Domestic Hot Water System Piping Insulation: Analysis of Benefits and Cost

Prepared for:

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Table of Contents

List of Figures

List of Tables

Domestic Hot Water System Piping Insulation:
Analysis of Benefits and Cost

Background

Increasing the efficiency of water heating equipment is one means to achieve energy savings in the hot water system; however, the piping distribution system itself is now being scrutinized to determine opportunities for further hot water system savings. Often accepted approaches to energy savings in the hot water piping system are to reduce the length of piping to the outlets and to insulate the hot water pipes. Less regarded as an energy savings feature is the reduction in size of the hot water lines to outlets, which can reduce pipe losses, as other plumbing system performance issues such a pressure drop and fluid velocity must be considered. All of these approaches will result in lower piping system losses. The purpose of this study is to outline the mechanisms of energy savings in the piping distribution system and to estimate the range of energy savings resulting from pipe insulation based on simulated hot water use profiles.

This study was commissioned by the National Association of Home Builders (NAHB) with the purpose of understanding the energy savings available by insulating hot water piping in homes relative to the cost of the insulation, both in materials and installation. The study includes references to the existing body of research as well as results of new analyses of hot water distribution systems with various options for insulating hot water piping.

Background: Hot Water Piping Energy, Water Use, and Loss Mechanisms

Domestic hot water piping systems are designed to deliver hot water from a source (the water heater) to the outlet. The piping design must account for the source pressure and the design flow rate to ensure an adequate supply of hot water volume to the outlet. These design constraints directly influence the energy loss of the piping system. For example, in long plumbing runs, the pipe size may be increased to reduce flow losses leading to larger volumes of hot water in the piping and increased energy losses, both during the draw and after the draw as the volume of hot water cools. In addition to these energy losses during a water use event, occupant control characteristics will affect the total energy loss from the hot water system such as wasted warm/hot water while waiting for hot water to arrive at the outlet and the desired water temperature at the outlet (that affects the amount of cold water mixing) to reach the desired level.

Given these hot water use characteristics that directly affect the total energy use of the hot water system, an outline of the specific mechanisms contributing to energy (and water) losses is shown in Table 1.

Table 1 - Factors Affecting Hot Water System Energy Use

Property	Energy Use Mechanism	Loss Consequence
Pipe material, length and location	Heat transfer through the pipe to the surrounding based on conductivity and the environmental temperature around the pipe	• Energy loss during flow • Energy loss at the end of the flow event (cool down) • Water loss waiting for hot water at the outlet
Intention of use	Volume of hot water in the piping based on a desired temperature (i.e. shower) or fixed volume (i.e. dishwasher)	• Water waste waiting for hot water at the outlet • Increase in water heating energy based on the need for hotter water at the outlet
Flow rate	Heat transfer through the pipe to the surrounding during use	Magnitude of loss relative to total volume of use increases with a decrease in flow rates
Interval between use	Heat loss during pipe cool down after a use event	Energy and water loss dependent on the time to the subsequent use
Cold water temperature at the outlet	Volume of hot water used dependent on the desired temperature at the outlet, if set	Larger volume of hot water is used with colder incoming water temperature

As outlined, the confluence of parameters involved in the determination of hot water system losses increases the complexity of determining the affect of any one aspect leading to higher energy losses relative to the total energy use in the hot water system. This affect is clearly seen in the energy factor (EF) rating for water heaters which is highly dependent on the time frame and use pattern of the test procedure. For any actual home, the EF may be significantly different from the equipment rating, for example, in homes where there is large hot water use throughout the day, the actual EF may be much higher, where the opposite would be true for homes that use much less hot water than the test procedure.

Furthermore, the losses from the hot water system are all relative to the total energy supplied to the hot water system such that homes with low hot water use due to consumer behavior (including the choice of low-flow faucets) may reduce the total energy used in the hot water system, the ultimate benefit desired. However, in all homes, the performance of the hot water system may be improved (e.g. faster hot water delivery, lower piping losses, etc.) through the system design.

This study focuses on one aspect of the system design – insulating hot water piping as a means to reduce energy (and corresponding water) losses. It must be noted that this study did not evaluate recirculation systems which presents a different set of analysis complexities including the type of recirculation system, the actual layout of the system, the pumping energy, and the control mechanisms based on occupant behavior at a particular use point.

Published Hot Water Energy Use Research

A literature search was performed to review the current information available relating to hot water energy use in homes and specifically concerning the application of insulation for the piping. The relevant literature is annotated in Appendix A. Few studies specifically focused on pipe losses from domestic hot water systems. The most significant studies were published in 2004 [Baskin et. El. 2004] through 2006 [Hiller] that used analytical and some laboratory test methods to demonstrate the scope of losses from domestic hot water piping. These studies, while not applied to realistic hot water use profiles in homes, demonstrate the mechanisms of heat loss from piping and conclude that the largest benefit of insulating piping is with under-slab configurations[1]. Other energy savings from insulated piping were highly dependent on the use pattern, piping location, and the start of a use event (i.e., whether it is a "cold start"). Similar results from laboratory testing and analytical estimates highlighted by Hiller [Hiller, 2005] concluded that insulating hot water piping provides the greatest benefit with moderately spaced hot water use patterns.

The bulk of the literature concerning hot water system energy use, however, dealt with three major areas of research:

- Model development to simulate hot water use
- Development of hot water use patterns and volumes
- Hot water system design and layout including recirculation systems

Other hot water research including use of pre-heat or tempering systems such as solar or desuperheaters as well as research on various water heating technologies are not included in this review as these technologies serve a different function in hot water energy savings with regard to piping losses.

To date, little information is available that provides large scale testing or modeling of various system designs, including accurate hot water use profiles, to quantify the energy loss from piping systems in various climates and across seasons. However, some basic characterizations of hot water systems, including piping, have emerged from the body of research:

- Under-slab hot water piping supply to outlets generally shows a benefit from piping insulation both in energy and water savings,
- Hot water use patterns including the outlet point, intended use of the hot water draw, subsequent use from the same pipe section, and total volume of hot water used affect the total energy use of the hot water system, and
- The proximity of the hot water heater to the outlets plays a large role in energy and water use.

The limitations of the available research remain in the areas of modeling tools and methodologies for standardizing use patterns for various housing types, climates and fixtures, range of piping layouts, materials and use patterns, and plumbing system designs.

Study Methodology

The analysis of simulated energy performance of hot water piping detailed in this report, including the cost benefit of insulation, seeks to combine various aspects of previous studies with newly available modeling tools. A software tool, HWsim[2] available through the Davis Energy Group to the Building America Program[3] is used in this study. HWsim has allowed for a more detailed simulation of hot water systems. The software can accommodate different domestic hot water piping lengths, materials, and sizes. The piping can be connected to outlet use points that can be configured in various modes to

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[1] Hiller's test results show a large benefit to insulating metal pipe buried in damp sandy soil, less benefit with plastic pipe. Further testing was considered for insulated pipe in saturated soil which is expected to reduce the effectiveness of the insulation. Baskin and Wendt et. Al. concluded that the use of insulation provides some benefit but the magnitude of the benefit is dependent on the use profile and the location of the pipe.

[2] HWSIM Hot Water Distribution Simulation Model Program, Version 1, Davis Energy Group, Inc. 2008. The software was developed through support from the U.S. Department of Energy and the California Energy Commission.

[3] The Building America Program (BAP) is a research program supported through the Department of Energy, whose purpose is to increase the efficiency of new and existing homes. The NAHB Research Center is a BAP partner team.

simulate, for example, a shower that uses hot water at a limited temperature versus a laundry that uses a set volume of hot water at any temperature. A significant feature of the software is the use of a “draw editor” in which flow rates and total volume can be assigned to a specific use point. The environmental temperature surrounding the pipe can also be defined for each month (or even hourly, if desired) and the cold water inlet temperature can be defined on a monthly basis.

A broad characterization study of the affect of installing pipe insulation on all domestic hot water pipes is performed through various approaches using the capabilities of the software coupled with use patterns defined specifically for homes. The approaches detailed in this report include:

> <u>Analysis 1:</u> Characterization of individual energy use and loss mechanisms of the piping system as outlined in Table 1 above,
> <u>Analysis 2:</u> Parametric study highlighting the interactions of various piping system loss mechanisms,
> <u>Analysis 3:</u> Whole house hot water system analysis based on a standard hot water system design, environmental conditions and use pattern, and
> <u>Analysis 4:</u> Cost-Benefit analysis.

The cost-benefit analysis (Item 4) is performed based on estimated installed cost of pipe insulation and current average utility rates for natural gas and electricity, to estimate the net energy cost savings from insulating the hot water piping. This analysis provides a cost and benefit comparison based on the simulation results.

This study is designed to analyze the current system designs and does not attempt to develop optimized piping layouts to specifically reduce the volume of hot water in the piping.

Analysis 1 - Characterization of the Domestic Hot Water Distribution System

The complexity of factors involved in the hot water distribution system design and use range from the layout of the system and number of outlets, which can be unique in even similar house models, to the daily variation in occupant use of the system. The use of hot water outlets, whether a sink faucet or washing machine, can change on a daily, weekly, and even seasonal basis throughout the year. These factors coupled with changing conditions of the house and cold water temperatures as well as the interval between hot water uses will change the system losses, including losses from the piping system.

