Hot-Water Distribution Systems – *Part I*

By Gary Klein

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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

Source: Gary Klein

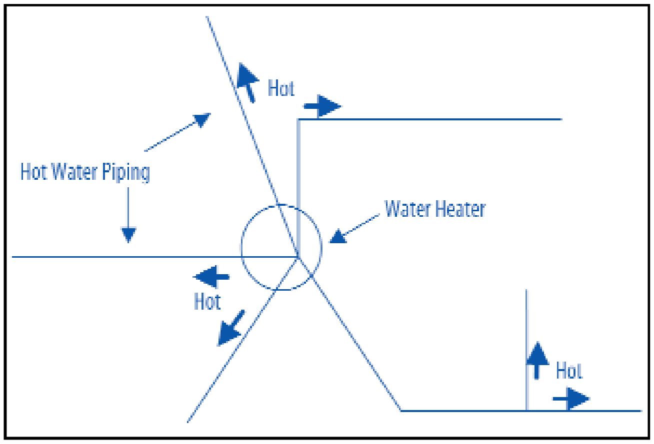

Figure 1. Radial, Manifold, Parallel Pipe Plumbing (Central Core).

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

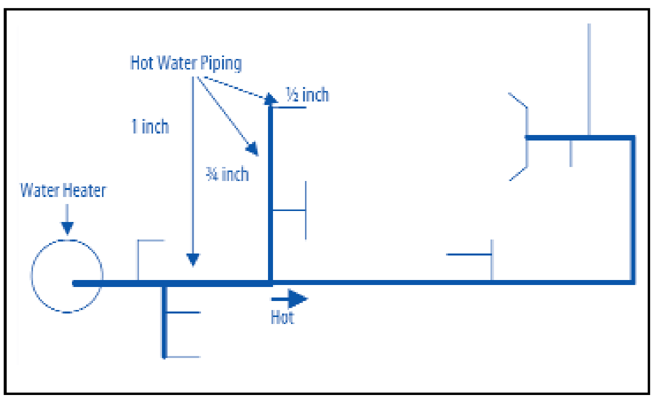

Figure 2. Single Trunk and Branch Plumbing

Source: Gary Klein

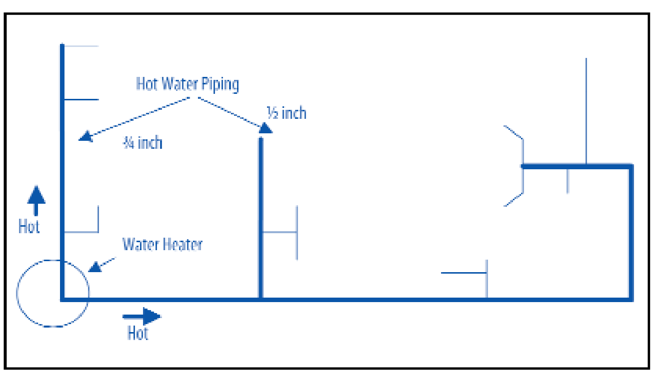

Figure 3. Multiple Trunk and Branch Plumbing

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).

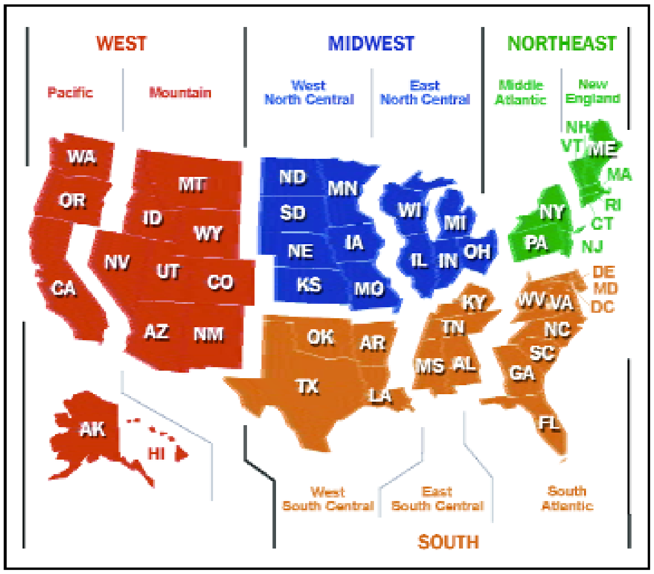

Figure 4. US Census Districts

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

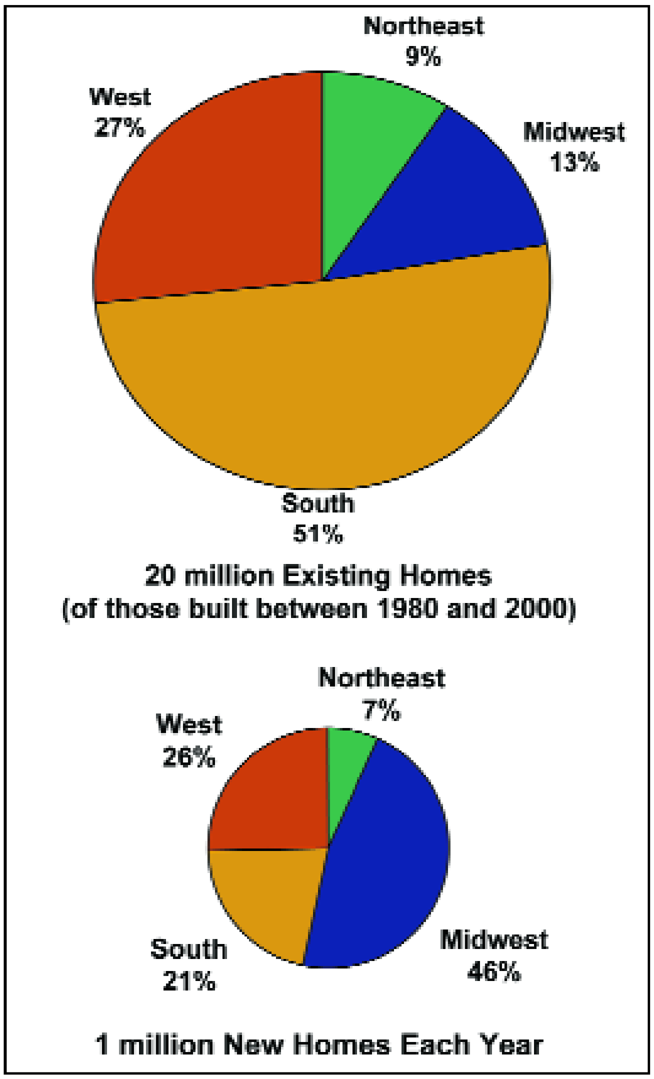

Figure 5. Estimate of homes with significant waits for hot water.

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

	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%

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.