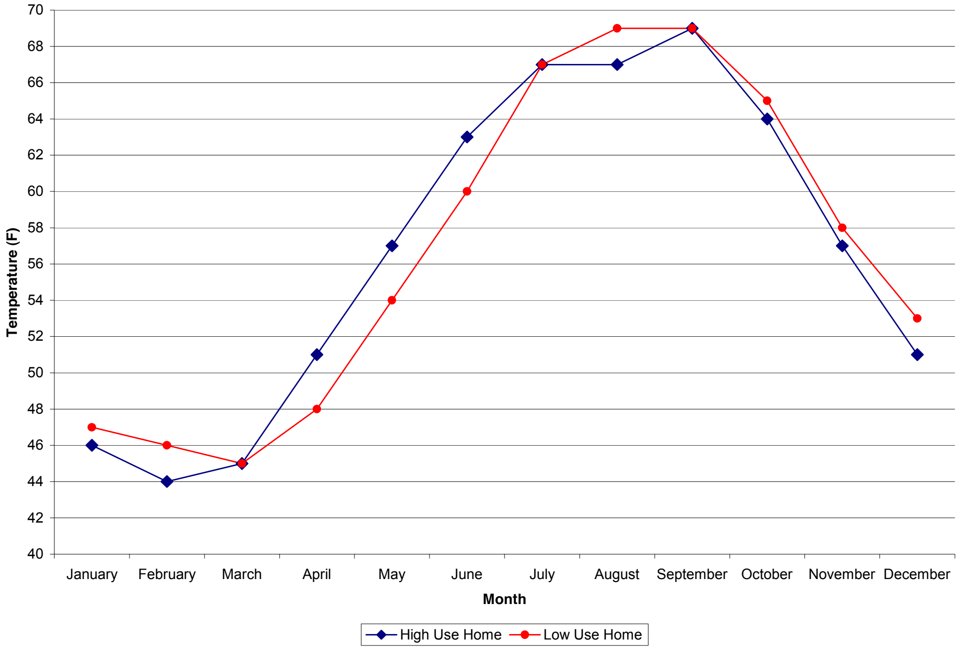

Figure 3: Average Monthly Cold Water Inlet Temperature for Each Home

The average daily hot water consumption for the high and low use homes differs dramatically. As shown in Figure 4, the use is variable throughout the year.

A previous literature review (see Appendix B) indicates that the average daily household hot water consumption in the U.S. is somewhere between 45 and 66 gallons per day (GPD) depending on the time of year. Since hot water usage in the homes used in this analysis (range of 66 to 86 GPD for the high use home and 15 to 41 GPD for the low use home) are significantly different from the national rate, they offer opportunities to understand the boundaries of potential savings.

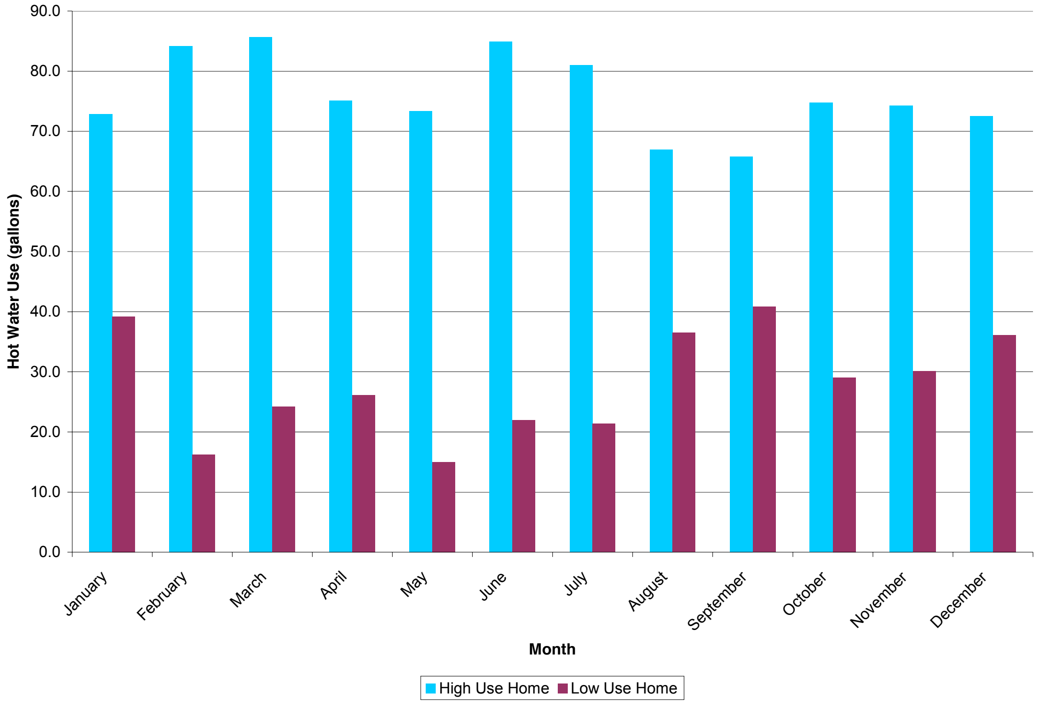

Figure 4: Average Daily Hot Water Consumption for Homes Used in Simulations

Another aspect of the actual hot water consumption data is the time-of-use of hot water throughout the day. Though daily variations exist, the general trend is for peak water use in the morning, relatively low usage throughout the day, and elevated water use in the evening. Refer to Figure 5 and Figure 6 for a review of hourly hot water use at both the high and low hot water use homes. Each data column is read from the bottom (January) to the top (December) with the column total in numerical format.

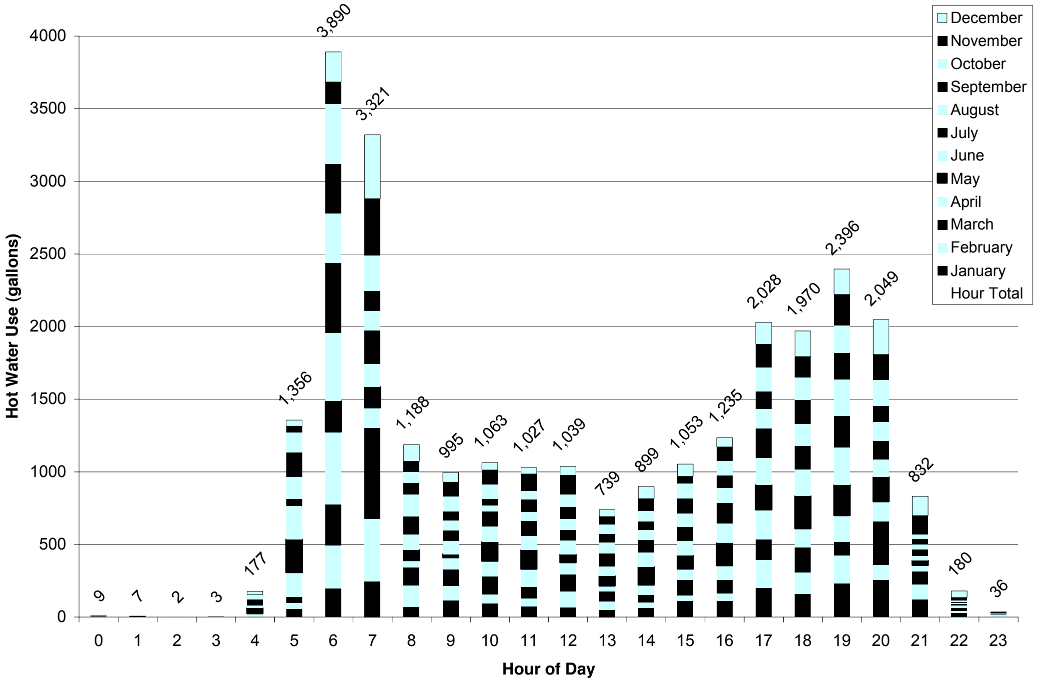

Figure 5: Annual Hourly Hot Water Use, High Use Home

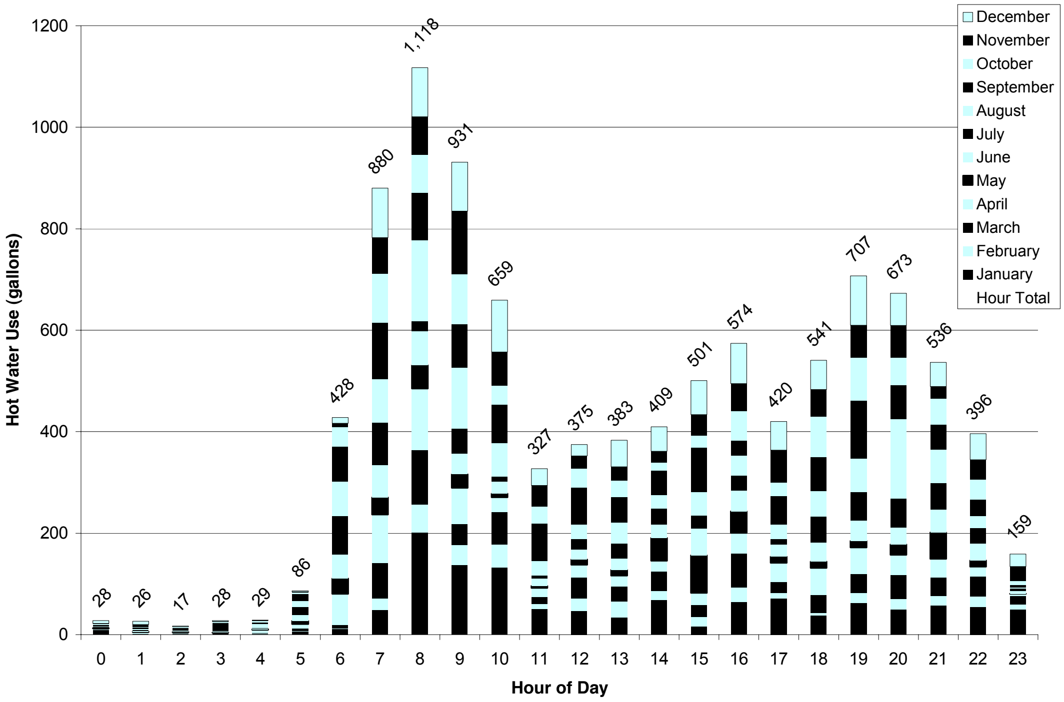

Figure 6: Annual Hourly Hot Water Use, Low Use Home

The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) publish an hourly load profile for domestic hot water use.[7] Figure 7 shows this load profile applied to the actual daily water consumption at the two homes. Comparison of the ASHRAE derived distribution with the actual hourly consumption from the data, in Figure 5 and Figure 6, shows similar profiles. The primary difference between the actual and ASHRAE derived data is that the water usage is less evenly distributed in the actual data—there are higher peaks and lower troughs and much less use in the early morning hours in the actual data.

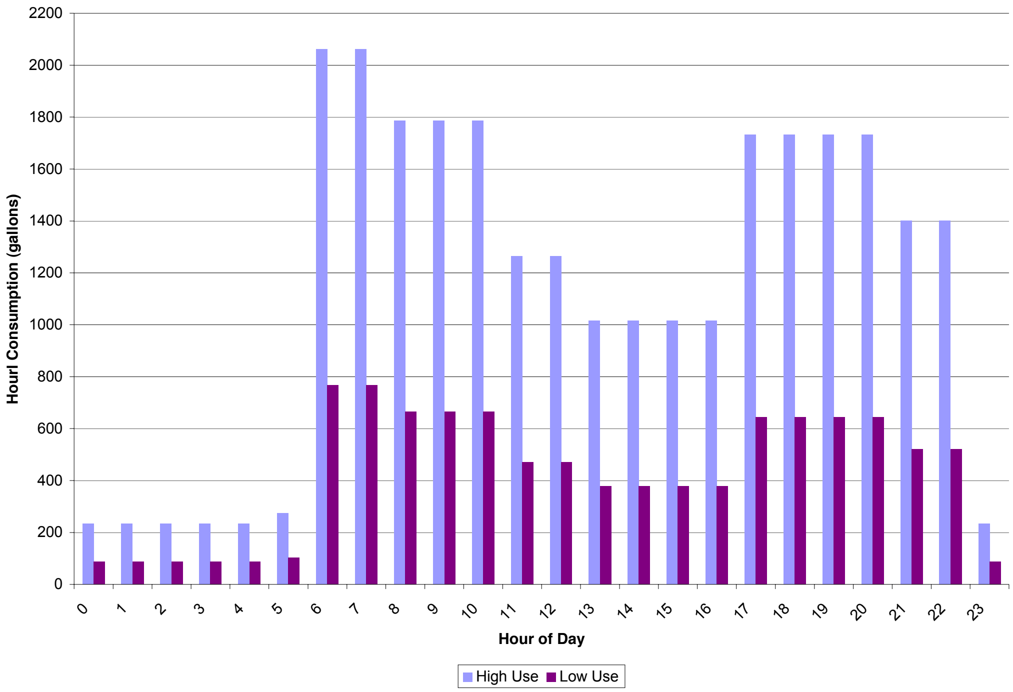

Figure 7: ASHRAE Hot Water Load Profile Applied to High and Low Use Home's Actual Use

Another important factor in hot water system design and function is the maximum hot water flow rate. Figure 8 and 9 show the maximum daily hot water minute flow for each home with the average for the year. For the low use home, the average does not include days where there were no draws. For the high use home, there are seven instances when the flow rate exceeds five gpm and 208 days when the maximum flow rate exceeded

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[7] ASHRAE Standard 90.2-1993, published by the American Society of Heating, Refrigeration and Air-

three gpm. These periods of high flow are potentially problematic for the demand water heater, and if sustained over several minutes, will also be challenging to the tank system as well. For the low use home, there are only four instances when the maximum hot water flow rate exceeds three gpm. As a reference, a 28 kW demand heater can raise 45°F water to 130°F at a maximum flow rate of 2.25 gpm, and 60°F inlet water temperature at a flow rate of 2.7 gpm.

