Efficient Hot-Water Piping

Smarter layouts and right-sized pipes save time, water, and energy

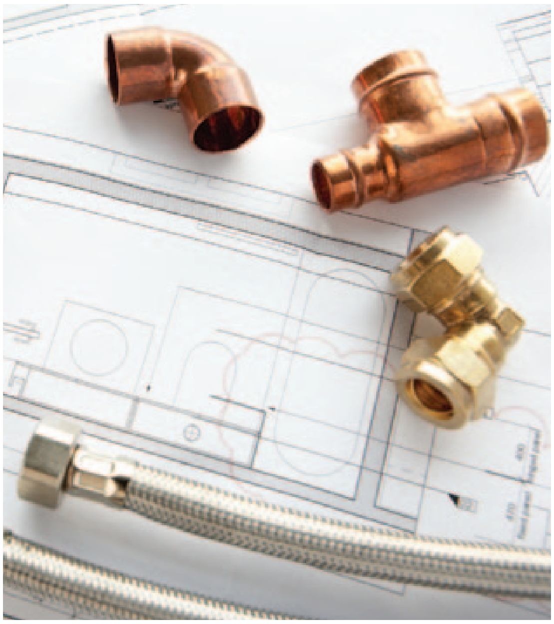
by Gary Klein

How long are you willing to wait for hot water when you turn on the tap? That's a question I began asking in 1993, while researching the design of hot-water systems for the California Energy Commission. Most people told me that they want "time to tap" to last only a few seconds. But in the real world, it often takes a minute or more before hot water begins flowing out the faucet.

That's because traditional methods of sizing distribution piping are based on maintaining adequate system pressure. Plumbers often use oversized pipes to overcome the pressure drop caused by excessive pipe lengths and sharp changes in direction. It's not unusual to see a ¾-inch-diameter supply line installed where a ½-inch-diameter pipe will provide adequate flow, even though this nearly doubles the volume of water contained in the pipe (**see Figure 1, next page**).

In cold-water piping, excess volume doesn't waste water or affect energy performance, but in hot-water piping, it's a different story. Unless that extra volume of water is already hot, it will have to be purged from the pipe before hot water is delivered to the fixture. This wastes both water and energy. In fact, in the typical household, as much as one out of every three gallons of heated water runs down the drain unused.

This waste can often be minimized by installing on-demand hot-water circulation (see "Hot-Water Circulation," 12/10). But the best strategy is to first squeeze as much inefficiency as possible from the hot-water distribution system. To do this, I size the hot-water piping to provide just the right amount of hot water to each fixture. I also try to minimize the number of branch lines and keep trunk lines and "twigs" (called "fixture branches" by the Uniform Plumbing Code, "fixture supplies" by the International Plumbing Code and the IRC) as short as possible. To maintain pressure, I try to minimize the number of fittings — particularly hard 90-degree elbows — and avoid pipe configurations that restrict water flow. And to conserve energy and keep the water hot for clustered hot-water events, I make sure the pipes are wrapped with adequate insulation.



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Feet of Pipe Per Cup (8 oz.) of Water

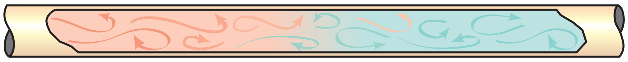
	Pipe Diameter			
	3/8″	1/2″	3/4″	1″
K copper	9.5	5.5	2.8	1.6
L copper	7.9	5.2	2.5	1.5
M copper	7.6	4.7	2.3	1.4
CPVC	n/a	6.4	3.0	1.8
PEX	12.1	6.6	3.3	2.0
“Copper rule”	8	5	2.5	1.5

Figure 1. Minimizing the volume of water in the piping between the hot-water source and each fixture is one key to reducing waste in a hot-water system. To find the volume of water contained in piping runs of various diameters, divide the total length of each trunk, branch, or twig by the corresponding ft/cup value. For quick approximations, divide by the “copper rule” values in the bottom row. An efficient layout for copper will perform even better with CPVC or PEX.

