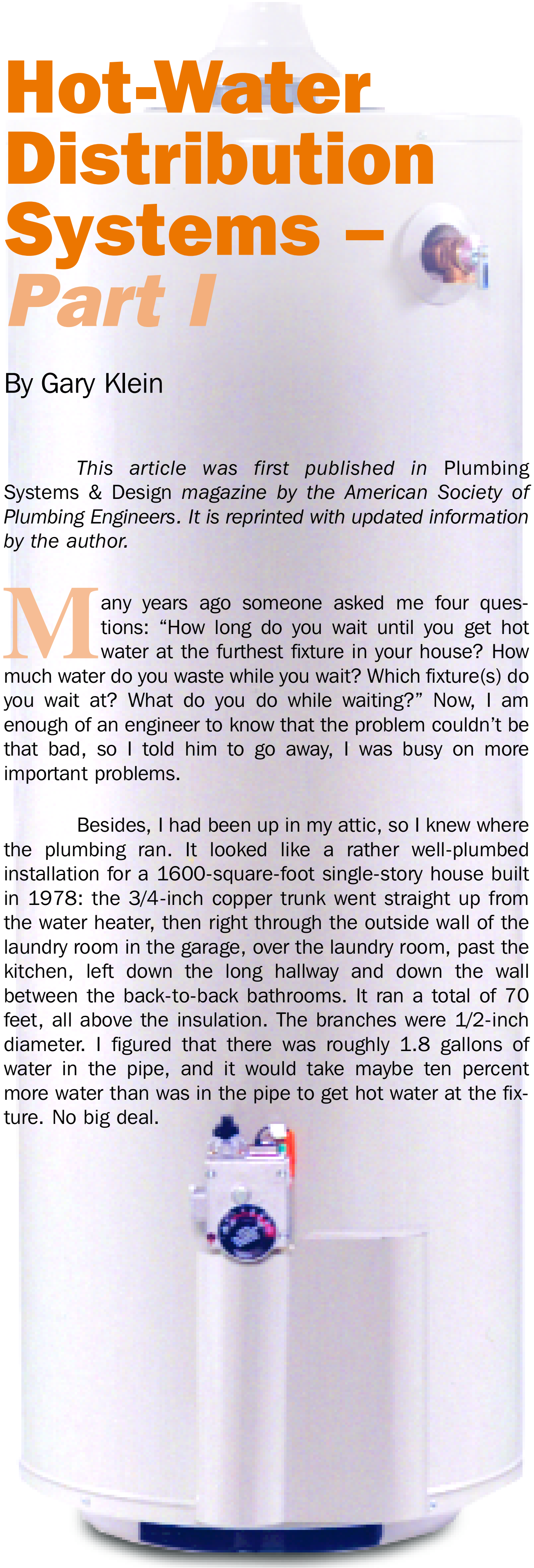


Hot-Water Distribution Systems – *Part I*

By Gary Klein

This article was first published in Plumbing Systems & Design *magazine by the American Society of Plumbing Engineers. It is reprinted with updated information by the author.*

Many years ago someone asked me four questions: "How long do you wait until you get hot water at the furthest fixture in your house? How much water do you waste while you wait? Which fixture(s) do you wait at? What do you do while waiting?" Now, I am enough of an engineer to know that the problem couldn't be that bad, so I told him to go away, I was busy on more important problems.

Besides, I had been up in my attic, so I knew where the plumbing ran. It looked like a rather well-plumbed installation for a 1600-square-foot single-story house built in 1978: the 3/4-inch copper trunk went straight up from the water heater, then right through the outside wall of the laundry room in the garage, over the laundry room, past the kitchen, left down the long hallway and down the wall between the back-to-back bathrooms. It ran a total of 70 feet, all above the insulation. The branches were 1/2-inch diameter. I figured that there was roughly 1.8 gallons of water in the pipe, and it would take maybe ten percent more water than was in the pipe to get hot water at the fixture. No big deal.

The Hot-Water Test

The questioner persisted for a year and finally, on a weekend in March (I live in Sacramento, Calif.) I got up early to run the test. I actually had two problem fixtures, both in the master bathroom. I decided to run the test in the shower stall, which had separate valves for hot and cold water. It took four minutes, during which I collected four gallons of cold water before water hot enough for me to shower in arrived at the fixture. This test allowed me to answer the first three questions, and during the year I had figured out what my wife and I had been doing to accommodate the situation. Whoever got up first in the morning had time to go to the toilet, go to the kitchen and make coffee, come back to the bedroom and undress before the water was hot enough for a shower. In the evening, we would turn on the hot water at the sink and wander around the house, straightening up, putting things away and returning whenever we remembered to wash up before going to bed. Too many times to admit, we wouldn't get there until the bathroom was steamed up, so I suspect that much more than four minutes had elapsed. What bothered me at the time was that more than two times the amount of water in the pipe went down the drain before I got hot water at the shower. I started asking everyone I talked with all over the country the same questions. A disturbing pattern emerged: it didn't seem to matter where people were from, but if they lived in a house built since the mid-1970s they had a similar problem and they told similar stories about their behavior. And the newer the house, the bigger the problem. I began to wonder what had changed to cause this problem, and I began to investigate possible solutions. I discovered the following: The good news is that the plumbing code is being implemented. The bad news is that the plumbing code is being implemented.

The Plumbing Code and the Modern Home

The mathematics behind the plumbing code we use today was developed in the 1930s by Roy B. Hunter. The calculations are based on fixture units and distance in the following relationship: the greater the number of fixture units and the greater the distance, the larger the diameter of pipe that is needed in order to minimize the effect of pressure drop and maintain proper flow. This is excellent engineering, I just wish it was followed in residential ductwork!

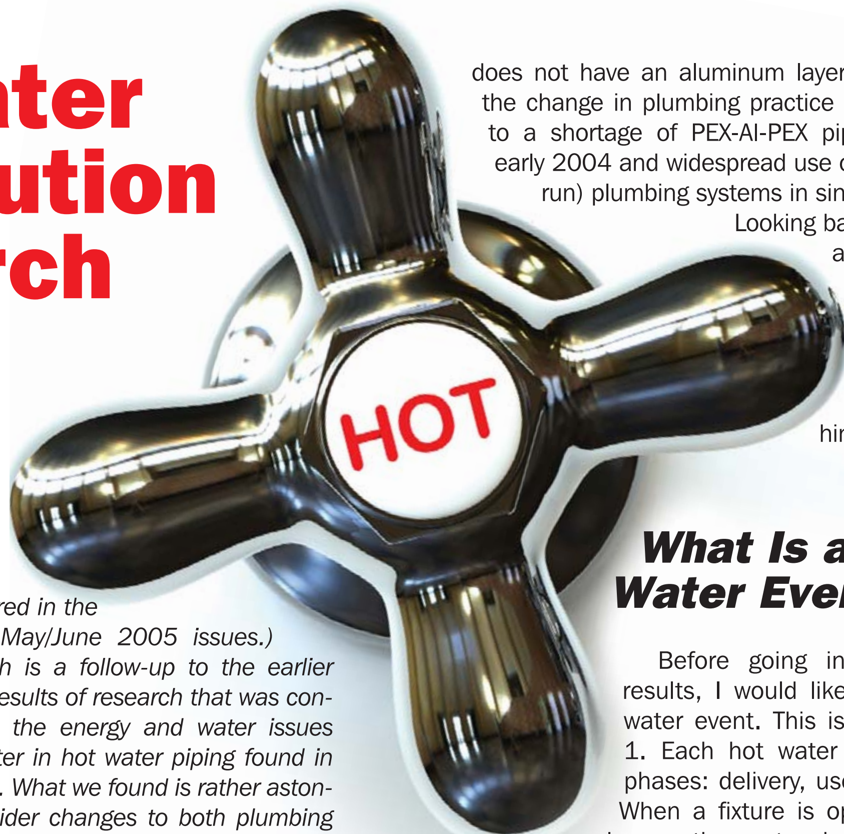
I also found out that half of the houses in the United States were built before 1970 and half of them since. The vast majority of the homes built before 1970 are in the north and east, and most have basements where the water heater is located. Since 1970, most of the home construction has taken place in the south and west. Since virtually none of these homes have basements, the water heater is generally in the garage.

In 1970 the median home was 1600 square feet and had one, maybe 1-1/2 bathrooms, a kitchen, and maybe a dishwasher, washing machine, and laundry sink. The full bathroom had a tub-shower combo and a single sink. This meant

Hot Water Distribution Research

By Gary Klein

Starting in the January/February 2005 issue of Official*, we ran a series of three articles on hot water distribution systems. (The other two articles appeared in the March/April 2005 and the May/June 2005 issues.) In the following article, which is a follow-up to the earlier series, we will document the results of research that was conducted to better understand the energy and water issues related to the flow of hot water in hot water piping found in typical residential applications. What we found is rather astonishing: we may want to consider changes to both plumbing and energy codes to take account of what we have learned.*



Background

The California Energy Commission funded a project to study the performance of hot water distribution piping. That research was conducted by Dr. Carl Hiller, P.E., president of Applied Energy Technology.*

The purpose of the research was to compare the performance of hot water flowing through insulated and uninsulated pipes of various diameters. Before we began the tests we developed a matrix of test conditions that was quite large. We decided to start with 1/2- and 3/4-inch nominal diameter piping since our observation was that these two sizes were the most commonly used in single-family residences, both in California and around the country. These pipe diameters are also commonly found in multi-family, commercial and industrial applications and what we learned is applicable to these situations, too. The tests were to be conducted in air, with the temperature surrounding the pipes in the 65-70°F range.

We also decided to test copper and PEX-Aluminum-PEX (PEX-Al-PEX): copper because of its historically wide-spread use, and PEX-Al-PEX, because it was in common use in California at the time we began the tests. Since that time, we have seen a rapid shift to PEX piping that does not have an aluminum layer. The reasons for the change in plumbing practice appear to be due to a shortage of PEX-Al-PEX piping beginning in early 2004 and widespread use of manifold (home run) plumbing systems in single-family homes. Looking back, it would probably have made better sense to test PEX instead of PEX-Al-PEX; so much for 20/20 hindsight!

What Is a Hot Water Event?

Before going into the research results, I would like to define a hot water event. This is shown in Figure 1. Each hot water event has three phases: delivery, use and cool down. When a fixture is opened, hot water leaves the water heater and heads through the hot water piping toward the fixture. Ideally, we want this delivery time to be as short as possible. In practice there are probably two parts to the delivery phase. The first part is technical or structural and depends on: the plumbing system configuration; the location of the pipes; the volume of the water in the pipes between the water heater and the fixture; whether the piping is insulated; the fixture flow rate; the temperature of the water in the pipes compared to the temperature in the water heater, etc.