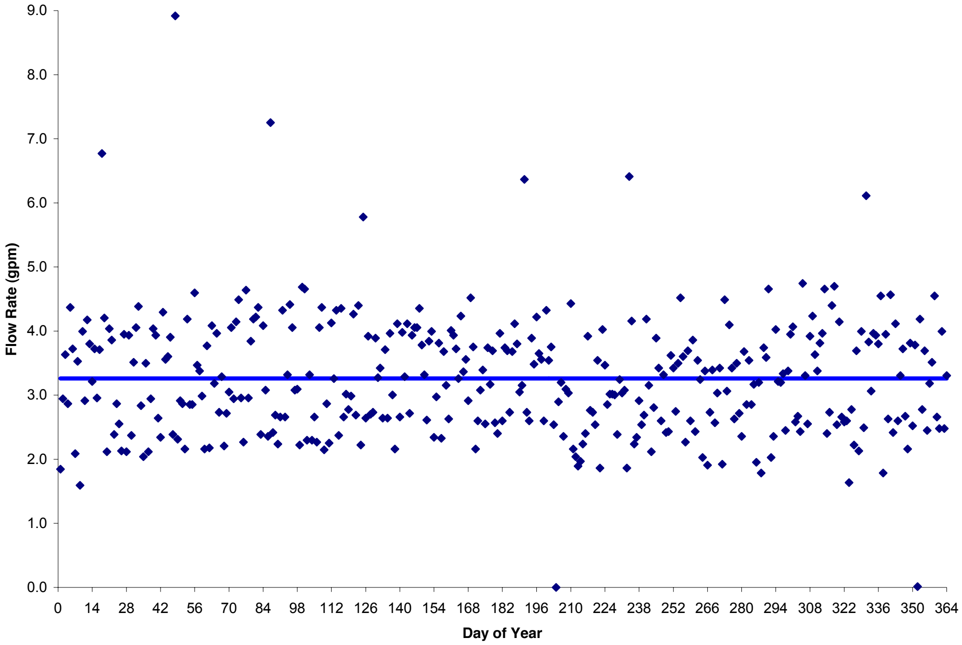

Figure 8: Maximum Daily Flow Rate, High Use Home

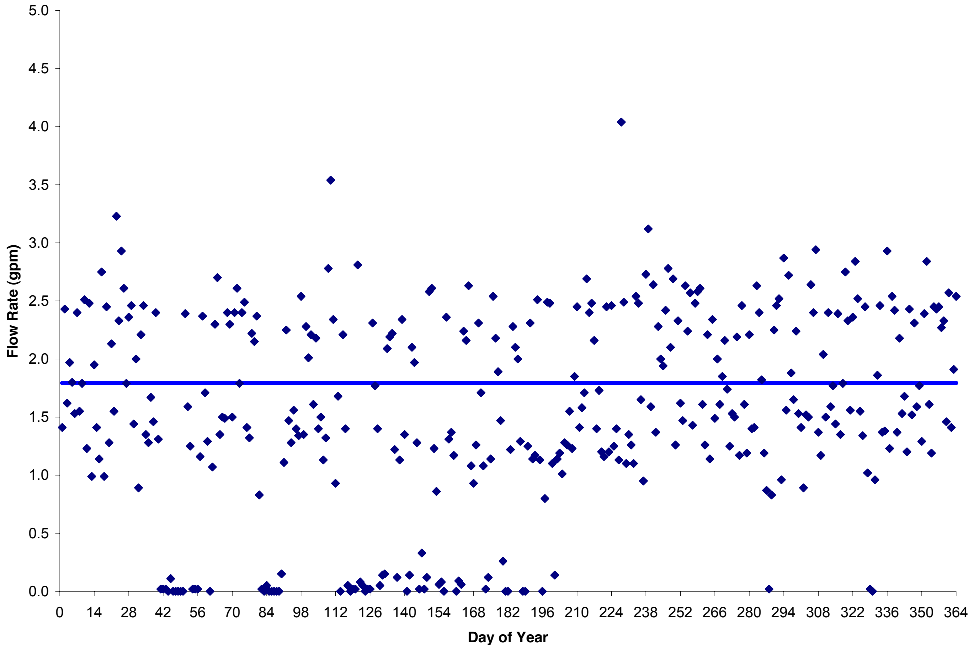

Figure 9: Daily Maximum Flow Rate, Low Use Home

Other flow rate data are described in Figure 10 through Figure 13. The distribution of flow is dramatically different between homes, however, the general trend is clear and consistent. In the high use home, higher flow rates are much more prevalent.

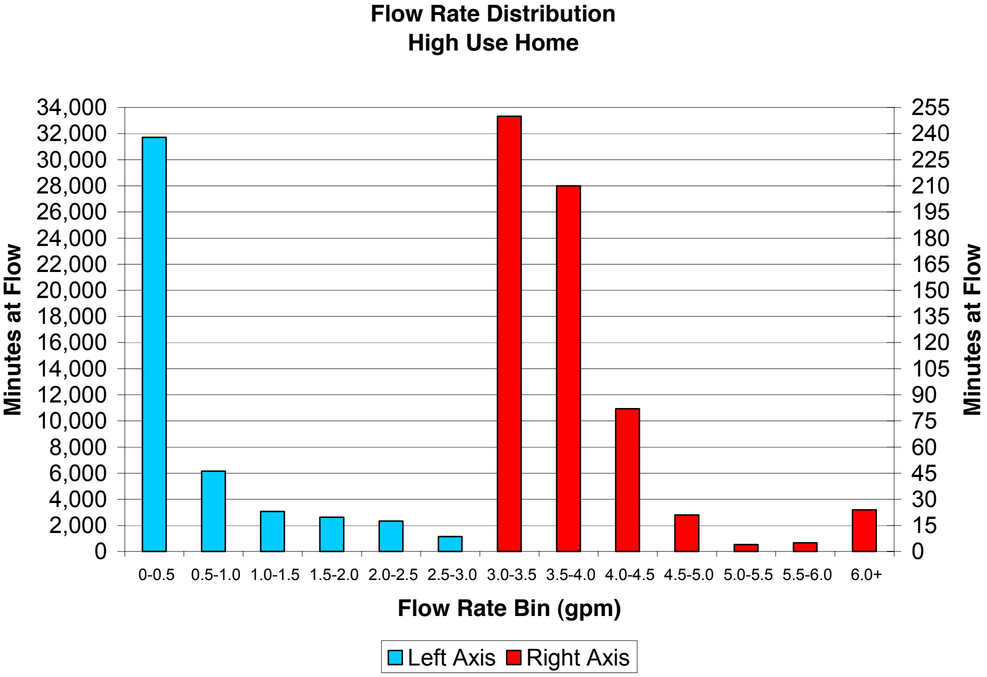

Figure 10: Frequency of Flow Rates in High Use Home

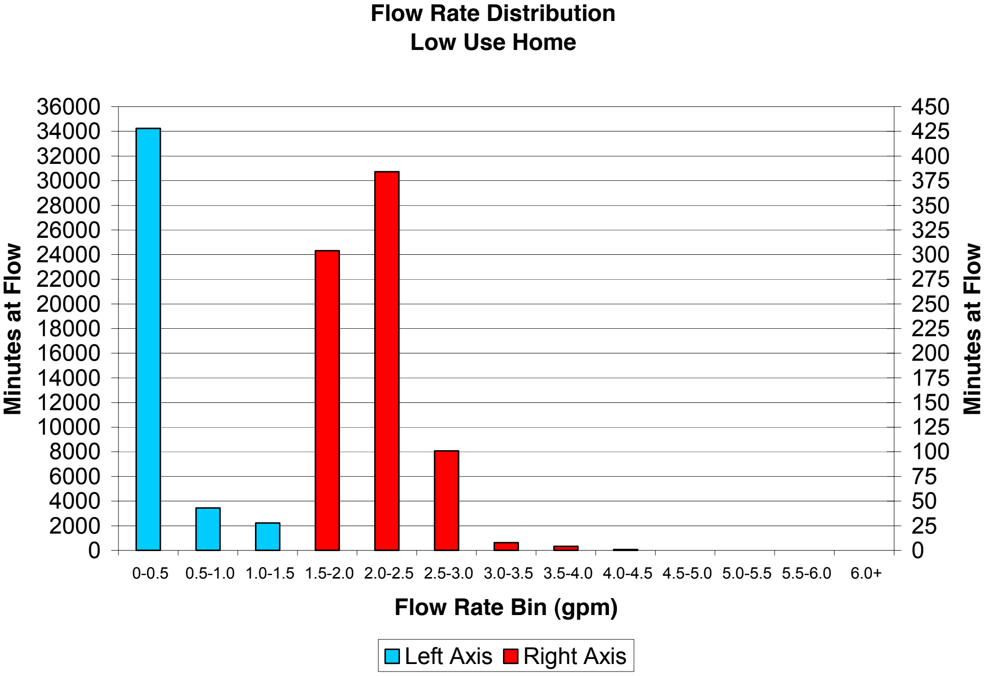

Figure 11: Frequency of Flow Rates in Low Use Home

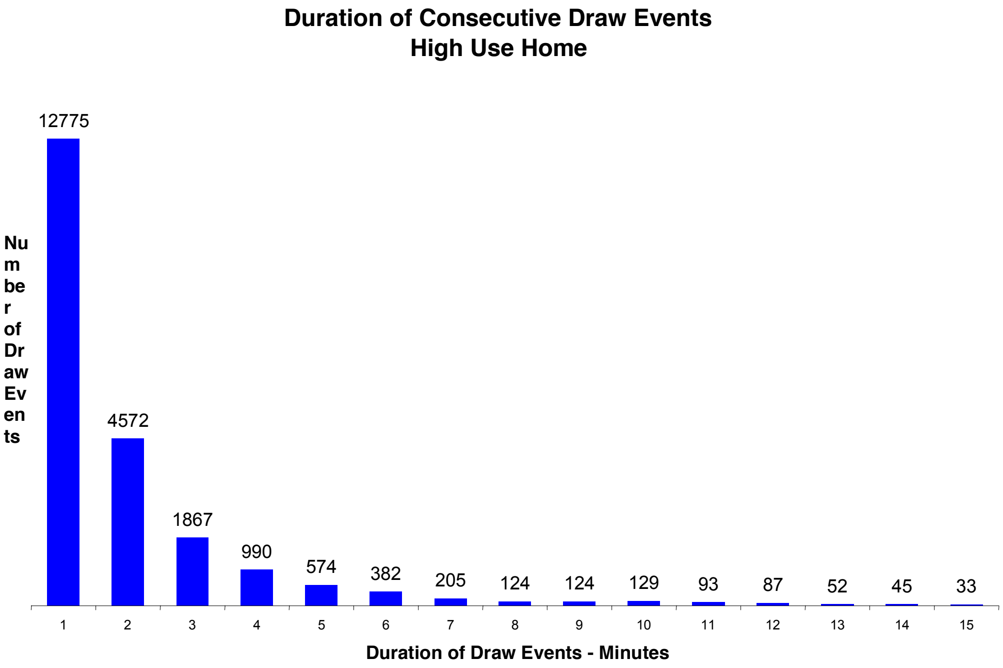

Figure 12: Draw Duration in High Use Home

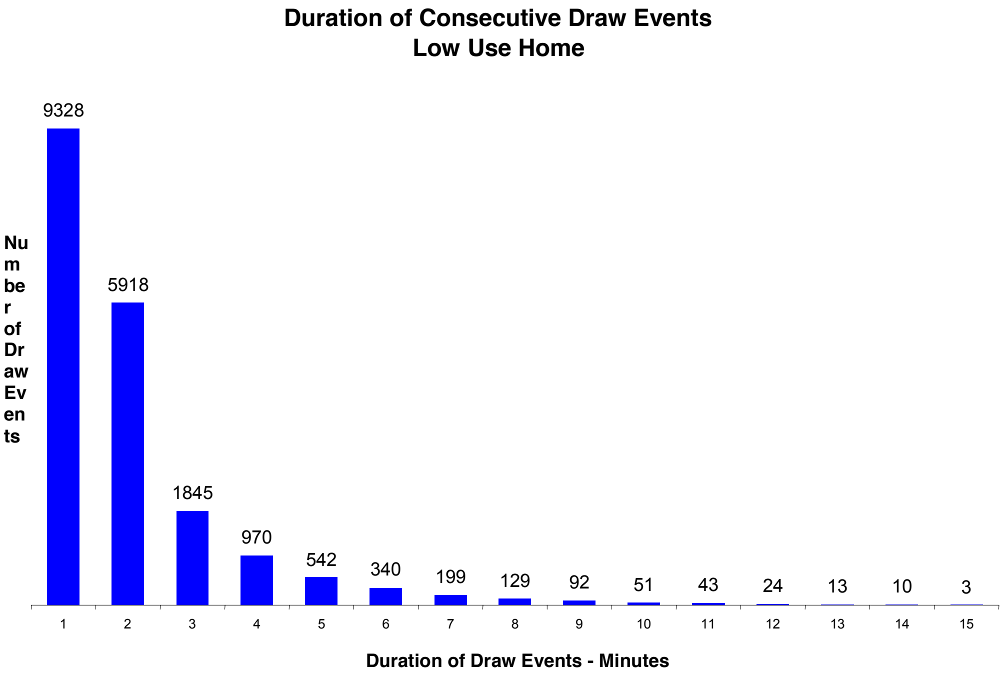

Figure 13: Draw Duration in Low Use Home

6 SIMULATION DESCRIPTION

A complete hot water system is modeled using a thermal systems simulation software package, TRNSYS.[8] TRNSYS is well known for its capability to handle many different system components and to solve for numerous heat transfer equations that describe the interaction of the components. Various components modeled by TRNSYS include water heating equipment, piping, and valves. Each of these components may be interconnected and/or controlled using equations or constants. The components may also be defined using specific characteristics such as heat transfer coefficient, length, or volume.

The model is constructed with the following components linked together to form a complete hot water system:

- A section of pipe representing the incoming water to the water heating equipment;
- Water heating equipment with or without storage;
- Sections of piping from the water heating equipment; and
- Control valves to shunt the water flow to various sections of piping and eventually to outlets.

