Getting Into Hot Water –
The New Energy Efficiency Frontier

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ABSTRACT

Improvements in hot water energy generation, distribution and use have not kept pace with the efficiency gains of building envelopes and HVAC systems. As a result, hot water energy consumption is increasingly becoming a larger proportion of a home's total energy use. In some climate zones, and particularly in dwellings built to meet or exceed energy efficiency codes, it has surpassed space conditioning to become the #1 consumer of energy in new buildings (Klein 2010).

Today's median home size is more than 50% larger than in 1973 (roughly 1500 square feet to 2400 square feet) and requires the use of longer and higher volume plumbing runs to distribute hot water. Over the same time period, fixture flow rates have been reduced. While this saves water during the use periods, the lower velocity in the same diameter piping increases heat transfer to the pipe during the delivery phase, which increases the amount of water wasted waiting for the hot water to arrive (Hiller 2005). The use of low flow fixtures further escalates energy consumption by increasing thermal losses during distribution, and the time it takes for hot water to arrive at the point of use. As a result, wait times for hot water have become unreasonably long and have spawned wasteful behaviors such as walking away from a running shower to do something else while waiting for it to become warm. Up to 30% of a shower is now wasted before bathers ever begin showering (Lutz 2011).

This paper explores the problems associated with generating and delivering hot water and emphasizes the importance of understanding hot water as a system that includes heating, distribution, plumbing fixtures and appliances, behaviors, and hot water that runs down the drain. Unless the relationships between these elements are well-understood builders, code officials, home performance professionals and efficiency programs may be inadvertently creating unnecessary unsafe conditions and missing opportunities to reduce waste of both water and energy

This paper will also explore the use of newer technologies, such as thermostatic shut-off valves (TSVs) and best practices for reducing hot water energy and water waste.

Hot Water Service – What Are We Aiming For?

Residents value efficient hot water service. However, it does not make sense to implement efficiency until an effective level of hot water service has been provided. Effective service is defined as: instantaneousness – fast arrival, and continuousness – never run out during the hot water event, particularly a shower.

To achieve instantaneousness the following hot water system components are necessary: a source of hot water that is already hot, and the source of the hot water must be located very close to the fixture or appliance being used.

To achieve continuousness the following hot water components are necessary; a large enough tank, a large enough burner, or a modest combination of the two.

Hot Water Service Performance Metrics

In order to provide a context for the discussion, we need to define a few performance metrics: the temperature of hot water, the time it takes for the hot water to arrive, and the volume that runs down the drain until hot water arrives.

- Temperature – ≥110F, hot enough to shower in at the point of use
- Time-to-tap – 10 seconds is acceptable according to the American Society of Plumbing Engineers (ASPE 2000)
- Volume-until-hot – less than 1 cup (goal); up to 3 cups (acceptable)

The temperature of 110F could be debated, as, based on temperature data from many showerheads, most American adults seem to shower in temperatures ranging from 100-105F (Lutz 2011 and Sherman 2014). The reason we have selected 110F is to provide the ability to down-mix the temperature by adding cold water; most plumbing fixtures do not have the ability to add heat just before the use.

The time-to-tap limit comes from ASPE in the document that defines the standard of care for their members. Due to a number of factors many, if not most, homeowners' hot water delivery times fall outside ASPE's acceptable and marginal performance criteria. In fact, a 2014 web survey conducted by the National Resources Defense Council (NRDC) respondents indicated average wait times of 68 seconds for hot water to arrive at the shower (Osann 2014). One of the authors has interviewed more than 40,000 people in the last 20 years about their hot water use and virtually everyone wants the hot water to arrive within 5 seconds, less than half the maximum acceptable performance recommended by ASPE.

The volume-until-hot from the source of hot water to the plumbing fixtures and appliances needs to be very small if the goal of instantaneousness is to be met. Sometimes the source is the water heater; it can also be the supply portion of a circulation loop or an electrically heat-traced pipe. Table 1 calculates the minimum time-to-tap for selected flow rates and pipe volumes. The green shading is for values up to 10 seconds. In the 1 gpm column, the maximum volume that can be in the pipe is less than 24 ounces, or three cups.

