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FINAL PROJECT REPORT

Code Changes and Implications of Residential Low-Flow Hot Water Fixtures

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with research, development, and demonstration entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency.
- Renewable Energy and Advanced Generation.
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research.
- Natural Gas-Related Transportation.

Code Changes and Implications of Residential Low-Flow Hot Water Fixtures is the final report for the Code Changes and Implications of Residential Low-Flow Hot Water Fixtures project (Contract Number: PIR-16-020) conducted by Gary Klein and Associates, Inc. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

This study investigated strategies to improve hot water delivery quality in single-family homes to reduce energy and water waste. The investigation examined a range of improvement strategies that include pipe layout optimization, using two water heaters, moving the water heater closer to the fixtures, pipe size reduction, compact architectural design, and lower-flow fixtures. Using the results of single-pipe testing from a 2005 Public Interest Energy Research project, the research team developed a distribution performance model to analyze the multi-pipe distribution networks found in homes. Since most hot water events are of very short duration, the water temperature rarely reaches steady-state. The model can account for the transient nature of the hot water delivery process found in realistic hot water use schedules. Based on performance assessment results, the study provided design solutions to reduce distribution loss by more than 50 percent and system energy and water consumption by more than 25 percent. Research results were shared with key stakeholders.

Improving architectural compactness and hot water distribution system designs can reduce the first costs and save energy and water, improve hot-water delivery quality, and reduce emissions over the operational life of the building. The researchers found that compact wet-room architectural designs can reduce the first cost of hot-water distribution system installation by $1,000–$2,000 per home. If low-flow fixtures are used in addition to compact wet-room architectural designs, an average home will save 19 therms and 3,180 gallons of water per year, which represent about 26 percent reduction from baseline. Correspondingly, California ratepayers will save about 1.9 million therms of natural gas and 318 million gallons of water in the first year.

Keywords: Hot water distribution, domestic hot water, energy efficiency, compact hot water distribution design, low flow fixture, water efficiency, hot water distribution model, wet room rectangle, architectural compactness, loads not met

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Natural gas consumption in buildings represents about 28 percent of California's total natural gas demand according to the 2015 building survey data provided by United States Energy Information Administration. Water heating represents about 40 percent of this natural gas use in residential buildings and 32 percent of the natural gas use in commercial buildings. Energy loss through hot-water distribution systems represents a major component of the energy consumption in domestic hot water systems. For the baseline case evaluated by this study, 40 percent of the energy supplied by the water heater was lost through the distribution system.

State laws and the California Public Utility Commission's zero-net energy policy goals require deep reductions of building energy use. Therefore, improving hot water system efficiency in buildings is critical to achieving the state's statutory energy goals.

The typical hot-water distribution configurations in common architectural designs have changed little over the years, resulting in long pipe lengths and large amounts of water between the water heater and individual hot-water fixtures and appliances. Users often experience long hot-water delays, wasting significant energy and water. Current California Title 24 Building Energy Standards (Title 24) include compact distribution design options; however, the market is slow to adopt these options. More effective Title 24 regulations on domestic hot water distribution designs may be required to change existing market practices. To support future standards development, a comprehensive understanding of distribution-design improvement strategies is necessary.

Although flow rates for hot-water fixtures have been reduced significantly over the last 20 years by California and Federal appliance standards, the rules for sizing supply-pipes have not been revised to account for these reductions. Current fixture flow rates can lower water and energy consumption, but when coupled with current pipe sizing, the result is longer hot-water wait times and lower delivered hot-water temperatures. There has not been any study that systematically addresses these two issues. Without carefully addressing these two issues, market adoption of even lower fixture flow rates could be hampered. The impact of flow rates on hot-water distribution performance must be evaluated to understand the possible consequences of reducing fixture flow rates even further.

Project Purpose

This research project identified strategies to significantly improve the energy and water efficiency of domestic hot water systems in single family homes. The researchers addressed two areas of efficiency improvement for domestic hot water systems in single-family homes: distribution system design and low-flow fixture applications. The researchers' goals were to develop recommendations for future standards development based on investigating improvement strategies for distribution designs, and the impact of low-flow fixtures on these designs. Objectives of the study included:

- Identify and assess the feasibility of improvement strategies for hot-water distribution designs in single family homes.