To understand the relationship between these factors, an initial set of simulations was developed to isolate individual variables and estimate the affect of each. A simulated piping system for a single shower outlet was configured of 3/4" pipe and a length of 50 feet from the tank to the outlet. The flow rate was set at 2.5 GPM and the total flow volume was set to 50 gallons. A delivery temperature of 105°F was set at the outlet with the tank providing 120°F water. Table 2 lists the combination of variables implemented in the simulations for the shower piping system.

Table 2 - Characterization Simulation Variables

Feature or Condition	Options for Analysis		
	Option 1	*Option 2*	*Option 3*
Pipe Type[a]	Metal	Plastic	n/a
Insulation[b]	Uninsulated	1" Insulation (~R-5)	n/a
Location (Environment)	Crawlspace (50 F)	Basement (65 F)	n/a
Cold Water Temperature	45 °F	55 °F	65 °F

[a] The most commonly used residential metal pipe material is copper and CPVC for plastic
[b] Insulation R-values vary by material and thickness; 1" thick insulation is on the larger side of common insulation thicknesses used in the residential market.

A set of 24 simulations were run to evaluate the various effects of the variables on pipe loss and Figure 2 provides a graphical representation of the various system pipe loss per foot of pipe for one flow even. Associated pipe loss percentages relative to the most severe condition of uninsulated metal piping at 50°F and with a cold water temperature of 45°F are also provided for the shower piping system.

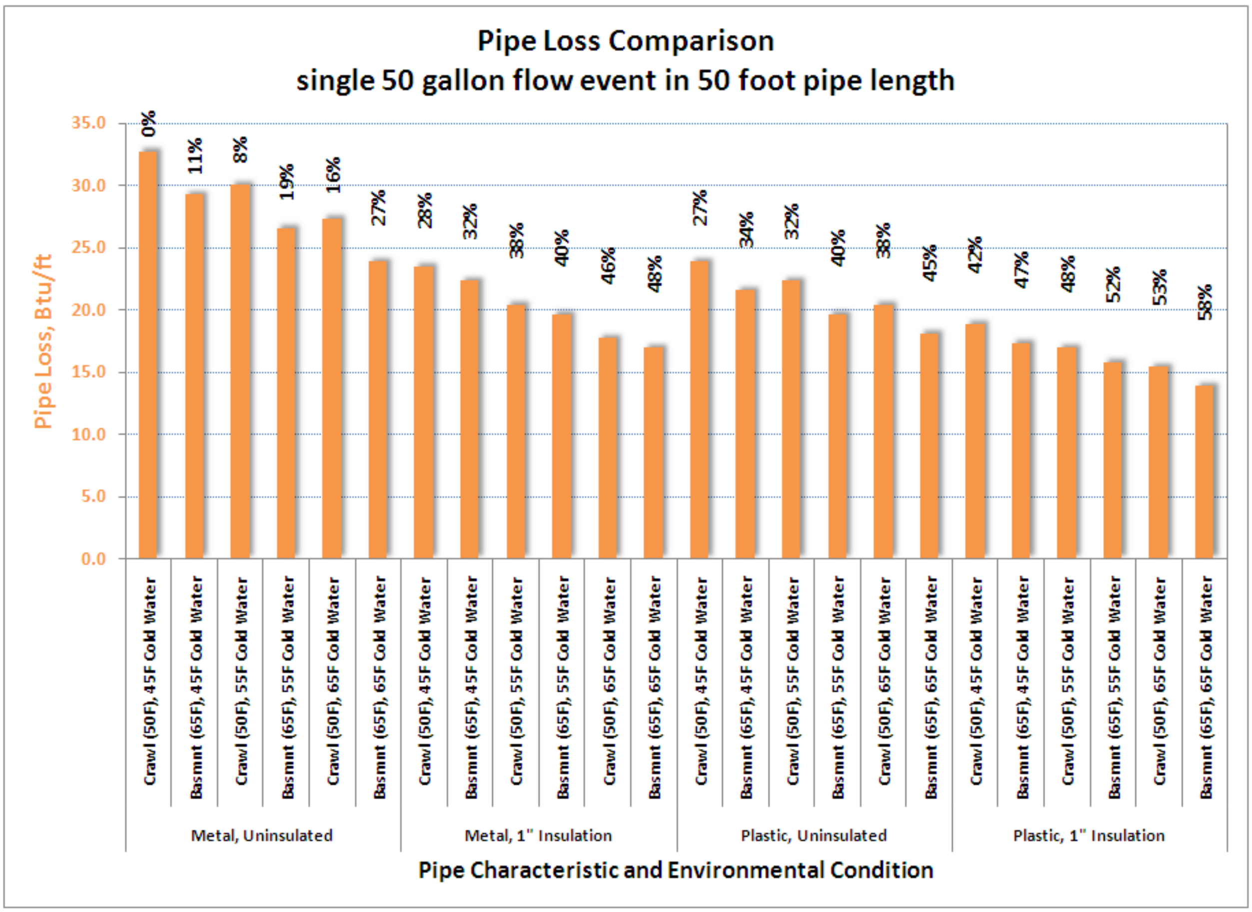

Figure 1 - Hot Water Pipe Loss Characterization

Pipe Loss Effect on Hot Water Energy Consumption

Figure 1 demonstrates the individual affect of various factors that affect the performance of a hot water piping system (Table 2 above). The energy lost from the piping system may or may not result in meaningful additional energy use at the hot water heater when evaluated both for insulated and uninsulated piping. For example, a 10% reduction in piping losses does not translate into a 10% reduction in hot water heating energy use since many of the piping losses are unrecoverable even if the piping is insulated. This is due primarily to the variation in hot water use between uses (where the pipe may cool even with insulation) and the amount of energy lost while using hot water (which is dependent on the pipe length, the temperature of the hot water, and the surrounding temperature). It is also dependent on the temperature of the hot water at the outlet (indicating the mixing of cold water) and the temperature of the cold water. Pipe energy loss can be estimated (and measured) but this estimate, while related to the energy purchased to heat water, is not represented at the same magnitude for insulated and uninsulated piping systems. The discussion in the following subsections will compare piping losses, but note that these losses are not intended to be considered energy savings at the water heater.

Volume of water in pipes

A major factor in the extent of energy loss from hot water piping is the volume of water in the piping from the water heater to the outlet. This volume of water (and the pipe itself) must be heated from its starting temperature to that of the hot water in the tank. The larger this volume, the longer it takes to deliver hot water to the outlet and the more water is left to cool in the pipes after a use. Figure 2 compares the volume of water in different pipe types and lengths.

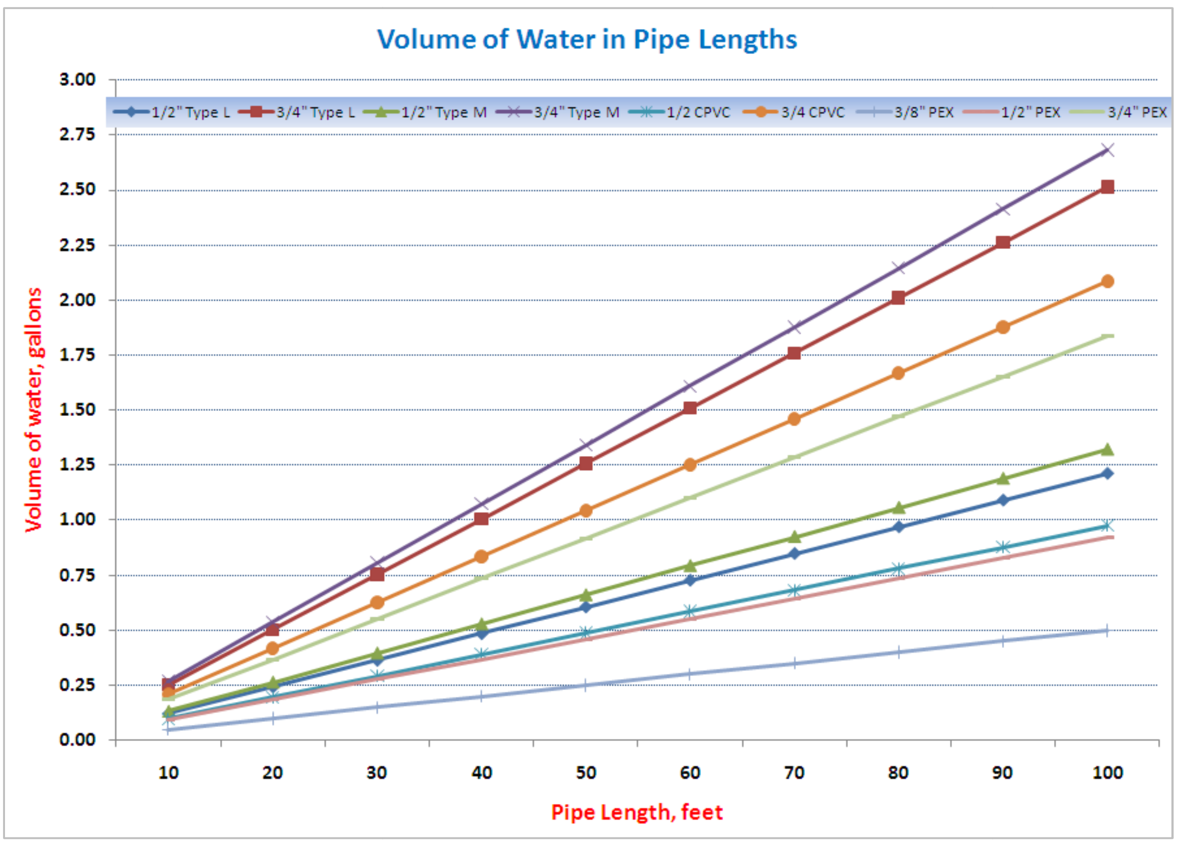

Figure 2 - Volume of water in pipe lengths by type

For example, using 20 feet of Type L copper pipe, there is a difference of over a quart of water from 1/2" to 3/4" pipe diameter. For a typical 2,200 square foot home plumbed with a combination of 3/4" and 1/2” Type L copper, there can be over 3 gallons of water in the hot water piping alone.