Hot-Water Flow in ¾″ Pipes

Optimal: Flow Rate 3–4 gpm; Velocity 2.2–2.9 fps

Typical: Flow Rate 1–2.5 gpm; Velocity 0.7–1.8 fps



Low: Flow Rate < 0.75 gpm; Velocity < 0.5 fps

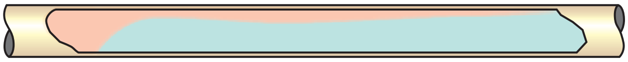


Figure 2. Flow rate affects how hot and cold water interact in the piping during hot-water delivery. A flow rate of 3 to 4 gpm creates a “plug flow” (top), which pushes cold water out of the pipe without much mixing, minimizing wasted water and time-to-tap. At low flow rates (bottom), a thin stream of hot water rides up on top of the cold water (or spirals around it) and cools quickly; up to twice the standing volume of water must flow through the pipe to achieve the desired temperature. At flow rates typical for many fixtures (center), hot and cold water mix reasonably well, but up to 1.5 times the standing volume of water in the pipe must flow through before hot water arrives.

Right-Sized Pipe

To avoid oversized pipes, I size the twigs according to the actual flow rates of the fixtures the pipes serve. I basically size branches and trunk lines the same way, but also take into consideration the likelihood (though small) of simultaneous draws from different fixtures on the same branch or trunk line. I always try to choose the smallest diameter pipe that will provide adequate flow at the available water pressure to meet the real demand.

Keep in mind that hot-water pipes no longer have to carry a large volume of water. Most homes now have water-saving 2.5-gpm showerheads and 2.2-gpm faucets, while fixtures that conform to the EPA’s WaterSense program have even lower flow rates.

Velocity and flow rate. Some rural homes served by wells may have less than 35 psi of static water pressure, in which case friction loss is a real concern, and pipes must be sized to maintain pressure. But static water pressures of 40 psi to 80 psi are now required under most plumbing codes, making pressure drop less of an issue. In houses where system pressures are greater than about 50 psi, pipe sizing should be dictated by the maximum allowable velocity.

To avoid excessive noise, erosion, and water hammer, the Uniform Plumbing Code (UPC) limits water velocity to 5 ft/sec in copper pipe and 10 ft/sec in most types of plastic pipes. Since hot water behaves differently at different flow rates, the optimal water velocity in hot-water piping is between 3 ft/sec and 4 ft/sec (**Figure 2**).

The flow rate through a hot-water pipe depends mainly on the pipe’s interior diameter and the velocity of water moving through it. Decreasing the diameter of a pipe while maintaining a given flow rate increases the water’s velocity. You can see from the charts prepared by the Oak Ridge National Laboratories for different types and sizes of pipe (**Figure 3**) that the velocity increases rapidly as the flow rate increases in a given diameter pipe. Many combinations of flow rate and diameter result in unacceptable pressure drops. Picking the right pipe diameter minimizes the loss of water, energy, and time spent waiting for hot water to be delivered to a fixture.

Trunks, Branches, & Twigs

A smart plumbing design starts with the location of the water heater. Sometimes the location is flexible, in which case I try to position the heater to minimize the length of the trunk lines. For example, simply moving the heater from an attached garage or corner in the basement to a more central location relative to the fixtures shortens the pipes, reducing the volume of water in the lines. Most of the time, though, the water heater and fixture locations are pre-determined.

Twigs. Since each twig serves a single faucet, shower, or appliance, its diameter should be determined solely by the flow rate of

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Water Velocity (feet/second) for Different Pipe Sizes and Flow Rates

	Flow Rate (gpm)												
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**7.0**
3⁄8-inch K Copper	1.3	2.5	3.8	5.1	6.3	7.6	8.9	10.1	11.4	12.7	13.9	15.2	17.7
3⁄8-inch PEX	1.7	3.3	5.0	6.7	8.3	10.0	11.7	13.3	15.0	16.7	18.3	20.0	23.4
1⁄2-inch K Copper	0.7	1.5	2.2	2.9	3.7	4.4	5.2	5.9	6.6	7.4	8.1	8.8	10.3
1⁄2-inch PEX	0.9	1.8	2.7	3.6	4.5	5.4	6.3	7.2	8.2	9.1	10.0	10.9	12.7
3⁄4-inch K Copper	0.4	0.7	1.1	1.5	1.8	2.2	2.6	2.9	3.3	3.7	4.0	4.4	5.1
3⁄4-inch PEX	0.4	0.9	1.3	1.8	2.2	2.6	3.1	3.5	4.0	4.4	4.9	5.3	6.2

Figure 3. Pipe sizing is determined by the flow rate of each fixture in gallons per minute (gpm) and the maximum acceptable velocity (in feet per second) of the pipe used to serve it. Note that velocity increases as pipe diameter decreases. Numbers in red exceed the recommended maximum hot-water velocity of 5 ft/sec for copper, or 10 ft/sec for PEX and CPVC (not shown).

the device it serves. For instance, a garden tub requiring a 10-gpm flow rate should have a larger-diameter twig than a 2.2-gpm lavatory sink.