- Develop a performance assessment tool to evaluate the effectiveness of improvement strategies for practical distribution designs under realistic operational conditions.
- Evaluate the performance of the improvement strategies.
- Assess market barriers to the adoption of each improvement strategy.
- Characterize the impact of low-flow fixtures on hot-water distribution system performance.
- Assess the lowest hot-water demand that can be achieved through distribution design improvement and fixture flow-rate reduction.
- Develop codes and standards improvement recommendations based on research findings.

Project Process

The research team identified multiple distribution design improvement strategies based on a literature review, communication with stakeholders, and team-member research experience in related areas. The identified improvement strategies aimed to provide deep energy and water savings beyond current practices. Five pipe-layout methods represent typical configurations of hot water distribution systems found in new construction:

- *Trunk and branch*: All fixtures share a relatively long common flow path (trunk). Fixtures in the same area of the building may also share a secondary flow path (branch). Individual fixtures are connected to the trunk or branches through a tee via a relatively short fixture branch.
- *Home run (central manifold*): Each fixture is connected through a relatively long fixture branch to a manifold (branch), which is connected to the water heater with a common pipe (trunk).
- *Hybrid (distributed mini-manifolds)*: Fixtures in the same area of the building are connected to a multi-port tee (mini-manifold). Each mini-manifold is connected to the trunk via a relatively long secondary flow path (branch). These secondary flow paths are connected to a relatively short trunk which is connected to the water heater
- *One-zone design:* This configuration has only one main flow path (trunk) which is shared by all fixtures which are connected to the trunk via relatively short fixture branches. This system can easily be converted to a recirculation system.
- T*wo water heaters:* Fixtures in different areas of the building are connected to separate water heaters located relatively close to the fixtures they serve. Splitting the hot water system in two, allows for shorter and smaller diameter trunks and branches reducing volume.

The team explored improvement strategies for these configurations: water heater location, fixture locations and small pipes. The researchers assessed each of these improvement strategies for the five pipe-layout methods in a prototype single family home used for Title 24 development (see Chapter 2). Distribution designs using individual, and combinations of improvement strategies based on the five pipe-layout methods were created and used for the detailed performance assessments.

For the performance improvement assessment, researchers used a baseline distribution system that reflected better than average architectural design and plumbing installation practices in the current market. Improvements beyond this above-average baseline reflect conservative savings opportunities for future codes and standards development

Hot-water distribution in residential buildings is dominated by isolated hot-water delivery events that are separated in both location and time. This results in transient water flow and heat transfer processes. However, most existing distribution performance models are based on steady-state water flow and heat transfer principles. These existing models do not adequately reflect transient hot-water delivery processes in real distribution systems, nor do they provide insights into the reasons for heat-loss and water-waste, information which is required for an in-depth analysis of the effectiveness of various improvement strategies.

Distribution system performance depends on hot water use schedules. The researchers used a daily hot-water use schedule with draws from different fixtures for performance assessments.

The researchers developed a transient distribution performance model — based primarily on data taken from a 2005 Public Interest Energy Research project — to assess the effectiveness of the identified improvement strategies. This model breaks down hot water delivery into three phases: 1) waiting for hot water, 2) use of hot water, and 3) pipe cool down after use. Each of these phases has a unique effect on overall distribution efficiency. The model is capable of simulating hot-water distribution in complicated pipe networks with realistic hot-water use schedules.

The hot-water waiting phase has the largest impact on distribution efficiency and was also the most challenging phase to be modeled. The hot-water energy supplied by the water heater to the distribution system can now be broken down into four components, which have different effects on distribution efficiency. The model enables the analysis of hot water flow paths with multiple pipes and different initial temperature conditions, so that all distribution conditions can be modeled.

More than 60 combinations of pipe-layouts and improvement strategies were evaluated. For each, the research team analyzed a scenario with normal fixture flow rates and a scenario with lower fixture flow rates. For the normal fixture flow-rate scenarios, maximum flow rates for the showerhead and kitchen sink faucet were 1.8 gallons-per-minute (GPM) and 1.2 GPM for the bathroom sink faucet, based on the California Appliance Standards adopted in 2015. For the low fixture flow-rate scenarios, maximum flow rates for the showerhead were reduced to 1.5 GPM and 0.5 GPM for the bathroom sink faucet based on recommendations provided by members of the project technical advisory committee. Comparisons between the two scenarios demonstrated the impact of using low-flow fixture.