Environmental Temperature
Energy losses from hot water piping systems are also dependent on the environmental temperature surrounding the pipe. Previous analysis [Baskin et. Al. 2004] has indicated that hot water pipes located in the ground beneath slab foundations would benefit from insulation in all cases since the pipe losses are increased both during and after the flow event. In addition, the pipe temperature is more quickly brought to that of the surroundings (if pipe not insulated) due to the direct contact with the earth.

For above-ground pipes, pipe losses due to the temperature of the environment surrounding the pipe were analyzed for 2 conditions to highlight the affect of placing hot water pipes in either an open crawlspace (at a constant temperature of 50 °F) or in a basement (at a constant temperature of 65 °F). The pipe losses (not hot water heater energy savings) are estimated to be reduced from about 4% to as much as 13% for the given flow event (refer to Figure 1, compare the first 2 columns in each piping configuration). In most homes, the temperature surrounding the pipe could have a large range depending on the climate, the location of the pipe, and the temperature set-points in the house. It is likely that not all of the piping would see a uniform temperature and the temperature around the pipe would be expected to change through the year.

Cold Water Temperature
Another factor that influences the use of hot water and the amount of losses in the piping system is the incoming cold water temperature. The cold water temperature influences the water heating energy (colder water requires more energy to heat to a set temperature), and the amount of hot water used (for a set temperature at the outlet, more hot water must be mixed with colder water). This variable is not obvious since it would seem that the cold water temperature would not change the hot water piping losses directly. The importance of the cold water is the mixing of the hot water required to bring the water to a comfortable temperature at the outlet. The colder the incoming water, the more hot water is required to keep the outlet temperature at the desired level. Based on the characterization simulations, the effect of the cold water temperature (either 55 °F or 65 °F from a 45 °F base) reduces the resulting hot water pipe losses from 7% to 33% when the pipes are located in a colder location (50 °F environment), and from 9% to 24% when the pipes are located in a warmer location (65 °F environment). The savings (refer to Figure 1, compare the 1st and 3rd and 1st and 5th columns in each piping configuration group) are somewhat consistent and independent of the pipe being insulated indicating that the cold water temperature is a secondary effect when analyzing pipe losses[4]. Figure 1 above charts the data by characterization test.

Pipe Material
Another factor that appears to influence the pipe losses is the material used for the piping. Metal pipes have a higher heat loss coefficient than plastic pipes. The HWsim simulation software incorporates heat transfer coefficients for materials for use in heat loss calculations. The conductivity for metal piping (copper) is significantly higher than that of the plastic materials except for PEX materials with a metal sleeve. Within the plastic materials, PEX has a much lower conductivity than CPVC but the difference is much less than the relative conductivity to the metal piping, resulting in little measurable loss reduction between PEX and CPVC. Based on the characterization study, plastic piping materials result in a

[4] The cold water temperature is a primary effect however in the total hot water energy used at the water heater. This effect is generally independent of the piping system.

reduction of pipe losses from 27% to about 13% over metal piping with higher savings occurring when the other factors result in more losses (e.g., with colder water temperatures or a colder location for the pipe). The summary data in Figure 1 shows this trend for plastic pipe material compared with metal.

Pipe Insulation
An often suggested solution for reducing losses in the hot water system is to use insulation around the piping materials. The characterization study detailed in Figure 1, including variables such as pipe material and environmental temperature, evaluated the use of pipe insulation on the entire length of pipe from the tank to the outlet. The insulation thickness selected, one inch, was the higher of what is typically found in domestic hot water systems. The reduction in piping losses from adding insulation for metal piping is about 24% to 35% and about 20% to 25% for plastic pipe. The absolute loss reduction (Btu value) when using insulation on each of the respective pipe materials is about 40% less for plastic pipe than that of metal. Figure 3, a subset of Figure 1, graphically charts these results.

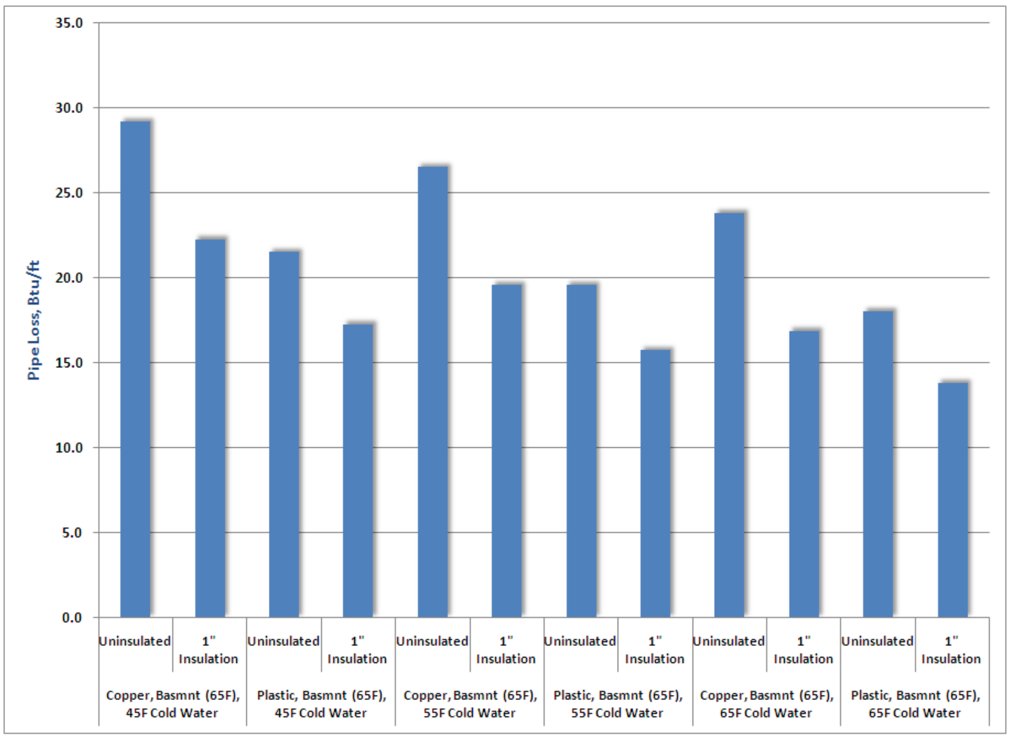

Figure 3 - Pipe Loss Reduction When Using Insulation with Pipe Located in 65°F Environment

Analysis 2 - Parametric Study of the Domestic Hot Water Distribution System

While the characterization of the hot water system summarized in Study 1 is valuable in understanding the various factors influencing pipe energy loss, this parametric study provides more detail on the interaction between performance variables such as the amount of hot water use, the interval between use events, and the length of pipe to the outlet. Based on previous studies [Hiller, 2005], these are the primary parameters of interest when evaluating the benefit of pipe insulation. Because these factors are difficult to define for a general analysis, a parametric study can help provide boundaries for the expected performance range within each factor. Table 3 outlines the parameters and the range of conditions used in the parametric study.

Table 3 - Parametric Study Parameters & Conditions

Parameter	Condition 1	Condition 2	Condition 3	Condition 4
Pipe Material	Metal (copper)	Plastic (CPVC)		
Environmental Temperature	60 °F			
Daily Hot Water Use	60 gpd			
Interval Between Draws	1 minute	10 minutes	30 minutes	60 minutes
Pipe Length to Outlets	30 feet	60 feet		
Insulation	0” thick	1/2" thick	1” thick	

The parametric study focused on evaluating the interaction of the parameters identified to contribute most to heat loss from the piping system. These parameters are based on the range of system designs (moderate and longer pipe lengths), a range of intervals between hot water use (1 to 60 minutes), a range of pipe insulation levels (none to 1” thick), and two different pipe types (metal and plastic). Other parameters such as the temperature surrounding the pipe (set as a conservative estimate of a cooler location) and the total water use (set at 60 gallons per day which is similar to average values used in various programs), are kept constant. The piping configuration was set such that there are three outlets representing a kitchen sink, a sink basin, and a shower, with all set to the same distance from the water heater tank (30’ or 60’). The pipe sizes for the parametric study ranged from a nominal 3/4" for the supply lines to a nominal 1/2" to the outlets. A water use profile was developed for three common outlets in the home as shown in Table 4.