In the model, each section of pipe is defined with a set of characteristics that include inside diameter and thermal conductivity. Calculating values for conductivity from the pipe surface to the surrounding environment is complicated, but is necessary for the purposes of this analysis for modeling uninsulated piping to capture piping losses. Uninsulated piping is chosen because the practice of insulating hot water pipes is sporadic and, when pipe insulation is used, the extent of insulation is varied. If insulated pipes are to be evaluated, piping losses may be directly reduced and applied to delivered hot water energy at the outlet.

The heat loss from pipes is described in Section 24.15 of ASHRAE Fundamentals (1997).[9] Considering uninsulated copper tubing, two primary components of heat

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[8] TRNSYS, a transient system analysis program developed at the University of Wisconsin-Madison.

[9] Refer to the 1997 ASHRAE Handbook of Fundamentals, Published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

transfer to the ambient environment are evaluated, namely heat losses associated with the convection and radiation components. The surface coefficient for convective heat transfer is calculated as follows:

$$h_{cv} = C\left(\frac{1}{d}\right)^{0.2}\left(\frac{1}{T_{avg}}\right)^{0.181}(\Delta T)^{0.266}\sqrt{1+1.277(Wind)}$$

$$\begin{aligned}
&where: h_{cv} = convection\,surface\,coefficient\\
&\quad d = diameter\ for\,cylinder\\
&\quad T_{avg} = average\,temperature\ for\,the\,air\ film\left({}^{\circ}R\right)\\
&\qquad between\,the\,ambient\,and\,surface\,temperatures\\
&\quad \Delta T = surface - to - air\,temperature\,difference\\
&\quad Wind = air\ speed,\ mph\\
&\quad C = shape\ factor\\
&\qquad (C = 1.016\,for\ horizontal\,cylinders)\\
&\qquad (C = 1.235\,for\,longer\,vertical\,cylinders)
\end{aligned}$$

The shape coefficient is weighted for the pipe length in each orientation. The weighting is based on the portion of pipe in an orientation relative to the total pipe length. The loss coefficient is always assumed to be in still air. The pipe surface temperature and ambient air temperature are assumed to be constant at 120°F and 72°F, respectively. Although these temperatures will vary, the heat transfer coefficient is not modified to reflect variations in temperature because significant modifications of the software would be required. The overall effect of this modification is anticipated to be small.

For the radiation component of heat loss, the methods outlined in ASHRAE Fundamentals (1997) are used. The radiation heat transfer coefficient is described as:

$$h_{rad} = \frac{\varepsilon\sigma\left(T_a^{\ 4} - T_s^{\ 4}\right)}{T_a - T_s}$$

$$\begin{aligned}
&where: h_{rad} = radiation\ surface\ coefficient\\
&\qquad \varepsilon = surface\ \ emissivity\\
&\qquad \sigma = Stefan - Boltzmann\ coefficient\\
&\qquad T_a = ambient\ air\ temperature\\
&\qquad T_s = pipe\ surface\ temperature
\end{aligned}$$

A dull surface emittance coefficient of 0.44 is used for copper. The heat transfer coefficients are not modified for other piping materials or pipe diameters since changing from copper to plastic materials results in a smaller diameter pipe having a lower convective loss and a higher radiative loss because of higher surface emittance. The net difference in the heat transfer coefficients is small, so they were left unchanged for all simulation runs.

For each month, a constant inlet water temperature is used in the simulation. All energy calculations are based in part on the inlet water temperature. The inlet water temperature ranges from about 44°F to about 69°F over the year. In the simulation, as in actual installations, the inlet water temperature impacts the ability of the water heating equipment to meet hot water demand.

The indoor air temperature is used in heat loss calculations for each piping section and for the water heating equipment. Although indoor air temperature was measured on the first floor in the homes that were used to create the data set, it is used directly in the model since it is the best approximation of the ambient air conditions and the changes in the ambient air temperature throughout the seasons. It is recognized that basements may be cooler and second floor areas may be warmer, influencing the losses from piping accordingly.

The output of the simulation is on the same time step as the simulation period, in this case, one minute. The following parameters were output for each simulation run:

- water heating equipment electric input;
- total flow rate to (and from) the water heating equipment;
- outlet temperature of the hot water at the water heating equipment;
- losses associated with the water heating equipment;
- hot water energy supplied by the water heating equipment;
- flow rate from each outlet;
- temperature at each outlet; and
- losses from each section of piping.

The simulation output data is analyzed further to determine the outlet energy delivered to each of the outlet points. This outlet energy, $\dot{q}$, is described by the equation:

$$\dot{q} = \dot{m} C_p \Delta T$$

Where $\dot{m}$ is the mass flow rate, C_p is the specific heat of water, and the temperature difference, ΔT, is the difference between the inlet water temperature to the water heating equipment and the outlet temperature at the fixture, based on the heat loss calculations in the simulation. The average monthly inlet water temperature is used as a reference point for making energy calculations, since it is from this temperature that the water must be heated to supply useful hot water output, and the calculations, therefore, represent total system efficiency. The simulation also uses the inlet water temperature as the basis for calculating the water heater energy required to supply hot water at the set point.

7 SIMULATION ANALYSIS PROCEDURES

As an additional measure of hot water system performance, simulation results are further processed to determine the delivered outlet energy at each fixture. For instance, with a more efficient hot water system the outlet energy will be greater because losses are lower and there is a greater supply of hot water at the outlets. Outlet energy is chosen as a basis for the system performance evaluation because it includes the performance of all system components up to the outlet.

Because the flow rate is fixed[10] at each time step, the outlet temperature from the tank system is used as a reference point for system performance calculations. The tank system outlet temperature is defined as 100 percent—any outlet temperature lower than the tank system is less than 100 percent and any outlet temperature exceeding the tank system is higher than 100 percent. The outlet temperature then, is the only variable from simulation to simulation that affects the outlet energy.

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[10] If the flow rate were variable it may be possible to use a feedback loop such that the outlet temperature is held constant, thus causing a change in the flow rate (to keep the outlet temperature constant).

8 SIMULATION RESULTS

A year of worth of one-minute data is processed on a monthly basis for each hot water system. Two flow rates are evaluated: one representing a home with high average hot water consumption and one representing a home with low average hot water consumption. From the evaluation of these extremes of hot water consumption, holding the piping design and equipment descriptions constant, the boundaries of energy consumption, losses, and hot water delivery issues may be understood.

An example of a monthly summary of the simulation output is shown in Table 2. The monthly summary provides details on the overall system performance. However, the summary does not address specific issues such as hot water delivery temperature at an outlet during a specific flow event. Evaluation of hot water delivery temperature was performed for one month for the high use home. The extreme case was selected, one winter month, because of the large amount of data processing required for this analysis.

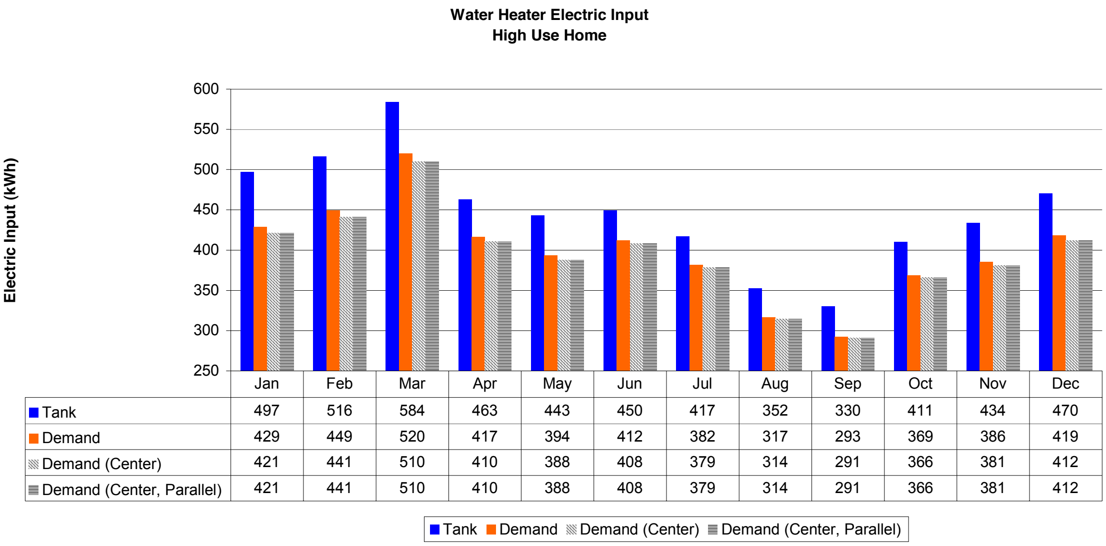
Table 2: Example of Monthly Summary Output of Hot Water System Model, January 1998 (31 Days)

Hot Water Simulation Run	High Use House		Tank System		
Total Gallons Flow	2259	Gallons	Tank Temperature Settings		
Average Gallons per Day	72.9	Gpd	130	°F Upper	
Maximum Tank Flow Rate	6.76	Gpm	130	°F Lower	
Inlet Water Temperature	46.0	°F			
Flow per Outlet					
Half Bath	59.2	Gallons	2.6%	of total	
Laundry	281.2	Gallons	12.4%	of total	
Kitchen (All)	843.5	Gallons	37.3%	of total	
Family Shower	401.9	Gallons	17.8%	of total	
Family Sink	134.0	Gallons	5.9%	of total	
Master Bath Shower	404.1	Gallons	17.9%	of total	
Master Bath Sink	134.7	Gallons	6.0%	of total	
Delivered Tank Energy	1,528,903	Btu			
Tank Losses	159,932	Btu			
Tank Lower Element	1,677,166	Btu			
Tank Upper Element	19,096	Btu			
Tank Electric Energy Input	1,696,262	Btu	497.13	kWh	
Table continued on next page					
Total Piping Losses	206,312	Btu			

Hot Water Simulation Run	High Use House		Tank System		
Delivered Outlet Energy	1,323,054	Btu			
Half Bath	33,016	Btu	558	Btu/gallon	
Laundry	175,212	Btu	623	Btu/gallon	
Kitchen (All)	509,147	Btu	604	Btu/gallon	
Family Shower	234,987	Btu	585	Btu/gallon	
Family Sink	76,227	Btu	569	Btu/gallon	
Master Bath Shower	224,216	Btu	555	Btu/gallon	
Master Bath Sink	70,248	Btu	522	Btu/gallon	
Outlet Losses					
Half Bath	6,697	Btu	113	Btu/gallon	
Laundry	13,427	Btu	48	Btu/gallon	
Kitchen (All)	56,769	Btu	67	Btu/gallon	
Family Shower	39,812	Btu	99	Btu/gallon	
Family Sink	15,372	Btu	115	Btu/gallon	
Master Bath Shower	51,961	Btu	129	Btu/gallon	
Master Bath Sink	21,811	Btu	162	Btu/gallon	
			Pipe Losses		
Delivered Outlet to Delivered Tank Energy	86.5%		section a	15,961	Btu
Delivered Outlet to Electric Input Energy	78.0%		section b	41,434	Btu
Pipe Losses to Electric Input	12.2%		section c	25,549	Btu
Tank Losses to Electric Input	9.4%		section d	28,053	Btu
			section e	32,653	Btu
Maximum Delivered Temperature			section f	14,610	Btu
Tank Outlet	130.2	°F	section g	16,100	Btu
Half Bath	128.7	°F	section 1	6,306	Btu
Laundry	129.5	°F	section 2	6,264	Btu
Kitchen (All)	129.3	°F	section 3	6,174	Btu
Family Shower	129.2	°F	section 4	3,468	Btu
Family Sink	129.0	°F	section 5	3,262	Btu
Master Bath Shower	128.7	°F	section 6	1,482	Btu
Master Bath Sink	128.0	°F	section 7	4,996	Btu

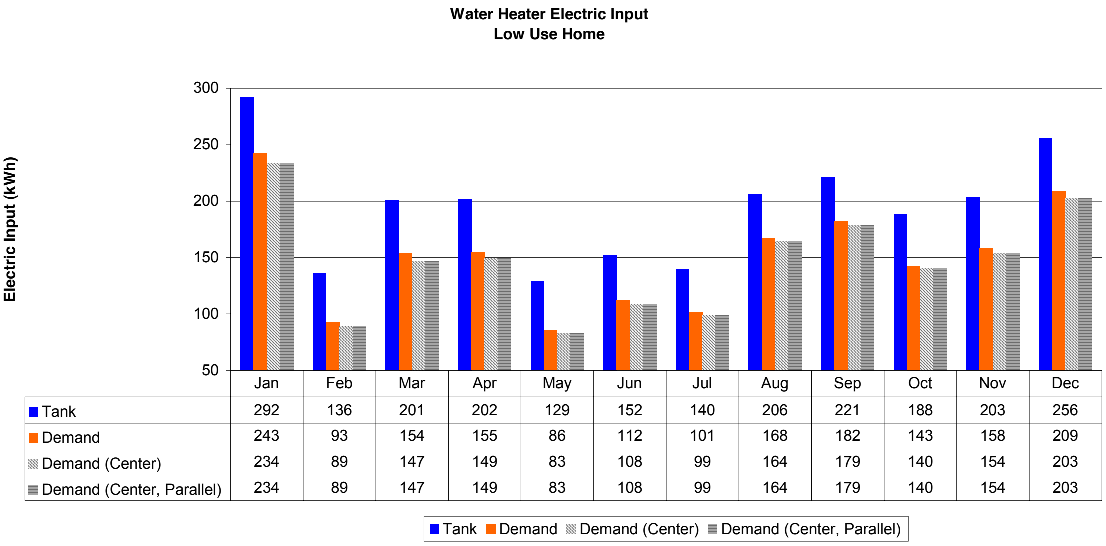
8.1 Energy Use

For each of the four hot water systems (tank, demand, centrally-located demand, centrally-located demand with parallel piping), the monthly electric consumption is simulated based on the inlet water temperature and the set point of the water heater. The simulated electric consumption does not reflect the outlet energy measured for each system. Figure 14 and Figure 15 compare the electrical energy consumption of the four systems for the high and low use homes.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
■ Tank	497	516	584	463	443	450	417	352	330	411	434	470
■ Demand	429	449	520	417	394	412	382	317	293	369	386	419
▨ Demand (Center)	421	441	510	410	388	408	379	314	291	366	381	412
▤ Demand (Center, Parallel)	421	441	510	410	388	408	379	314	291	366	381	412

Figure 14: Water Heater Electric Use, High Use Home



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
■ Tank	292	136	201	202	129	152	140	206	221	188	203	256
■ Demand	243	93	154	155	86	112	101	168	182	143	158	209
▨ Demand (Center)	234	89	147	149	83	108	99	164	179	140	154	203
▤ Demand (Center, Parallel)	234	89	147	149	83	108	99	164	179	140	154	203

Figure 15: Water Heater Electric Use, Low Use Home

Ignoring delivery temperature, the demand system shows energy savings over the tank system, primarily because of reduced tank losses. The demand heater located in the utility room shows higher energy use than the central location because longer pipe runs to the outlets result in higher energy losses. With the demand heater located in the center of the basement, the two piping systems (tree and parallel piping) show equal amounts of electric consumption since the flow rate through the demand heater is identical in each case and heat transfer coefficients were assumed identical. However, the energy supplied to each outlet is of direct interest since this energy is controlled by the user and will have a direct impact on the electrical energy consumption. Figure 16 and Figure 17 show the total outlet energy for each system on a monthly basis.