Volume in the Pipe (ounces)	Minimum Time-to-Tap (seconds) at Selected Flow Rates					
	0.25 gpm	0.5 gpm	1 gpm	1.5 gpm	2 gpm	2.5 gpm
2	4	1.9	0.9	0.6	0.5	0.4
4	8	4	1.9	1.3	0.9	0.8
8	15	8	4	2.5	1.9	1.5
16	30	15	8	5	4	3
24	45	23	11	8	6	5
32	60	30	15	10	8	6
64	120	60	30	20	15	12
128	240	120	60	40	30	24

ASPE Time-to-Tap Performance Criteria

(green)	Acceptable Performance	1 – 10 seconds
(orange)	Marginal Performance	11 – 30 seconds
(pink)	Unacceptable Performance	31+ seconds

Table 1. Comparing Pipe Volume, Flow Rate and Time-to-Tap

For all fixtures other than public lavatory faucets, where the flow rate is generally no greater than 0.5 gpm, we recommend using 1 gpm as the design flow rate; we recommend using 0.25 gpm for public lavatory faucets. (We recommend these design flow rates to help "future-proof" the building from the undesirable affects of lower future flow rates. If the time-to-tap and volume-until-hot values are acceptable at these lower flow rates, then they will be fine at current flow rates, which are generally higher.) In addition to the times shown in the table, additional time is needed based on heat losses from the water to the pipe. Based on research conducted for the California Energy Commission (Hiller, 2006), the additional amount can range from 25 percent to more than 100 percent. The additional time also means that it takes more than the actual volume in the pipe for hot water to reach the uses. Both of these factors are absent from most design calculations. Based on experience, we recommend selecting a pipe volume from Table 1 that results in half the acceptable time-to-tap (An example of how this works is discussed in a later section).

So, what's going on with our homes and their ability to deliver hot water?

Domestic Hot Water System Components and Their Impact On Efficiency

In order to understand the challenges associated with delivering hot water we must first understand the four primary components of a home's hot water delivery system. These components include:

- Hot Water Creation (water heating)
- Hot Water Distribution (plumbing architecture)
- Hot Water Fixtures and Appliances (faucets, showers, dishwashers and washing machines)
- Human Behavior

Although meaningful advances in efficiency have been achieved in the areas of hot water creation, distribution and use (fixtures and appliances), these advances have been singularly focused on the operation of the individual component without regard for its interaction with or impact on the hot water use as a whole.

Hot Water Creation – Gas Tankless Systems Increase Water Waste

Gas tankless water heating systems continue to grow in popularity and now comprise 5-10% of the water heating market in new construction. All evidence points to their being more energy efficient than gas storage water heaters. Additionally, within their range of operating flow rates, they provide continuous hot water service; that is they will never run out of hot water. However, due to inherent latencies between start-up and hot water production gas tankless systems introduce additional volumes of cold water into the hot water line. A typical gas tankless system will increase the volume of structural waste that needs to be purged for hot water to arrive by 0.25-1.0 gallons and increases hot water waits by 15-30 seconds.

Hot Water Distribution - Growing Homes Mean Growing Waste

The growing size of our homes is having a large and growing impact hot water use. The median new home size in the U.S. has grown from 1,500 SF in 1973 to nearly 2,400 SF in 2013 according the US Census. This represents a 56% increase in home size over the past 40 years.

Greater distances require longer and higher volume plumbing architectures resulting in increased waits for hot water arrive. An all too common floor plan results in the water heater being located diagonally opposite the furthest fixture in the home, which is often the master bathroom. For a single story 1500 SF home, this means the length is about 90 feet (Length + Width + Vertical height), or a bit less than 2 gallons assuming ¾ inch nominal PEX or CPVC piping for the trunk line. At 2 gpm, reasonable for a shower, it will take 1 – 1.5 minutes for hot water to reach the furthest fixture, much longer if the piping is uninsulated and runs below the slab. If the flow rate is 1 gpm, reasonable for a faucet, it will take more than twice as long. The waste grows for a single story 2400 SF home. The piping length increases to about 110 feet, and assuming that the pipe diameter is not required by code to increase from ¾ inch to 1 inch, it will take about 1.25 – 2 minutes for the hot water to arrive. Length and volume are less for two and three story dwellings of the same floor area, but the ratios are much less than what might be assumed from the change in footprint. On average 20% of hot water's energy is now lost during distribution and 3,650 gallons of water per year are wasted while residents wait for hot water to arrive (Lutz 2004 and 2011).

Hot Water Fixtures and Appliances - Efficient Fixtures Create Inadvertent Waste

Increased home size resulting in longer plumbing runs is only one factor impacting hot water waste. The use of lower flow rate fixtures affects waste too. Prior to EPAct of 1992 showerhead flow rates were unregulated. Flow rates up to 5 gpm were not uncommon. The implementation of EPAct reduced maximum flow rates to 2.5 gpm. While the 2.5 gpm flow rate cut water and energy use in half, it more than doubled the wait for hot water to reach the shower. The arrival of the WaterSense certification program for showerheads in 2010 reduced flow rates even further, to a maximum of 2.0 gpm. As a result of reducing flow, wait times for hot water to reach the shower have grown by 2 to 3 times over the past 25 years. Similar changes have occurred for faucets. Another reason that wait times have grown is because the allowable pipe diameters in the plumbing codes have not been revised to account for either reduced flow rates or for the very small probability of simultaneous uses. This means that the velocity is slower than expected and the water gives up its heat to the piping more effectively.