Table 4 - Parametric Study Use Points and Draw Levels

Daily Hot Water Use for Three Fixtures						
	Volume per Event		**Events**	**Daily Use**	**Flow Rate**	**Duration**
Fixture C[1]	0.5	gallon	24	12 gallons	1.50 gpm	20 sec
Fixture B[2]	1.0	gallon	12	12 gallons	1.00 gpm	60 sec
Fixture A[3]	18.0	gallons	2	36 gallons	2.25 gpm	480 sec
Outlet similar to [1]Kitchen sink, [2]lavatory sink, [3]shower						

The size of the pipe is a secondary factor as is the flow rate and duration of the use (which are dependent on the occupant use). The parametric study is focused primarily on the length of pipe and the time between hot water events. The other factors are set (e.g., the piping system design and layout) and a flow regime is specified for each outlet. The flow rate and total volume is set for the outlet providing a range of draws, albeit limited, to represent what might be expected in a typical household. *The artificial specification of the time between draws does not represent a typical household but does highlight the differences between the different draw profiles.*

Figures 4 and 5 graphically represent the interaction between pipe material (metal or plastic), pipe length to the outlets (30 or 60 feet), the interval between draws (1, 10, 30, or 60 minutes), and the amount of insulation on the pipe (none, ½”, or 1”). Insulation is assumed to fully cover all hot water pipes in the system from the hot water tank to the outlets. The results are based on an annual simulation with the same daily draw profile and volume use for each day of the year.

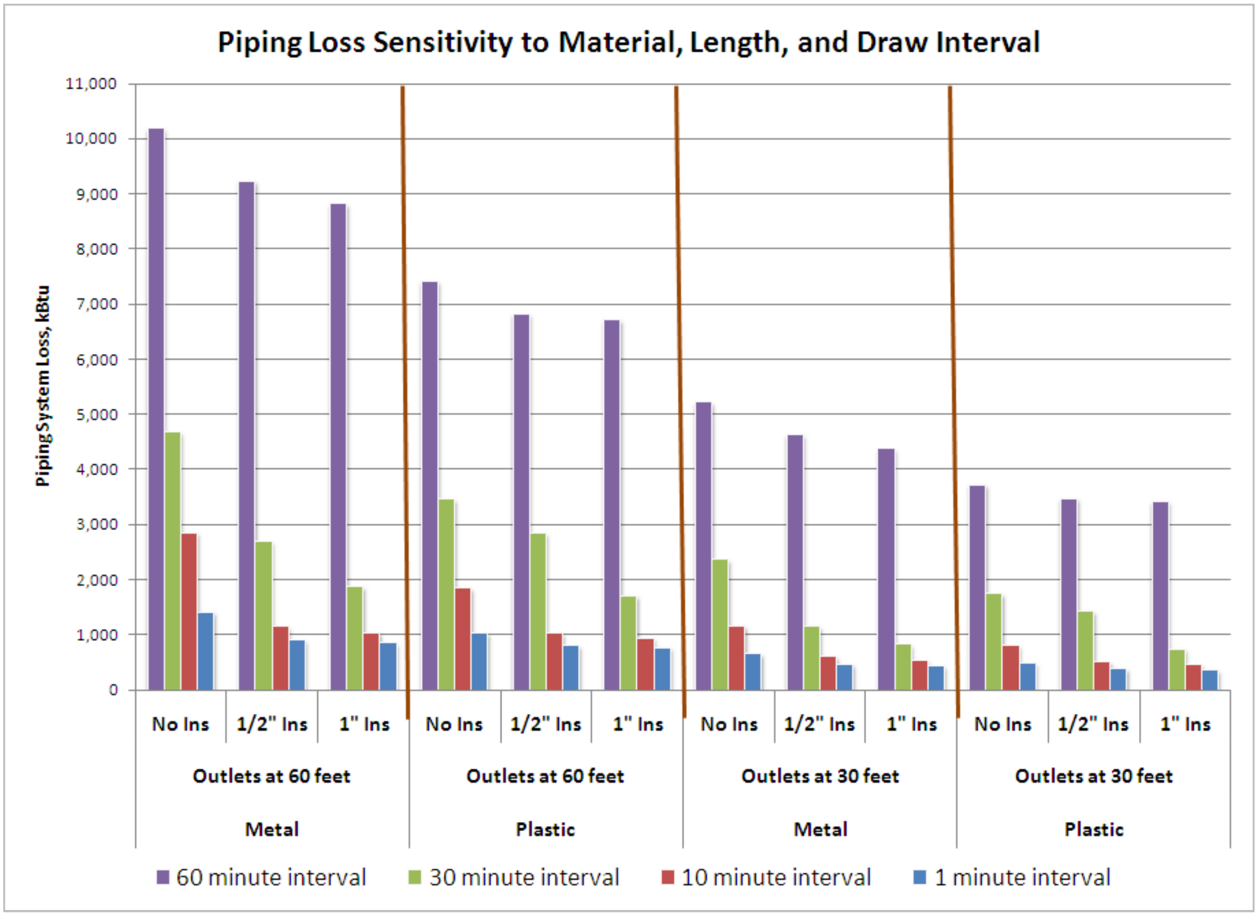

Figure 4 - Pipe Loss Comparison using Parametric Analysis

Each bar series in Figure 4 represents the time between draw events. The comparison for each bar series is shown for the other parameters. For example, looking at the 60 minute interval series, the effect of the insulation in reducing the piping loss for outlets at 60 feet and metal piping is about 1,000 kBtu for ½" thick insulation and about 1,400 kBtu for the 1" insulation relative to the configuration without insulation. In addition to the comparison between the pipe materials and outlet distance, each pipe material for the given distance to the outlets may be compared. . For example, for uninsulated pipe at 60 feet to the outlets, the plastic pipe material results in a pipe loss reduction of about 2,800 kBtu, a higher reduction than insulating the metal pipe. However, this result applies to the 60 minute interval between hot water use events only. Results from the parametric study include the following summary conclusions (also refer to Figure 5):

- When draw events are spaced over 30 minutes apart, the effectiveness of insulation diminishes significantly.
- When draw events are spaced between 10 and 30 minutes, 1" thick insulation on the pipes can reduce pipe losses by over 50%.
- Draw events spaced at 30 minutes apart show the largest benefit to insulation use.
- For draws less than 10 minutes apart, pipe insulation provides little additional benefit to reduce pipe losses.
- Plastic pipe materials reduce the pipe losses by about 25% compared with metal pipe materials.

- For metal pipes, the addition of 1/2" of insulation provides the majority of the benefit, whereas 1" insulation is more beneficial for plastic pipe.