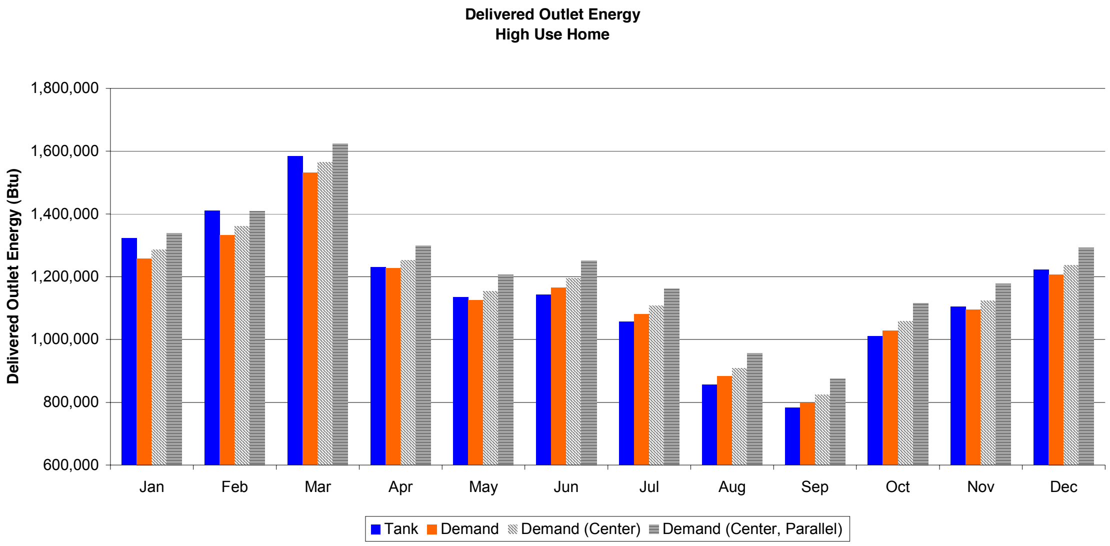


Figure 16: High Use Home, Outlet Energy

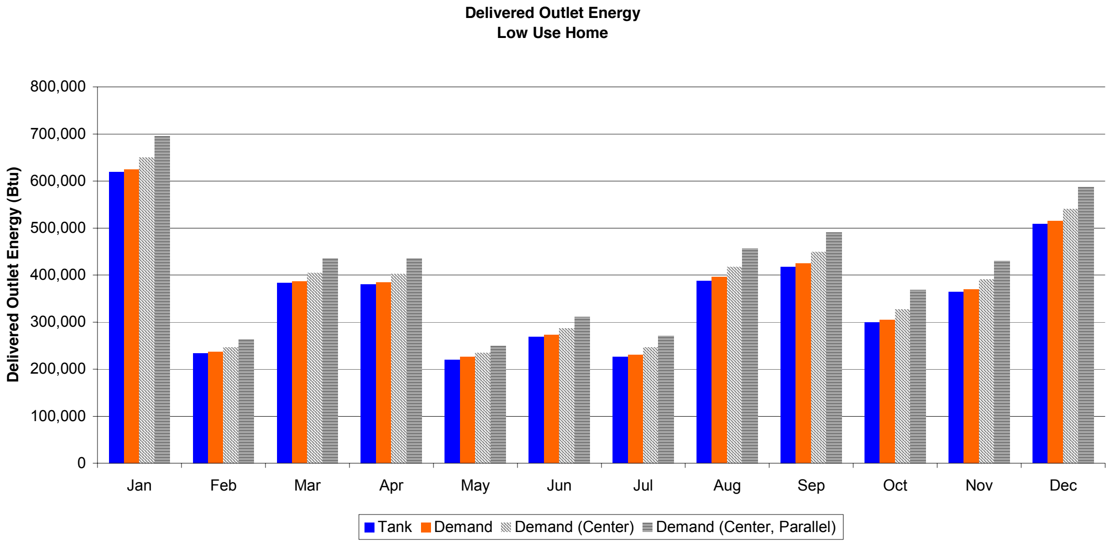
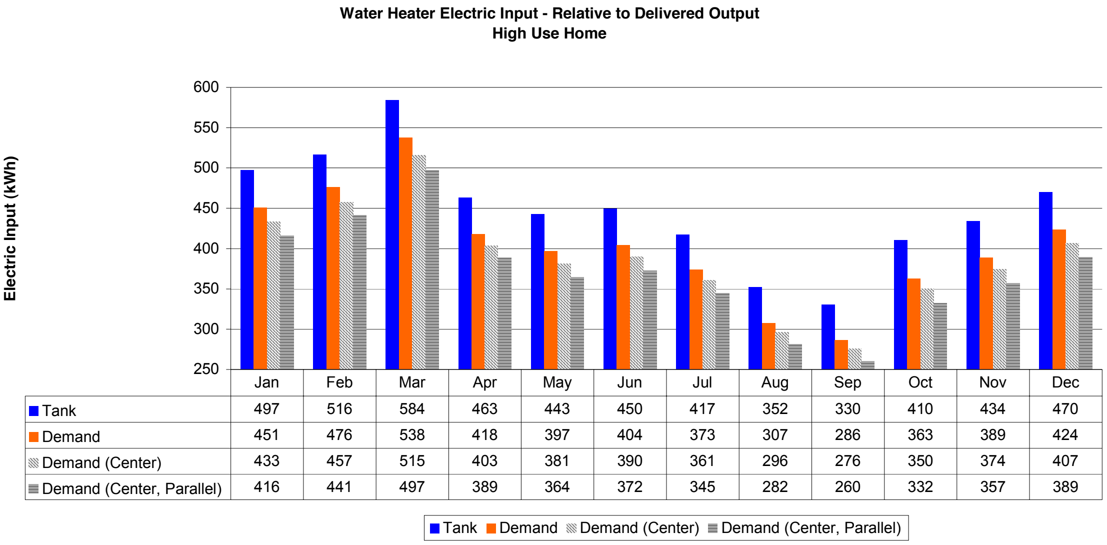


Figure 17: Low Use Home, Outlet Energy

One indicator of system performance is outlet energy—the amount of energy delivered to fixtures. Because flow rates are the same for all systems, a difference in outlet energy is proportional to the difference in delivery temperatures.

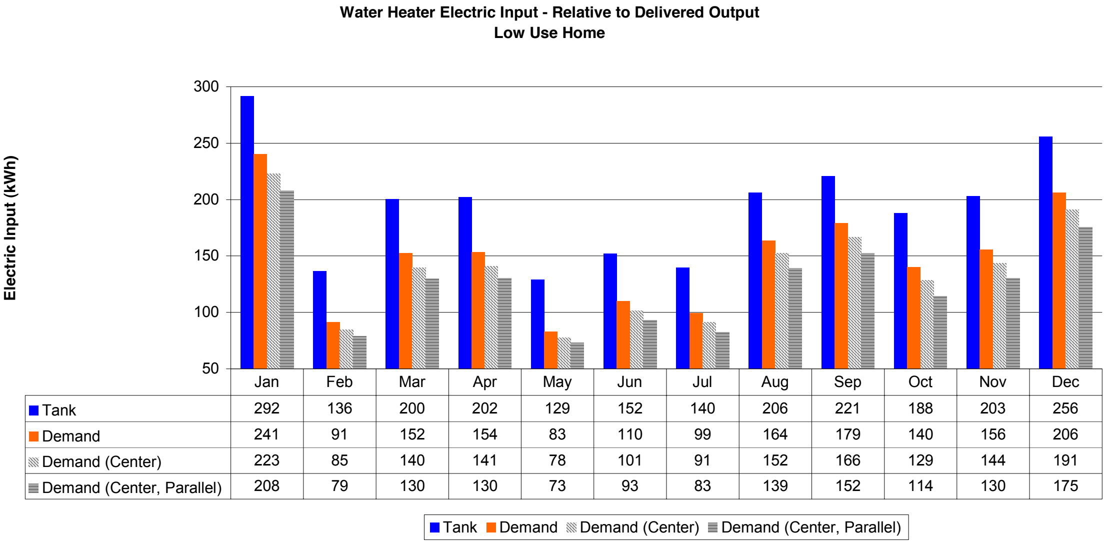
In the high use home, with the tank and demand heaters in the same location, total monthly delivered outlet energy is lower for the demand heater in seven of the twelve months. When the demand heater is moved to a central location, the delivered outlet energy is lower than the tank for three of twelve months. Finally, when the demand heater is centrally located and combined with a parallel piping system, the outlet energy is found to be greater than that of the tank system for all but one month. In the low use home, the demand heater delivers higher outlet energy than the tank system in all scenarios.

One method for evaluating any energy savings (or losses) due to increased or decreased outlet energy is to recalculate the demand heater input energy based on outlet energy. This recalculation is possible because the demand heater is designed to supply only the energy needed to raise the water to a desired set point. Any additional outlet energy may result in less hot water use—for example when a user reduces the amount of hot water flow because of the increased outlet temperature — although not all outlets may be directly controlled by the homeowner. Directly modifying the input energy based on outlet energy is one method for quantifying system performance. For example, if the demand system outlet energy is 95 percent of the tank system outlet energy, the input energy of the demand system is divided by 0.95 to account for the added energy required to match the outlet energy of the tank system. Figure 18 and Figure 19 show the results of this analysis when using the tank system results as the base.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
■ Tank	497	516	584	463	443	450	417	352	330	410	434	470
■ Demand	451	476	538	418	397	404	373	307	286	363	389	424
▨ Demand (Center)	433	457	515	403	381	390	361	296	276	350	374	407
▤ Demand (Center, Parallel)	416	441	497	389	364	372	345	282	260	332	357	389

Figure 18: Modified Electric Input Relative to Output Energy, High Use Home



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
■ Tank	292	136	200	202	129	152	140	206	221	188	203	256
■ Demand	241	91	152	154	83	110	99	164	179	140	156	206
▨ Demand (Center)	223	85	140	141	78	101	91	152	166	129	144	191
▤ Demand (Center, Parallel)	208	79	130	130	73	93	83	139	152	114	130	175

Figure 19: Modified Electric Input Relative to Output Energy, Low Use Home

Table 3 summarizes the simulated hot water electric energy supply, with the simulation results modified by the outlet energy with the tank system as the base. On an annual basis for the high use home, the demand heater uses 12 percent less energy than the tank system, or a savings of 646 kWh. When the energy use of the demand heater is modified due to the increased outlet energy, the savings are increased by about 5 percent to 920 kWh annually. Similarly for the low use home, the maximum annual savings is increased from 24.8 percent (576 kWh) to 35.1 percent (817 kWh).

Table 3: Summary Hot Water Energy Use

High Use Home-Summary Data Across Systems											
	Delivered Outlet Energy Relative to Tank Outlet Base				Water Heater Electric Input Energy Per Simulation and Modified Based on Outlet Energy						
						Demand System		Central Demand		Central Demand/PP*	
	Tank (%)	Demand (%)	Central Demand (%)	Central Demand/ PP* (%)	Tank System	Simulation	Modified	Simulation	Modified	Simulation	Modified
Jan	100.0	95.1	97.2	101.2	497	429	451	421	433	421	416
Feb	100.0	94.4	96.4	99.8	516	449	476	441	457	441	441
Mar	100.0	96.8	98.9	102.6	584	520	538	510	515	510	497
Apr	100.0	99.7	101.7	105.6	463	417	418	410	403	410	389
May	100.0	99.2	101.7	106.4	443	394	397	388	381	388	364
Jun	100.0	102.0	104.7	109.6	450	412	404	408	390	408	372
Jul	100.0	102.2	104.9	109.8	417	382	373	379	361	379	345
Aug	100.0	103.1	106.0	111.6	352	317	307	314	296	314	282
Sep	100.0	102.2	105.5	111.9	330	293	286	291	276	291	260
Oct	100.0	101.6	104.6	110.3	410	369	363	366	350	366	332
Nov	100.0	99.2	101.8	106.7	434	386	389	381	374	381	357
Dec	100.0	98.8	101.3	105.8	470	419	424	412	407	412	389
Year	100.0	99.1	101.6	106.1	5,367	4,786	4,829	4,721	4,648	4,721	4,447
Electric Use As Percent of Tank System					100.0	89.2	90.0	88.0	86.6	88.0	82.9

Table continued on next page

Low Use Home-Summary Data Across Systems

	Delivered Outlet Energy Relative to Tank Outlet Base				Water Heater Electric Input Energy Per Simulation and Modified Based on Outlet Energy						
						Demand System		Central Demand		Central Demand/PP*	
	Tank (%)	Demand (%)	Central Demand (%)	Central Demand/ PP* (%)	Tank System	Simulation	Modified	Simulation	Modified	Simulation	Modified
Jan	100.0	100.9	104.9	112.4	292	243	241	234	223	234	208
Feb	100.0	101.3	105.1	112.8	136	93	91	89	85	89	79
Mar	100.0	100.8	105.4	113.5	200	154	152	147	140	147	130
Apr	100.0	100.9	105.7	114.3	202	155	154	149	141	149	130
May	100.0	103.1	106.8	113.5	129	86	83	83	78	83	73
Jun	100.0	101.8	106.9	116.2	152	112	110	108	101	108	93
Jul	100.0	102.0	108.5	119.8	140	101	99	99	91	99	83
Aug	100.0	102.3	107.9	118.0	206	168	164	164	152	164	139
Sep	100.0	101.7	107.4	117.4	221	182	179	179	166	179	152
Oct	100.0	101.7	109.2	123.0	188	143	140	140	129	140	114
Nov	100.0	101.7	107.3	118.2	203	158	156	154	144	154	130
Dec	100.0	101.3	106.2	115.5	256	209	206	203	191	203	175
Year	100.00	101.5	106.6	115.9	2,326	1,803	1,776	1,750	1,641	1,750	1,509
Electric Use As Percent of Tank System					100.0	77.5	76.3	75.2	70.8	75.2	64.9

**PP-Parallel Piping System*

8.2 Sample Water Delivery Temperatures

A sample winter month in the high use home is considered when evaluating the delivery temperatures of the demand heater versus the delivery temperatures of the tank system. The tank system is considered the base with all other delivery temperatures relative to this base. The delivery temperature of the other systems may be either higher or lower than the tank system.

