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Numerical Evaluation of Alternative Residential Hot Water Distribution Systems

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ABSTRACT

Subsequent to space conditioning, domestic hot water is the second largest consumer of energy in American homes. Improvements have been made in the energy efficiency of water heating equipment, but few gains have occurred in the distribution system's energy performance. Energy and water waste associated with distribution system performance can be a significant fraction of the total expenditure of delivering and generating hot water. Improving hot water delivery systems will reduce the energy usage and system performance. Results from numerically simulating four different hot water distribution systems in three different system locations in a conventional house reveal that system configuration and location as well as pipe material and insulation noticeably impact the overall performance of the distribution system. Model results based on two usage profiles reveal that:

- *In most CPVC distribution systems, significantly more energy is wasted from previously heated water remaining in the pipe than heat loss through the pipe walls while hot water is flowing. Changing the assumed hot water use patterns can dramatically change the performance of an individual system and its performance compared to copper systems.*
- *Demand recirculation systems reduce the waiting time for hot water as well as the energy and water waste, while continuous recirculation systems also reduce waiting and water consumption but increase energy consumption about 600%.*
- *Parallel pipe systems made of PEX reduce the waiting as well as energy and water waste compared with conventional branch and trunk systems.*
- *Adding pipe insulation does not have a significant impact on heated water energy waste or piping heat loss for hot water delivery initiated from a "cold start" but can be effective if hot water uses are clustered in a short time frame.*
- *Distribution systems located in the attic (buried in attic insulation) should not be insulated because it looses additional energy when standard pipe insulation is added.*
- *Copper pipes have ~10 times more heat loss when they are located below the floor slab in the soil (clay) for "cold start" compared with a clustered use hot water delivery.*

INTRODUCTION AND SIMULATION DESCRIPTION

A numerical model of hot water distribution systems was developed that allows analysis of various types of piping configurations with and without insulation. The model was derived from a model by Stewart et al. (1999) that calculates and compares the hourly heat loss and exit temperature of a copper or steel straight pipe (100 ft maximum) in still air. In this model, the systems may be exposed to a convection environment, buried in attic insulation, or buried beneath a floor slab. The distribution system model is Windows-based and versatile. The simulation is written in a programming language with a graphical user interface (different programming language).

The temperatures in the fluid, pipe, and insulation are calculated by applying a finite element technique to two heat transfer equations. The temperature distribution in the fluid ($T(x,t)$ shown in Figure 1) is simulated by the one-dimensional energy transport in the axial direction of the piping system

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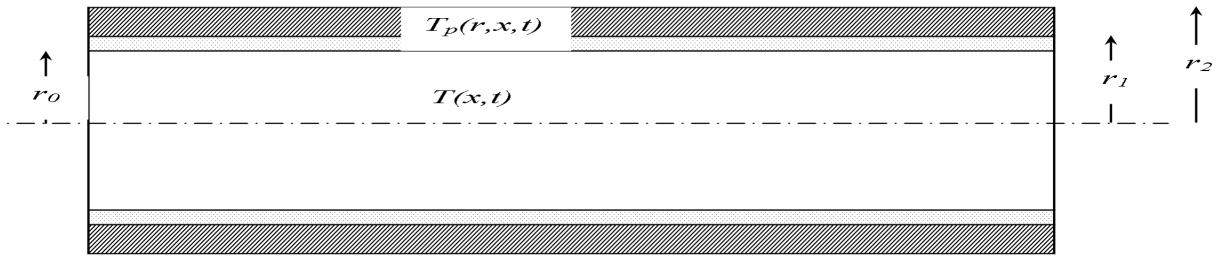

Figure 1 *Pipe and flow temperature distribution.*

with lateral heat losses to the pipe wall. The temperature distribution in the pipe wall and insulation, $T_p(r,x,t)$, is calculated using two-dimensional calculations, coupled to the one-dimensional pipe solution through a heat transfer coefficient.

Mathematically the (axial) temperature distribution of the fluid is governed by

$$\dot{m}c_p\frac{\partial T}{\partial x} + \rho c_p A_{cs}\frac{\partial T}{\partial t} + pq''_{loss} = kA_{cs}\frac{\partial^2 T}{\partial x^2}\,, \tag{1}$$

where p is the perimeter of the pipe, A_{cs} is the cross-sectional area, and k, c_p, and ρ are properties of the fluid. The heat loss from the fluid to the pipe wall is modeled using a heat transfer coefficient stated as

$$q''_{loss} = h(x,t)(T(x,t) - T_s(x,t))\,, \tag{2}$$

where $T_s(x,t)$ is the temperature of the surface of the pipe. The temperature distribution in the pipe and insulation is calculated from the solution of the two-dimensional heat conduction equation in radial coordinates:

$$\rho c_p\frac{\partial T_p}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T_p}{\partial r}\right) + k\frac{\partial^2 T_p}{\partial x^2} \tag{3}$$

where the radial variation in k must be retained (to allow for insulation over the pipe) but the axial variation in k is ignored. $T_p(r,x,t)$, the solution for the temperature in the pipe and/or insulation and the temperature $T_s(x,t)$ in Equation 2 are equal at the pipe inner radius:

$$T_s(x,t) = T_p(r_0,x,t) \tag{4}$$

Equation 2 is used to couple the solution for $T_p(r,x,t)$ to that for $T(x,t)$. The boundary condition on Equation 3 is an external convection environment that has a known reference temperature:

$$-k\frac{\partial T}{\partial r}\bigg|_{r_2} = h(T_p(r_2,x,t) - T_\infty) \tag{5}$$

The radiation is handled on the exterior by a radiant heat transfer coefficient expressed as