Even though a 3⁄8-inch-diameter twig may provide an adequate flow rate for a particular fixture, remember that most plumbing codes specify a minimum pipe diameter for each type of fixture. While the 2012 IPC/IRC allows 3⁄8-inch-diameter pipe for lavatory sinks, the UPC requires at least 1⁄2-inch-diameter pipe for all fixtures unless the design has been engineered and approved by an inspector.

Branches. Branch lines serve two or more twigs. For best performance, I try to keep branch lines to a minimum, and connect twigs directly to a trunk line.

Trunks. Trunk lines serve a combination of twigs and branches, and — in a well-designed system — act as an extension of the water heater. In other words, once a trunk line has been charged with hot water after an initial use (or with a recirculation pump), hot water is then available almost instantaneously to the remaining twigs connected to the trunk.

To determine the diameter of the twig, branch, and trunk lines, I add up the flow rates of the outlets that they serve. I also estimate how many fixtures are likely to be operated simultaneously for any significant period of time. (One reason most hot-water lines are oversized is that plumbing codes assume more than one fixture is drawing hot water about 70% of the time. But research with more than 17,000 days of data on more than 150 homes from climate zones throughout the U.S. and parts of Canada shows that this occurs only about 10% of the time.)

Once I know the pipe diameters and lengths, I can calculate the volume of water contained in each twig, branch, and trunk line. This volume and the fixture's flow rate determine the time-to-tap for hot water to arrive at each fixture.

My goal is to achieve a time-to-tap of two to three seconds at a flow rate of about 2 gpm. If there is only one cup of water between the fixture and the hot-water source, time-to-tap will be less than four seconds at 1 gpm; at 2 gpm it will take less than two seconds for the hot water to arrive.

Improved Layout

Right-sizing the piping is only part of the answer. To reduce time-to-tap, you also have to keep the water in those pipes hotter longer. That means shortening the length of runs, and reducing heat loss from the piping.

About 60% of homes built in the U.S. since 1970 have slab-on-grade foundations, 20% have crawlspaces, and 20% have basements. In a hot-water distribution system, the type of foundation a house has usually determines where the plumbing and the water heater are located.

Below-slab plumbing is an accepted practice in some jurisdictions, but it presents a number of problems. Pipe runs in homes plumbed this way are generally much longer than needed, because the pipes are often placed in drain or utility trenches rather than in separate trenches that follow the shortest route between fixtures. I've even seen water supply piping routed back underground rather than directly through a wall when the fixtures were located on the same wall.

In a two-story slab-on-grade house, plumbing trunks should run between floors, with twigs dropping down to first-floor fixtures and rising up to second-story fixtures. In a home with a basement or crawlspace, trunk lines should generally be located in the floor system to have the shortest possible twigs.

Insulation. Besides increasing pipe lengths, these practices have energy consequences. Water in uninsulated piping loses heat five to 10 times more quickly under a slab than in room-temperature

Figure 4. Pipe insulation prevents heat loss and improves system performance, especially when pipes are located underground or outside the thermal envelope. Wall thickness of the insulation should at least equal the nominal diameter of the pipe.

air. For this reason, I think it's better to run piping for single-story slab-on-grade houses within the thermal envelope, either in the ceiling framing or buried within the attic insulation. Unless the ceiling will be insulated with blown-in insulation, the pipes should be wrapped with pipe insulation.

Most local codes don't require insulated hot-water pipes unless there is a circulation loop, but they should. When hot-water events on the same twig, branch, or trunk occur between 10 and 45 minutes of each other, insulation significantly lowers the time-to-tap by reducing the rate at which the water cools down. For example, R-4 insulation doubles the cooldown time of ½-inch pipe, and triples the cooldown time of ¾-inch pipe. In addition, insulation reduces temperature drop between the water heater and the fixtures while hot water is being used, regardless of the time between uses.

The 2012 IECC (R403.4) now requires minimum R-3 pipe insulation for most hot-water piping. My rule of thumb has been to size insulation thickness so that it is equal to the pipe's nominal diameter (**Figure 4**). If you're using hardware-store-variety polyethylene pipe sleeves, check their R-value; some ½-inch wall pipe insulation is rated as low as R-2.2.