Project Results

After analyzing all the combinations of improvement strategies researchers found that:

1. For draws that do not need to wait for hot water, reducing the flow path volume increased the amount of hot water delivered to the fixture. However, there was no impact on hot water energy consumption. There will be an impact on indirect energy use by dishwashers as they heat water that wasn’t hot enough when delivered.

2. Shower draws and some faucet draws require hot water to be delivered to the fixture before use. For these draws, reducing flow path volume can reduce both energy and water waste.
3. There are no significant performance differences among trunk and branch, home run, and hybrid pipe layout methods, if they are properly designed.
4. Long, large diameter one-zone trunk and branch layouts have somewhat higher distribution losses, but they provide a higher percentage of the desired hot water service.
5. For trunk and branch, hybrid and one-zone configurations, replacing 1-inch diameter pipes with ¾ inch diameter pipes reduces losses more than does replacing ½ inch diameter fixture branches with 3/8-inch diameter pipes. However, with central home run manifolds, the opposite is true.
6. In a distributed architectural design, placing the water heater within the wet-room rectangle reduces distribution losses by a small amount. By contrast, doing this in a compact architectural design results in very large reductions of the distribution losses. This strategy also performs best at meeting hot water loads, and it costs much less to install the plumbing, reducing first costs by $1,000–$2,000. (Wet rooms include kitchens, bathrooms, laundry rooms, wet bars, pantries — rooms that have water distributed to them. Wet room rectangle is the area of the building in plan view that contains all the piping to wet rooms and to plumbing fixtures. Appendix E Sample Floorplans provides examples of various wet room rectangles).
7. For homes with distributed wet rooms (typical floorplans), using two water heaters, each installed close to different clusters of fixtures, provides large reductions in distribution losses.

There were two surprising findings:

1. A very large percentage of hot water draws are too short in duration and too small in volume for hot water to reach the fixtures. Even in the cases where the volume was very small, there were still a significant number of events when hot water would not arrive. Using lower flow rate faucets increases the number of draws that do not receive hot water.
2. Models used to evaluate hot water energy use, including Title 24 energy budget calculations, assume that all water produced by a water heater is considered to be delivered to the fixtures at a useful hot water temperature. However, as discussed above, hot water does not reach the user in a very large percentage of events. If the idea is to provide hot water as desired by consumers, then the models need to be revised so that they evaluate the same level of service for all hot water distribution system options. The relevant service for hot water distribution systems is the time-to-tap or volume-until-hot.

Knowledge and Market Transfer

In addition to obtaining the environmental and economic benefits that come from implementing the results of this research, the team shared the interim and final results with plumbing and energy professionals in California and elsewhere in the nation.

The project team participated in conferences both as organizers and presenters to inform the audiences about the knowledge gained from the research and to obtain feedback from them on any concerns they had. The team also shared the results with California Energy Commission staff working on the 2021 changes to Title 24 and submitted code change proposals to the 2021 Uniform Plumbing Code and the 2021 International Energy Conservation Code. The research team intends to continue the knowledge transfer activities after the project is complete.

The approach to understanding the location of the hot water fixtures to each other and to the source of hot water that serves them has been generally well-received. The fact that there are a large number of hot water draws that are too short to reach the fixture (mostly faucets), even in dwellings with a compact wet-room architecture surprised the participants; particularly since the industry has long thought that bringing the sources of hot water closer to the uses (by reducing the length or diameter or both) would make a significant impact on hot water distribution system efficiency.

Recommendations

Based on the results, the researchers suggest these recommendations for future codes and standards:

- Title-24 Part 6 California Energy Code should set appropriate requirements to prevent the use of 1-inch diameter pipe in hot water distribution systems for most single-family or multi-family dwelling units.
- Title-24 Part 6 California Energy Code should provide compliance credits to compact wet-room architectural designs with the water heater installed close to fixtures. This credit for the distribution system should be applied to dwellings with one or more compact wet-room cores.
- Title-20 Appliance Efficiency Regulations should explore requirements for single-handle faucets with a "cold-start" function. This would help eliminate the energy waste due to unintentional hot water draws.
- The California Energy Commission should support efforts of the Department of Housing and Community Development to adopt Appendix M of the 2018 Uniform Plumbing Code for use throughout the state. Appendix M Water Demand Calculator provides the tools for the plumbing industry to reduce pipe sizes based on modern flow rates and plumbing materials. It is applicable to all new residential construction in California