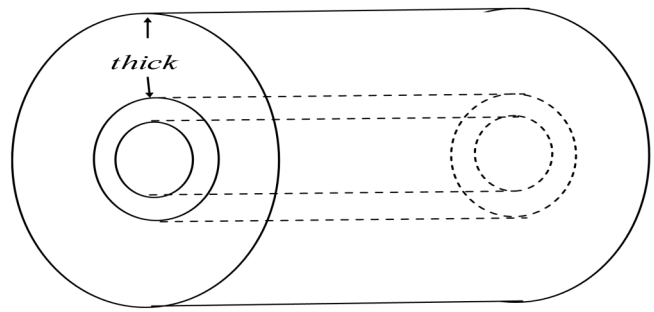

Figure 2 *SOIL/ATTIC material of thickness* thick *surrounding pipe/insulation.*

$$h_{rad} = \varepsilon\sigma(T_{sur}^2 + T_\infty^2)(T_{sur} + T_\infty)\,. \tag{6}$$

Piping systems surrounded by a large layer of attic insulation, soil, or concrete slab are treated in the model as a finite radial thickness of the external material. This is basically the same as if the pipe (with or without pipe insulation) is further insulated with a thickness of attic insulation (piping buried beneath attic insulation), soil, or concrete (piping buried in soil underneath the slab).

The condition is depicted in Figure 2. The layer of surrounding material is characterized by a thickness parameter, *thick*, and this thickness of material is assumed to be all around the pipe. The outer surface of the composite cylinder is assumed to be subjected to a convective/radiative boundary condition. It is assumed that the simulation time is rather short, and the temperature on the outside of this large cylinder of added material will not change substantially during the simulation. Therefore, the solution will not be affected if one surface of the material is exposed to convection and the others are semi-infinite (as in the case of a buried pipe) or if one surface has convection/radiation to a lower temperature than the other (as for attic insulation). The outer radius boundary is assumed to be at a constant temperature during the operation of the hot water system. Both the constant temperature that is assumed and the radius of the material are user inputs.

When there is no water flowing in the piping system, the model exercises one of the pure conduction options using the equations above.

- If the flow rate is specified as zero, the initial fluid temperature is taken as that of the environment and the piping is treated as a fin on the hot water heater.
- If the flow rate is specified as any value less than zero, a special calculation is performed whereby the initial fluid temperature is set equal to the supply temperature or a specified temperature, and the heat loss during the cooldown is calculated.

For no flow in the pipe, a new heat transfer coefficient accounting for the heat conduction from the fluid to the pipe was developed by using a correlation based on an analytical solution for heat conduction in a solid cylinder that is subjected to a step increase in temperature at its surface. The no-flow heat transfer coefficient applies to all configurations. Heat loss is computed using the conduction equation (Equation 3) plus the new heat transfer coefficient. During flow conditions all of the above equations are used. The time between a cluster draw is calculated as a no-flow cooldown of water in the piping between draws. The no-flow cooldown temperature is used as the pipe and/or insulation surface temperature in the subsequent draw in the cluster. During hot water use, a small depth of the soil and attic insulation is penetrated by heat and this same depth is affected during cooldown. Since the depth is small, it is not used when the cooldown piping surface temperature is calculated for the subsequent cluster draw.

SIMULATION METHOD

The model solves for the temperature distribution in the water, pipe, and insulation along the length of the pipe as a function of time using a finite element technique capable of modeling various piping configurations, the entire piping layout, and hot water use events. The use events can originate from a cold start (water in pipe at temperature of surroundings—most wasteful) or determined by entering a daily use profile that defines the cooldown periods between events. The simulation can be used to do comparative studies, such as:

- Establishing the heat loss differences between different pipe materials
- Identifying the impact of an insulated versus non-insulated pipe
- Calculating the effect of various pipe diameters on the outlet water temperature
- Calculating the waiting period for hot water to arrive at a fixture.

The simulation requires the following data to calculate the heat loss and outlet water temperature: the pipe parameters (length, inside diameter, and wall thickness); the pipe and insulation properties (thermal conductivity, specific heat, and density); the water flow rate; the insulation thickness; and the distribution system location. The model accepts spreadsheet inputs files, which define the daily water use and events based on the physical properties of the pipe sections and usage pattern. Pipe and insulation property data are automatically selected based on pipe and insulation type as specified in the spreadsheet. Each pipe section is defined by five columns of data. There is a limit of 50 sections of pipe per event. There is no limit on the number of hot water draw events. It is assumed that all the sections in one event have the same pipe material. The time needed to calculate each section depends on the length and location of the piping, usage pattern, specified simulation time step (~1 second), and maximum simulation time. The output results of the simulation are stored in a spreadsheet file and then further analyzed. The model requires a usage file to determine the hot water use pattern and an input file to determine the layout of the system.

APPARATUSES: PIPING LAYOUTS IN SAMPLE HOUSE

A typical home (one-story, single family, 2010 ft^2, three bedrooms, and two baths) is used as the sample case to evaluate the model results. The house represents a typical single-story house that contains a laundry room, one bath with a combined tub and a shower with two lavatories, and another full bath with a tub/shower and one lavatory. The kitchen includes a sink and dishwasher. The water heater is in the garage, and the distribution layout spreads the hot water consuming devices (point-of-use) throughout the house. Figures 3 through 6 show the distribution system layouts by the dark black line on the house plan.

SIMULATION PERFORMANCE RESULTS

All draws are initiated at the hot water heater at 120°F (48.9°C) and terminate at the point-of-use. Results from cold start (all water in the pipe is at the surrounding temperature—most wasteful case) simulation runs using the conventional, demand recirculation and parallel pipe distribution configurations are presented in Table 2. The parameters used for the sample house simulations are shown in Table 1. The temperatures are a seasonal average for California.