When installing pipe insulation, slightly compress the sections lengthwise and seal the joints at the slits and between sections. (If you use foam pipe insulation that doesn't comes with integral sealing tape, check with the insulation manufacturer for the recommended sealant.) Orienting the slits so that they face down will prevent the sleeves from falling off the pipe if the sealed joints fail.

Performance

To illustrate the advantages of high-performance distribution piping, I've compared the performance of three different plumbing configurations in the same floor plan (**Figure 5**). In each case, the water heater is located in the same place in the basement, and I've evaluated performance both with and without on-demand circulator pumps. These could be located either at the hot-water heater, which would require a dedicated return line for each zone, or underneath a fixture, in which case the cold-water line would act as a return. (To keep the schematic simple, the pump locations are not shown.)

Zoned trunk-and-branch. In our example, the location of the water heater created a two-directional plumbing configuration, with one trunk line going up to the second-floor master bathroom and the other going past the kitchen and powder room on the first floor, then up to Bath #2. Depending on how the upstairs laundry room is supplied with hot water (our example shows it supplied from the master bath), this layout contains about 61 feet of ¾-inch pipe, 67 feet of ½-inch pipe, and 10 feet of ⅜-inch pipe (these are stems from the angle stop to the fixture), for a total of 138 feet. Assuming an average total of 20 daily cold-start events,

How To Measure Hot-Water Flow Rates

Knowing the flow rate of each hot-water outlet can help you understand the layout of an existing hot-water distribution system without seeing the pipes. It might come in handy, for example, if you were trying to decide whether an under-sink circulating pump would satisfy a homeowner's complaint about having to wait too long for hot water. Here's how to test the system.

1. Fixture flow rate. Focusing on sinks and showers one fixture at a time, turn the hot tap on full and capture the water for 15 seconds. Measure the volume in gallons (16 cups per gallon), and multiply the result by 4. This is the flow rate in gallons per minute for each fixture.

2. Cold-start volume. Record the time-to-tap at each hot-water outlet. Allow the system to completely cool down after each fixture test (consider testing a different fixture each morning). Multiply time–to–tap by flow rate to get the cold-start volume for each fixture.

3. Hot-start volume. At the sink with the largest cold-start volume, turn the hot water on full, and record the time-to-tap again (it should be similar to the first measurement, but it may not be identical). Turn off that tap and immediately go back to each previously measured hot-water outlet, and repeat the time-to-tap test. Multiply time-to-tap by flow rate to get hot-start volume.

4. Compare results. Fixtures with a decrease in hot-start volumes of 50% or more are on the same trunk line as the sink with the largest cold-start volume. The greater the reduction, the closer the outlet is to the trunk line. Fixtures with two similar wait times are likely on separate trunks from the sink with the longest cold-start time.