The second part is behavioral and depends on when the occupant decides the water is hot enough to use and "get in." As discussed in the first series, the behavioral waste can be significantly greater than the structural waste. The delivery phase may be short at some fixtures and long at others. It may be short or long at the same fixture, depending on when hot water was last needed somewhere else on the same line that serves the fixture. Some people hover near the fixture, checking to see when the water is hot enough, while others know from experience that it takes a long time, so they leave, returning when they are good and ready! From the occupant's point of view, this may appear to be totally random and hard to "learn," in which case I suspect their behavior defaults to the worst case condition at all fixtures.

In the articles that appeared in 2005, we showed how it is possible to deliver hot water, wasting no more than one cup. At flow rates between 0.5 and 2.5 gpm, this means the water will be delivered in 7.5 down to 1.5 seconds, which is pretty darned fast.

(*Hiller, Dr. Carl, P.E., 2005. Hot Water Distribution System Research – Phase 1, California Energy Commission, Sacramento, California, November 2005, CEC 500-2005-161. The full report can be found at: http://www.energy.ca .gov/pier/final_project_reports/CEC-500-2005-161.html)

The use phase needs to be whatever length it takes to perform the task for which hot water is desired. The cool down phase begins the moment the fixture is turned off. If the time until the next hot water event is short enough, the water in the pipes all the way back to the water heater will be hot enough to use. If it is too long, water coming from the water heater will be run down the drain until water hot enough to use arrives at the fixture.

At the fixture, hot water is generally mixed with cold water to reach the desired useful hot water temperature. The thermostat on the water heater needs to be set high enough to overcome the heat losses in the piping system and still provide water that is hot enough to be mixed at the farthest fixture with the highest desired useful hot water temperature. For purposes of our experiments, we selected 105°F as the nominal useful hot water temperature.

From our research, we have learned about all three phases of this process.

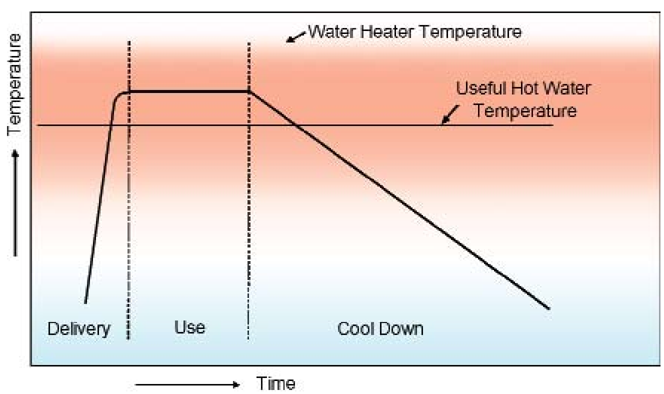


Figure 1. *Hot Water Event Schematic*

The Test Rig

We set up a test rig to measure the performance. This is shown schematically in Figure 2 and in pictures in Figures 3 and 4.

Calculations and observations helped us decide to test roughly 120 foot-long sections of pipe. Since our lab was only 40 feet long, we needed to create a serpentine piping layout. When we used hard copper pipe, the long legs were nominally 20 feet long (the pipe is actually a bit longer) and the short legs were roughly 18 inches long. Temperature sensors were located at the beginning and end of the serpentine shape and at the center of each short leg.

We thought these two layouts, one for hard pipe and one for flexible pipe, were essentially identical. It turns out that they weren't identical and we learned a great deal from this mistake.

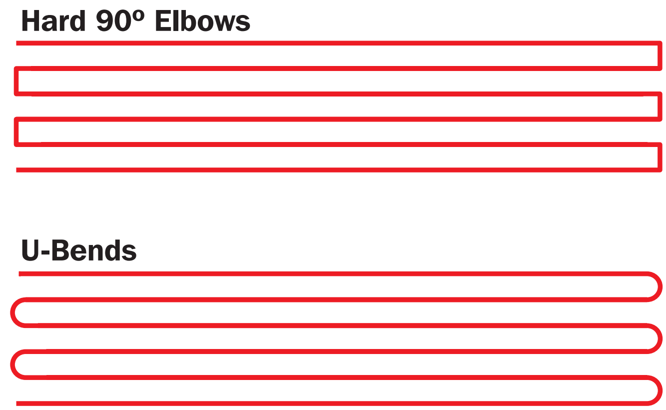


Figure 2. *Serpentine Test Rig Schematic*

Figure 3. *Test Rig for Uninsulated (Top) and Insulated (Bottom) Copper Piping*

Figure 4. *Test Rig for Uninsulated PEX-Al-PEX*

The Delivery Phase

We learned three things from our research about the delivery phase:

1. During the delivery phase, hot water acts differently than cold water.
2. Low flow rates (< 1 gpm) waste much more water than high flow rates (> 4 gpm).
3. At typical fixture flow rates (1-3 gpm), sharp (standard) 90-degree elbows increase turbulence, heat loss and water waste.

Perhaps one of the most surprising things that we learned is that it is possible for significantly more water to come out of the pipe before hot water gets from the water heater to the fixture than is actually in the pipe. During the tests, our researcher found that the temperature sensor on the first turn was getting hot sooner than was theoretically possible assuming perfect plug flow. The difference in time was significant – otherwise he probably wouldn't have noticed it. To figure out what was going on, he used his hands to feel the pipe and found that there was a thin stream of hot water riding on top of the cold water that was running many feet ahead of the plug of hot water coming from the water heater. After some time, mixing would occur, but until that happened, there was a much greater surface area of hot water touching both the cold water and the relatively cold pipe than would normally have been expected.

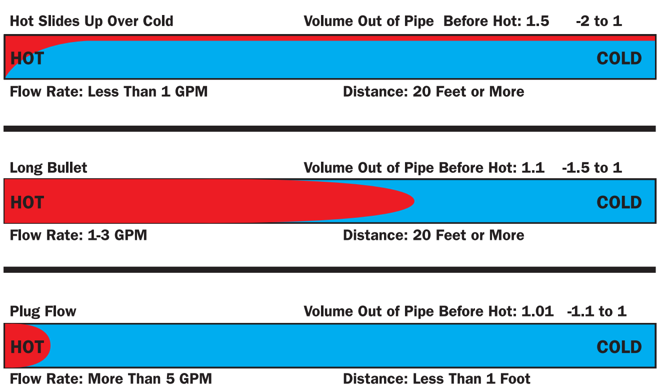


Figure 5. *Delivery Phase Schematics (drawings not to scale)*

This is depicted in the top portion of Figure 5. At the beginning of a hot water event, the cold water is much more viscous than the hot water. The length of the thin stream of hot water could be more than 20 feet long and would go around the elbows. The volume of water that would come out of the pipe (or past a given temperature sensor) before hot water arrived could be twice the volume that was in the pipe.

We found this condition most prevalent at flow rates less than 1 gpm. These flow rates are typical of commercial lavatory sinks, low flow showers and the hot water portion of the flow in a single lever sink when the valve is opened halfway between hot and cold.

As the flow rate increased into the range typical of many sinks and showers (1-3 gpm), the thin stream gave way to a more normal mixing front, which we have depicted as a long bullet. The length of the bullet was several feet ahead of the hot water plug. The extra volume of water that came out of the pipe before hot water arrived was generally 10 to 50 percent more than the volume of water in the pipe. The waste was larger for a given flow rate in the hard-piped test rig that had standard elbows than it was in the flexible pipe test rig that used wide-radius bends in the pipe itself to make the 180-degree turns.

At higher flow rates, typical of those found in garden or Jacuzzi tubs, some laundry sinks, washing machines and dishwashers, we saw what looked like plug flow – the idealized type of flow I heard described in engineering school. In these cases, the length of the much shorter bullet was only a very short distance ahead of the hot water plug. The extra volume of water that came out of the pipe before hot water arrived was generally much less than ten percent more than the volume of water in the pipe. We found this condition some of the time at high flow rates in the hard-pipe test rig with hard elbows. We found it much more often and at lower flow rates in the flexible test rig with wide-radius bends.

If you recall from the first article in the series, I had delivery problems when I measured my house. Looking back, I had installed a low flow showerhead (1 gpm) specifically to save water. However, both the low flow rate and the elbows in the copper piping created conditions that wasted a significant amount of water before the hot water arrived (more than twice what was in the pipe). This was certainly an unintended consequence of my attempt to save water! The extra water that came out had to be heated by the water heater and so my energy consumption was increased during the delivery phase. As we will see in the next section, the low flow rate fixture also frustrated my attempt to save energy during the use phase, too.

The Use Phase

We learned four things about the use phase:

1. Uninsulated PEX-Al-PEX piping has a greater temperature drop at a given flow rate than does copper piping of the same nominal diameter. Insulating the pipes minimized the difference.
2. The temperature drop at a given flow rate is less in 1/2-inch piping than in 3/4-inch piping.
3. The temperature drop over a given distance is greater at low flow rates than at high flow rates. There is a significant difference in the rate of change of the temperature drop at flow rates below 1 gpm.

4 Insulation decreases the temperature drop at a given flow rate.

Figure 6 shows the comparison between nominal 3/4-inch PEX-Al-PEX and 3/4-inch copper piping over a length of 100 feet. The figure is based on steady state flow rates with the hot water entering the pipe at 135°F and the ambient air temperature surrounding the pipe at 67.5°F. The water in the uninsulated PEX-Al-PEX pipe lost more temperature at the same flow rate than did the water in the copper pipe. We suspect that this additional heat loss is due to a combination of two effects: the nominal 3/4-inch PEX-Al-PEX pipe has a larger surface area than the nominal 3/4-inch copper pipe – once it is hot there is more surface area to lose heat; and because the PEX-Al-PEX has a larger internal diameter than the copper piping, the face velocity of the water in the PEX-Al-PEX is slower and the rate of heat loss is greater than it is in copper. Once the pipes were insulated, the difference in temperature drop essentially disappeared.