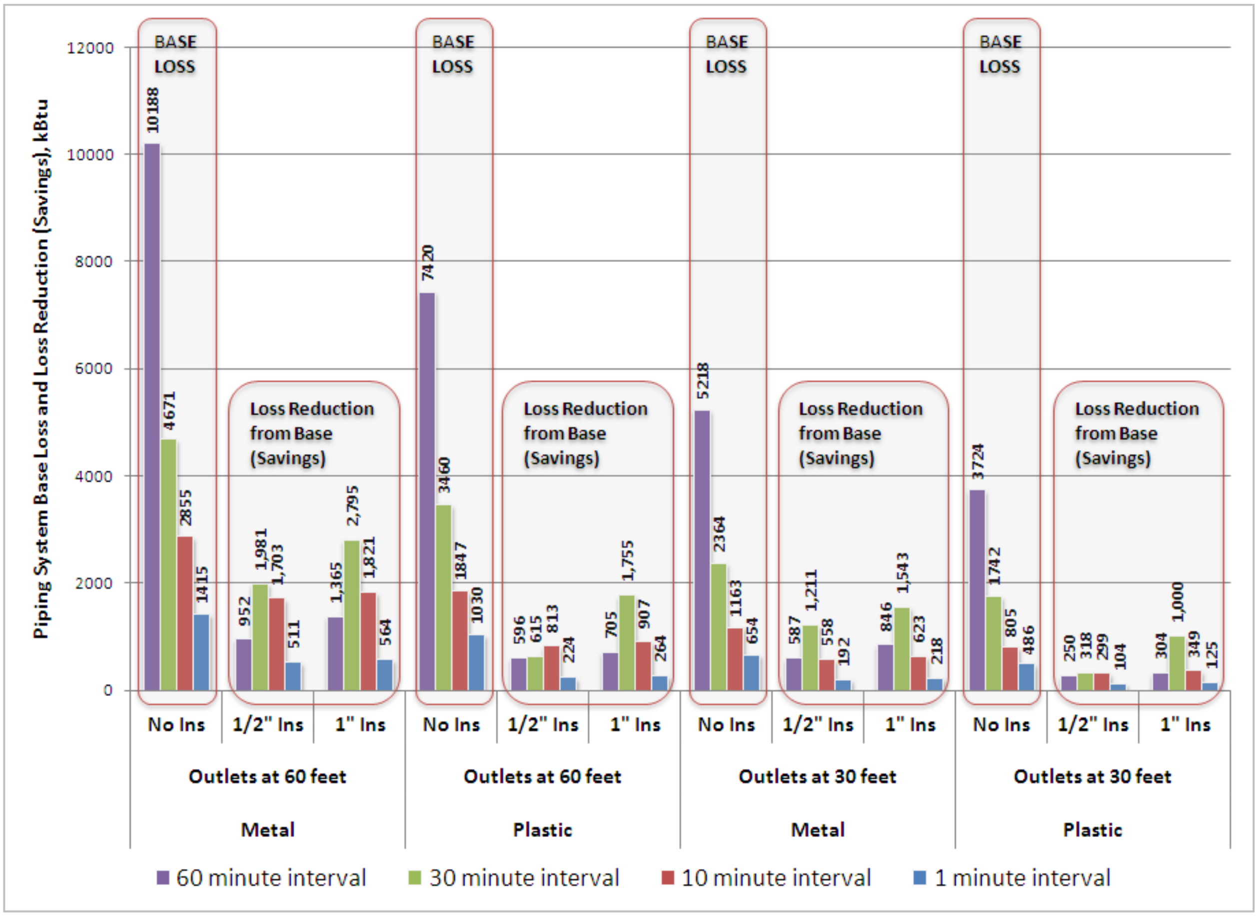

Figure 5 - Piping System Loss and Loss Reduction for Insulated Pipes

The results shown in Figures 4 and 5 are intended to demonstrate the extreme values for hot water piping system losses in any household. The extremes encompass both the length of pipe and the time between draws. In addition, an estimate of hot water use was incorporated that assumed all hot water use began once hot water arrived at the outlet. This is not the case for most dishwashers and clothes washers and may not be true for all sink uses. Typically, hot water use is much more varied throughout the day both for flow rate and the time between uses and the wait time for hot water to arrive at the fixture. Furthermore, the hot water system design generally incorporates various lengths of pipe to the outlets. Given these constraints, the energy use estimated outlines the various influencing factors in hot water energy use and compares the various factors with respect to the pipe material and the level of insulation. However, they do not represent actual losses (or savings) in a real household.

However, as Figures 4 and 5 describe the energy savings, the assignment of cost to the savings when using insulation on the entire length of hot water piping can provide additional perspective for the various systems and use profiles. Figures 6 and 7 detail the annual energy cost savings with pipe insulation for gas and electric water heaters and also compares the average annual energy cost savings over 1, 10, 30, and 60 minute intervals.

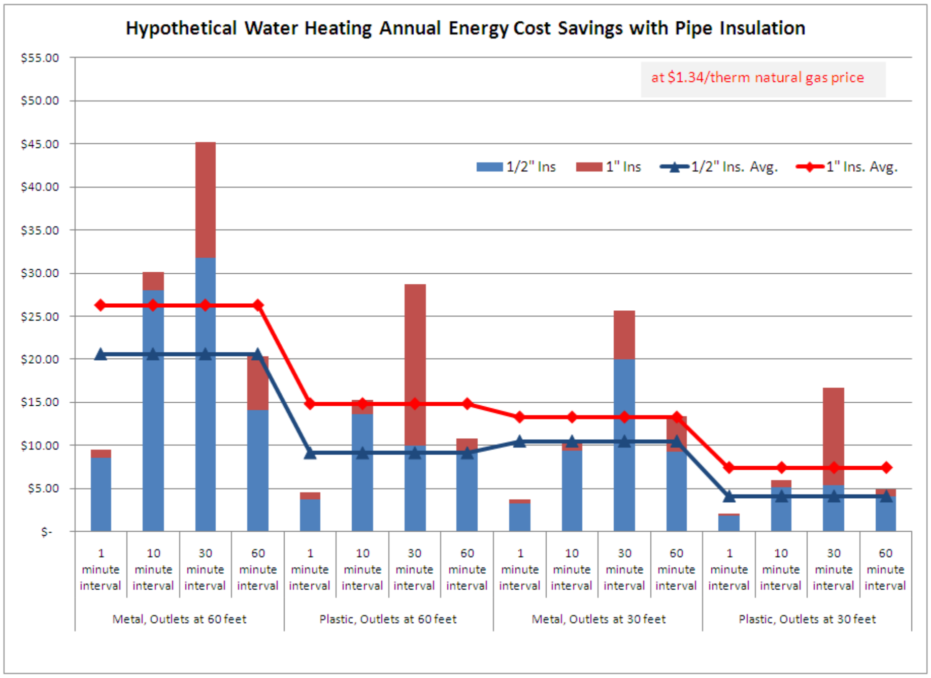

Figure 6 - Cost Value of Savings for Insulated Pipe Given the Stated Parameters - Gas Fuel

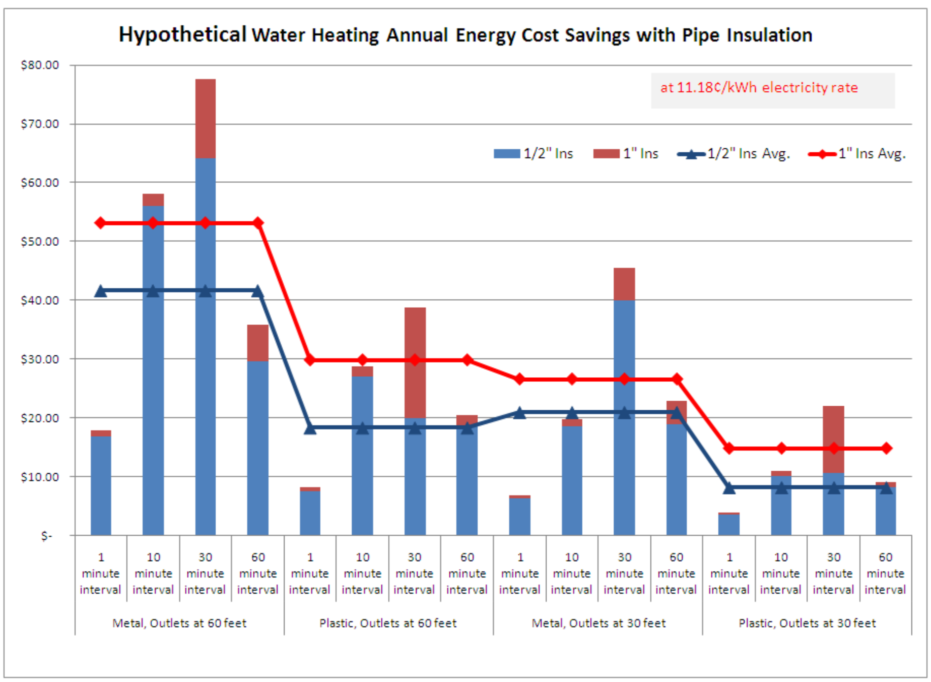

Figure 7 - Cost Value of Savings for Insulated Pipe Given the Stated Parameters - Electric Fuel

Fuel prices are taken from the Energy Information Administration data for the average annual U.S. price. Any changes in the fuel prices will be reflected directly in the savings. For example, if electric rates increase by a third to 15 cents/kWh, the savings would increase by a comparable amount. Figures 6 and 7 demonstrate the cost savings when using both 1/2" and 1" thick insulation on all hot water piping sections. The data can be summarized in the following details:

- The majority of the savings when using insulation is from the initial layer. Adding more insulation provides more limited benefit. The exception is plastic pipe when the interval between draws is 30 minutes where the benefit is equally divided between the first 1/2" of insulation and 1” thick insulation.
- Plastic pipe, due to its lower conductivity, results in average savings similar to reducing the length of metal pipe by a half.
- Reducing pipe length is of significant benefit, both in operating cost and in the cost of installation.
- The consistent 30 minute intervals between uses show the most benefit from insulation.

Although the performance issues afforded through a parametric analysis are of value in determining beneficial design details, an analysis of a “typical” home will provide an overall picture of the hot water system performance using insulated piping.

Analysis 3 - Whole House Hot Water System Simulation

A third analysis of hot water system performance using HWsim was performed using a plumbing system layout design from a typical 2-story home with a basement. The layout is considered a typical hot water piping system using both 3/4" and 1/2" pipe sizes. The outlets are representative of typical new homes with multiple baths, kitchen and lavatory sink basins, dishwasher and laundry. Figure 8 diagrams the layout modeled for the hot water system analysis.

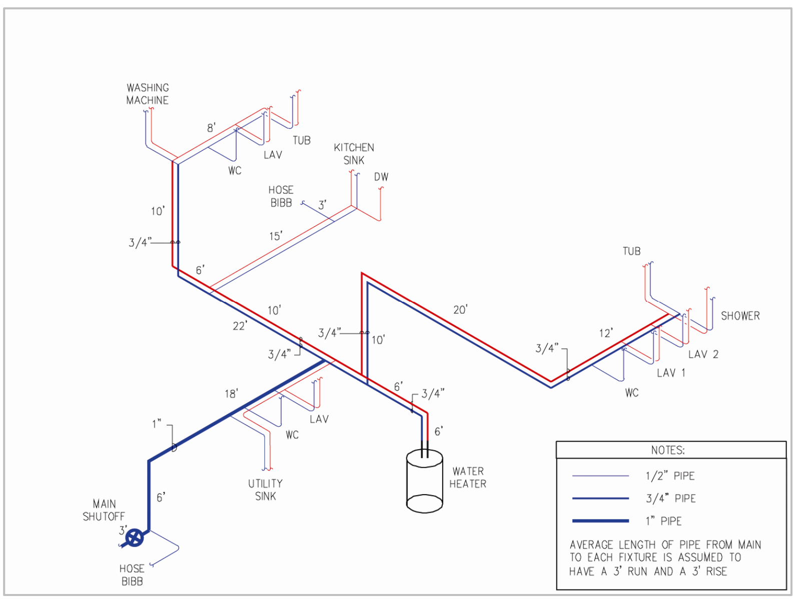

Figure 8 - Plumbing System Layout for Simulation

The simulation model incorporates various tee and branch pipe runs to the outlets. The pipe is assumed to be installed both in the basement area and in the first and second floor walls. The temperature surrounding the pipe is based on simulation runs of a house located in the Washington DC area with temperature variations modeled by month[5]. The cold water temperature is assumed to change throughout the year, by month, based on a methodology[6] developed through the Department of Energy’s Building America Program (BAP).