The demand heater delivery temperatures depend on the incoming water temperature, the flow rate, and the available electric input. A limit is placed on the electrical input to the demand heater based on realistic typical residential electric capacity and available sizes of residential demand heaters. Figure 20 shows the delivery temperatures from one of the outlet points most distant from the water heater (outlet 6) for both the tank system and the demand system located in the utility room.

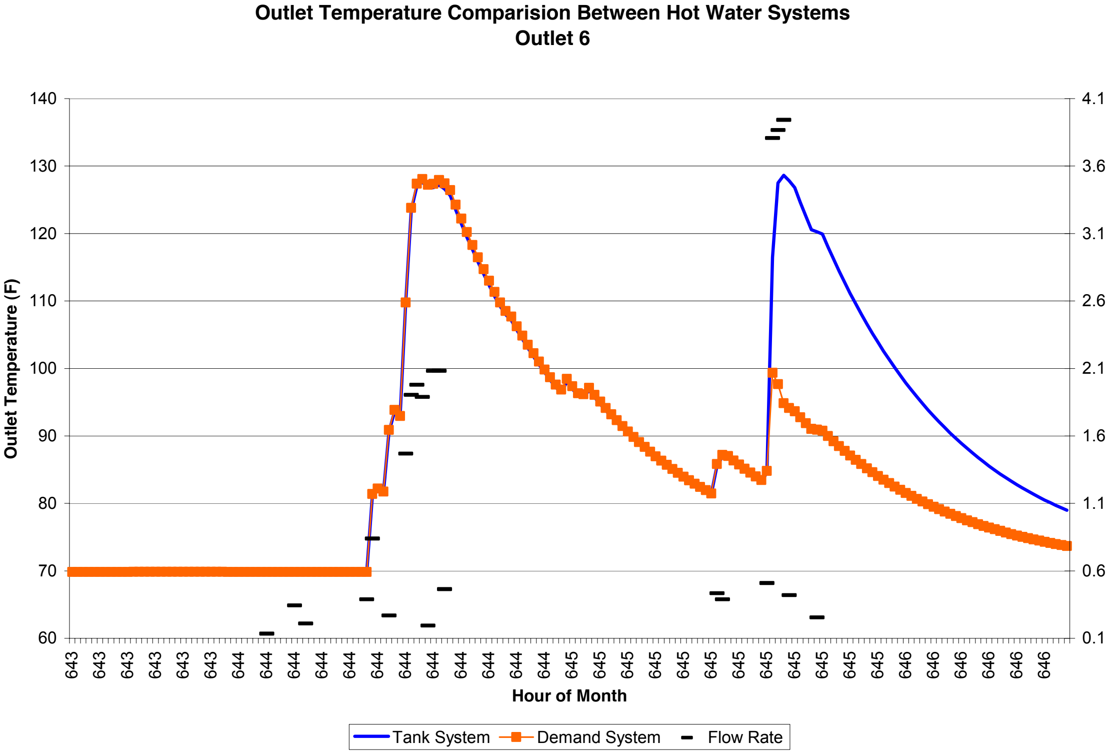


Figure 20: Comparison of Delivery Temperatures over a Three-Hour Period

During periods of low flow rate, both the demand and the tank systems deliver near-set point water temperatures at the outlet and, therefore, are performing adequately. However, during some periods of high flow rate, the demand heater is unable to supply the same water temperature as the tank system. In the case in Figure 21, the difference between set point and delivery temperature is 28°F at which point the delivery temperature is probably unacceptable to the homeowner. The tank system delivers colder temperatures than the demand system during periods of long, low flow rate draws, on the order of four or more minutes, as shown in Figure 21. During these periods, the demand heater is able to continually supply high temperature water to the outlet whereas the tank system recovery rate is exceeded.

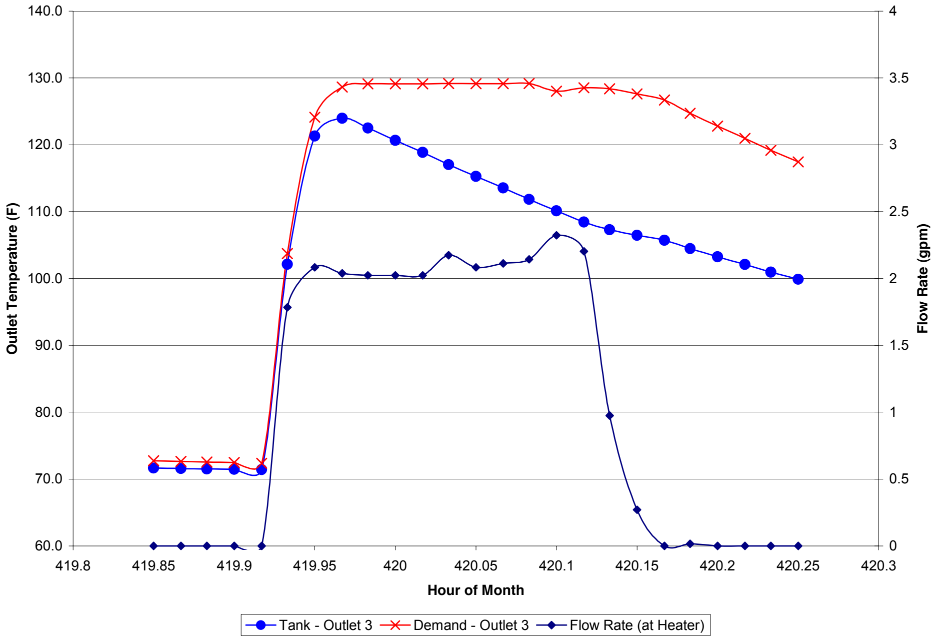


Figure 21: Outlet Temperature during Period of Sustained Flow for Both Tank and Demand Heater System

For the month evaluated, the tank delivery temperature exceeded the demand heater delivery temperature. Figure 22 and Figure 23 show the temperature difference between the tank and demand delivery temperatures at outlet 6 for the entire month (during periods of flow). The tank delivery temperature exceeds that of the demand system located in the utility room connected with the tree piping system more frequently than the demand system outlet temperature exceeds the tank delivery temperature. When the tank temperature exceeds the demand temperature, the difference is as high as 35°F. Much smaller temperature differences exist when the demand delivery temperature exceeds the tank delivery temperature. Figure 22 shows instances where the difference between the tank and the demand systems delivery temperature exceeds 5°F. Examining Figure 22, it is evident that outlet delivery temperature is dependent on flow rate and that flows above 5 gpm, with an inlet temperature of near 50°F, severely limit the outlet delivery temperature with the demand system.

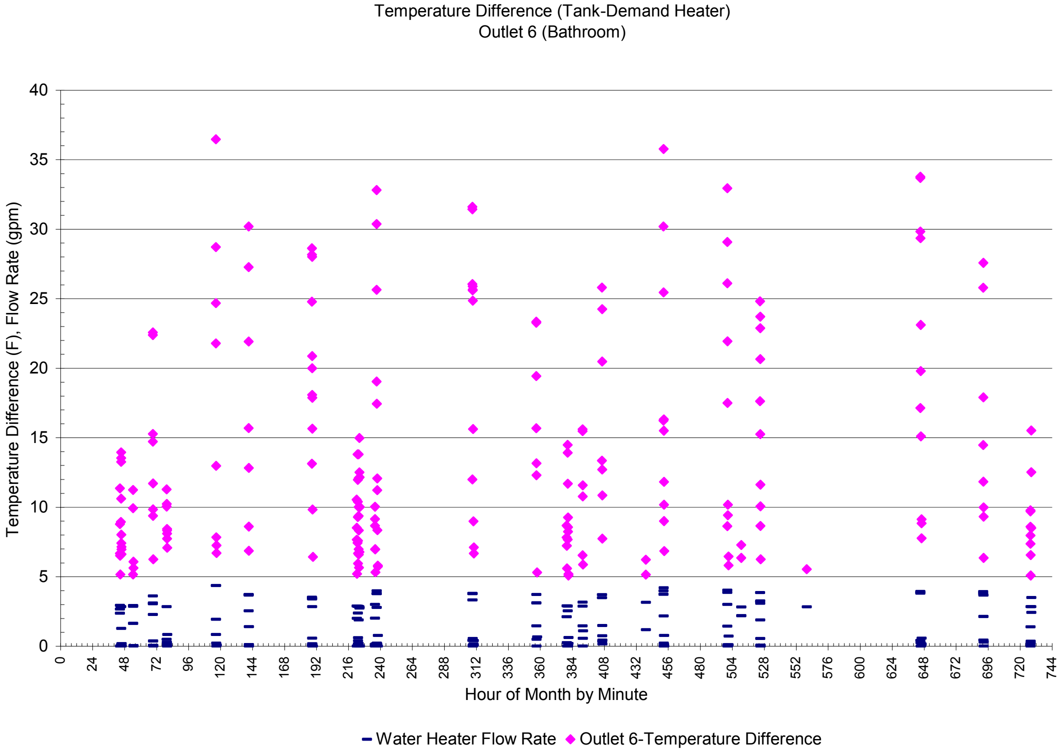


Figure 22: Temperature Difference from Tank to Demand Heaters over 5°F

Changing the plumbing configuration and materials can improve the delivery temperature of the demand system. In the low use home, delivery temperature of the demand system at high flow rates is not as problematic as it is with the high use home because peak flow rates are lower. The delivery temperature of the various systems is useful in showing the effect of demand heater location and water piping design on the hot water delivery temperature. The demand heater, regardless of piping system, delivers lower temperature water than the tank system during periods of high flow rates. This is simply a function of the capacity of the demand heater. However, during periods of low flow rates, the number of instances where the demand parallel piping system supplies water at a temperature higher than the tank temperature is significant; many more times than the demand heater located in the utility room connected with a tree piping system. Figure 23 shows instances during the month of January in which delivery temperature for the demand system was measurably different than the tank system. With the demand heater located in the utility room, the outlet temperature from the tank system exceeded that of the demand system by 5°F or more for 107 out of 1,621 minutes (6.6% of the time). By moving the demand heater to a central location and replacing the tree system with a parallel piping system, the frequency with which the tank outlet temperature exceeds the demand heater outlet temperature by 5°F or more is reduced to 4.6%.

Conversely, there are instances when the demand heater outlet temperature exceeds the tank outlet temperature by 5°F or more. For the demand heater in the utility room, this occurs 24 out of 1,621 minutes. For the demand heater centrally located and combined with a parallel piping system, the demand heater outlet temperature is higher than the tank outlet temperature for 296 out of 1,621 minutes.

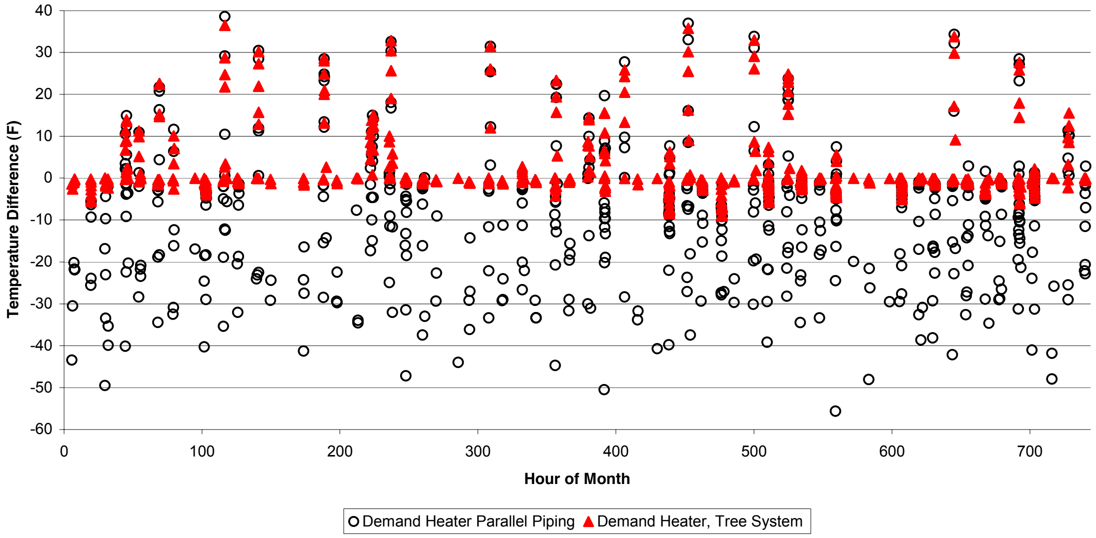


Figure 23: Outlet 6 Delivery Temperature between Two Demand Systems and the Tank System

Both demand heater systems, however, suffer from significantly lower delivery temperatures than the tank system during periods of high flow. However, the parallel piping system routinely supplies higher-than-tank temperatures, providing an opportunity for energy savings by requiring less hot water to meet the load.