The wait time for hot water (the time it takes for the water to reach a usable temperature of 105°F at the point-of-use) and heat loss through the piping to the surroundings for each point-of-use are determined based on the pipe and water initiate temperatures. The draw profile is performed for a day and the monthly result is computed by multiplying the daily use result by 30. The results reveal substantial piping heat loss and wait time differences based on the pipe material, configuration, insulation level, and system location as described below and shown in Figure 7.

- *Pipe Material*: CPVC pipe has significantly less (~50%) piping heat loss reduction through the pipe compared to copper pipe for conventional (standard and central water heater location) and demand recirculation configura-

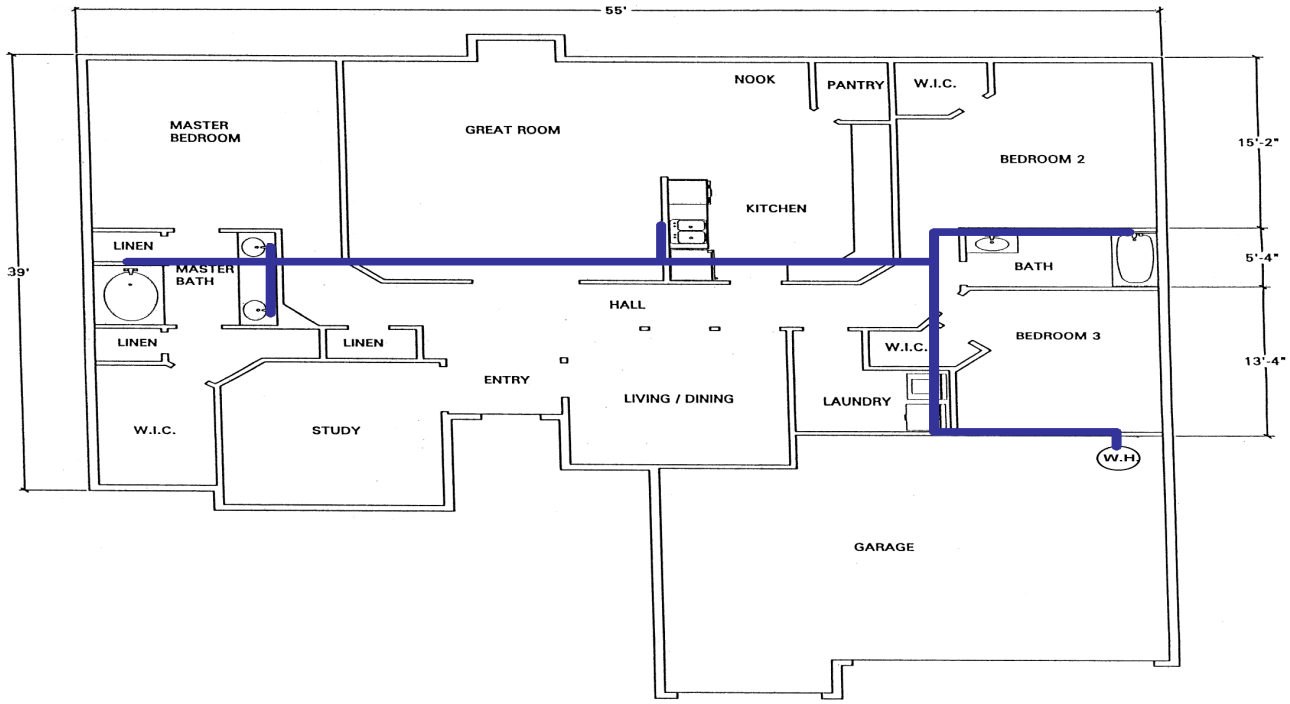

Figure 3 *Conventional hot water distribution system.*

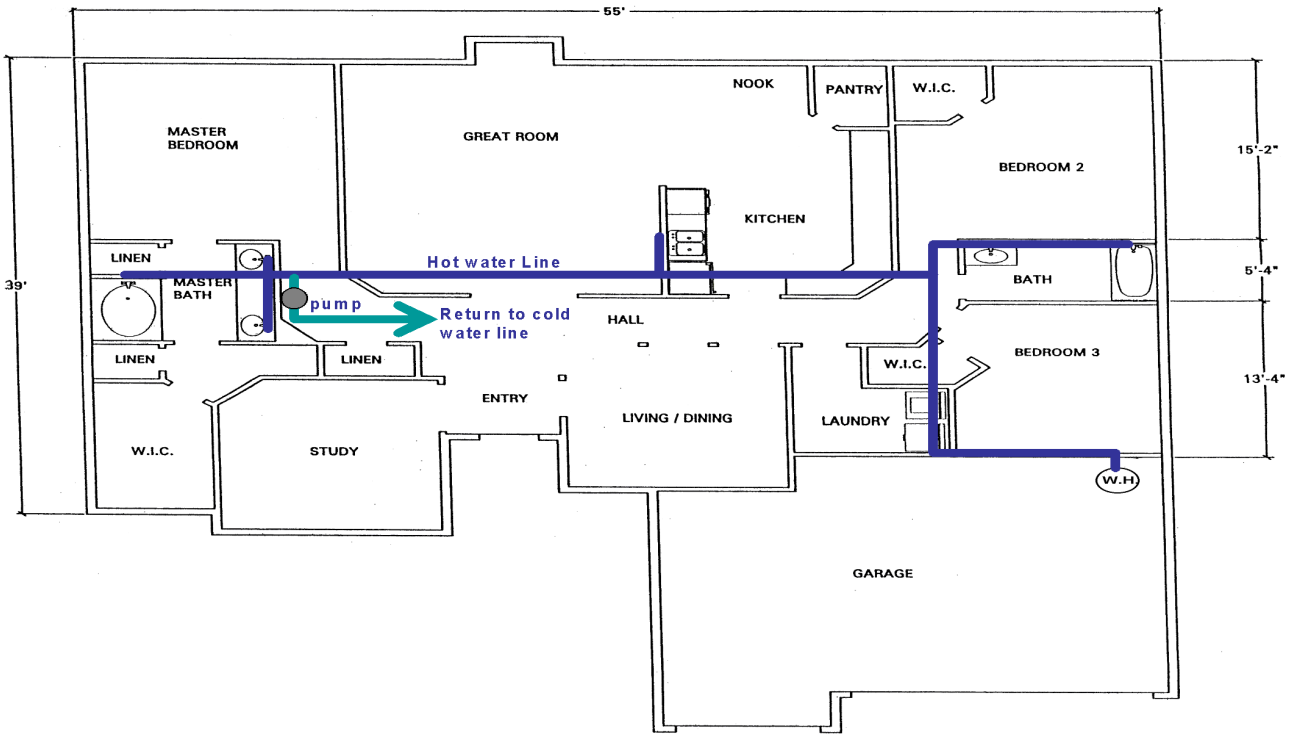

Figure 4 *Demand recirculation layout.*

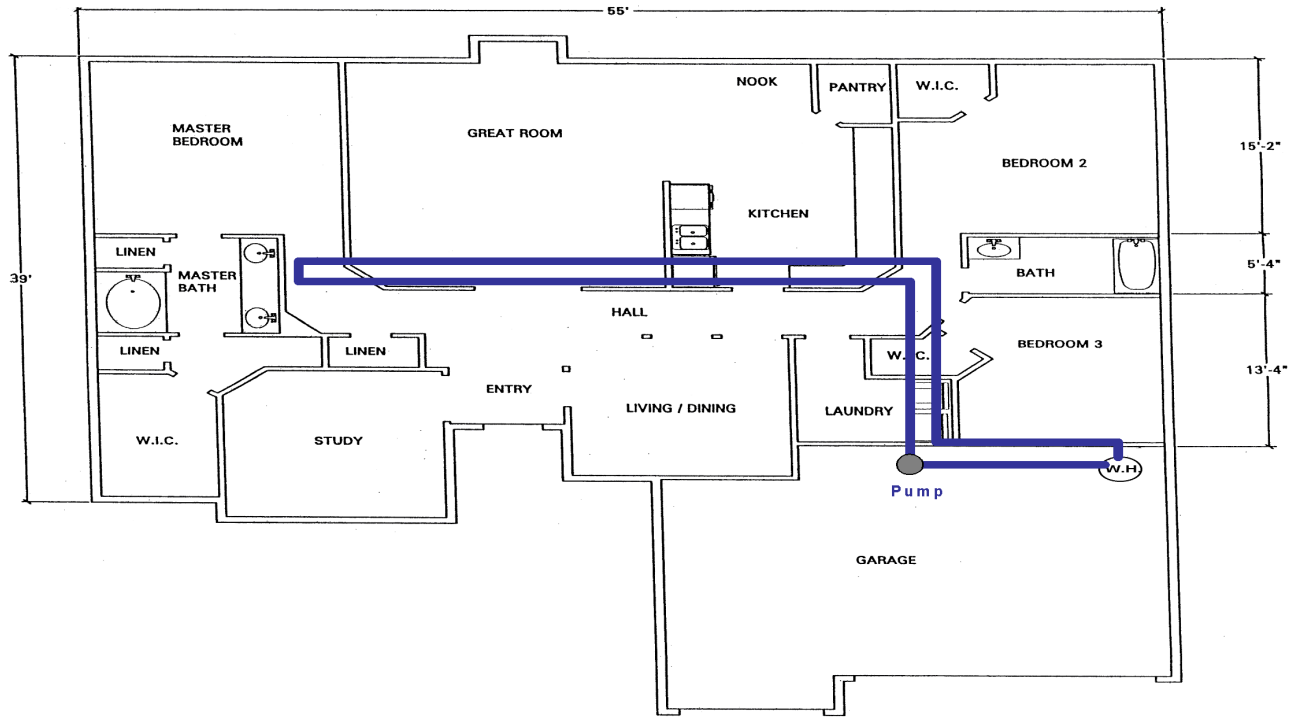

Figure 5 *Continuous recirculation layout.*

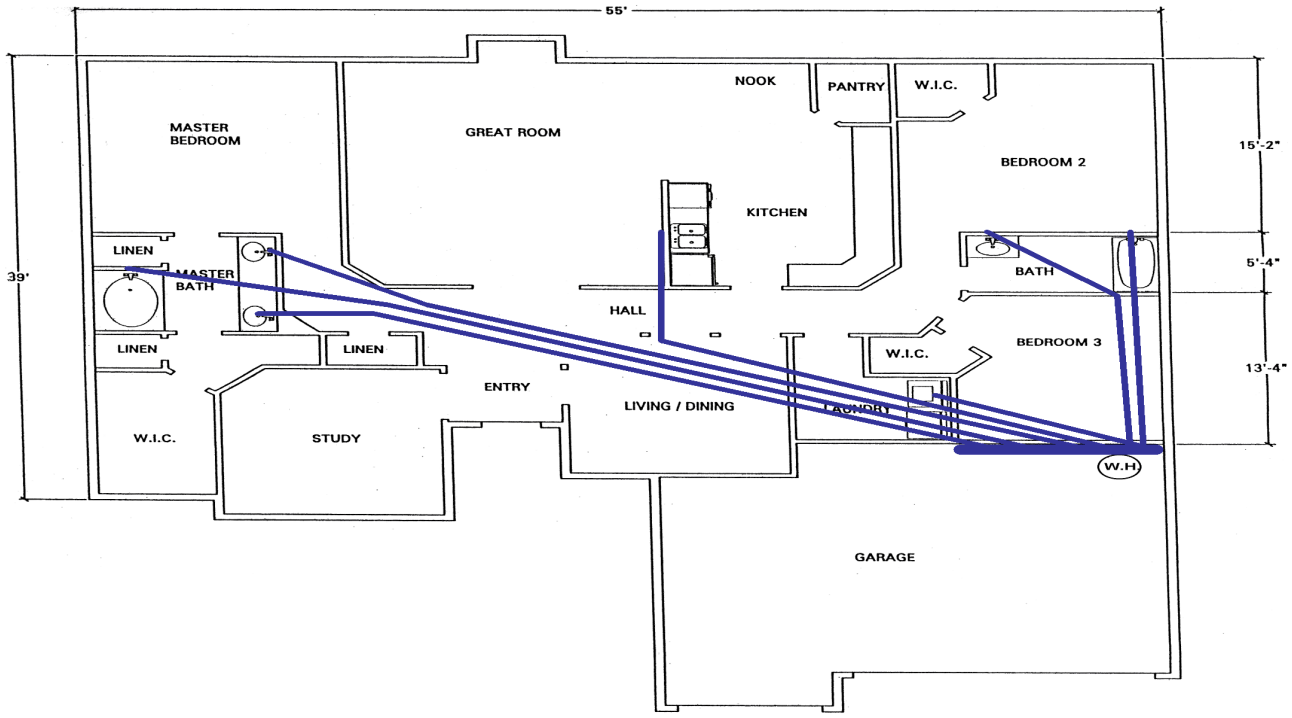

Figure 6 *Parallel pipe layout.*

Table 1. Simulation Parameters

Pipe Main Branch Diameter (inch)	Copper	3/4	Location Temperature (°F)	Attic	76