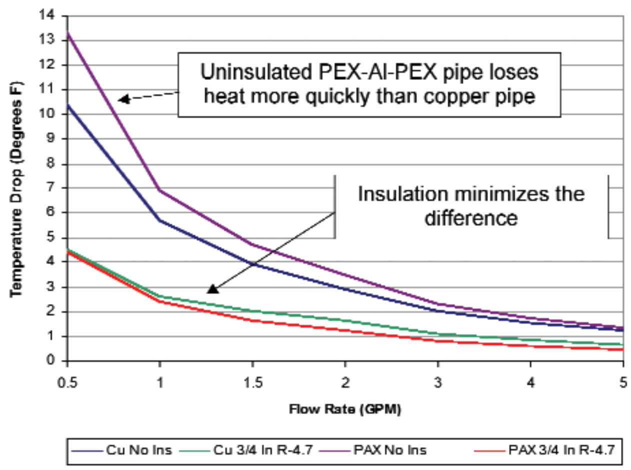


Figure 6. *Comparison of Nominal 3/4-Inch PEX-Al-PEX and 3/4-Inch Copper Piping*

We did not have enough funding to run tests on 1/2-inch PEX-Al-PEX. Based on the fact that uninsulated copper performed better than PEX-Al-PEX and, with insulation, the performance was very similar, we think we can use the performance of copper pipe at 1/2- and 3/4-inch, with and without insulation, as a reasonable first order proxy to better understand what generally happens in hot water piping.

Figure 7 compares the performance of nominal 1/2- and 3/4-inch diameter copper piping, both insulated and uninsulated. As in the prior figure, the graph is based on steady state flow rates with the hot water entering the pipe at 135°F and the ambient air temperature surrounding the pipe at 67.5°F over a length of 100 feet.

At a given flow rate, the temperature drop in 1/2-inch nominal piping is less than in 3/4-inch nominal piping. This is due to the increased face velocity of the water, which reduces the heat loss rate. While from a thermal perspective it is beneficial to use the smallest pipe diameter possible, frictional losses increase exponentially with increased face velocity and result in increased pressure drop over a given length. We did not measure pressure drop during the tests. Future tests should do this so as to better understand its impacts.

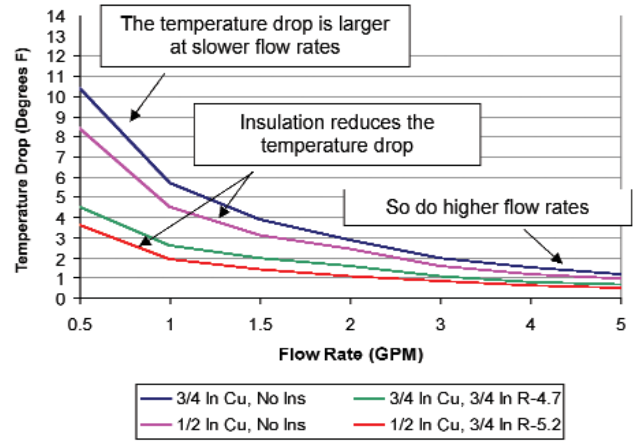


Figure 7. *Comparison of Nominal 1/2- and 3/4-Inch Copper Piping*

The temperature drop over a given distance is greater at low flow rates than at high flow rates. At 2.5 gpm, the highest flow rate allowed for showerheads, the temperature drop in uninsulated copper piping is between 2°F and 2.5°F. At 1 gpm, the temperature drop in uninsulated pipe climbs to between 4.5°F and 5.5°F. At 5 gpm, the temperature drop goes down to roughly 1°F, and the difference between 1/2- and 3/4-inch diameter goes away.

There is a significant difference in the rate of change of the temperature drop at flow rates below 1 gpm. At 0.5 gpm, the temperature drop almost doubles. The curve will get even steeper if the flow rate is reduced still further and, for a given length at some low flow rate, hot water will never reach the fixture. The same thing would happen if length was increased while flow rate was held constant, or if the piping was located in a higher heat loss environment, say in damp soil under a slab or between buildings in a campus situation.

Insulation reduces the heat loss overall and, for a given flow rate, the temperature drop is cut roughly in half. Insulation also reduces the difference in temperature drop between 1/2- and 3/4-inch diameter piping.

The Cool Down Phase

We learned three things about the cool down phase:

1. If the time between hot water events is long enough, the pipes cool down to below the useful hot water temperature for the next hot water event.

2. Larger diameter pipes cool down more slowly than smaller diameter pipes.

3. Insulation extends the time it takes for the pipes to cool down to a given temperature.

The first point seems obvious, since if you wait long enough, the temperature of the water in the pipes will eventually reach equilibrium with the ambient temperature surrounding the pipes. The real question is: how long does it take to cool down to a non-useful hot water temperature? This depends upon the starting temperature of the water in the pipes, the diameter of the pipes, the amount of pipe insulation, the environmental conditions in which the pipes are located, and the temperature of water needed for the next hot water event.

Figure 8 compares how long it took for the water in 3/4-inch diameter copper pipes to cool down from a given starting temperature to 105°F. The ambient temperature surrounding the pipes was between 65°F and 70°F and the pipes were located in air. Without insulation, it took between 5 and 22 minutes for the temperature to reach 105°F. The hotter the water began, the longer it took.

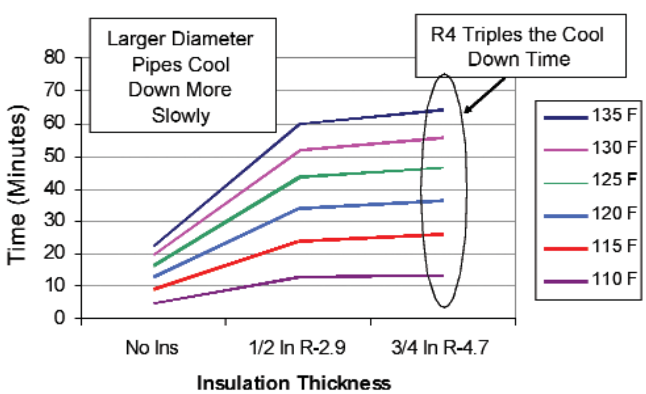


Figure 8. *Time Required for 3/4-Inch Diameter Pipes to Cool Down to 105°F With and Without Pipe Insulation*

When 1/2-inch wall thickness and 3/4-inch wall thickness insulation were added, it took significantly longer for the water to cool down to 105°F. Use of the 3/4-inch thick insulation (>R-4) roughly tripled the cool down time. The 1/2-inch wall thickness insulation did almost as well.

Figure 9 compares how long it took for the water in 1/2-inch diameter copper pipes to cool down from a given starting temperature to 105°F. As with the tests on 3/4-inch diameter pipe, the ambient temperature surrounding the pipes was between 65°F and 70°F and the pipes were located in air. Without insulation, it took between 5 and 20 minutes for the temperature to reach 105°F, almost exactly the same as for the uninsulated 3/4-inch piping. Use of the 3/4-inch thick insulation (>R-4) roughly doubled the cool down time. The 1/2-inch wall thickness insulation did almost as well.

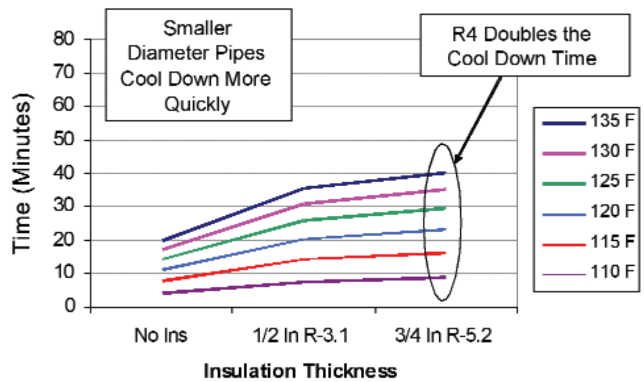


Figure 9. *Time Required for 1/2-Inch Diameter Pipes to Cool Down to 105°F With and Without Pipe Insulation*

Although the time it took the water in the uninsulated pipes to cool down was very similar for the 1/2-inch and 3/4-inch diameter pipes, when insulation was added, the water in the 3/4-inch pipes took roughly 1.5 times as long to reach the same temperature as the 1/2-inch pipes.

If the pipes were located in a colder environment, such as in a crawl space or an attic, used at night or early in the morning, or throughout much of the winter, they would have cooled down much more quickly. If the pipes were in a high heat loss environment, such as in the damp soil under a concrete slab, they would cool off even faster. If the ambient temperature were higher, such as in an attic in the middle of a summer afternoon, the pipes would take much longer to cool down. (On the other hand, the water in the cold water pipes might be too hot to use!)

In future articles in this series, we will apply the lessons learned to improving the performance of hot water distribution systems. We will also look at possible changes that might be made in plumbing and energy codes to take advantage of what we have learned and identify some additional research that should be done. Finally, we will look at the implications of making these improvements on the overall connection between water and energy use.

About the Author: ***Gary Klein***

Gary Klein has been intimately involved in energy efficiency and renewable energy since 1973. One fourth of his career was spent in Lesotho, the rest in the USA. Gary has a passion for hot water: getting into it, getting out of it, and efficiently delivering it to meet customers' needs. He currently helps administer California's Public Interest Energy Research program and chairs the recently formed Task Force on Residential Hot Water Distribution Systems. He can be contacted at Gklein@energy.state.ca.us

Source: Gary Klein

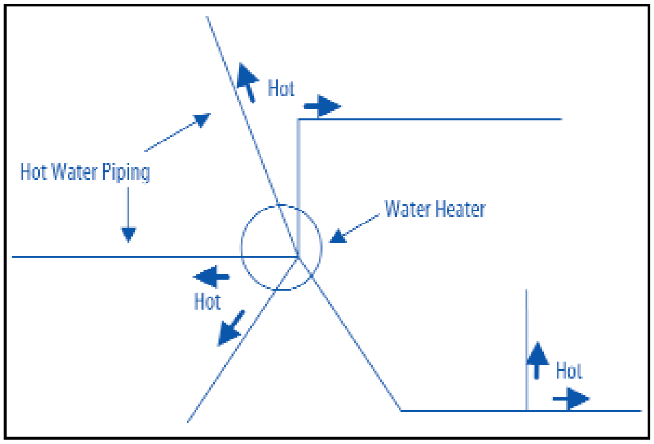


Figure 1. Radial, Manifold, Parallel Pipe Plumbing (Central Core).

that there were five to seven hot water fixtures in the median home. The distance to the farthest fixture was less than 30 plumbing feet even in a two-story house (piping ran over two rooms and up a couple of feet; or over one room, up one floor, and over a few feet). Since there were so few fixtures, the typical trunk line served only one or two fixtures. This meant that 1/2-inch-diameter lines were the norm. (See Figure 1.)