8.3 Piping Losses

The simulated piping losses are shown in Figure 24 and Figure 25. Losses are shown both as absolute in Btu's and as a percentage of the electric input to the water heater. Since each home's water use is different both in quantity and time-of-day, the losses are different. One common feature, however, is that the parallel piping system results in the lowest loss of all systems, even when considering the higher delivery temperatures of the demand system. The losses are not modified based on the outlet energy in the two figures.

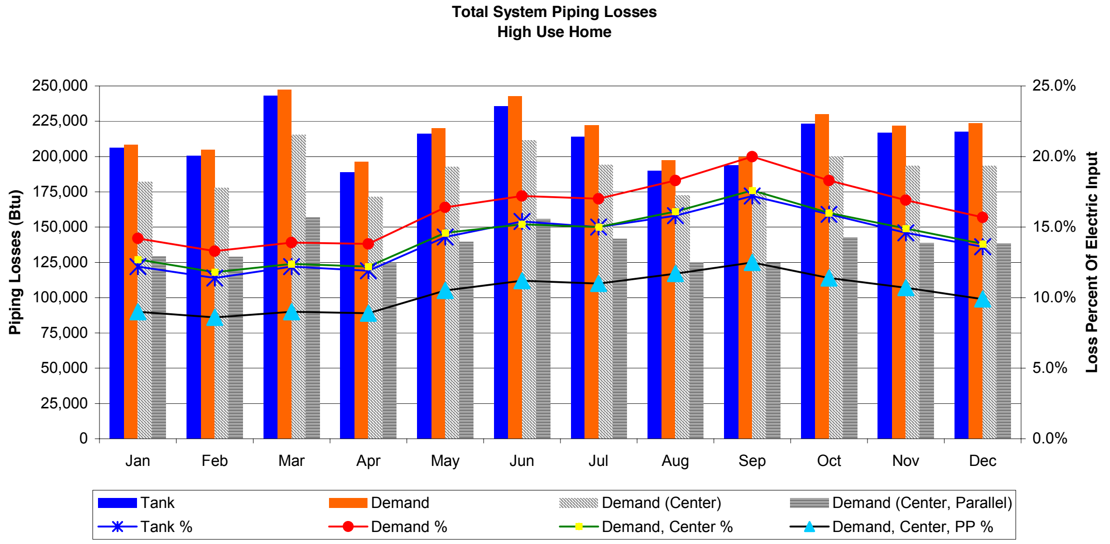


Figure 24: System Piping Losses, High Use Home

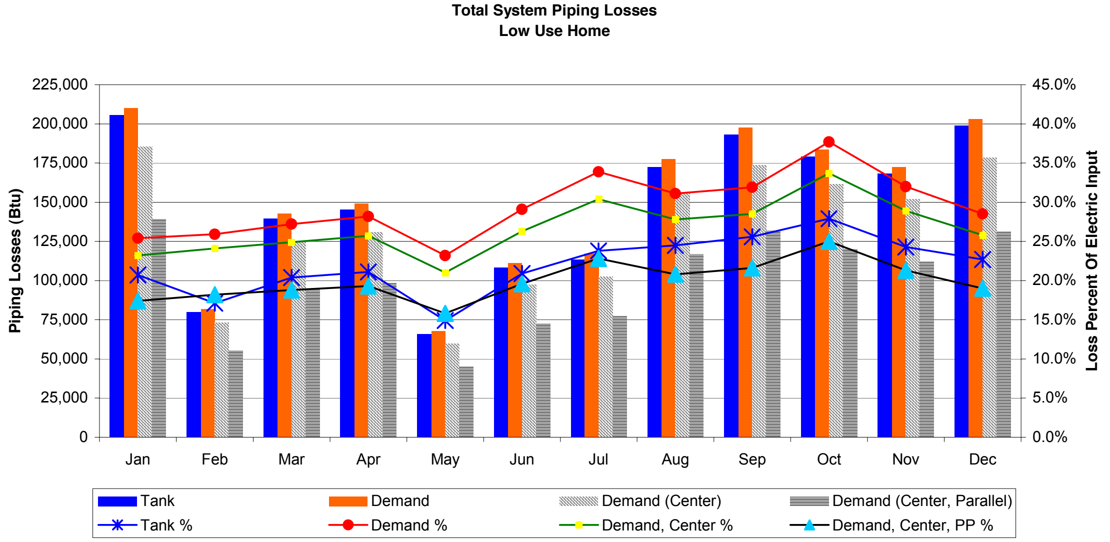


Figure 25: System Piping Losses, Low Use Home

9 SUMMARY AND CONCLUSIONS

Simulations estimating the energy use of different hot water systems were performed to quantify the benefits of demand water heating equipment when used in residential single family housing. A hypothetical plumbing system was developed to which actual hot water flow data was applied. Seven outlets were assigned a percentage of each minute's flow depending on the time of day. Flow data was used for one single family home that had higher than average daily water consumption and one home having lower than average daily water consumption.

Simply replacing a tank heater with a demand heater resulted in an annual hot water energy savings of about 10 percent (538 kWh) for the high use home and 24 percent (550 kWh) for the low use home. By moving the demand heater to a central location in the home, the savings in the high use home increased to about 13 percent (719 kWh) and to 29 percent (685 kWh) for the low use home. When further changing the hot water plumbing to a parallel piping system, the savings for the high use home are further increased to 17 percent (920 kWh) and to 35 percent (817 kWh) for the low use home. *These results, based on variable hot water demand for the same plumbing system, indicate that significant savings are expected for all homes switching to demand heaters regardless of the average daily hot water consumption.*

These savings include modification of the electrical energy input based on the outlet energy normalized to the tank outlet energy for the month. For example, if the outlet energy for the demand system was lower than the tank outlet energy by five percent, the electric energy input for the demand system was increased by a proportional amount to reflect the additional energy required to match the tank system performance. A similar approach is used to decrease electric energy input when the outlet energy is found to be greater than the tank outlet energy for the month. This procedure is necessary to equate the outlet energy in all cases as would be practically accomplished by the consumer in adjusting the outlet temperature to a constant level.

While energy savings are significant with the demand heaters, performance issues must be resolved. *Because the demand system is limited by electrical capacity, outlet delivery temperatures with the demand system are found to be inadequate to meet the load and therefore may be unacceptable to the consumer.*

When evaluated on the basis of *total monthly delivered energy*, the centrally located demand heater with a parallel piping system is found to be acceptable in all months. This configuration not only results in the highest energy savings but also provides more "acceptable" delivery temperatures in most cases. However, during the highest flow rates, the delivery temperature is still problematic.

Though not evaluated in detail at this time, the energy savings associated with using a demand heater in place of a tank system may be estimated in the hundreds of dollars. The additional cost of installing a parallel pipe plumbing system on the hot water side may be estimated at close to zero, considering the labor savings offset additional material costs. With annual energy savings in the range of $75 for electric water heating systems, the simple payback may be in the range of 4 to 6 years. If the demand heater were financed as part of a 30 year, 7.5% mortgage, there is an immediate positive cash flow.

10 POTENTIAL SIMULATION VARIATIONS

The results realized in this simulation effort are viewed as a beginning point. System design variations, including the use of an inexpensive water storage tank as a reserve or buffer, may well result in the potential for higher savings while allowing for use of waste heat or renewable energy systems. Variations that may be evaluated include:

- Addition of a tempering tank to allow the ambient house environment to temper the incoming water. Preliminary estimates using TRNSYS indicate that this system alone results in at least 3% additional savings (~1050 kWh annually for the high use home). In addition, a tempering tank would improve the performance of the demand water heater, potentially eliminating the problem of lower than desired outlet water temperature.

- Addition of a drain waste heat collector used in conjunction with a tempering valve at the shower supply.

- Use of solar hot water collectors (as preheat for the incoming water) in conjunction with a tempering tank. Evaluate an optimized system whereby limited area solar collectors are utilized.

- Use of a low temperature (80 to 90°F) tempering tank, in conjunction with controls that preclude the tank element from operating when the demand heater is operational.

- Individually located demand heaters sized for specific loads, with and without controls to limit overall electrical demand.

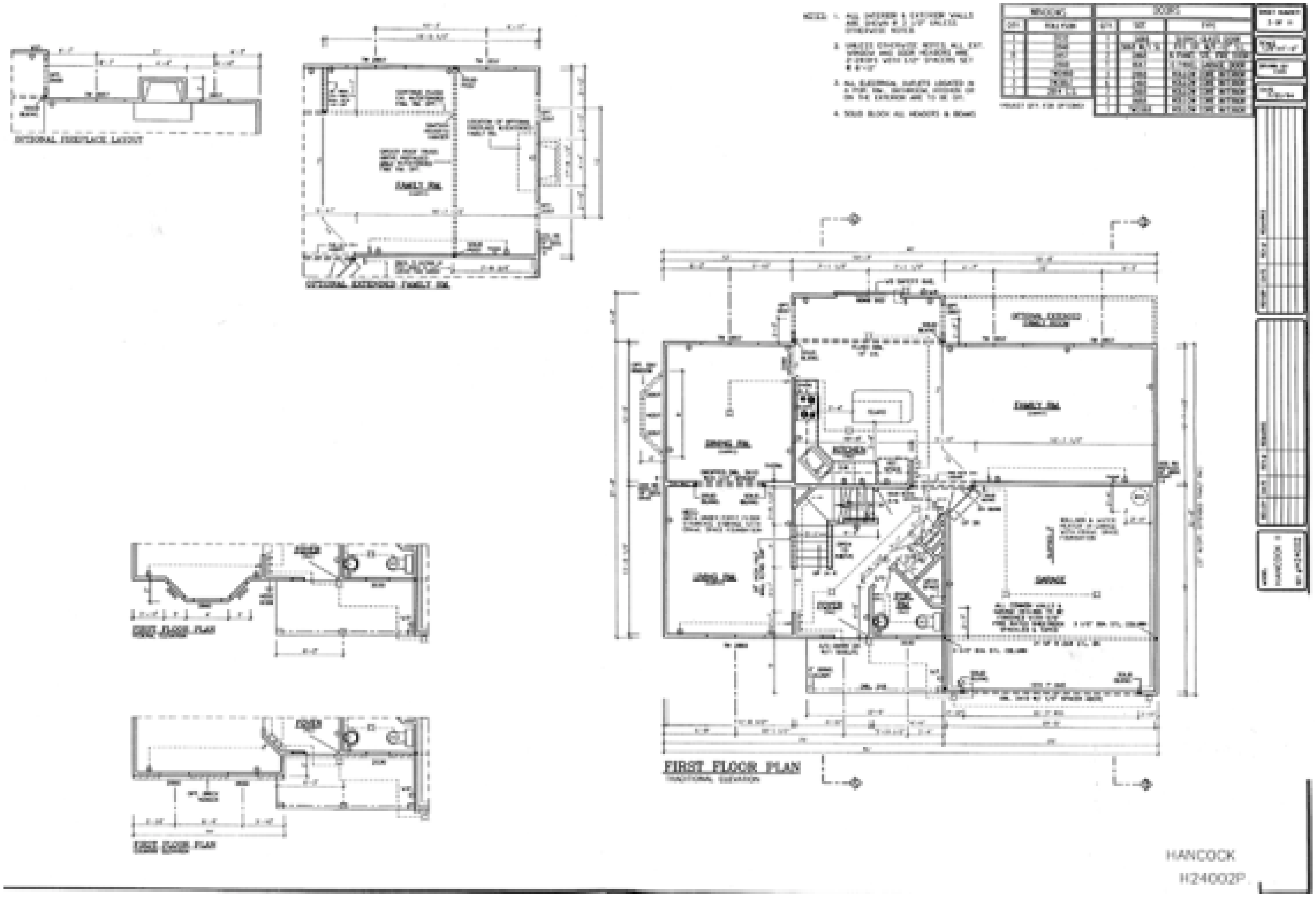
11 SUGGESTED LABORATORY AND FIELD TESTING

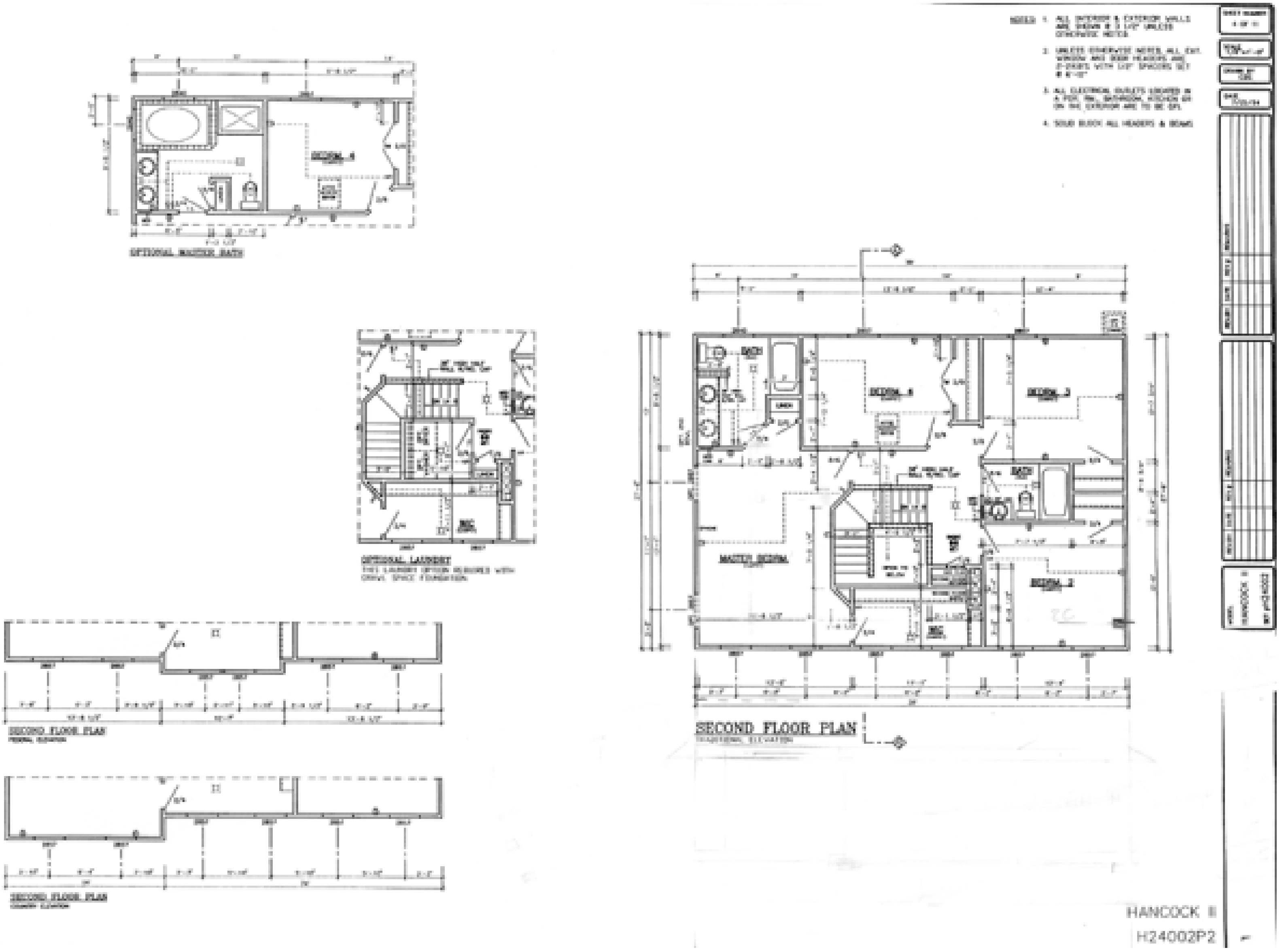
The results of this simulation effort indicate that efficiency gains are sufficient to warrant field testing of various systems. Preliminary tests in a laboratory setting could identify installation or performance issues that might be problematic in field tests as well as provide validation for the results of the modeling effort. Laboratory tests also provide a means of understanding delivery temperature when the flow rate is capable of being adjusted based on the desired outlet temperature. System modifications may be implemented prior to field application and verification. Laboratory tests also help quantify actual demand water heater performance under varied draw patterns and rapidly changing flow rates.