	PVC	3/4		Crawl Space (CS)	68
	PEX	3/8		Soil	64

Table 2. Monthly Energy loss and Wait Time for Cold Start Hot Water Delivery

Sample House (System Layout)	Wait Time for HW (sec)		Water Wasted (Water Down Drain)	Energy Loss From (Btu)	
	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe
Conventional					
Attic Cu - Central	42	44	436	257,697	26,728
Attic CPVC - Central	41	42	426	251,851	13,509
Attic Cu	60	103	882	521,391	53,097
Attic Cu-Ins	60	104	883	522,140	54,079
Attic CPVC	57	99	839	496,431	29,394
Attic CPVC-Ins	57	99	839	496,431	29,668
CS Cu	60	104	892	527,612	62,054
CS Cu-Ins	60	104	892	527,612	60,371
CS CPVC	57	100	849	501,902	33,231
CS CPVC-Ins	57	100	849	501,902	32,977
Slab Cu	63	111	932	551,223	117,388
Slab Cu-Ins	60	104	884	522,890	82,956
Slab CPVC	58	100	855	505,950	38,839
Slab CPVC-Ins	58	100	855	505,950	34,291
Demand Recirculation					
Attic Cu	6	9	99	58,390	54,536
Attic CPVC	6	9	100	59,140	29,565
Slab Cu-Ins	5	8	83	48,871	85,417
Slab CPVC-Ins	5	8	85	50,295	35,134
Parallel					
Attic PEX	23	36	314	185,440	23,848
Slab PEX	24	38	324	191,361	29,817

Ins-insulation, CS-crawlspace, Cu-copper, HW-hot water, Typical = median wait time of all daily profile draws, and Max is the maximum wait time of all daily profile draws

tions, both with and without insulation. Using CPVC causes an estimated 50% energy loss reduction below that of copper pipe as shown in Table 2. The typical hot water wait time is about 5% less than that of the standard conventional copper system. Since water waste is proportional to the hot water wait time, the CPVC pipe has roughly 5% less waste water than that of copper pipe.

- *Configuration*: Having the hot water heater centrally located—reducing pipe length from the water heater to point-of-use (water heater not in the garage—centrally located in the house)—yields an energy reduction of roughly 50% compared to that of the conventional system (with the water heater in the garage). The parallel pipe configuration using PEX pipe material reveals similar reduced piping heat loss (~25%) compared to that of the centrally located water heater, but the maximum hot water wait time is about half that of the centrally located water heater. The parallel pipe system has ~35% less piping heat loss and typical waiting time than that of the standard conventional copper system placed in the attic or crawl space. The demand-actuated recirculation sys-