Lower flow rates as required by EPAct 1992 and WaterSense actually increase the volume of structural waste that must be purged before hot water arrives. Due to the unique way hot and cold water mix in the hot water distribution pipe at flow rates below 3 gpm, resulting in lukewarm temperatures for longer periods, the volume to purge can become 10% to 100% greater than the volume of structural waste in the hot water line immediately prior to a hot water event (Koeller 2007).

Human Behavior

So far, we have discussed the structural wastes in hot water distribution systems. What are the behavioral consequences of these construction decisions? Our homes' structural inability to deliver hot water in a timely manner has resulted in behaviors causing, on average, up to 30% of the total volume of water used for showering to be wasted before residents ever begin showering (Lutz 2011).

Because it takes a significant amount of time for hot water to reach the shower, most residents have developed a habit of turning on the shower and then leaving to do something else while waiting for hot water to arrive. Approximately 75% of bathers leave on a regular or occasional basis to brush teeth, shave, use the washroom, pick out clothes – and 52% perform multiple activities while they are away (Sherman 2014).

The length of these activities exceeds the time it takes to purge the cold water (structural waste) from the hot water line. As a result, on average, about a minute's worth of hot water (behavioral waste) is inadvertently wasted and runs down the drain while residents are waiting for their showers to become warm (Sherman 2014).

Solutions for Improved Hot Water Distribution and Behavior

Too often we are focused on hot water creation and fixture and appliance efficiency without considering their interaction with the home's hot water distribution system and the residents' behavior. If we don't address distribution and behavior, resident interactions with their hot water systems will not improve and improvements in water heating sources and fixture and appliance efficiency may not result in the expected improvements in real world applications.

Improved Plumbing Architectures – Structural Waste

The homes we build will last for decades. Therefore, it is critical that we design their plumbing systems to support and enable the efficient use of hot water over a wide variety of use patterns and possible significant reductions in flow rates and fill volumes. The structural waste that is built into the home will stay with it until the piping fails or a major remodel is undertaken; otherwise, the cost of relocating the plumbing is likely to be prohibitively expensive.

Based on a time-to-tap wait of 10 seconds, we previously determined the plumbing between the source and tap should ideally hold no more than 1 cup of water (Table 1). The next question is how many feet of pipe contains one cup? Obviously it depends on diameter and because of our use of nominal pipe sizes, it also depends on the wall thickness of the piping material. Table 2 shows the length of pipe containing one cup for copper, CPVC and PEX, the three most common piping materials used in residential plumbing. (CTS stands for Copper Tube Size; dimensions are nominal and outside diameters are the same for all materials) Because plastics (CPVC and PEX) have thicker walls than copper, they have less volume per foot. This means they give a bit more flexibility in reaching between the source and the use points. However, regardless of the material, a one-cup limit is a tight requirement, particularly if the minimum pipe allowable pipe size is ½ inch nominal, which it is in most code jurisdictions.

So, how would you get the piping down to one cup? So far, we have found five ways to do this:

1. Locate all fixtures and appliances within one cup of \one water heater
2. Group some fixtures and appliances within one cup of one water heater and other fixtures and appliances within one cup of another water heater
3. Locate a water heater within one cup of every fixture and appliance
4. Install electric heat trace on all piping from the water heater to within one cup of every fixture and appliance

   Install a circulation loop so that the supply portion is within one cup of every fixture and appliance

	3/8" CTS	1/2" CTS	3/4" CTS	1" CTS
	ft/cup	ft/cup	ft/cup	ft/cup
"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

Table 2 Length of Pipe Containing 1 Cup (8 ounces)

Items 1 and 2 in the list essentially define compact design, where much thought has gone into the placement of the building's plumbing infrastructure. This does not happen very often, but it is the goal of good design. For Item 3 it is generally too expensive to install a water heater for every fixture and appliance; you need to supply each one with power (gas or electric), venting if gas in addition to purchasing multiple water heaters. Item 4, electric heat trace allows for as many feet of pipe as needed between the water heater(s) and the uses, but installation and operating costs are not well understood by the energy regulating community at this time. Item 5, locating the supply portion of a circulation loop within one cup of every fixture and appliance is generally the most buildable option, particularly given current floor plans. For overall energy and material efficiency, it is important to minimize the length of the circulation loop, which may result in grouping the fixtures into more than one zone, each with its own pump and controls.