Laboratory testing of domestic water heating systems would be most useful to evaluate the following general areas:

- Simulate different piping systems and configurations to quantify pipe losses;
- Quantify outlet temperatures under varied flow conditions;
- Evaluate water heating system performance when subjected to various flow rates and draw periods;
- Evaluate demand heater performance including losses in the heater equipment under a range of flow and temperature conditions;
- Evaluate numerous storage-demand heater configurations to increase performance while preserving energy savings; and
- Determinate water heating system design configurations acceptable for application in field trails in new housing.

12 APPENDIX A: FLOOR PLAN FOR SIMULATED HOT WATER SYSTEM




OPTIONAL MASTER BATH
OPTIONAL LAUNDRY
SECOND FLOOR PLAN
SECOND FLOOR PLAN
SECOND FLOOR PLAN
MASTER BEDRM
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BEDRM 4
BATH
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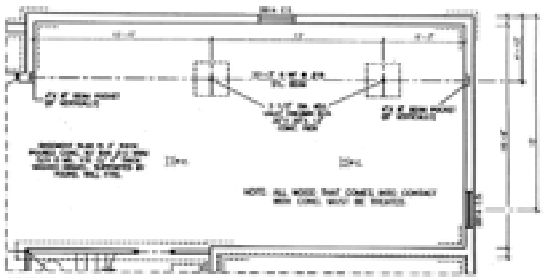
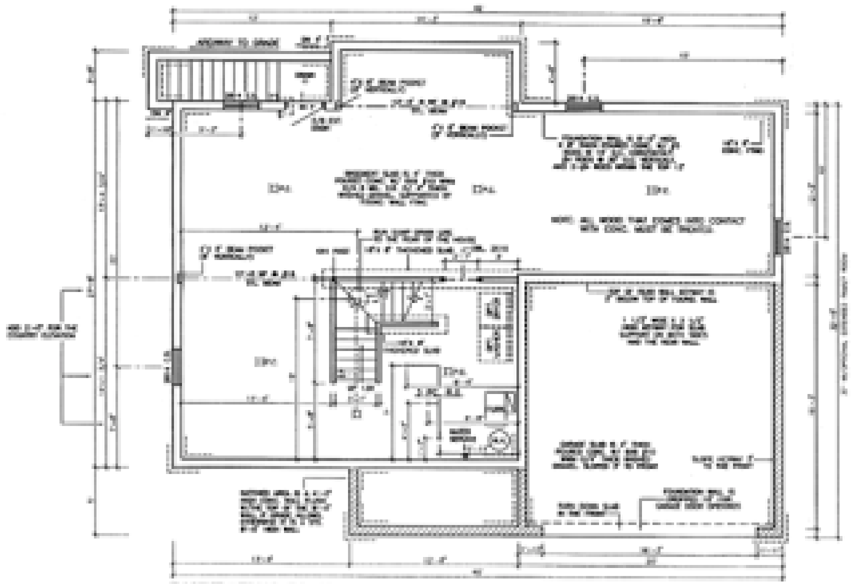
OPTIONAL FULL LENGTH STL. BM.

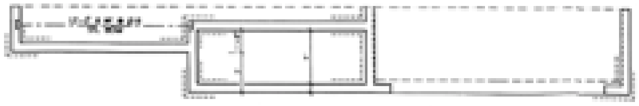


OPTIONAL EXTENDED FAMILY ROOM FOUNDATION



FOUNDATION PLAN

TRADITIONAL & FEDERAL ELEVATIONS



FOUNDATION PLAN

COUNTRY ELEVATION

HANCOCK II

H24002F1

13 APPENDIX B: RESIDENTIAL HOT WATER SYSTEM ENERGY EFFICIENCY RESEARCH

13.1 Introduction

Water heating represents about 20 percent of residential energy use in the United States. Advances are continually being made in the area of building energy performance, especially in reducing building space-conditioning energy consumption. Field implemented advances in hot water energy use reduction, on the other hand, have generally focused on reducing hot water demand. Slower progress has been made in the area of energy-efficient water heating equipment and system design. With some notable exceptions such as heat pump water heaters and solar hot water systems, there has been very little innovation in residential hot water systems. This research project will evaluate the basic design of residential hot water systems to determine areas where energy savings may be realized and to evaluate to what extent point-of-use and instantaneous water heaters can reduce hot water energy requirements.

To identify areas of energy savings it is necessary to understand the various aspects of the water heating system. The average hot water use from various studies indicates an average household use of about 62.4 gallons per day.[11] The peak hourly use is close to five gallons per hour and occurs near 8:00 a.m. The average size of a new single family detached home in 1997 was 2,130 square feet and contained 2.64 bathrooms.[12] With this and specific flow rate information, a basic hot water system can be designed and modeled to find the hot water usage of a typical household. Variations in use and system design may then be analyzed. The purpose of this modeling is to evaluate new or uncommon energy efficient hot water system designs based on instantaneous water heating equipment. A second benefit is to develop a simulation to incorporate new equipment and designs for future analysis.

A first step in the project is to conduct a literature search to identify the existing body of information relative to instantaneous water heating and existing hot water system design.

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[11] Becker and Stogsdill (1990)

[12] *Annual Builder Practices Survey*, NAHB Research Center, 1998. Based on 1,732 builders constructing 38,190 homes.

This report summarizes the literature found regarding previous testing and/or modeling of demand-type (tankless) water heaters, residential hot water consumption, residential hot water systems in general, and common methods and technologies to reduce hot water energy consumption. The literature search, initially devised to research demand water heater performance, was quickly expanded to include any residential hot water system and related system details due to the limited information available for demand water heater systems in residential buildings.

13.2 Demand Hot Water Heating Equipment

A primary focus of the effort to reduce hot water energy consumption is to evaluate the performance of demand (instantaneous or tankless) hot water heating equipment.[13] The greatest energy benefit of demand water heaters over storage water heaters is the elimination of stand-by losses from the tank. Other benefits include pipe loss reduction through location of the water heating unit closer to the load (faucet) and, with some equipment, more control over the delivery temperature of hot water. An important related energy benefit may also lie in the opportunity to reduce the hot water temperature setting of the demand heater to a level below that of tank systems (usually 120°F to 140°F). Tank systems may be set at elevated temperatures to increase the effective capacity of the tank. The elevated temperature allows longer draws at a lower flow rate since the higher temperature water is mixed downstream with cold water to reduce the temperature to comfortable levels.

One related technology to the demand water heater is the point-of-use water heater unit. Point-of-use units are essentially small water heaters with storage capacities of between one and four gallons. The units typically will not heat water "instantaneously" over a large temperature rise since the heating elements are small and often operate from a 120-volt source. However, point-of-use units have reduced standby losses since the tanks are very small and are located close to the load. This benefit assumes the volume of hot water from the point-of-use tanks is significantly less than that of a single central hot

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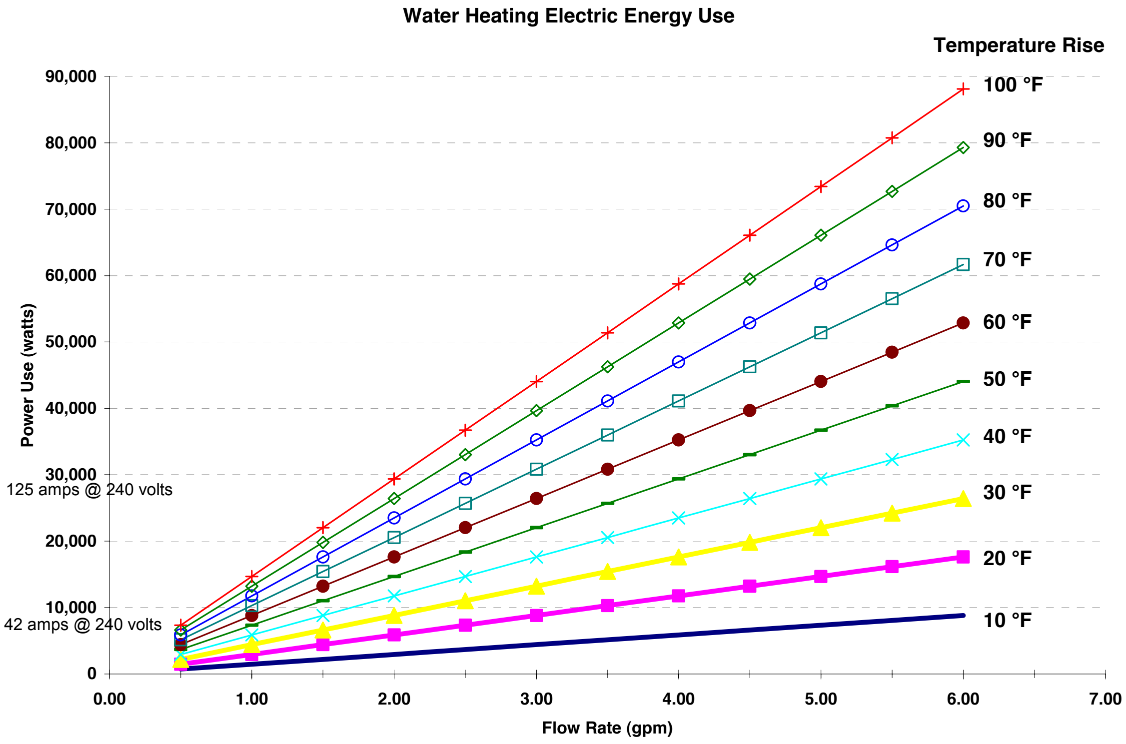
[13] Instantaneous or tankless water heaters are often referred to as **demand** water heaters in that their operation is dependent on hot water demand at any given moment.

water tank. Small demand heaters without any storage may also be located at the outlet point and are sometimes referred to as point-of-use water heaters.

Demand water heaters are fueled by gas or electricity. It takes approximately 147 watts (502 Btu/hr) to heat water flowing at one gallon per minute (gpm) by one degree Fahrenheit (°F). Figure 1 shows the power draw of an electric demand water heater at different flow rates and temperature rises.

Figure 26. Electric Energy to Heat Water at Various Flow Rates



The water heating calculations described by Figure 1 show that, when using demand water heaters, it is important to either limit the flow rate or limit the temperature rise to avoid large power draws. Flow rate can be limited by incorporating various water saving technologies and by using only one, or at most two, hot water fixtures simultaneously.[14] Also, use of methodologies to passively pre-heat domestic hot water, such as solar hot water systems, can substantially reduce the required power of a demand heater.

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[14] du Pont, (1989).

In typical homes with standard gas service and standard electrical service of up to 200 amps, gas-fired demand heaters tend to be capable of higher flow rates and temperature rises than electric heaters. For example, a gas demand heater with an output of 117,000 Btu per hour (Btuh) can raise four gallons per minute by 45°F. A similar performance would require about 26.5 kilowatts (kW) of electricity, or about 110 amps at 240 volts. However, given an electrical service capable of high current supply to an electric demand heater, any theoretical hot water load may be satisfied.

Prior to the state-of-the-art, demand water heaters had to be carefully sized to account for the variation in temperature rise based on flow rates and supply cold water temperatures. Currently, many electric demand systems are capable of producing a fixed outlet water temperature regardless of flow rate by using sophisticated controls that vary electric input to the heating elements. Of course, the unit will still have a maximum temperature rise based on the supply water temperature and flow rate at full power conditions.

Electric demand water heaters range in size from about 2.4 kW to 28 kW. The smaller units may operate on 120-volts while the larger units, over about 3.5 kW, will operate on 240-volts. Many older residential electrical services may be insufficient to handle a large demand water heating load, and many new electrical systems may not have been designed to do so. However, with the use of smaller demand units and a reduction in the flow rate, electrical demand may be compatible with many electrical services.

Similar supply concerns must be considered for gas demand units. Fuel gas pressure requirements, combustion air, and flue requirements must all be adequately provided. Most natural gas units will require at least seven inches of water column gas pressure. Assuming typical infiltration rates, the air requirements for combustion are on the order of 50 cubic feet (cf) per 1000 Btuh of rated input, although they may vary according to the manufacturer. For example, a 100,000 Btuh unit must be located in a room having about 625 square feet (sf) of floor area with an 8’ ceiling. Venting requirements are specified by the manufacturer and may be sized anywhere from a 3-inch to a 6-inch vent for most residential models. Power and direct vent options are available on some models.