Source: Gary Klein

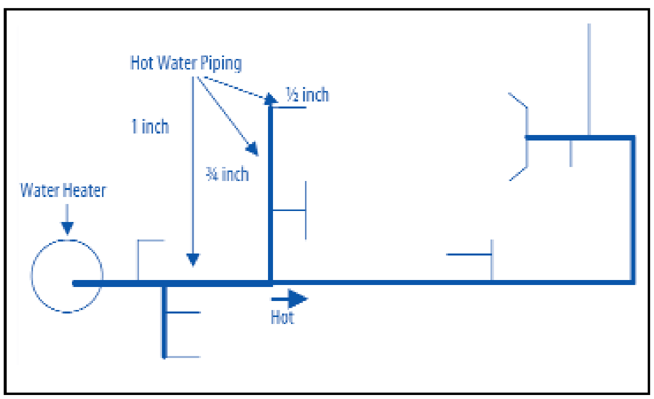


Figure 2. Single Trunk and Branch Plumbing

Source: Gary Klein

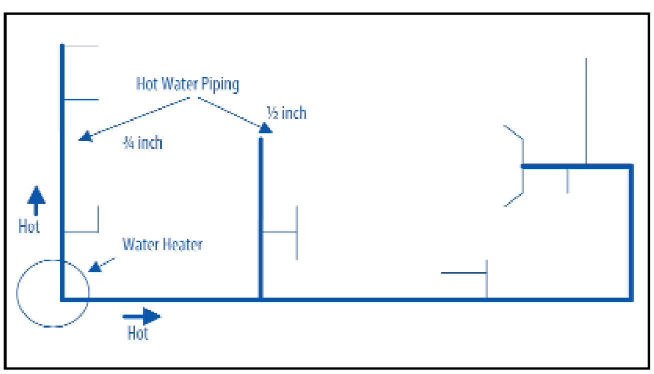


Figure 3. Multiple Trunk and Branch Plumbing

Today the median home is 2400 square feet. There are 2-1/2 or three full bathrooms. The master bath has two sinks, a large tub, and a separate shower; the second bath has two sinks and a tub-shower combo; the third bath has one sink and, if applicable, a tub-shower combo. There is a kitchen sink, a dishwasher, and a washing machine. Sometimes there is an extra sink in the island, and sometimes a laundry sink, and a wet bar. In total, this means that there are 11 to 14 hot water fixtures in the current median home. Since houses are generally stretched out from the driveway to the back yard on long, skinny lots, the distance to the furthest fixture has increased to over 60 feet. There is generally one main trunk, often with one large branch. This means that there is a one inch trunk line in and out of the water heater, which reduces to 3/4 inch after the large branch. The individual fixtures are served by 1/2-inch branches. (See Figure 2.) An alternative pattern, with two trunk lines is shown in Figure 3.

In short, there are twice as many fixtures in the current median home as there were in 1970. The distance to the farthest fixture has more than doubled. And there are a lot more fixtures served by the trunk line. In consequence and in accordance with the plumbing code, the diameter of the trunk line has increased from 1/2 to 3/4 inch for much of its length and to 1 inch for a significant portion. This means that the cross-sectional area of the pipe has increased by a factor of 2.25 to 4.0, so let's say an average of 3.0.

All other things being equal, this means there is an equivalent decrease in the face velocity of the water in the pipe. In addition, because the distance to the farthest fixture has more than doubled, the time it takes hot water to reach the farthest fixture has increased by another factor of two for a total increase of six times longer. Unfortunately, all things did not remain equal.

Enter the energy crises of the 1970s. In response, what is now the Department of Energy quickly figured out the major residential energy end-uses and identified ways to reduce the energy consumption associated with those end-uses. Water heating was near the top of the list and two major initiatives were implemented in the late 1970s and early 1980s: water-heater efficiency standards and later, fixture-flow-rate standards. The fixture flow rate standards are of interest here.

Regulating fixture flow rates reduced typical flows from 5 to 8 gallons per minute down to less than 2.5 gallons per minute for most fixtures today. Eventually, these standards impacted dishwashers and washing machines. In addition, water utilities have taken additional steps to reduce water consumption by promoting more-water saving fixtures. They also have reduced supply pressures, both to reduce leaks in their aging systems and pump costs and to effectively increase supply for the ever-growing population in their service areas.

The result is that the time it takes hot water to get to the farthest fixtures has increased by roughly another factor of three. In short, it now takes 18 times as long for the hot water to arrive. For example, if it used to take 5 seconds to get hot water, it now takes 90 seconds. The wait is no longer perceived of as trivial.

Now I know that this number is not perfect. However, it is robust. Remember that the test pressure for fixtures is 80 pounds per square inch (psi). Since the pressure at most customers' homes is between 45 and 60 psi, the actual flow rate is less than the rated flow rate. While this may be good for saving energy, it means that the typical flow rate is even lower than the nominal amount.

In addition, since basements generally cost more to build than a slab-ongrade, many builders don't offer homes with basements. We have found out that about half the plumbers install the trunk lines under the slab. They dig trenches between the water heater and the appropriate fixture or wall locations and install the pipes before the slab is poured. The pipes are almost never insulated. This installation practice increases the time still more.

Now as I recall, when we asked our thermodynamics professor to define an infinite heat sink, he pointed to the slab beneath our feet. And if I remember correctly, he also said that it took about ten diameters to make the heat sink infinite. Since most residential plumbing is less than one inch in diameter, we are talking about uninsulated copper trunk lines being surrounded by ten inches of earth or concrete. (So here is another experiment for the ambitious: figure out the fixture flow rate at which hot water never arrives at the fixture farthest from the water heater.)

I will concede the difficulties in pinning this problem down, but it is certainly a solid factor of ten. And when something changes by a factor of ten, it is worthy of our attention.

Energy, Consumption, and Cost

We have determined that waiting for hot water to arrive is a problem worthy of study, but just how big a problem is it? How much energy and water are we talking about? How many homes does it impact? What can be done to reduce the waste in existing homes and new construction? Does this problem manifest itself differently in multi-family homes than in single-family homes? What solutions have been identified?

Table 1 shows the energy and water consumption and costs associated with a home using 64 gallons of hot water a day—the amount of hot water assumed when rating water heaters in accordance with the Department of Energy test method. It is almost certain that this daily estimate of hot water consumption is inaccurate, but it gives us a place to start. In addition, the prices for energy are probably low. The relative efficiencies of natural-gas and electric-tank water heaters are high but reasonable. The energy going into the water assumes a 90°F rise in water temperature. The numbers shown in the table are probably conservative.

Table 2 presents a range to estimate the amount of water that is wasted while waiting for hot water to arrive. To the author's knowledge, no studies have been done that accurately characterize this loss. However, the range is similar to the losses that were found in residential ductwork, so it seems like a reasonable place to begin. For convenience, water supply and sewer costs have been combined for a total of $0.01 per gallon. All costs have been rounded off; the data are not that precise.

	Natural Gas	Electricity
Gallons Per Day	60	
Gallons Per Year	21,900	
Energy into Water	16.4 Million Btu	
Efficiency	0.6	0.9
Cost per Unit	$0.92/therm	$0.087/kWh
Cost per Year	$250	$465

Source: Gary Klein

Table 1. Estimate of Annual Hot Water and Energy Use

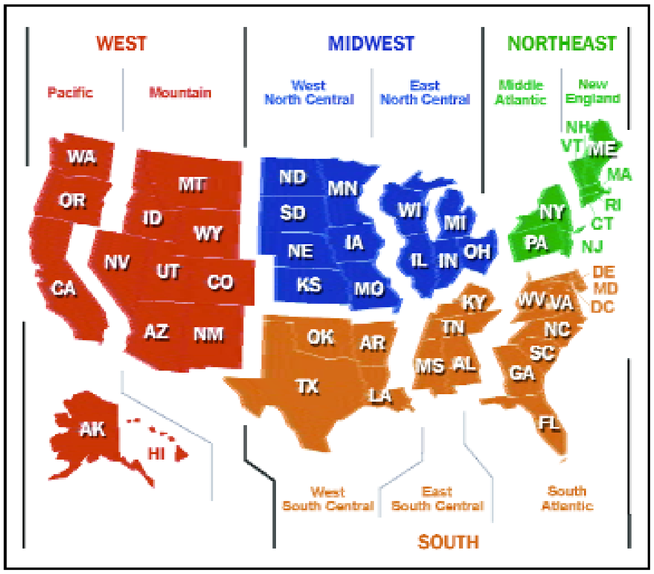
Annual Water Waste and Cost		
	Water Waste	Cost (Water and Sewer)
5 Gallons Per Day (8%)	1825 gallons	$ 9
10 Gallons Per Day (17%)	3650 gallons	$18
20 Gallons Per Day (33%)	7300 gallons	$36
Annual Energy Cost		
	Natural Gas	Electricity
5 Gallons Per Day	$21	$ 39
10 Gallons Per Day	$42	$ 78
20 Gallons Per Day	$82	$156

Source: Gary Klein

Table 2. Range of Annual Water and Energy Waste

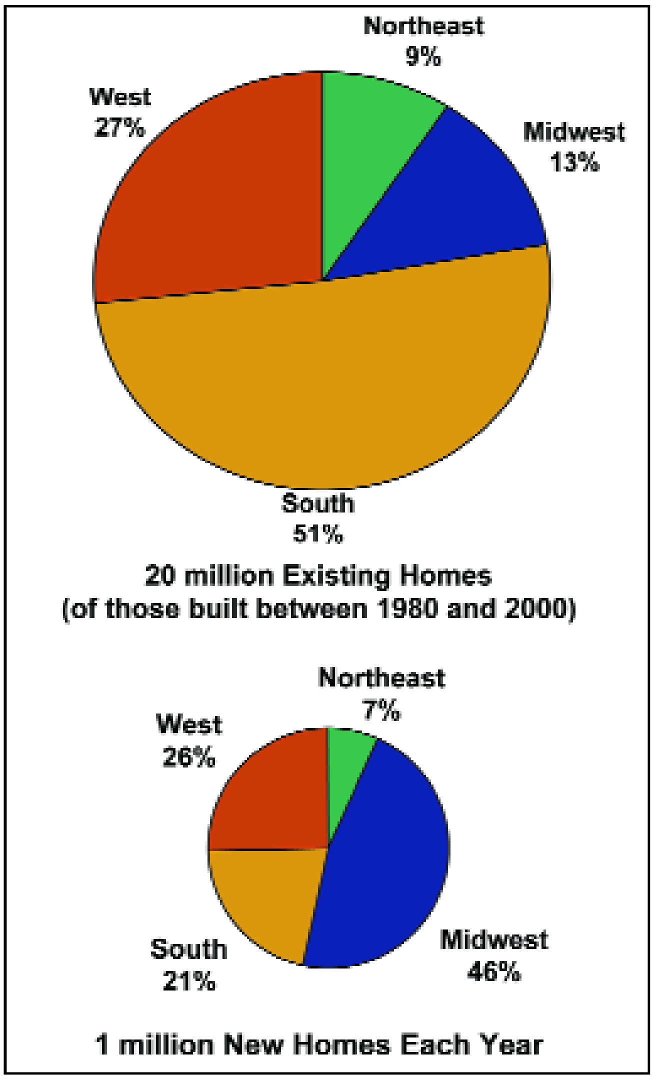
It is fairly easy to see how homes can waste ten gallons per day waiting for hot water to arrive. Let's say that you wait an average of one minute only ten times per day. If the flow rate is one gpm, this is ten gallons per day. If the flow rate was 2 gpm and you waited an average of 30 seconds each of 10 times, you still waste the same amount. In homes with some of the more common plumbing problems, losses of 20 gallons per day are certainly plausible.