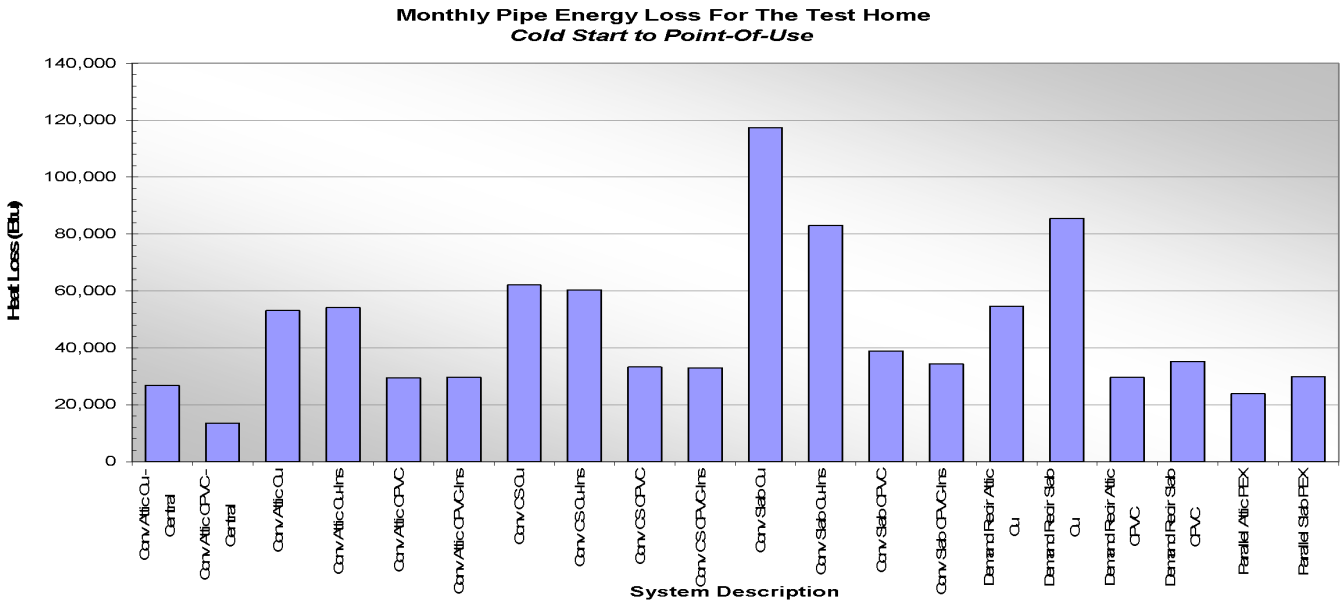

Figure 7 *Total energy losses through the pipe for evaluated configurations.*

Table 3. Loss through Pipe Located In Soil (Clay)

Property	Copper	CPVC	Soil	Impact
k (Btu/h-ft-F)	227	0.08	0.08	Cu higher conductivity- gives up heat quicker, $k_{CPVC} = k_{Soil}$
ρ*Cp (Btu/ft^3°F)	51.2	9.58	13.9	CPVC and soil have similar volumetric heating capacity
α =k/ ρ*Cp	4.44	0.01	0.01	Cu higher thermal diffusivity readily transfers heat from fluid to surrounding
$h_{Thickness}$(in.)	0.045	0.113	-----	CPVC thicker pipe wall acts as an insulating layer that reduces heat transfer

tem has similar (to the standard conventional system) piping heat loss through the pipe for the attic location using CPVC pipe and ~3% piping heat loss using the copper; the system reveals ~ 3% lower losses for the slab piping location. The typical hot water wait time and piping heat loss in the water contained in the pipe are reduced by ~ 90%. The demand-actuated recirculation layout is identical to the conventional layout; therefore, the results differ mainly in wait time and heated water energy waste with the demand system having 3% higher pipe heat loss for Cu in the attic and 3% and 2% higher losses for insulated Cu and CPVC in the slab, as shown in Table 2.

- *System Location and Insulation*: Attic located system has the least piping heat loss through the pipe while the below slab location has the greatest piping heat loss.
    - When the pipe is insulated, the heat loss is reduced except for distribution systems located in the attic. Insulating a pipe already buried in attic insulation causes the heat loss through the pipe to slightly increase. This is due to the fact that the bare pipe plus the attic insulation roughly double volumetric specific heat compared to that of the bare pipe plus the polyethylene pipe insulation. Therefore, the region immediately around the pipe absorbs more energy before its temperature increases and causes a higher temperature gradient between the pipe and the surroundings, thereby increasing the heat transfer.
- Locating copper pipe in soil (underneath the slab) would cause the piping heat loss to increase enormously by 56% (with insulation) to 121% over the attic location piping, as shown in Table 2. This occurs because of the triple effect of thermal conductivity, diffusivity, and pipe thickness and is outlined in Table 3. The increase in thermal conductivity of copper increases the rate of heat loss. The large increase in volumetric specific heat coupled with the increased heat loss imply that the region around

Table 4. Monthly Energy Loss and Wait Time for Clustered Use Profile

Sample House (System Layout)	Wait Time for HW (sec)		Water Wasted (Water Down Drain)	Energy Loss From (Btu)	
	Typical	Max	(gallons)	Previously Heated Water Wasted	Pipe
Conventional					
Attic Cu - Central	5	40	117	69,334	6,847
Attic CPVC - Central	5	39	119	70,458	3,342
Attic Cu	5	99	196	115,881	11,435
Attic Cu-Ins	5	99	195	115,207	11,145
Attic CPVC	5	95	191	113,108	6,200
Attic CPVC-Ins	5	95	191	113,108	6,151
CS Cu	9	103	410	242,631	22,360
CS Cu-Ins	5	102	203	119,854	12,837
CS CPVC	8	98	359	212,499	12,196
CS CPVC-Ins	5	98	200	118,205	7,305
Slab Cu	54	109	845	499,878	90,351
Slab Cu-Ins	4	102	192	113,708	16,245
Slab CPVC	50	98	767	453,631	31,538
Slab CPVC-Ins	5	98	192	113,783	7,076
Demand					
Attic Cu	5	9	77	45,273	12,030
Attic CPVC	5	9	78	46,397	6,418
Slab Cu-Ins	4	8	66	39,052	17,997
Slab CPVC-Ins	4	8	70	41,600	7,826
Parallel					
Attic PEX	11	36	196	115,881	15,042
Slab PEX	19	38	286	168,875	24,098
Recirculation					
Attic Cu-Ins	5	9	77	45,273	267,509
Attic CPVC-Ins	5	9	78	46,397	291,240
Slab Cu-Ins	4	8	66	39,052	872,443
Slab CPVC-Ins	4	8	70	41,600	790,345

Ins-insulation, CS-crawlspace, Cu-copper, HW-hot water, Typical = median wait time of all daily draws, and Max is the maximum wait time of all daily draws

the pipe will absorbs more energy before its temperature increases, thus increasing the potential difference for heat flow. The higher thermal diffusivity (thermal conductivity relative to volumetric heat capacity) causes heat to transfer readily from the fluid to the surrounding medium. The combined effect is to increase the heat loss from the pipe significantly. CPVC pipe has a thicker wall than the copper pipe and the added wall thickness and lower conductivity act as insulation.