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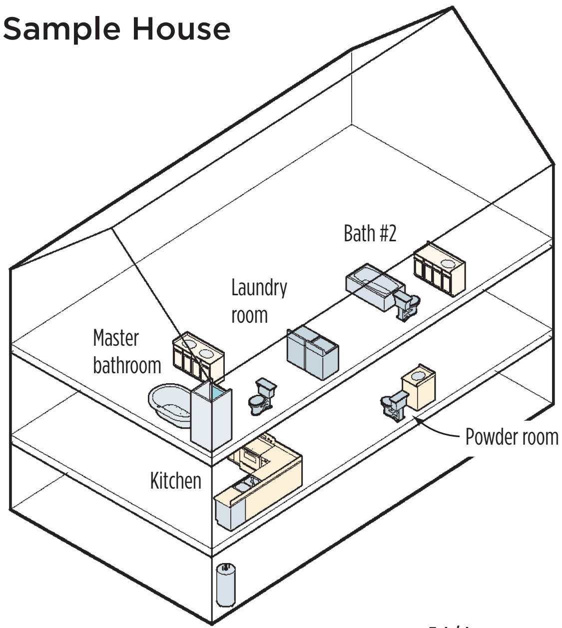
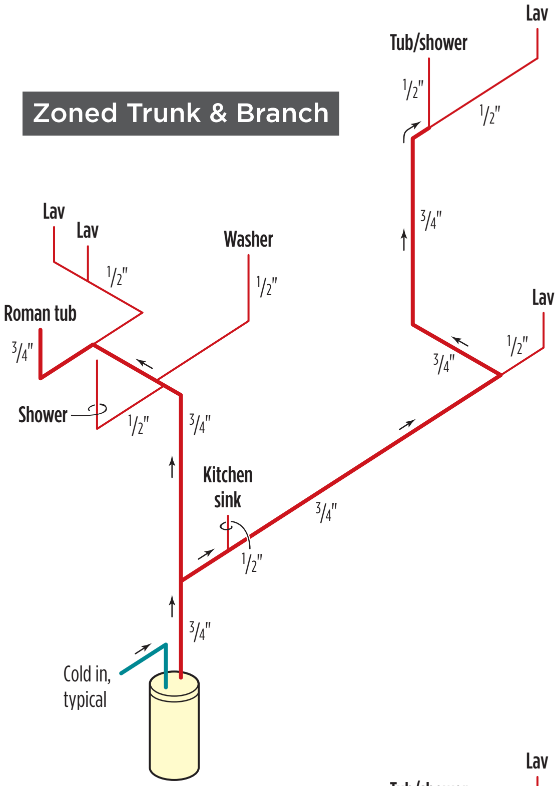
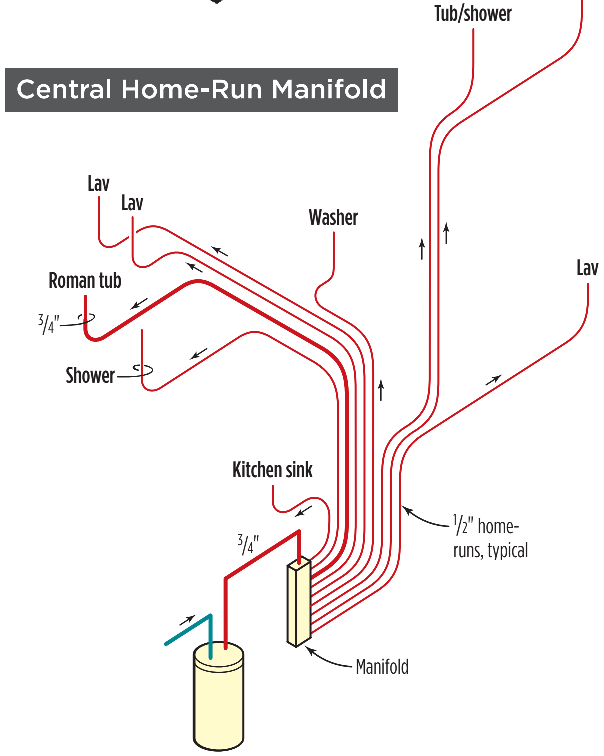
Comparing Efficiency in Three Hot-Water System Designs



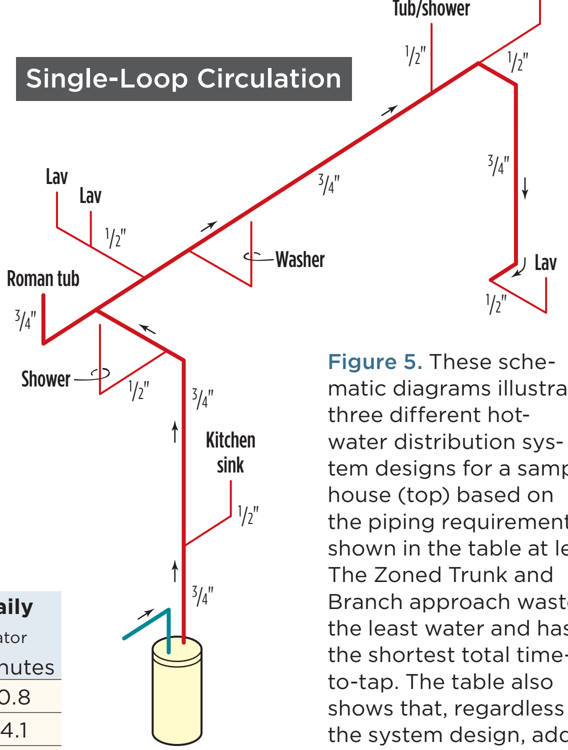
Sample House



Zoned Trunk & Branch



Central Home-Run Manifold



Single-Loop Circulation

	Length of piping (feet)				Water and Time Wasted Daily			
					As Shown		With Circulator	
	¾″	½″	⅜″	Total	Gallons	Minutes	Gallons	Minutes
Zoned	61	67	10	138	12	7	1.3	0.8
Manifold	65	259	10	334	23	8	6.6	4.1
Loop	72	53	10	135	19	12	1.7	1.0

Piping for circulator pumps is not included. All ⅜-inch piping is for stems between shutoffs and fixtures. Wasted water and time are estimated based on 20 cold starts per day.