These are national averages. Let's see the distribution of the problem in homes across the country.



Source: U.S. Census web site (www.census.gov).

Figure 4. US Census Districts



Source: U.S. Census, National Association of Home Builders

Figure 5. Estimate of homes with significant waits for hot water.

	Northeast	Midwest	South	West	Total
Number of Existing Households					
Owner Occupied	12,644,000	17,568,000	25,180,000	13,403,000	68,795,000
Renter	7,314,000	6,792,000	11,209,000	8,693,000	34,008,000
Total	19,958,000	24,360,000	36,389,000	22,096,000	102,803,000
Households Built 1980-2000					
Owner Occupied	2,666,400	4,411,400	10,274,000	4,711,200	22,062,000
Renter	1,542,396	1,705,500	4,573,521	3,055,619	10,877,036
Total	4,208,796	6,116,900	14,847,521	7,766,819	32,939,036
Households Built From 1980-2000 Where Problem is Worth Solving					
Percent	50%	50%	80%	80%	71%
Households	2,104,398	3,058,450	11,878,017	6,213,455	23,254,320
Projected New Housing Units Each Year from 2001-2010					
	Northeast	Midwest	South	West	Total
Owner Occupied	104,818	495,777	217,036	229,894	1,047,524
Renter	60,632	191,673	96,614	149,106	498,026
Total	165,450	687,450	313,650	379,000	1,545,550
Projected New Housing Units Each Year from 2001-2010 Where Problem is Worth Solving					
Percent	50%	80%	80%	80%	77%
Households	82,725	549,960	250,920	303,200	1,186,805
Data for Graphs					
	Northeast	Midwest	South	West	Total
Existing Homes	2,104,398	3,058,450	11,878,017	6,213,455	23,254,320
	9%	13%	51%	27%	100%
	Northeast	Midwest	South	West	Total
New Construction	82,725	549,960	250,920	303,200	1,186,805
	7%	46%	21%	26%	100%

Source: U.S. Census, National Association of Home Builders

Table 3. Estimate of Homes with Significant Waits for Hot Water

Figure 4 shows the US census districts. Table 3 presents an estimate of the percentage of homes built in each census district between 1980 and 2000 that are likely to have a wait that is cost-justified to solve. The table also shows the National Association of Home Builders' projection of the number homes that will be built each year between 2000 and 2010, by census district, and an estimate of the number of homes that will have significant waits for hot water. Figure 5 shows the same data in graphical form. The estimates are conservative.

Several ideas have been proposed and tried in pursuit of solving this problem. Part II of this article will address some of those ideas.

Gary Klein has been intimately involved in energy efficiency and renewable energy since 1973. One fourth of his career was spent in Lesotho, the rest in the USA. Currently, he helps administer the public Interest Energy Research (PIER) Program at the California Energy Commission. He also is the chair of the recently formed Task Force on Residential Hot-Water-Distribution Systems. He can be contacted at Gklein@energy.state.ca.us.

Hot-Water Distribution Systems – *Part II*

By Gary Klein

This article was first published in Plumbing Systems & Design *magazine by the American Society of Plumbing Engineers. It is reprinted with updated information by the author.*

In Part 1 of this article (see January/February 2005 – *Official*, pp. 19-22) we determined that waiting for hot water to arrive was a problem worthy of study, that it impacts a large number of homes, and that the related energy and water waste are significant. In this article we examine what people want from their hot water systems and, within this context, three possible solutions to reduce the waste and wait in existing homes and new construction.

What People Want

Several ideas have been proposed and tried in pursuit of solving this problem. As I learned about these ideas, I started asking people what they wanted from their hot water systems in order to provide me with a measure of determining how well each option met their desires. What I found was that people wanted many things—such as an endless shower, the ability to control the temperature, and an end to the "shower dance"—none of which included water or energy savings. Table 1 presents the results of several thousand informal surveys of what people want from their hot water systems. What people want generally falls into two categories, safety and convenience.

- **Safety**
  - Not too hot
  - Not too cold
  - No harmful bacteria or particulates
- **Convenience**
  - Adjustable temperature and flow
  - Never run out
  - Quiet
  - Hot water immediately

Source: Gary Klein

Table 1. *What People Want From Their Hot Water Systems*

Safety. Under safety, "not too hot" generally refers to the prevention of scalding young children when they draw a bath. It also refers to the uncomfortable experience of having to immediately dance around the shower to avoid getting burned after someone flushes a toilet.

"Not too cold" means that it must be hot enough for the task at hand, which is often a problem in homes with plumbing that runs below the slab. I have found many people who have turned up the temperature of their water heater in order to get hot water at distant fixtures more quickly. Turning up the temperature doesn't bring hot water more quickly, although it can help to overcome the problem of heat loss in the pipes. However, turning up the temperature increases the likelihood and severity of scalding, and increases the stand-by losses of the water heater, which means energy costs go up.

"No harmful bacteria or particulates" usually refers to hard water. However, in recent years we have seen concerns over Legionella, a.k.a. Legionnaire's disease. The most-often proposed solution for these problems is to raise the temperature of the water heater to kill the bacteria, although it increases the possibility of scalding and will cost more energy to do so.

Convenience. Under convenience, people want to be able to "adjust both temperature and flow." While this is possible at sinks and tubs, it no longer seems common in the single-lever fixtures installed for showers and tub-shower combination faucets.

It is annoying to run out of hot water while taking a shower. The strategies to "never run out" include turning up the temperature of the water heater, getting a larger water heater, limiting the time teenagers spend in the shower, and scheduling hot water use to accommodate the limitations of the water heater. Turning up the temperature of the water heater can help increase capacity by providing a higher starting point to mix with cold water at the fixtures. However, it does so at the expense of increased stand-by losses. Installing a larger tank-type water heater, if there is space, gives you additional hot water too, again at the expense of increased standby losses. A better alternative is to select a tank-type water heater with a larger-than-standard burner or element without increasing tank size. This keeps stand-by losses low while providing an increased recovery rate, but may require increasing the fuel capacities, e.g. gas pipe size or electrical breaker size.

Water heaters with essentially no tank and very large burners or elements look like tankless water heaters. As with all water heaters, tankless water heaters must be matched properly to the intended application. It is likely that some combination of a relatively small tank and a relatively larger burner or element will prove to be optimal, but that discussion is for another article.

Concerning "quiet," most of us remember pipes that tick as they warm up and knock when the faucet is shut off. Water hammer seems to have been solved, although you can still hear the pipes tick as the hot water arrives. Some people can hear the flow of water in recirculation systems particularly in the middle of the night (on evenings when they can't sleep), hence part of the need for timers to turn off the pump. This problem can also be reduced with careful selection of pipe materials, insulation and routing locations.

Reliability. Under reliability, people want their hot water system to work, "first time, every time" essentially forever, and without any maintenance. Unfortunately, while the basic hot water system is very reliable, water quality varies quite a bit and often interacts in ways to reduce the longevity of the water heater and sometimes the fixtures. Two of the most common problems are hard water and sediment, which result in deposits in both the water heater and in the fixtures. The proper selection of an anode rod and regular cleaning of the tank and checking the rate of decay of the anode rod can greatly improve the longevity of the typical tank water heater. However, this falls under the category of maintenance, which most people don't want to do!

Several Solutions?

There are several techniques to get "hot water right now," and this article will cover three of them: multiple water heaters, heat trace, and manifold systems.

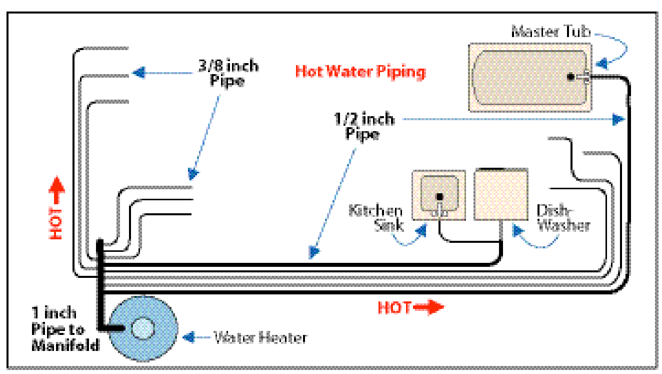
Multiple Water Heaters. Installing one or more additional water heaters at the problem locations is often the first solution that people think of to get hot water to each fixture quickly. If done to reduce the time waiting for hot water to arrive, installing more than one water heater should result in a house with more than one central core plumbing system, which is defined by short, small-diameter runs to each fixture. (See January/February 2005 *Official*, Figure 1, page 20.) If you don't end up with short, small-diameter runs, installing multiple water heaters won't reduce the wait. This is difficult and expensive to do in retrofit applications. In new construction, most builders and buyers don't want to give up the space or include the extra cost in the price of their homes.

Several factors need to be considered. First, there is the cost of running gas pipe or electrical wire to the additional water heater(s). This is almost always more expensive than the cost of running the equivalent length of hot water pipe. Second, there is the cost of installing the additional flue(s) if the water heater is gas-fired. Third, there is the cost of the additional water heater. Fourth, there is value of the space needed for the water heater. Assuming a tank-type heater, you need about 10 square feet of space. At sales prices of $100 to $200 per square foot, the value of the space inside the house is worth $1,000-$2,000. I suppose you could install the water heater in the attic, but have you ever tried to get a new one through the attic hatch? Fifth, there is the additional energy consumption of the additional water heater(s). Tankless water heaters don't have the stand-by losses that tank-type water heaters do, so they are a better alternative for energy reasons. They also take up much less space. Finally, there are the future costs of maintaining multiple water heaters.