A demand water heater is activated by water flow. Different manufacturers use various technologies to sense flow and initiate the heating cycle. The typical flow rate required for flow detection is about 0.5 gpm. Therefore, very low flows of hot water cannot be delivered. At least one manufacturer of an electric unit will detect flows at 0.25 gpm. Of course, point-of-use equipment with small storage capacities will not be affected by this performance issue.

An important feature of demand and point-of-use water heaters is the flexibility in locating the unit. Electrically-powered units may be located anywhere near the load point while gas-fired units need to be located with access for a vent to the outdoors. By serving only a small number of loads (faucets), load demand is limited and the water heater may be precisely sized to satisfy maximum flow rates. Multiple units may be used to serve all hot water outlets in a home.

13.3 Performance of Demand Hot Water Heating Equipment

There is little published independent test data available on the performance of demand water heaters. Energy savings are attributed to the elimination of stand-by losses associated with tank systems. While not all manufacturers quantify the energy benefits, one electric heater manufacturer claims hot water heating costs will be reduced by 30 to 50 percent while another claims a 60 percent reduction. Another manufacturer's third-party test compared an electric 40 gallon water heater (set point 135 °F) to an electric demand heater (120 °F set point) with an energy savings of 27 percent identified.[15] Manufacturer-claimed energy savings for gas demand water heaters range from 20 to 25 percent.[16]

Benefits of demand water heaters often cited by manufacturers have less to do with energy savings than convenience (unlimited hot water), comfort, reliability, and longevity. This lack of emphasis on energy savings is attributed to the often-difficult task of documenting energy savings when comparing two systems with different use characteristics. For example, energy benefit claims of demand heaters focus on reduced

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[15] Refer to published data from Microtherm, Inc. including *SEISCO® Microtherm, Inc. Addresses Electrical Demand and Other Major Issues*, April 1999.

hot water delivery temperatures since the supply of hot water does not need to be controlled in a similar way as with storage tanks.[17] Ancillary benefits of demand water heaters are the result of lower hot water set point that reduces pipe losses, stand-by losses, and eliminates hysteresis loss.[15]

Evaluation and simulation of demand water heaters will provide valuable information about the anticipated performance of demand units installed in various configurations within the home. Previous efforts in analyzing performance are limited and have been concerned with the impact on the utility infrastructure. Additionally, new technologies available for controlling the delivery temperature from demand heaters, new flow sensing technologies, and larger electrical service capacity in new homes support a renewed interest in the use of demand water heating systems.

13.4 Methods to Reduce Hot Water Energy Consumption

A portion of the task of considering demand water heaters to reduce hot water energy consumption is to identify other methods, equipment, and systems that reduce hot water consumption and energy use in general. A literature and Internet search was performed to identify any new technology and/or system that could decrease hot water energy used in new homes. No attempt is made here to identify cost savings or even to quantify potential hot water energy reduction. The purpose of this search is to document potential technologies, plumbing methods, and systems that may be useful in future simulations and/or field tests designed to decrease hot water energy consumption in homes.

A number of hot water and energy-saving systems and methodologies are widespread in new home construction. Other technologies, such as additional tank insulation, may be incorporated in new hot water tank designs. Other energy efficient technologies, such as gas-fired, forced-combustion, tank water heater devices are available on higher efficiency models but not on lower cost models.

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[16] Manufacturer's published data, advertisement or Internet pages used for savings reference.

[17] In some cases, water heater tank temperature settings may be set higher than needed for household use in order to have sufficient hot water supply for the entire draw episode.

A list of common recommendations to reduce hot water consumption or increase the efficiency of the hot water system is included from the literature. Many technologies are applicable to hot water tank systems but not to demand systems. Some technologies are designed to decrease the energy required to heat hot water while other technologies, such as horizontal axis clothes washers, reduce hot water consumption and hence water heater energy use.

Methods and technologies to reduce hot water energy use most often cited include.[18]

- Decreasing the set point of the water heater thermostat;
- Adding insulation to the hot water tank;
- Adding insulation to the hot water delivery piping;
- Using a hot water tank anti-convection valve or heat trap;
- Using a dishwasher booster heater (in order to allow tank T setpoint to be reduced); and
- Using a timer on electric water heaters.

Common hot water conserving methods and technologies include:

- Low flow showerheads and faucet aerators;
- Repair of leaks and drips;
- Use of “cold wash/rinse” selection on clothes washer with appropriate detergent;
- Hot water circulation systems to eliminate hot water waste when waiting for hot water at the tap; and
- Appliances that consume less hot water than similar units such as horizontal axis washers, specially-designed vertical axis washers, and low-consumption dishwashers.

Apart from the above modifications, previous analysis[19] of hot water tank equipment shows efficiency increases for both gas and/or electric hot water tanks by:

- using sealed combustion designs;

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[18] Sources: U.S. Department of Energy, Energy Efficiency and Renewable Energy Network; Residential Energy efficiency database, ITS-Canada, Rocky Mountain Institute, and others.

[19] Wilson, R. P., (1978).

- using electronic ignition;
- increasing the flue baffling;
- using a heat pump; and
- pre-heating the inlet water.

Water pre-heating technologies discussed in the literature are primarily solar hot water systems and have been applied to both gas and electric tank systems. All solar hot water systems have some type of storage capability that may be used with different types of water heating systems. Other types of pre-heating technologies include:

- desuperheaters;
- drainwater heat recovery;
- and at least one system[20] (not yet commercialized) that uses attic space for heating water and air.

Other research and testing has been performed to evaluate various configurations of dual-tank (electric) systems where each tank has one or two operational heating elements. The results of this testing provides a basis for connection and element operation of dual tank systems in order to reduce overall hot water energy consumption.[21]

One building system designed to decrease water heating energy use is the "manufactured residential utility wall" system. Not yet commercialized, this wall system concept is included since it potentially decreases water heater energy use by minimizing hot water piping runs.[22]

Other applicable but limited research has been performed concerning the use of different piping materials. Metal and plastic hot water piping have different heat loss coefficients and therefore affect the overall performance of a hot water system. One study used simulation runs to evaluate hot water heating distribution system losses, including piping

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[20] Refer to Solar Attic company literature, Elk River Business Incubator, 16820 Highway 10, Elk River, Minnesota 55330

[21] Hiller, (1996).

[22] Wendt, Robert et. al., Energy Efficient Building Association Conference, 1997.

with lower heat-loss coefficients.[23] Another study evaluated the performance of parallel piping systems including use of materials with lower heat-loss coefficients.[24]

The information in these and other studies may be applicable to future simulations designed to evaluate the performance of domestic hot water systems using demand water heating equipment.

13.5 Hot Water System Modeling

A literature search was initiated to identify previous modeling and field tests of demand water heaters. Although demand water heaters are widely used in Europe and elsewhere, the result of the literature search was scant. A broader literature search on water heating including water heating tank systems and water heating systems for residential applications was then performed. The broader search for information on hot water system modeling is discussed here.

The earliest identified study that included modeling of hot water systems was a 1977 report [Hirst] [25] that concentrated on hot water tank losses. The study evaluated annual consumption and various energy efficiency upgrades. Losses were categorized but not detailed for any specific period other than annual summaries. Good agreement of annual consumption estimates were found with previous studies dating back about three years. Efforts to increase the efficiency of the hot water system involved adding insulation to the tank, adding pipe insulation to 25-feet of hot water pipe and, for gas water heaters, modifying the burner characteristics. The application of this study to the current study is limited, but reference may be made to the insulation results. No modeling details were provided.

A number of studies have concentrated on measurements and algorithms to accurately estimate the draw from specific fixtures. This information is used either to estimate behavioral patterns associated with hot water use or to estimate the hot water energy use

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[23] *Residential Water Heating Study*, Performed for the California Energy Commission, 1991.
[24] *Parallel Piping Studies*, Prepared for the Plastic Pipe and Fitting Association, 1991.
[25] *Residential water Heaters: Energy and Cost Analysis*, Eric Hirst and Robert A. Hoskins, Energy Division, Oak Ridge National Laboratory, 1977.

associated with specific loads. One notable example is from Weihl and Kempton,[26] in which algorithms are developed to disaggregate the hot water load use by point of use based on one flow meter and numerous temperature sensors on hot water piping. An important aspect to the work by Weihl and Kempton is that the hot water tank is not considered the end use appliance but rather the individual tap is considered the end of a "domestic energy distribution system". This perspective enables a logical separation of each technology in a hot water delivery system used at a particular point of use such as a shower, faucet, or laundry. Technologies could include the hot water heater, the piping system, valves, flow restrictors and even drain water energy recovery equipment.

Two studies mentioned above (footnotes 23 and 24), represent previous hot water system analysis using a proprietary hot water system simulation program. In the California Energy Commission study, the simulations were performed in order to develop hot water system energy efficiency guidelines. That study is applicable to the current effort to compare distribution and tank losses, however, it approaches hot water simulation from the perspective of hot water draw episodes and not on a uniform time step. Use of the Plastic Pipe and Fitting Association study is valuable for analysis of the parallel piping system and may be useful for comparison with the current study's results. In another simulation analysis, a numerical model for estimating hot water distribution pipe losses was developed.[27] Much of the simulation results are based on piping materials not commonly used in residential construction. Some of the results may be compared with piping loss results that will be performed in future simulations in this study.

Numerous others [Lane, Dolan, Fanney, among others] have modeled water heater loads applicable to whole or portions of utility systems. Aggregate models are used for various purposes such as peak-load shifting, demand-side management routines, and time-of-use load estimates.

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[26] *Residential Hot Water Energy Analysis: Instruments and Algorithms*, Weihl, Jeffrey S. and Kempton, Willett, 1985.

[27] *Evaluation of Service Hot Water Distribution Losses in Residential and Commercial Installations…*, ASHRAE Transactions, Vol. 1, 1999.

13.6 Hot Water Consumption

A portion of the literature search was dedicated to examining the hot water draw profile as outlined in previous studies. While actual end-use and flow rate data is rarely available, analysis of "typical" end-use and flow rate data may be applied to existing hot water flow data. Both hot water consumption and usage patterns are cataloged for reference in subsequent modeling.

Becker and Stogsdill (1990) summarized several studies examining average household water usage in single family homes in the United States. Average daily hot water usage was found to be affected by many factors including season, time-of-day, day of the week, and demographics. Seasonal effects were found to have a major impact on the amount of hot water used daily, with hot water usage in the coldest months being typically higher than usage in the warmest months. Gilbert, et al. (1985) studied 110 single-family homes and found average daily hot water use to be 66.2 gallons per day, with maximum hourly average usage ranging from 4.1 to 8.9 gallons per hour. Perlman, et al. (1984) monitored hot water use for 55 residences in Canada and found average daily hot water use per household to be 63.1 gallons, ranging from 45.2 gpd in July to 65.7 gpd in January. Merrigan (1988) monitored 98 domestic water heating systems in single family homes in Florida and North Carolina. They found peak average daily hot water use to be 63.6 gallons per day (in February).

Kempton (1987) examined eight single-family residences and found daily hot water usage to range from 11.7 to 33.3 gpd per person.

Perlman and Mills (1985) measured hot water consumption over a period of four years for 59 residences in Canada and found average daily hot water consumption to be 62.4 gpd. Average hourly hot water use was found to be 9.8 gallons per hour (gph) and average peak hot water use 17.3 gph. The researchers also analyzed hot water use in gallons per day per person and found it to range from 12.3 to 22.6.

Hiller (1998) found, in a study of 14 single family residences, an average daily hot water consumption of 59.2 gpd.

13.7 Hot Water Usage Patterns

Several studies have looked at the patterns of residential hot water use. Many factors influence the variable usage seen in homes. Results from the literature detail average hourly hot water consumption, breakdown of point of use, and characteristic hot water draws of various appliances. While all the compiled information will be useful in developing a model of domestic hot water use, none will be on the short time step (i.e. minute intervals) needed for in-depth thermal analysis of hot water energy use.

Hiller (1998) and Lowenstein and Hiller (1998) measured water consumption from 14 single family homes over two years for the purpose of developing a new system sizing methodology. Although their study did not attempt to measure hot water consumption for various points of use in the home, they analyzed hot water draws and developed "worst-case scenarios" of hot water draws. They used the worst-case-scenario draw patterns to predict required system capacity. No further information is available on the hot water draw patterns at their research sites.

Kempton (1987) analyzed the hot water usage patterns at eight houses in detail. Using a flow meter and the temperature of the hot water pipe at each tap, Kempton analyzed water use events, the loads each event served, and the efficiency of the hot water system in meeting the load. (Energy delivery at the tap compared with energy to the hot water tank.) Hot water usage at the eight study sites are analyzed by hot water use per day (and per capita per day), number of hot water draws per day, and usage per fixture per day.

Becker and Stodgsill (1990) compiled data from several different studies and developed hourly use profiles for seniors, renters, and single family homes in Canada and the United States.

Lowenstein and Hiller (1996) analyzed the hot water consumption patterns of 13 single family residences. Using only data on the pattern of water flow from the hot water tank, the researchers attempted to disaggregate hot water use into its points of use. The researchers characterized the flow patterns of hot water appliances and used this information to disaggregate hot water draws into their points of use. Lowenstein and Hiller (1998) then placed thermocouples on the hot water lines at three of the 13 sites to test and refine their disaggregation method. They developed a table of usage (in gpd) for each hot water appliance in the three homes for weekdays and weekends.

Lutz, et al. (1996) developed a computer model for simulating domestic hot water consumption that includes 14 variables such as age and number of occupants, day of the week, and season of the year. Output of the model is hourly hot water usage.

13.8 Summary

The results of the literature search indicate that further modeling of demand water heater systems including ancillary equipment such as pre-heaters and different piping technologies and configurations is warranted. Previous efforts have either not relied on actual flow data, as would be used in this effort, or have not accounted for various system configurations available with demand heaters.

13.9 Bibliography

The bibliography represents applicable documents found to have some relevance to the current study out of over 300 abstracts reviewed.

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