Results in Table 4 describe simulation runs based on a clustered—a 9-hour draw separation--hot water use pattern (Figure 8) supplied by the model user, which employs the conventional, demand recirculation, parallel pipe, and continuous recirculation distribution system configurations. The wait time for hot water at the point-of-use and heat loss through the piping are the summation of all point-of-use where the water temperature has reached 105°F (40.6°C). The water is initiated from the hot water heater at 120°F (48.9°C) for all point-of-use, and its use pattern is determined based on the use

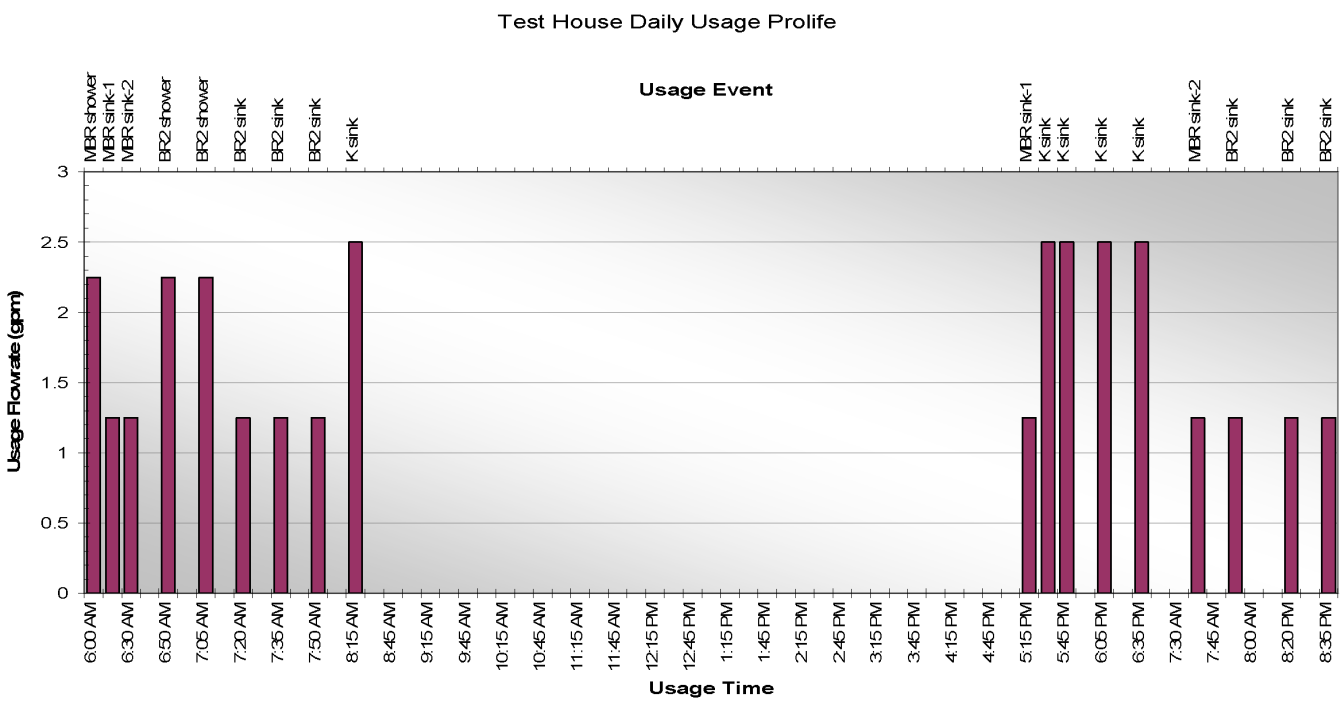

Figure 8 *Usage profile assumption for test cases.*

profile presented in Figure 8. The heat loss through the pipe is drastically (~54 times) greater for the continuous recirculation system than any of the conventional configured systems with similar material and location. The continuous recirculation and demand recirculation systems both have short wait times and minimum water wasted down the drain while waiting for hot water at the point-of-use, but the continuous recirculation system has significantly more piping heat loss. Notable exceptions to the patterns seen in the "cold start" profile are shown in Figures 9 and 10 and Table 4 and include:

- Insulating the pipes in the attic slightly decreases the piping heat loss, while the crawlspace has noticeable reductions through the piping (heat loss reduced by ~43%), and insulating pipes below the slab reduces heat loss by ~80%.
- The parallel pipe system (PEX) piping heat loss is 38% higher for the slab location than for the attic. The parallel piping attic location heat loss is 24% higher than that of the conventional attic location, while the slab location piping heat loss is 73% lower than that of the conventional slab location.
- The demand and continuous recirculation layouts have the shortest hot water wait time, but the continuous recirculation layout losses significantly more heat through the pipe wall. The maximum wait time of the parallel piping system is roughly one-third of that of the conventional system in similar locations.

CONCLUSIONS

When hot water delivery monthly cold start results are simulated based on cold start daily use to each point-of-use, the following concluding observations can be made:

- A centrally located water heater, demand recirculation system, and parallel pipe system all reduce wastewater use, piping heat loss, and the waiting time for hot water to arrive.
- A demand recirculation configuration has the shortest wait time for hot water (reduces water use, thus, the least water waste).
- CPVC piping distribution systems have roughly 50% less piping heat loss and 9% less heated water energy waste compared to that of the copper distribution systems.
- Using standard polyethylene pipe insulation on any pipe buried in attic insulation slightly increases heat loss through the pipe.
- Copper piping distribution systems located underneath the slab in clay have substantially higher (2.4 - 3 times) piping heat loss than those with CPVC piping.
- The most efficient systems with this use pattern are the demand recirculation (CPVC in the attic) and parallel pipe (PEX in the attic).