Selecting the right control strategy for the pump is also critical to overall energy consumption, but is not the focus of this paper. Currently, priming the line with hot water shortly before needing hot water is the most efficient strategy. This is often called demand activation or demand control.

Insulation and Right-sizing Pipe Diameters

Research has shown the importance of insulating the hot water piping, even within conditioned space (Hiller, 2005). There are various amounts shown in different codes and standards, but the easiest one to remember is that the wall thickness of the pipe insulation shall be at least equal to the nominal diameter of the pipe for all pipe up to 2 inch nominal. This will cut the temperature drop in half over a given length at a given flow rate. It also doubles the cool down time in ½ inch piping and triple it in ¾ inch piping.

The pipe serving an individual fixture or appliance should be sized only for the flow rate of the fixture or appliance, and not for any amount of simultaneity, since this can only occur on branches or trunks serving more than one fixture. At present, most plumbing codes do not easily allow the use of pipe diameters less than ½ inch nominal. However, the reasons for this date back to before flow rates were limited in the 1990s. Research is underway to help the industry understand when it is acceptable to use smaller diameter tubing, such as 3/8 inch nominal. In the meantime, we need to keep the distance from the source to the use short based on ½ inch nominal fixture branches.

The Human Factor – Behavioral Waste

Minimizing structural waste through the use of insulation, compact plumbing design, right sized pipes and priming the plumbing lines is critical. Hot water should arrive within 10 seconds to meet the ASPE acceptable performance recommendations for time-to-tap. However, field data collected by Lawrence Berkeley National Lab (Lutz 2012 and Sherman 2014) indicates that fast hot water delivery (low structural waste) does not eliminate or even mitigate behavioral waste. Residents' warm-up behaviors are deeply ingrained and they do not, for the most part, begin showering as soon as hot water reaches the shower, no matter how quickly their hot water arrives. Figure 1 shows the variation of structural waste and behavioral waste for the showers in 18 homes. Even when the structural waste is very small, behavioral waste can be very large.

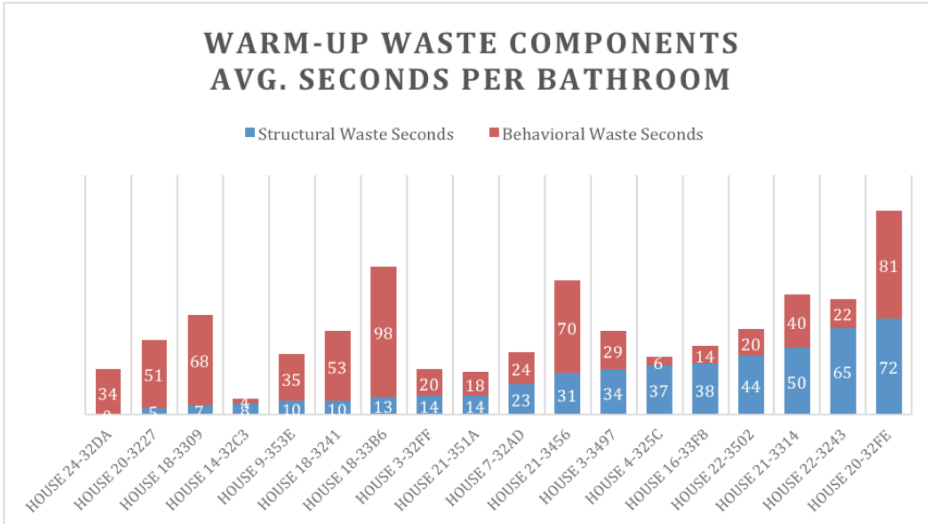

Figure 1. Components of Warm Up Waste for 18 Homes

Rather, it appears as if fast hot water delivery primarily shifts structural waste savings into the behavioral waste component of the warm-up waste volume. In other words, residents remain away from the shower for a consistent period of time and as result, the volume of behavioral waste within the warm-up waste volume actually increases when hot water arrives quickly. As illustrated in Figure 2,even though total waste was reduced, behavioral waste increased by 21% for bathrooms with structural waste of 20 seconds or less on average. (Sherman 2014).