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[5] The temperature surrounding the piping would apply to a large number of homes across the US where the piping is installed indoors (either in a basement or in the walls or floors of the house). Differences in results would occur if the piping were installed under the slab or in unconditioned spaces, however the differences in the results would also vary from season to season based on the ambient air temperature.

[6] Refer to the Building America Research Benchmark Definition, Updated December 2009, NREL/TP-550-47246

With most hot water simulations, the major challenge in the simulation specification is the hot water draw profile. Numerous studies have been performed to develop hot water use profiles for equipment ratings, to estimate water use, and for energy analysis. An extensive research project was conducted at the National Renewable Energy Laboratory (NREL) that resulted in a use profiles for "typical" homes of various bedroom number [Hendron et. Al. 2008]. The profile selected for this study is the three bedroom profile. The profile is available on a six minute time interval for every day of the year except for a two-week period that represents a vacation period. The profile is based on a statistical analysis but provides a realistic estimate of the hot water use that might be expected in a home, including the variation in draw volumes and the time between draws. A significant feature of this profile is the assignment of outlets for various draw events[7], which were utilized in this analysis.

From the full year profile, a one-week period was extracted to represent the typical weekly profile of the household. The simulation software is limited to a 1-week profile that is repeated for all weeks of the year. The week selected was fairly representative of the overall daily use in a winter month (which uses more hot water than summer profiles). The data set selected sums to a hot water use of about 63 gallons per day (gpd) and a combined cold and hot water use at the fixtures of about 76 gpd. This average is close to the DOE water heater test standard[8] that uses 64.3 gpd. Figure 9 graphically displays the weekly hot water use profile set selected for simulation.

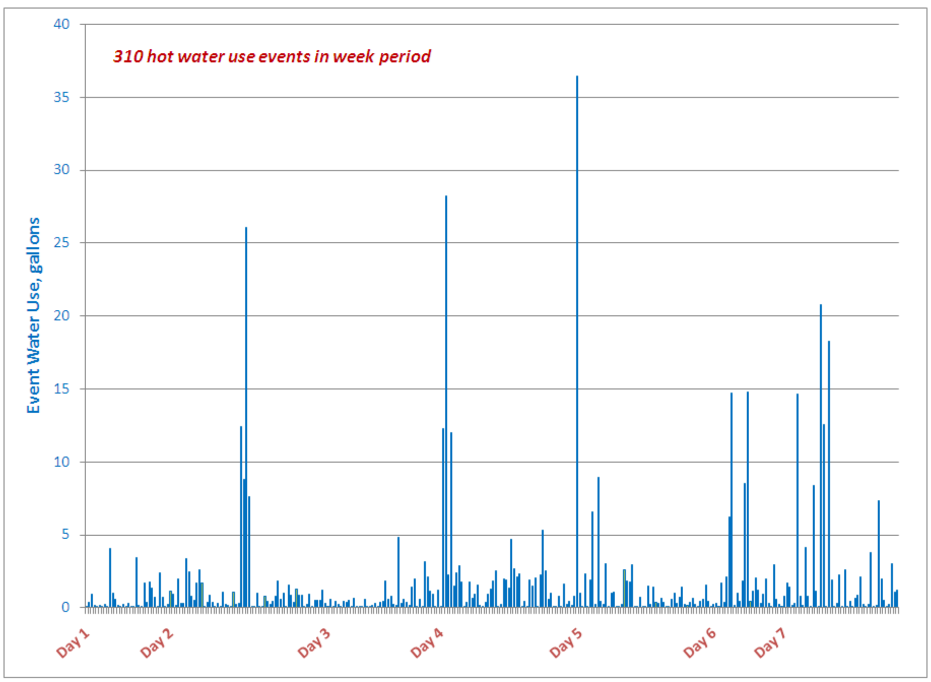

Figure 9 - Hot Water Use Profile

This weekly profile results in variations based on the outlet, the flow rate, the duration of flow, and the temperature set at the outlet, if applicable. For the whole house analysis, specific flow events are assigned to specific outlets which then are simulated with specific pipe lengths and sizes (see Figure 8).

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[7] A common resource for residential hot water use profiles is the ASHRAE 90.2 standard, ANSI/ASHRAE Standard 90.2-2007. This standard does specify a daily profile on an hourly basis of the use factor (a percent of the total daily hot water use). The profile incorporates a diversity factor and therefore does not assign use by outlets.

[8] http://www1.eere.energy.gov/buildings/appliance_standards/residential/pdfs/d-2.pdf

The simulation repeats the daily profile for the week, for every month of the year. The software modifies the incoming cold water temperature and the environmental temperature around the pipes based on the time of year[9]. The software can accept a one-week profile only, however, the plumbing system layout detailed in Figure 8 with the weekly profile in Figure 9 resulted in approximately 300 flow events that were input to the software including start times, flow rates, and duration.

One other parameter defined for simulations is the outlet water temperature at specifically selected outlets that utilize a set temperature, such as a shower faucet. In this case, the software will flow hot water until the faucet is at the set temperature and then mix in cold water to keep the faucet temperature constant. This profile is applied to some sink faucets as well as the showers. Other faucets, the dishwasher, and the laundry are specified as appliances such that the hot water use is by volume only and the temperature is not a controlling factor.

The simulations were conducted for an annual period using the weekly use profile repeated for 52 weeks. The environmental conditions were varied monthly based on seasons. The simulation summary results are shown in Table 5.

Table 5 - Simulation Results for Typical Hot Water System and Use Profile

Performance Parameter	Metal Pipe, Uninsulated	Metal Pipe, Insulated, 1”	Plastic Pipe, Uninsulated	Plastic Pipe, Insulated, 1”
Annual Hot Water Use, gal	23,673	23,362	23,577	23,358
Daily Hot Water Use, gpd	64.9	64	64.6	64.0
Hot Water Waste, gal	430	221	290	174
Piping Loss, kBtu	2,416	1,226	1,860	1,108
Water Heater Energy, kBtu	21,377	21,041	21,227	21,010
Distribution Piping Efficiency	82%	91%	86%	92%
Water Heating Energy Cost, gas	$286.45	$281.95	$284.44	$281.53
Water Heating Energy Cost, electric	$525.38	$514.22	$520.31	$513.11
Annual Water Heater Energy Savings, gas (electric)		1.6% (2.1%)		1.0% (1.4%)
Total Annual Water Heater Energy Savings (Gas Fuel)	@ $1.34/therm	$4.50		$2.91
Total Annual Water Heater Energy Savings (Electric Fuel)	@ $0.1118/kWh	$11.16		$7.20

The summary data from the simulation indicates limited performance and cost benefits from the use of insulated piping based on statistical use profiles and a typical hot water piping system. Whereas the simulations are based on as complete system specifications as is available, the results are accurate in as much as an individual home mimics the simulation parameters.

[9] The values for the environmental temperature surrounding the pipe were based on house simulations in the climate.

Analysis 4 - Pipe Insulation Cost Estimates

The cost of pipe insulation products and estimated installation costs were developed as a reference point for evaluating the cost/benefit of using pipe insulation. Pipe insulation is typically sold in specific lengths and available in various thicknesses and can be foamed plastic (polyethylene), elastomeric, or fiberglass. Table 6 provides the summary of the cost estimates for installed insulation (1) developed based on retail material pricing and construction labor rates or (2) referenced directly from RS Means.

Table 6 - Installed Piping Insulation Cost Estimates

Insulation Specification		Material Cost (per foot)[1]	Installed Estimate[2,3]	Means[4] Estimate
Wall Thickness	Nominal Pipe Size			
1/2"	1/2"	$0.61 - $1.14	$510.68	$942.50
	3/4"	$0.46 - $1.29		
	1"	$0.82 - $1.55		
3/4"	1/2"	$0.91	$555.98	$1,034.60
	3/4"	$0.93 - $1.95		
	1"	$0.83 - $1.55		
1"	1/2"	$1.63	$703.34	$1,263.30
	3/4"	$1.89 - $3.22		
	1"	$2.23		

[1] *Retail material cost, no builder's O&P*
[2] *Hot water piping estimate at 80 feet of 3/4" and 98 feet of 1/2", using least cost material option*
[3] *An estimate of 1 day labor for a skilled mechanic with O&P is $392.40*
[4] *RS Means 2010 Residential Cost Data*

Using the least cost estimates for the piping insulation for 1" insulation thickness used in the simulations and the maximum estimated cost savings for an electric water heater, the payback period would be in the range of 60 to 100 years depending on the pipe material used. This estimate assumes all hot water piping is insulated completely from the hot water heater to the outlet.