Figure 5. These schematic diagrams illustrate three different hot-water distribution system designs for a sample house (top) based on the piping requirements shown in the table at left. The Zoned Trunk and Branch approach wastes the least water and has the shortest total time-to-tap. The table also shows that, regardless of the system design, adding demand-controlled circulator pumps (not shown) dramatically improves efficiency.

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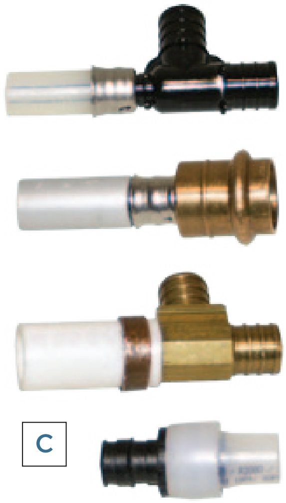
Fittings

Tees, hard 90-degree elbows, and other flow-restricting fittings create friction and add to the equivalent length of piping. For example, a 20-foot length of pipe with 10 elbows is equivalent to 40 feet of straight pipe. Replacing right-angle elbows with wide-radius sweeps **(A)** will lower pressure drop and improve performance. In fact, I've observed that if the radius of a bend is at least 10 times the nominal pipe diameter, water in the pipe behaves as if the pipe were straight (though I don't think this has ever been tested properly).

One of the advantages of PEX pipe is that it bends, so fittings aren't required to make changes in direction. Copper tubing can also be bent, though it's not common practice. In all cases, it's important not to deform the pipe when bending it, which will restrict flow as much as a fitting.

Whenever possible, I try to minimize the number of fittings except for the tees needed to serve branches and twigs. When installing PEX piping, I recommend "outie" expanded PEX fittings **(B)**, which maintain the internal diameter of the piping, rather than standard "innie" insert fittings **(C)**, which restrict flow.



this system performs reasonably well, wasting about 12 gallons and seven minutes per day. However, 12 gallons is about 20% of the daily hot-water volume used by a family of three. With proper use of a circulation pump, waste drops to 1.3 gallons and 0.8 minutes. This is better than the two alternative designs, even when they include use of circulator pumps.

Central home-run manifold. In this configuration, one trunk line runs from the water heater to the manifold, then individual twigs run from the manifold to each fixture. At 334 feet of pipe, this layout uses almost two-and-a-half times as much pipe as the other configurations. (It is likely to have a similar amount of cold-water piping, too.) This system would waste about 23 gallons and 14 minutes per day for cold-start events (6.6 gallons and 4.1 minutes with a circulating pump).

Single-loop circulation. The third configuration consists of a single trunk line that goes upstairs to the master bath, through the laundry room to Bath #2, then down to the powder room; the kitchen is on its own branch. This layout contains a total of 135 feet of hot-water supply pipe, the least of the systems evaluated. However, when operated without an on-demand pump, it would waste about 19 gallons and 12 minutes per day for cold-start events, the second-worst-performing system evaluated. With the pump in operation, waste drops to 1.7 gallons and 1 minute per day, making it the second-best-performing system.

Choosing the best design. Thanks to a compact wet room layout (unusual for a modern house), the zoned trunk-and-branch system performs quite well for both cold- and hot-start events. Splitting the floor plan into zones is a good strategy for reducing the volume of water in trunk lines, but if the plumbing is ever upgraded with on-demand hot-water circulation, it will require separate pumps for each zone.

The central home-run manifold system requires more pipe and does not perform as well as the other configurations evaluated. The biggest drawback to a manifold system is that it is difficult to improve performance significantly without multiple on-demand circulation pumps, one for each fixture.

In this house, the single-loop circulation configuration contains the least amount of pipe (second smallest if the pump is located at the water heater), but without an on-demand pump it actually wastes almost as much water and time as the central home-run manifold system. On the other hand, it would probably be the least expensive system to install, since it contains the fewest feet of pipe and only one pump.

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