Heat Trace. Installing heat trace on the pipes is another method that has been used to reduce the time to get hot water to fixtures. Heat trace is a thermostatically controlled resistance heater that is installed between the pipes and the pipe insulation. It is used to maintain the temperature of the water in pipes that have already been heated to the desired temperature. Assuming the heat trace draws 5 watts per foot, that there is only 100 feet of pipe to keep warm (very conservative), and it operates half the time or 12 hours per day, it will cost more than $190 per year to keep the pipes warm. Although heat trace will eliminate the time to get hot water if it has been installed all the way from the water heater to every fixture, it does so at a cost that far exceeds the cost of heating the water that currently runs down the drain.

Manifold Systems

Another alternative is to install manifold systems (also called parallel pipe or home run systems) with a dedicated line that goes from the manifold directly to each fixture. As with multiple water heaters, this is generally difficult and expensive to retrofit. We will consider them from the perspective of new construction.



Source: Gary Klein / Illustration: Jeff Ortiz

Figure 1. *Radial, Manifold, Parallel Pipe Plumbing (Distributed)*

You can site-fabricate a manifold or you can purchase one that looks similar to an electrical circuit breaker box and is located near the water heater. Figure 1 shows a schematic of a manifold system in a 2400-square-foot, 2-story house with 12 hot water fixtures. There is a 1-inch pipe

Table 2. *Time for Water to Travel 50 Feet*

Type of Pipe	Time in Seconds at 1 GPM				Time in Seconds at 2 GPM				Time in Seconds at 3 GPM			
	3/8"	1/2"	3/4"	1"	3/8"	1/2"	3/4"	1"	3/8"	1/2"	3/4"	1"
"K" copper	20	34	68	121	10	17	34	61	7	11	23	40
"L" copper	24	36	75	129	12	18	38	64	8	12	25	43
"M" copper	25	40	80	136	12	20	40	68	8	13	27	45
CPVC	N/A	29	63	104	N/A	15	31	52	N/A	10	21	35
PEX	16	28	56	93	8	14	28	46	5	9	19	31

Type of Pipe	Time in Seconds at 4 GPM				Time in Seconds at 5 GPM				Time in Seconds at 10 GPM			
	3/8"	1/2"	3/4"	1"	3/8"	1/2"	3/4"	1"	3/8"	1/2"	3/4"	1"
"K" copper	5	8	17	30	4	7	14	24	2	3	7	12
"L" copper	6	9	19	32	5	7	15	26	2	4	8	13
"M" copper	6	10	20	34	5	8	16	27	2	4	8	14
CPVC	N/A	7	16	26	N/A	6	13	21	N/A	3	6	10
PEX	4	7	14	23	3	6	11	19	2	3	6	9

Source: Gary Klein, based on gallons per foot from standard pipe tables

connecting the water heater to the manifold. This distance should be as short as possible, but given construction limitations, there is often ten or more plumbing feet between the water heater and the manifold. The drawing shows the use of 1/2-inch pipe to the master tub and to the split for the kitchen sink and dishwasher. There are 3/8-inch lines to all other fixtures. There are four 80-foot lengths of pipe to the farthest bathroom, in this case the master bath.

With these systems, the least wait and water and energy waste occurs when 3/8-inch-diameter pipe is used. While fixture flow rates, distance, applications and code restrictions sometimes make it possible to combine the lines serving more than one fixture—such as the kitchen sink and the dishwasher or the pair of sinks in a bathroom—doing so generally requires the use of 1/2-inch-diameter lines, thus increasing the wait and the water and energy waste.

Just how long you wait depends on the distance, pipe diameter, and fixture flow rate. Table 2 shows the time it takes for water to travel 50 feet in several diameters of pipe at representative residential fixture flow rates, assuming there are no pipe heat losses to overcome. The cells in red show the cases when the wait is longer than 15 seconds.

Compared to the time it takes hot water to arrive in 3/8-inch-diameter pipe at a given flow rate, it takes roughly 1.5 times as long in 1/2-inch-diameter pipe, three times as long in 3/4-inch-diameter pipe, and six times as long in 1-inch diameter pipe. If the pipe length is 25 feet, the time would be cut in half; if it is 100 feet, the time would double.

Regardless of the pipe length, if the wait is only 15 seconds, the waste of water waiting for hot water to arrive is one quart at 1 gpm, one-half gallon at 2 gpm, three-fourths gallon at 3 gpm, 1 gallon at 4 gpm, 1-1/4 gallons at 5 gpm, and 2-1/2 gallons at 10 gpm. If the wait is 30 seconds the amount of water waste doubles; if it is 1 minute, it doubles again. And there are all too many houses where the wait is longer than 2 minutes, which doubles the waste once again!

Some waste occurs at each fixture, every time it is turned on, until water of the desired temperature arrives. As pointed out in the first article, when all daily uses are accounted for, the total waste can be quite large. The actual wait and waste for 50-foot pipe runs are longer than those shown in the table due to three other factors:

(1) The human factor. If people have to wait, they often leave, returning when they are done with the intervening task. It is rare that they arrive just when the hot water arrives. Consequently, the waste and wait are often much larger and longer than we might calculate based on technical parameters alone.

(2) There are heat losses to consider. It takes energy to heat the pipe, which means that more water than is in the pipe must come out of the pipe before hot water arrives. It turns out that the amount of extra water is relatively large, often two to four times as much water as is in the pipe.

(3) The volume of water between the water heater and the manifold, and the volume of water in the manifold itself, also must be accounted for.

Let's assume that there is a 1-inch-diameter pipe between the water heater and the manifold, and a 1-inch diameter manifold. The 1-inch pipe contains six times as much water per foot as the 3/8-inch pipe. So, assuming there is only eight feet of 1-inch pipe from the water heater to the far end of the manifold, and 48 feet of 3/8-inch pipe from the manifold to the fixture, this would double the time for the hot water to arrive. It would also double the water and energy waste. Figure 2 shows the relationship between the water heater and the manifold that was installed in a house in San Ramon, California, in early 2004. There are two runs to the kitchen of 100 feet and there are four runs to the master bath of 80 feet. The line serving the kitchen sink and dishwasher and the two lines serving the shower and the separate tub in the master bath are 1/2 inch diameter, which increases the wait and waste.

Photo by Carl Hiller

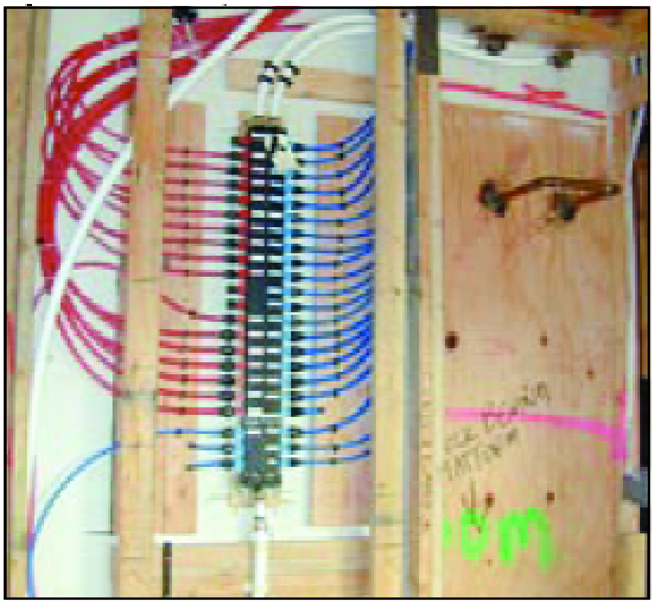


Figure 2. *Manifold system in home in San Ramon, CA*

Source: Gary Klein, based on gallons per foot from standard pipe tables

Type of Pipe	3/8"		1/2"		3/4"		1"	
	gal/ft	ft/gal	gal/ft	ft/gal	gal/ft	ft/gal	gal/ft	ft/gal
"K" copper	0.0066	152	0.0113	88	0.0226	44	0.0404	25
"L" copper	0.0079	127	0.0121	83	0.0251	40	0.0429	23
"M" copper	0.0083	121	0.0132	76	0.0268	37	0.0454	22
CPVC	N/A	N/A	0.0098	103	0.0209	48	0.0346	29
PEX	0.0052	193	0.0094	106	0.0187	53	0.0309	32

Table 3. *Gallons Per Foot and Feet Per Gallon*

Manifold systems are generally presented as water and energy savers compared to standard trunk and branch plumbing systems. However, let's consider the master bath in the San Ramon house with four hot water fixtures: Two sinks, a master tub, and a separate shower. In an idealized standard trunk and branch case, there would be 80 feet of 3/4-inch pipe between the water heater and the master bathroom and 10 feet of 1/2-inch branch line to each fixture. In a similarly idealized manifold case, there would be 10 feet from the water heater to the far end of the manifold and four 80-foot runs to the fixtures, one to each sink at 3/8-inch and the two to the master shower and the master tub at 1/2 inch. Table 3 presents the amount of water contained in different diameters and types of pipe.

Source: Gary Klein

	Trunk and Branch			Manifold		
	Feet	Diameter	Gallons	Feet	Diameter	Gallons
Trunk	80	3/4 in	1.50	10	1 in	0.31
Shower	10	1/2 in	0.09	80	3/8 in	0.41
1st Sink	10	1/2 in	0.09	80	3/8 in	0.41
2nd Sink	10	1/2 in	0.09	80	3/8 in	0.41
Master Tub	10	1/2 in	0.09	80	1/2 in	0.75
		Total	1.87		Total	2.00

Table 4. *Amount of Water Contained in Two Systems Serving a Master Bath*

For this example, we will assume that both systems use PEX piping. Table 4 shows the results of these calculations. The trunk and branch case contains 1.5 gallons in the main line and 0.09 gallons to each fixture. The manifold case contains 0.31 gallons in the 1-inch "trunk line" between the water heater and the manifold and 0.41 gallons in each of the 3/8-inch lines and 0.75 gallons in each of the 1/2-inch lines. There is more water in the pipes in the manifold system than in the trunk and branch system.

Let's look at a morning get-ready-for-work routine where the uses are close together. The first person gets up and takes a shower, then goes to the sink where he/she uses more hot water. The second person gets into the shower before the trunk line has cooled down (while the first person is at the sink) and when done, uses hot water at the other sink. The master bath is not used during this example. We will assume that the flow rate is 2 gpm for the sinks and the shower.