Summary

Four different analyses were performed to characterize the performance of hot water piping systems and in particular to evaluate the energy and cost savings from insulating the hot water piping. The major factors that affect the energy loss from the piping systems were outlined and their affect on piping losses was demonstrated. Simulation software was used to compare the performance of different hot water system configurations, flow rates and hot water use profiles. Combining many factors together, the simulations demonstrate that the benefit of insulation is greatest when all of the hot water uses are spaced apart from 10 to 30 minutes. The benefit of insulation is diminished with shorter and longer time between uses. Individually, it was shown that pipes located in colder locations such as an unconditioned crawl space, benefit more from pipe insulation than pipes located in more conditioned spaces. Plastic pipe was shown to have less loss than metal pipe and commensurately insulation is more beneficial on metal pipe than on plastic pipe.

When a full hot water system is simulated in a single-family house using standard hot water use profiles with varying flow rates, time between draws, and pipe lengths from the hot water heater to the outlet, the benefit of pipe insulation is much less significant and the cost benefit to using pipe insulation is on the order of approximately $3 to $11 per year depending on the fuel rates, resulting in simple paybacks of 60 to 100 years based on a range of installed insulation costs.

Appendix A

Annotated Bibliography

Studies relevant to domestic hot water piping systems

Baskin, Evelyn, Robert Wendt, Roberto Lenarduzzi, and Keith A. Woodbury. 2004. "Numerical Evaluation of Alternative Residential Hot Water Distribution Systems." Report NA-04-5-3, *2004 ASHRAE Transactions: Symposia*: 671-681.

> This research investigated energy and water waste in residential domestic hot water delivery systems. Four different distributions systems in three different locations of a typical house were simulated. Results showed that hot water use patterns, pipe material, pipe layout, and recirculation systems have a significant impact on the energy and water waste. Pipe insulation decreased piping heat loss slightly in attics, noticeably in crawl spaces, and significantly below slabs. Conclusions for cold start usage results included CPVC systems have less piping heat loss compared to copper systems particularly in clay under slabs, pipe insulation on pipes buried in attic insulation slightly increases heat loss, and the most efficient systems with this use pattern are demand recirculation using CPVC in the attic and parallel pipe using PEX in the attic. Conclusions for clustered hot water usage results included conventional systems have the greatest heat loss in slabs and the least in attics, pipe insulation in crawl space and slab noticeably reduces pipe heat loss, and the most efficient systems for this use pattern are demand recirculation using CPVC in the attic and conventional with a centrally located water heater using CPVC in the attic. Both use patterns showed that continuous recirculation systems significantly increase piping heat loss and total heated water energy waster.

Review comments: Development of a simulation model to estimate energy losses from piping systems. Simulation modeling temperatures of the attic, crawl space, and soil (slab) appear quite moderate; different climate zones could produce significantly different results when the pipe is located outside of the conditioned space. The use profile modeled is a limiting factor in a broad application of the results except for the location of the pipe.

Wendt, Robert, Evelyn Baskin, and David Durfee. March 2004. *Evaluation of Residential Hot Water Distribution Systems by Numeric Simulation*. Report for Davis Energy Group by Building Technology Center Oak Ridge National Laboratory.

> The goal of this project was to evaluate the energy and water performance, economics, and barriers to use of various domestic hot water distribution systems in new and existing California residences. Heat loss was modeled for insulated and non-insulated hot water pipes; two draw cycles were investigated: cold start and clustered use; five new construction and two existing residences were studied; numerous changes were evaluated: alternative piping materials, centrally located water heater, additional pipe insulation, and demand and continuous recirculation systems. Model results showed consistent energy and water performance for the various scenarios however the results varied significantly (25-600%) with cold start or clustered water use patterns. The study concluded: continuous recirculation systems can reduce water

waste but should not be installed due to high cost and energy waste; demand recirculation pump systems reduce water waste and energy waste but add a significant first cost; water heaters should be centrally located for new homes; parallel pipe distribution systems may be an attractive alternative but energy and water savings are sensitive to hot water use patterns. The report included numerous specific recommendations for policymakers, designers, builders, and plumbers, and new and existing homebuyers.

Review comments: A useful analysis in the comparison between types of draw patterns. Analyzes the application of circulation systems on energy use. Simulation modeling limited to one state and uses a limited piping system. The use profile modeled is a limiting factor in a broad application of the results.

Hiller, Carl. November 2005. *Hot Water Distribution System Research - Phase I*. Report CEC-500-2005-161 to the California Energy Commission Public Interest Energy Research Program.

This extensive report quantified the time, water, and energy waste characteristics of the most common hot water distribution piping systems. One notable result was that hot water pipe insulation can increase piping cool-down time by a factor of two to four.

Review comments: Detailed laboratory effort to analyze and quantify heat loss from domestic hot water piping systems. Results however are not translated into estimated energy savings for homes operating under a use profile.

Hiller, Carl C. 2005. "Comparing Water Heater vs. Hot Water Distribution System Energy Losses." Report DE-05-1 *ASHRAE Transactions*, Volume III, Part 2: 407-417.

This paper compared hot water distribution system piping heat loss to standby losses of common water heater types based on laboratory tests on a variety of piping configurations in order to evaluate when it makes sense to have more than one water heater. Various energy losses due to distribution systems were categorized, including the three components of piping energy loss: cool-down of water left standing in the pipes after a draw, energy lost to ambient during hot water flow, and heated water that is wasted down the drain. This paper addressed heat energy losses during the delivery phase and during piping cool down. Measured UA factors are given for ½" and ¾" copper pipe with 0, ½", and ¾" thick closed cell polyethylene foam insulation. Test results included the observations that even a small amount of pipe insulation provides a large reduction in heat loss, that UA value increases at a low rate as a function of water flow rate and appears to become constant at higher flow rates, and that energy lost to water cooling down in the pipes between draw events is greater than energy lost during hot water flow or wasted down the drain. Calculated results included the observation that for non-recirculation loop systems, pipe insulation is of little benefit for draws spaced far apart and also when clustered within a short period of time, but pipe insulation can significantly reduce energy and water waste when many draws are spaced moderately close together. Tables were provided for lengths of various pipes that would equal various water heater standby losses in order to decide when installing two water heaters may make sense. This paper concluded that using multiple water heaters may be desirable compared to both large recirculation loop systems and non-recirculation applications.

Review comments: The report demonstrates the heat loss mechanisms from domestic piping systems and the effect on energy loss in the hot water system. The study is not designed to estimate the heat loss from piping systems in residential buildings using standard hot water use profiles and standard plumbing system designs.

Hiller, Carl C. 2006. “Hot Water Distribution System Piping Heat Loss Factors - Phase I Test Results.” *ASHRAE Transactions* Vol. 112(2):436-446.

This paper reports on the laboratory testing of piping heat loss for PEX-aluminum-PEX (PAX) hot water piping under a variety of different temperature and flow conditions, including no flow, with various insulation levels and compares the results to previous test results on rigid copper pipe. The tests resulted in calculated piping heat loss factors for several commonly used pipe sizes, and examples are provided to show how to use this information to calculate energy losses.

Stewart, William E. Jr., Charles K. Saunders, and Carol L.G. Dona. 1999. “Evaluation of Service Hot Water Distribution System Losses in Residential and Commercial Installations: Part 1 – Field / Laboratory Experiments and Simulation Model.” Report 4249 (RP-696) *ASHRAE Transactions* V. 105, Pt.1:1-10.

Laboratory and field experiments were performed to determine heat loss in various piping systems and a numerical model was developed to simulate heat loss. The simulation is considered more accurate and useful and the experiments were used as a comparison to the simulation results. The simulation method included pipe insulation as an input variable. Simulation results were given in a companion paper.

Wiehagen, J., and J.L. Sikora. 2003. *Performance Comparison of Residential Hot Water Systems*. NAHB Research Center Report NREL/SR-550-32922

The goals of this research project were to conduct laboratory testing to validate hot water energy savings estimated by prior simulations, measure energy performance of tank versus demand water heater and tree-type copper piping versus PEX parallel piping, and use updated software to evaluate different hot water system designs. The simulation model was calibrated with heat-transfer coefficients determined by experimental results. Simulations showed energy savings of 14%-34% for an electric demand heater with parallel piping compared to an electric storage tank heater and standard copper piping; a parallel piping system represented a and 6%-13% energy savings when modeled with either a tank or demand heater. A point of use system consisting of multiple demand heaters modeled 28%-50% energy savings compared to a storage tank heater with tree-type distribution piping. Additionally, reductions in water use associated with improving the energy efficiency of a hot water system may be significant. This study concludes that demand water heaters with a parallel piping distribution system are the most efficient of the systems evaluated, and recommends further evaluation of actual installation

costs and field performance data for the systems that are identified in this report as energy efficient and cost effective.

Cheng, Cheng-Li, Meng-Chieh Lee, and Yen-Hsun Lin. 2006. "Empirical Prediction Method of Transmission Heat Loss in Hot Water Plumbing." Energy and Buildings 38: 1220-1229.