When hot water delivery monthly clustered results are simulated based on the clustered daily use profile, the following observations can be made:

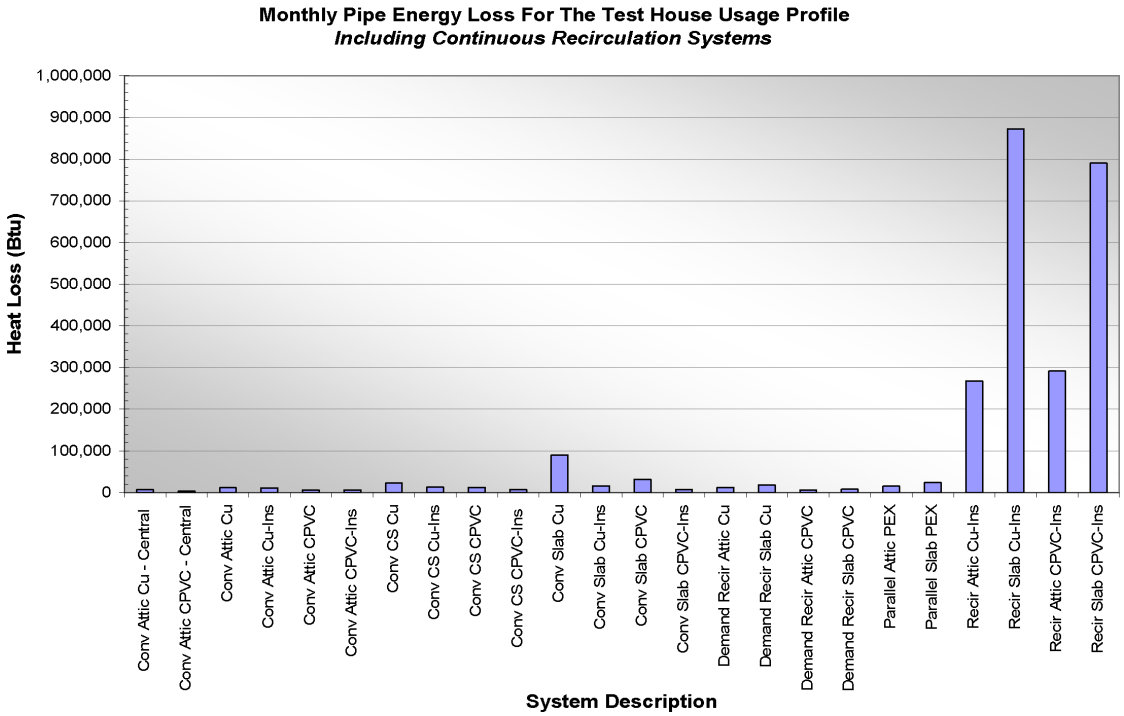

Figure 9 *Heat losses through pipe with continuous recirculation system for usage profile.*

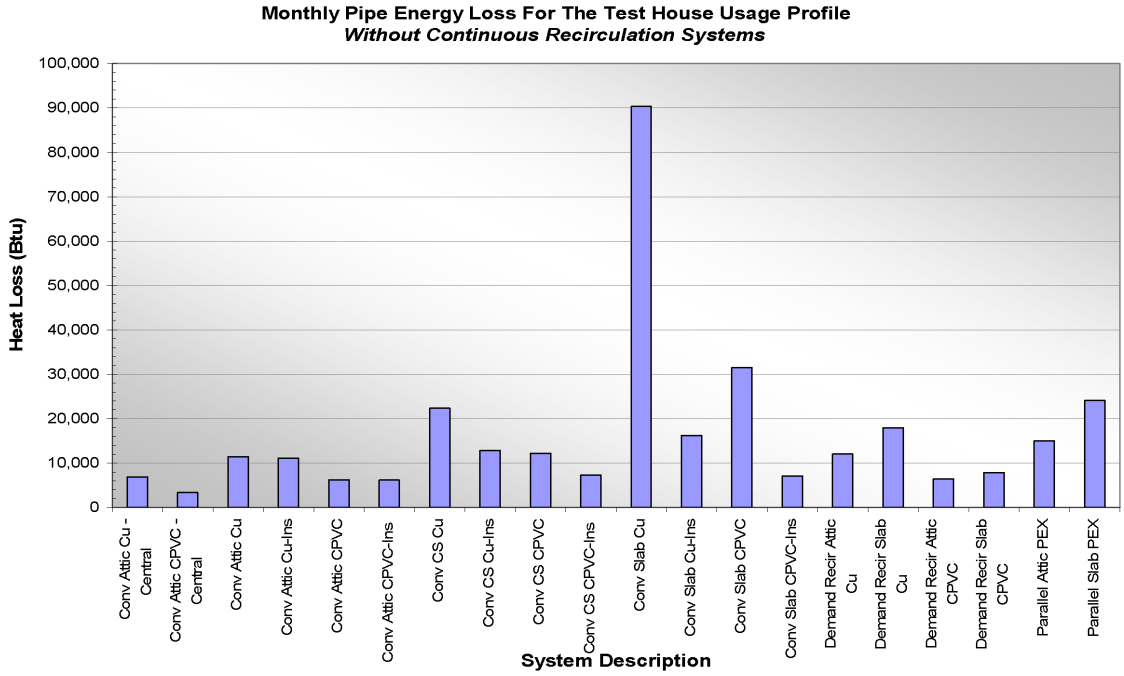

Figure 10 *Heat losses through pipe without continuous recirculation system for usage profile.*

- A continuous recirculation system reduces wait time but significantly increases the piping heat loss and total heated water energy waste.
- Conventional systems located in the slab have the greatest heat losses while those located in the attic has the least losses.
- Insulating the pipes in the crawlspace and slab noticeably reduces the piping heat loss by 44% and 82%.
- The most efficient systems for this use pattern are the demand recirculation (CPVC in the attic) and the conventional with a centrally located water heater (CPVC in the attic).

Since these results are based on numerical simulation, future work should focus on the validation of the simulation by experimental data.

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