In the trunk and branch case, 1.59 gallons comes out of the pipe before hot water arrives for the first use. Since the first person started using the sink very shortly after leaving the shower, the temperature of the water in the main trunk line hasn't cooled down very much, so when he/she turns on the sink, it is only necessary to warm up the last 10 feet of 1/2-inch pipe. This means that only 0.09 gallons runs down the drain before the water is hot. In the meantime, the second person is using the shower, which means that the trunk and two branches are hot. When the second person goes to his/her sink, only the last branch needs to be heated, so only another 0.09 gallons runs down the drain.

In the manifold case, 1.06 gallons runs down the drain for the first shower. Once that person gets out, the temperature of the pipe begins to cool down. In fact, the long 1/2-inch branch line cools down more rapidly than the long 3/4-inch trunk line used in the previous example. This is due primarily to the smaller volume of water contained in the pipe; less mass means less ability to store heat. After several minutes, the 1-inch trunk line between the water heater and the manifold is still reasonably hot; however, the 3/8-inch pipe has cooled down to the point where the water temperature is unacceptable. This means that the second person will need to run 0.41 gallons down the drain before he/she gets hot water.

Meanwhile, the first person has moved over to his/her sink. The 1-inch line between the water heater and the manifold is still hot, but the 3/8-inch line to the first sink is cold so another 0.41 gallons of water will need to run down the drain before the hot water arrives. When the second person goes to his/her sink, the waste and wait is repeated once again.

Table 5 presents the water waste and wait for these two examples. Both the waste of water and the delay to get hot water is slightly less for the trunk and branch system when the uses are close-enough together so that the trunk line remains hot enough to use. It also shows the impact of taking a bath after using the other fixtures. The trunk and branch system's performance gets relatively better because there is a lot of water in the 1/2-inch pipe serving the master tub.

Source: Gary Klein

	Trunk and Branch		Manifold	
	Gallons	Seconds	Gallons	Seconds
1st Shower	1.59	48	1.06	32
1st Sink	0.09	3	0.41	12
2nd Shower	0.09	3	0.75	23
2nd Sink	0.09	3	0.41	12
Total	1.86	57	2.64	79
Master Tub	0.09	3	0.75	23
Total	1.96	60	3.39	102

Table 5. *Amount of Water Contained in Two Systems Serving a Master Bath*

Source: Gary Klein

	Trunk and Branch		Manifold	
	Gallons	Seconds	Gallons	Seconds
1st Shower	1.59	48	1.06	32
1st Sink	1.59	48	0.72	22
2nd Shower	1.59	48	1.06	32
2nd Sink	1.59	48	0.72	22
Total	6.36	192	2.96	108
Master Tub	1.59	48	1.06	32
Total	7.95	240	4.02	140

Table 6. *Waste and Wait When the Water in Pipes Has Cooled Down*

Table 6 shows how the two idealized systems perform when the pipes have cooled down completely before the next use. In this "cold start" example, the manifold system has approximately 54 percent less waste and wait than the trunk and branch system, before considering the use of the master tub. When the tub is added, the percent the manifold system is better declines to just under 50 percent.

As discussed earlier in this article, the actual waste and wait will be longer than in these idealized cases. Since smaller-diameter pipes cool down more quickly than larger-diameter pipes, pipe heat losses will impact manifold systems more severely because they are designed to have only a few feet of large-diameter trunk piping and many feet of small-diameter branches. In short, manifold systems cool down more quickly than trunk and branch systems.

Manifold systems help reduce the wait and the waste part of the time, but they aren't always better. Part 3 of this article will cover recirculation systems, whether or not to insulate hot water pipes, and discuss ways to deliver hot water to every fixture—wasting no more than one cup while waiting for the hot water to arrive.

Gary Klein has been intimately involved in energy efficiency and renewable energy since 1973. One fourth of his career was spent in Lesotho, the rest in the USA. Currently, he is an Energy Specialist at the California Energy Commission and is the chair of the recently formed Task Force on Residential Hot-Water-Distribution Systems. He can be contacted at Gklein@energy.state.ca.us

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Hot-Water Distribution Systems – *Part III*

By Gary Klein

This article was first published in Plumbing Systems & Design *magazine by the American Society of Plumbing Engineers. It is reprinted with updated information by the author.*

In Part 1 (see January/February Official*, page 19), we described the magnitude of the energy and water waste associated with waiting for hot water to arrive. In Part 2 (see March/April* Official*, page 20), we discussed three ways to reduce that waste and wait. In this article, we will discuss the fourth method: recirculation systems and how to deliver hot water to every fixture, wasting no more than one cup.*

Recirculation Systems

In major remodels or in new construction it is possible to install a recirculation system, although it is not done very often in single-family residential applications. Table 1 shows six types of recirculation systems.

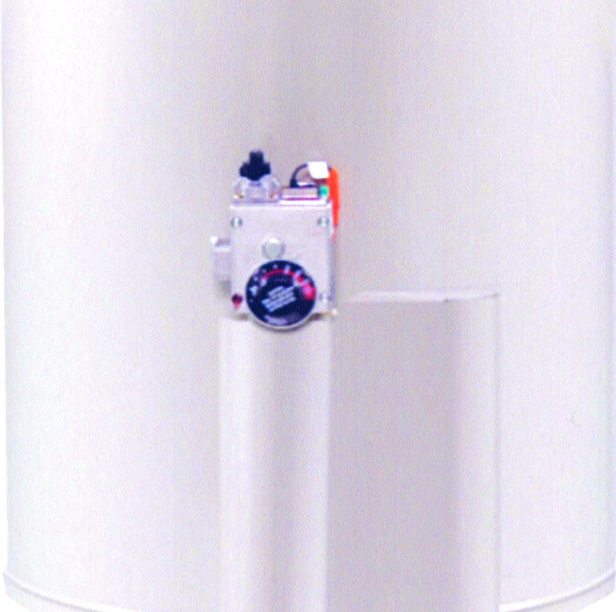


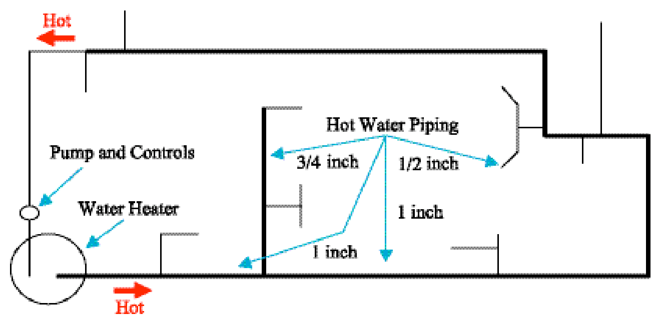
Table 1. *Types of Recirculation Systems*

Thermosyphon (24 hours per day, gravity)
Continuous Pump (24 hours per day)
Timer-Controlled Pump (16 hours per day)
Temperature-Controlled Pump (12 hours per day)
Time and Temperature-Controlled Pump (8 hours per day)
Demand-Controlled Pump (10 minutes per day)

Source: Gary Klein

All but the demand-controlled pump are what I call a full-loop recirculation system. A full-loop recirculation system (Figure 1) is characterized by fixtures located most of the way around the loop and the distance between the last fixture and the water heater is relatively short. Return lines, even in larger commercial installations are generally 1/2 inch diameter. It is necessary to heat the entire loop in these systems, because the controls and associated sensors are located at the pump.

Figure 1. *Full-Loop Recirculation Systems*



Source: Gary Klein

Thermosyphon

Thermosyphon-based recirculation systems use the temperature difference between the hot and cold water and the height of the building to drive the water around the loop. They work because heat is lost from the time the water leaves the water heater until it returns at some colder temperature to the water heater. It takes energy to reheat the water; how much depends on the heat loss and the flow rate. Pipe insulation is often neglected, which means that there is significant heat loss as the water moves around the loop. Assuming that there is only a 5° F temperature drop as the water moves around the loop and that the water is flowing at 1 gpm, the energy cost to keep the loop warm 24 hours per day would be $336 per year with natural gas ($619 with electricity). (See the note in Table 2 for the prices.) This is significantly more than the cost of heating the water that is actually used in the home.

The costs to operate recirculation systems are proportional to both flow rate and temperature drop. If the temperature drop is larger–say 10° F–the costs to operate the loop would double. If the flow rate is lower–say 0.25 gpm–the costs would drop in half. The cost estimates in this article are based on a conservative combination of flow rate and temperature drop.

Continuous-Pump

A continuous-pump 24-hour recirculation system is thermally very much like a thermosyphon system, with the addition of a small pump. Assuming a 40-watt pump, this will add $30 per year to the cost.

Timer-Controlled Pump

Installing a timer to control the hours of operation of the pump has the effect of reducing the costs in proportion to reduced hours of operation. Assuming the timer is set for 16 hours per day, roughly the waking hours, the cost would be $244 per year.

Temperature-Controlled Pump

Another method of controlling the pump is to install an aquastat, which is a method of temperature control similar to that used in an automobile radiator. The aquastats that are often used in single family applications are set to open when the temperature drops to 95° F and to close when the temperature rises to 115° F—a 20° F bandwidth. Assuming that the minimum desired hot water temperature is 105° F, the temperature in the recirculation line is colder than desired at least half the time. A better choice from a water temperature perspective would be to use an aquastat with a minimum set point of more than 105° F. However, with a bandwidth of 20° F, the lowest water heater setting must be above 125° F, otherwise the pump will never shut off. An aquastat can be installed without a timer. For purposes of this article, we will assume that the pump will run half the time, or 12 hours per day, for an annual cost of $183.

Time- and Temperature Controlled Pump

Sometimes both a timer and an aquastat are used together. Assuming a 16-hour time clock, the aquastat will allow the pump to come on roughly half that time, or eight hours per day. This brings the annual cost down to $122, which is still more than the energy cost associated with the wasted water.

Demand-Controlled Pump

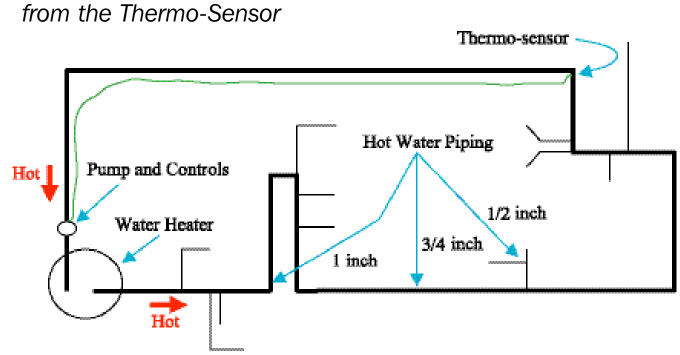
Demand control is the last method of operating a recirculation system. This system uses one or more consumer-activated devices (button, remote, flow switch, door switch, motion sensor)–located, where convenient, near the hot water fixtures–to tell the pump to come on. A thermo-sensor, looking for a small (5-10° F) rise in temperature above the ambient pipe temperature, tells the pump to shut off. There are two ways to install the pump and the thermo-sensor in what I am calling a half-loop recirculation system. (See Figures 2 and 3.)