The purpose of this paper was to present a simplified theoretical calculation of transmission heat loss in hot water piping. The study investigated different pipe materials, with and without insulation, typically found in Taiwan. Results were verified by comparing empirical data and theoretical calculations. This paper concluded that transmission heat loss in hot water piping is an important factor when estimating hot water energy consumption and that this simplified calculation method is an accurate approach.

Lutz, James. 2005. *Estimating Energy and Water Losses in Residential Hot Water Distribution Systems.* Lawrence Berkeley National Laboratory paper LBNL-57199.

This research investigated energy and water losses in residential domestic hot water distribution systems. Three types of loss were identified: the waste of water while waiting for hot water at the point of use, waste heat as water cools down after a draw, and the energy used to reheat water that was already heated once before. Shower losses, sink losses, and dishwasher losses were estimated based on the Residential End Uses of Water Study report (Mayer 1999) and various usage assumptions. Results estimated an average of 6.35 gallons per day is wasted while waiting for hot water and 10.9 gallons per day of wasted hot water that was heated but either not used or used after it has cooled off. This paper concluded that approximately 20% of total hot water use in single-family residences appears to be wasted.

Klein, Gary. 2005. "National Impact of Hot Water Distribution System Losses in Residences." Report DE-05-1-3 *ASHRAE Transactions,* Volume III, Part 2: 423-429.

The purpose of this paper was to assess whether or not the waste of energy and water associated with the poor design and installation of residential hot water distribution systems is large enough to warrant further study and remedial actions. The research estimated the average water wasted and associated costs for showers, long faucet draws, and short faucet draws (energy loss but no water loss). The study recognized losses associated with water heater set point temperatures raised to overcome piping losses, multi-family recirculation system losses, and that there is a large variation in waste based on usage patterns and distribution design (longer or shorter runs and proximity to water heater). This paper concluded that average daily household hot water waste is at least 10 gallons per day, resulting in very large national water and energy losses that appear to be growing and therefore recommended further study of how to cost-effectively reduce this waste for new construction.

Mishustin, V.I. and Yu. A. Chistyakov. 2003. "Thermophysical Measurements: Procedure for Determining Heat Losses Through the Insulation of Hot-Water Pipes." *Measurement Techniques* vol. 46, no. 9: 880-885. (Translated from Izmeritel'naay Teknika, No. 9, pp. 47-51, September, 2003. Original article submitted April 26, 2003)

This paper described a procedure to determine steady-state heat losses through the insulation of inaccessible pipes of heating systems.

Energy Saving Potential Through Optimal Pipe Insulation. Armacell Engineered Foams

Technical article and study by the manufacturer investigated the energy savings of insulating heating and hot water pipes. The study was based on calculated piping heat losses, for heating and domestic hot water piping, of a single family house located in six different European countries. The study concluded that pipe insulation significantly reduces energy use, non-recoverable heat losses occur even on pipes in conditioned space, and the vast majority of non-recoverable heat losses are due to heat losses from domestic hot water pipes in summer.

Masiello, John A. and Danny S. Parker. "Factors Influencing Water Heating Energy Use and Peak Demand in a Large Scale Residential Monitoring Study." *Residential Buildings: Technologies, Design, Performance Analysis, and Building Industry Trends:* 1.157-1.170.

This paper evaluated various factors affecting water heating energy efficiency based on a utility research project that monitored 171 residences in Central Florida. Reported factors included hot water electric demand, day of week and seasonality variations, water heater types, element size, and tank wrap insulation, but did not include hot water pipe insulation.

Studies relevant to hot water use profiles in homes

Hendron, Robert, and Jay Burch. Draft 1/17/2007. *Development of Standardized Domestic Hot Water Event Schedules for Residential Buildings*. Report ES2007-36104, National Renewable Energy Laboratory Proceedings of Energy Sustainability 2007.

The purpose of this study was to use published data of hot water events to develop standard event schedules for the Building America Benchmark performance analysis. Drivers of domestic hot water events were identified as occupant behavior (most important), number of occupants (approximately linear), mains temperature, and magnitude of hot water distribution losses (very important); seasonality was not addressed by this study. Limitations were identified: the use of 6-minute time-steps for events (NREL planned to release another set of event schedules using 1-minute time-steps); increased energy loss using recirculation and other than standard trunk-and-branch systems; ENERGY STAR or other non-standard appliances may consume very different amounts of hot water; differences among households may not be consistent with typical family usage; conditional probability of events were not considered. NREL developed a series of residential hot water event schedules for sinks, showers, baths, clothes washer, and dishwasher.

Jordan, Ulrike and Klaus Vajen. 2005. *DHWcalc: Program to Generate Domestic Hot Water Profiles with Statistical Means for User Defined Conditions.* Proc. ISES Solar World Congress, Orlando 2005.

This report describes a program designed to generate domestic hot water profiles that are used primarily for annual system simulations. The program can be downloaded free of charge at: www.solar.uni-kassel.de.

DeOreo, William B. and Peter W. Mayer. *The End Uses of Hot Water in Single Family Homes from Flow Trace Analysis*. Aquacraft, Inc. Water Engineering and Management, Boulder, CO.

This paper explained how simultaneous flow trace data, from the main water meter and a meter installed at the feed line to the hot water tank, were used with specialized software to characterize hot water demand according to end use and presented results from ten homes tested in Seattle over 14 days. Results showed hot water end use statistics for baths, dishwashers, showers, faucets, and clothes washers, as well as household and per capita hot water use. This paper concluded that this method is an accurate and efficient method to collect data without the need for thermocouples or other devices, in order to provide detailed information on demand patterns useful to accurately design advanced hot water systems.

"Home and Outdoor Living Water Requirements, Plumbing Fixture and Appliance Water Flow Rates." *USDA Water Systems Handbook*. February 14, 2007 http://www.inspect-ny.com/septic/wateruse.htm

Table of usage requirements and typical fixture flow rates for U.S. homes and outdoor living.

Other related research

Aquilar, C., D.J. White, and David L. Ryan. April 2005. *Domestic Water Heating and Water Heater Energy Consumption in Canada*. Canadian Building Energy End-Use Data and Analysis Centre report CBEEDAC 2005-RP0, available at: http://www.ualberta.ca/~cbeedac/publications/documents/domwater_000.pdf

The purpose of this study was to review literature and technology for domestic water heating energy consumption that was estimated to be approximately 22% of total household energy consumption in Canada. Areas investigated included water heater types and efficiencies, factors influencing hot water usage and energy consumption, and energy modeling.

Mayer, Peter W., William B. DeOreo, Erin Towler, and David M. Lewis. July 2003. *Residential Indoor Water Conservation Study: Evaluation of High Efficiency Indoor Plumbing Fixture Retrofits in Single-Family Homes in the East Bay Municipal Utility District Service Area.* Aquacraft, Inc. Water Engineering and Management, Boulder, CO.

This study measured the impact of a variety of indoor water conservation measures for the EBMUD publicly owned utility in California. The methodology used was to collect two weeks of baseline water use data from 33 homes, retrofitting these homes with high efficiency toilets, clothes washers, showerheads, and faucets; next two weeks of flow trace data were collected on two different occasions. Results included a 35% reduction in total water usage; 88% of this savings was the result of three end uses: toilets, clothes washers, and leaks. Ten of the 33 homes had water meters installed on the water heaters and showed in the post-retrofit period that 30% of all water used indoors was hot water and that on a daily basis 83% of that hot water was used for faucets, showers, and baths. This study concluded that significant indoor water savings can be achieved by the installation of high efficiency fixtures and appliances and that these products pay for themselves within the expected life spans.

"Sizing of Water Piping System" *2003 International Plumbing Code* 2003: 118-119.

Wiehagen, J. March 2007. *Domestic Hot Water System Research System Design for Efficiency and Performance.* NAHB Research Center report prepared for National Renewable Energy Laboratory.

This study was a preliminary investigation of a high performance (high energy and water efficiency while delivering a satisfactory amount of hot water) hybrid water heating system design. Previous research of hot water equipment and distribution systems including various piping layout and materials, piping energy loss, and effects of piping insulation were reviewed. A systems approach was identified to examine all aspects of a high performance design that considers preheating, efficiency, delivering hot water quickly, providing sufficient capacity, and minimizing the amount of wasted water and energy. The hybrid solution is a centrally located storage water heater combined with multiple, small capacity distributed water heaters. Simulated results lead to the conclusion that such a hybrid system has the potential to deliver more hot water, more quickly, and more efficiently that a tank-only system. Additional simulations and field studies to continue the evaluation of hybrid hot water systems were recommended.

Davis Energy Group. March 21, 2006. *Field Survey Report: Documentation of Hot Water Distribution Systems in Sixty New California Production Homes.* Report for Lawrence Berkeley National Laboratory.

This field survey was completed to better understand how hot water distribution systems (HWDS) are being installed in California production homes. The methodology investigated 60 single family houses statewide and four HWDS types (conventional trunk and branch using copper or PEX, PEX parallel-manifold, hybrid, and recirculation systems). Results quantified site characteristics, pipe characteristics, plumbing layout, type of water heater, fixture characteristics, industry trends, installation practices, and gathered anecdotal feedback. Specific conclusions and recommendations were made for the four HWDS types, notably with respect to excessive pipe length.