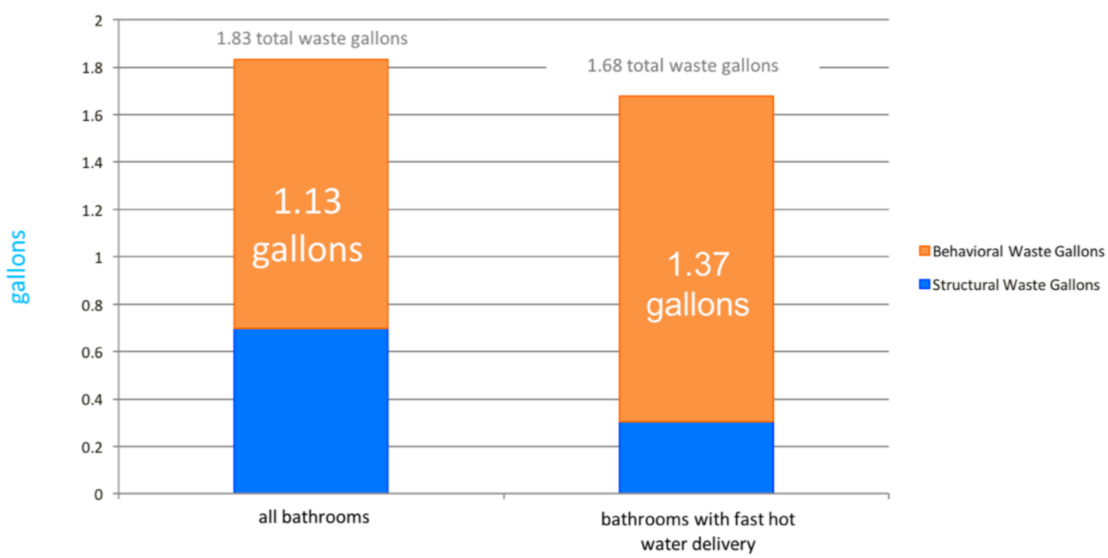

Figure 2. Comparing Bathrooms with Short Delivery Times to All Bathrooms

Guaranteeing Structural Savings By Eliminating Behavioral Waste

Human behavior will most likely render structural improvements to hot water delivery systems less effective than the physics alone would indicate. To counter this probability, the effects of human behavior must be eliminated from the warm-up waste equation. Since showering represents more than half of typical hot water use, and a significant fraction of the wasted water and time while waiting for hot water to arrive, it makes sense to see if there are any solutions to make it easy for consumers to reduce the behavioral waste. An ideal solution for accomplishing this is the use of a Thermostatic Shut Off Valve (TSV) at the showerhead point of use.

TSVs work by monitoring the shower's temperature and then automatically reducing the flow to a trickle as soon as bathing temperature water arrives. This allows bathers to continue with their habitual practice of turning on the shower and then leaving to do other things while waiting for the hot water to arrive – only now they're not wasting hot water while they're away. Once the bathers finish their routine and return to the shower, they simply pull a cord to trigger the shower's normal flow and begin showering. After bathing is completed the TSV automatically resets itself for its next use.

In a study that metered 22 showers, Cadmus found that TSVs installed in single-family homes saved an average of 59 seconds of behavioral waste per shower (Wood 2015). This is consistent with the data presented in Figures 1 and 2. The same study indicated that TSVs in homes with electric water heating would save an average of 121 kWh per year. Other studies have shown similar savings of water, energy and time.

The use of TSVs is not limited to shower-only bathrooms. More than half of all showers take place in a tub-shower combo. In these cases, the user often starts the process by running water out of the tub spout and when hot water arrives, switching up to the shower. A TSV can be installed at the tub spout. This allows the water to flow more quickly from the source, reducing the time to clear the structural waste compared to the shower flow rate. Once the TSV has shut off, water is diverted to the showerhead, which is normally off, waiting for the bather to pull the cord.

Conclusions

Hot water is a major subsystem in dwellings. It is critical to understand the interactions of the components of the system, not just their performance individually. One of the key problems that we face is that flow rates have been reduced without codes and designers taking these reduced flow rates into account when specifying pipe diameters or plumbing fixture layouts. This has led to increased wait times before hot water arrives and occupants develop behaviors to accommodate the relatively long waits. These behaviors are time efficient to the users, but energy and water wasteful.

It is possible to design and build dwellings with small amounts of water in the piping between the water heater(s) and the plumbing fixtures and appliances. However, even if the structural waste is minimized, it is not clear that occupant behavior will change to account for the reduced time-to-tap.

The use of thermostatic shutoff valves at showers and combination tub/showers enable users to continue their behaviors, but effectively eliminate the water and energy waste associated with these behaviors. TSVs should be incorporated into programs, codes and standards to help ensure that the savings expected from reducing structural waste will be achieved in practice.

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