A half-loop system differs from a full-loop system in two ways: (1) all of the fixtures are on the "supply" portion of the loop, and the distance from the last fixture to the water heater is large (one-third to one-half the loop length); and (2) the thermo-sensor is located just after the last fixture.

Locating the thermo-sensor just after the last fixture means that it is not necessary to heat half the loop, which reduces the heat loss from the pipes. In general, the return line should be no smaller than 3/4 inch. This is to accommodate the higher velocity found in demand pumps, since they are intended to "prime the line" quickly and then shut off.

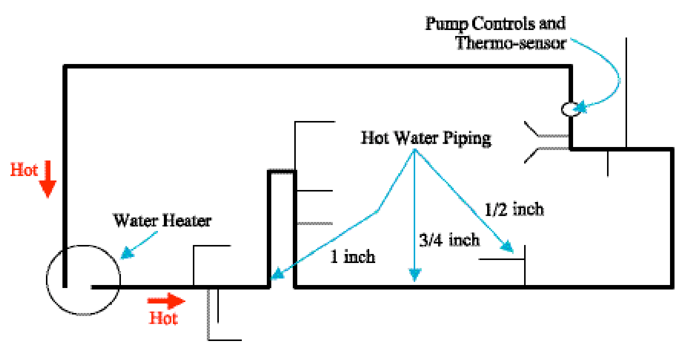
Both of these features reduce the cost of operating the half-loop system to less than $15 per year in either configuration.

Figure 2. *Half-Loop Recirculation System: Pump Separated from the Thermo-Sensor*



Source: Gary Klein

Figure 3. *Half-Loop Recirculation System: Pump Located with the Thermo-Sensor*



Source: Gary Klein

Table 2 compares the operating costs of each alternative discussed in this series to the costs of standard distribution systems. Standard distribution systems cost $116 for

Table 2. *Relative Costs of Operating Standard and Alternative Distribution Systems*

Standard Distribution System	**Water and Wastewater**	**Natural Gas**	**Electricity**
Total Annual Cost for Hot Water Including Waste	$116	$250	$465
Annual Cost Associated with the Wasted Water	($36)	($84)	($156)
Annual Cost Associated with Intended Water Use	$80	$166	$309
Additional Energy Costs to Operate Recirculation System			
Thermosyphon (24 hours per day, gravity, 5F temperature drop)		$336	$619
Continuous Pump (24 hours per day, 5F temperature drop)		$366	$649
Timer-Controlled Pump (16 hours per day, 5F temperature drop)		$244	$433
Temperature-Controlled Pump (12 hours per day, 5F temperature drop)		$183	$325
Timer and Temperature-Controlled Pump (8 hours per day, 5F temperature drop)		$122	$216
Demand-Controlled Pump (10 minutes per day)		$15	$27
Additional Costs Associated with Residual Wasted Water			
Manifold Systems (approximately 25% reduction)	$27	$63	$117
Heat Trace (approximately 90% reduction)	$4	$284	$284
All 6 Recirculation alternatives (approximately 80% reduction)	$7	$17	$31
Notes: Water and wastewater costs are $0.05 per gallon combined. Natural gas costs are $0.92 per therm. Electricity costs are $0.087 per kWh. Heat trace is only operated with electricity. The costs are the same whether the water heating fuel is natural gas or electricity.			

Source: Gary Klein

the water and wastewater and $250 for the natural gas to heat the water, for a total of $366 per year. We have assumed that in the standard system, 20 gallons are wasted every day waiting for the hot water to arrive at the fixtures. This means the "intended" hot water use is less than the total that was heated or brought into the house. For the standard system this lower number is a combined cost of $246 per year.

It is necessary to add the costs to operate each alternative to the costs associated with the "intended" hot water use to get the new total cost for reducing the waste of water and providing convenience. As discussed in Part 2, manifold systems are only better than standard distribution some of the time. Assuming that the average reduction in the waste and wait while waiting for the hot water to arrive is about 25 percent, the annual cost to operate manifold systems is $336 ($246 plus $27 for water and wastewater plus $63 for natural gas). This is less than the cost of operating a standard distribution system, but it is still relatively wasteful of hot water.

Heat trace can be installed on all trunk and branchlines and has the greatest potential to reduce waste and wait. However, it requires more electricity to operate than is associated with wasted water. Assuming that there is only 100 feet of hot water piping, which is very conservative, the annual cost to operate heat trace is $534 ($246 plus $4 plus $284).

Recirculation systems have the potential to reduce the waste and wait the same amount as heat trace. However, the branchlines still have water in them that must be run out of the pipe before hot water arrives, so we have assumed that there is more residual waste. The operating costs, assuming natural gas water heating, range from $636 ($246 plus $366 plus $7 plus $17) for the continuous pump down to $285 ($246 plus $15 plus $7 plus $17) for the demand-controlled pump.

Among all the alternatives we have examined, only manifold systems and demand-controlled recirculation systems cost less to operate than it costs to run water down the drain waiting for the hot water to arrive. Of these, demand recirculation systems are the most efficient, increasing convenience, minimizing the waste of water and consuming less energy for a combined savings of $81 ($366 - $285) per year compared to current practice. A reasonable marginal cost to install a demand-controlled recirculation in single-family new construction is roughly $500 including insulation for the circulation loop and the branchlines, the additional plug and the sensor and activation mechanisms. This makes it a very sensible investment, particularly when included in the mortgage where the monthly operational savings are greater than the increase in the monthly mortgage costs.

Hot Water, Wasting Less Than One Cup

The key to delivering hot water to a fixture while wasting less than one cup waiting for it to arrive is that there cannot be more than one cup of water in the branchline between the fixture and the source of hot water (see Table 3).

Table 3. *Number of Feet Containing One Cup of Water*

	Feet per Cup			
Type of Pipe	**3/8"**	**1/2"**	**3/4"**	**1"**
"K" Copper	9.48	5.52	2.76	1.55
"L" Copper	7.92	5.16	2.49	1.46
"M" Copper	7.57	4.73	2.33	1.38
CPVC	N/A	6.41	3.00	1.81
PEX	12.09	6.62	3.34	2.02

Source: Gary Klein

In fact, because it takes energy to heat the pipe, there must be less than one cup in the branchline. For short branchlines, a good estimate is to assume that 1.5 to 2 times the volume of water that is in the pipe must come out of the pipe before hot water gets from the source of hot water to the fixture. Practically speaking, this means that 1/2 inch copper branchlines need to be less than 3 feet long and 3/8 inch branchlines need to be less than 5 feet long. If you use PEX, the length increases slightly to 4 and 8 feet respectively. These are tight but buildable constraints whenever it is possible to plumb up from the floor below, for example, in single-story houses over a basement or between the first and second floor of a two-story house. It is still possible to get close to this when plumbing from above, but unless the circulation loop is brought down into the wall, it is more practical to expect the waste will be closer to 2 cups.

The source of hot water can either be a water heater or a circulation loop. The analysis presented in this series has shown that the most energy-efficient and cost-effective alternative is a circulation loop with a demand-controlled pump, so it makes sense to combine the demand-controlled circulation system with small volume branchlines.

To provide the best system for your customers, the circulation loop and the branchlines to each fixture need to be insulated. The major benefit of insulation is that the hot water lines will stay hot longer between uses. Selecting the R value so that the temperature stays above 105° F for 45-60 minutes will generally cover the delay between uses during the morning and evening peak periods. The effective pipe length of the circulation loop should be kept to a minimum. This reduces the pressure loss in the loop and minimizes the time it takes for the demand-controlled pump to prime the loop with hot water.

If the waste is limited to one cup, at a flow rate of one gpm, it will take less than four seconds for the hot water to arrive. At two gpm it will take less than two seconds. Even if the waste is closer to two cups, the time will still be less than eight seconds at one gpm. Given that many people wait more than 90 seconds, this system will provide hot water at least ten times faster, a significant improvement over current practice. At these short delays, many people will feel that their convenience desire for “hot water immediately” (see Part 2, page 20 in *Official,* March/April 2005) will have been met.

The data presented in Table 2 assumed that all recirculation systems reduced the waste of water by 80%. Assuming that the typical waste per event is 0.5 to 1 gallon, this translates into a residual waste of 1.6 to 3.2 cups per event. Limiting the waste of water to one cup increases the efficiency to an average of 90%, roughly halving the water and energy costs associated with the wasted water shown in Table 2. This reduces the operating costs by $3.50 per year for the water and waste water and $8.50 per year for the natural gas, bringing the combined cost of operating a demand-controlled circulation system down to $273 per year, a savings of $93 per year.

Conclusions and Observations

This series of articles has shown that there is a significant amount of water and energy wasted while waiting for hot water to arrive. The focus has been on the costs to the consumer. There are additional savings that will accrue to the water and wastewater utilities, including reductions in energy consumption and chemical use due to the reduced throughput of water.

A circulation system with a demand-controlled pump has been shown to use the least energy, waste the least water and do so the most cost-effectively of all alternatives examined. If designed and installed correctly, in new construction it is possible to reduce the waste and wait by more than 90 percent compared to standard practice. It is also possible to retrofit demand-controlled circulation systems. The savings will still be significant, particularly in homes with single trunk and branch systems.

Demand-controlled circulation systems are also relatively resource efficient during construction. In Part 2, we discussed a manifold system installed in a 3000-square-foot home in San Ramon, California. There were more than 900 linear feet of hot water pipe in the house. The same home with a demand-controlled circulation system would use fewer than 300 linear feet.

Although single-family homes were used for the examples in this series, the same principles apply to multifamily and commercial buildings. As we learn more about how they perform in these installations, we will share our findings.

Gary Klein has been intimately involved in energy efficiency and renewable energy since 1973. One fourth of his career was spent in Lesotho, the rest in the USA. Currently, he is an Energy Specialist at the California Energy Commission and is the chair of the recently formed Task Force on Residential Hot-Water-Distribution Systems. He can be contacted at Gklein@energy.state.ca.us