Benefits to California

Improving architectural compactness and hot water distribution system designs can reduce the first costs. These strategies can also save energy and water, improve hot-water delivery quality, and reduce emissions over the operational life of the building. The researchers found that compact wet-room architectural designs can reduce the first cost of hot-water distribution system installation by $1,000–$2,000 per home. In addition, assuming current fixture flow rates an average home will save 11 therms and 1,750 gallons of water per year, which represents about a 14 percent reduction from baseline. Assuming construction of 100,000 new homes each year, California ratepayers will save about 1.1 million therms of natural gas (and associated emissions) and 175 million gallons of water in the first year. If low-flow fixtures are used in addition to compact wet-room architectural designs, an average home will save 19 therms and 3,180 gallons of water per year, which represents about a 26 percent reduction from baseline. Correspondingly, California ratepayers will save about 1.9 million therms of natural gas and 318 million gallons of water in the first year.

CHAPTER 1: Introduction

This project investigated research topics to significantly reduce domestic hot water system energy and water waste. The study explored practical solutions to improve hot water distribution systems, assessed the performance of improved designs and low flow fixtures, and evaluated the lowest acceptable flow rates that provide hot water use performance requirements without degrading distribution efficiency. This report contains recommendations for future code changes to hot water distribution systems that should result in improvements in piping design and distribution for existing and future buildings.

Why This Research is Important

According to a Pacific Gas and Electric Company (PG&E) 2019 Title 24 codes and standards enhancement (CASE) study on compact hot water distribution systems, market adoption of compact distribution design is very low (less than 0.1 percent), despite past Title 24 development efforts in the area.[1] This suggests that there are still significant market barriers to high-performance distribution system design practices and Title 24 building standards need to provide more effective solutions to change market practices.

Appliance regulations have been steadily reducing the maximum allowed flow rates for hot water fixtures. However, with little change in floor plans, or distribution system designs, building occupants using low-flow fixtures will experience longer waiting time for hot water and lower delivered hot water temperatures. There has not been any study that systematically addresses these issues and the impact of low-flow fixtures or low volume plumbing appliances on hot water system performance, or vice versa. Without carefully addressing these issues, low-flow fixtures may not achieve the intended energy and water savings and market adoption of low-flow fixtures could be hampered.

State laws, such as Assembly Bill 32 (Nuñez, Chapter 488, Statutes of 2006), Assembly Bill 758 (Skinner, Chapter 470, Statutes of 2009), and Senate Bill 350 (De Léon, Chapter 547, Statutes of 2015), and the California Public Utility Commission's zero-net energy policy goals require deep reductions of building energy use. Based on 2015 U.S. Energy Information Administration data, natural gas consumption in buildings represents about 28 percent of California's total natural gas demand. Water heating consumes about 40 percent of the natural gas use in residential buildings and 32 percent of the natural gas use in commercial buildings. Therefore, improving hot water system efficiency in buildings is critical to achieving the state's statutory energy goals. This project addressed two areas of hot water system efficiency improvement: distribution system efficiency and the application of low flow fixtures. Improvement in these

[1] Hoeschele, Marc and Peter Grant. *Compact Hot Water Distribution – Final Report*. Codes and Standards Enhancement (CASE) Initiative 2019 California Building Energy Efficiency Standards, July 2017. http://title24stakeholders.com/wp-content/uploads/2017/09/2019-T24-CASE-Report_Cmpct-HW-Distbtn_Final_September-2017.pdf.

areas can also provide significant water savings to address the long-term drought conditions faced by the state.

Past California Energy Code development efforts have had limited success in improving hot water distribution system in buildings. One of the reasons is that existing code requirements are not based on detailed considerations of plumbing and building architecture designs. In addition, past code development efforts have not addressed the most important performance parameter to building occupants, specifically the time waiting for hot water to arrive during cold start events (such as first thing in the morning, or first use when returning home from work and school). Therefore, past code development efforts do not adequately inform market practitioners how to design an efficient system and the levels of performance they can obtain by meeting the code requirements.

Roy Hunter of the National Bureau of Standards was the first to seriously study the sizing of plumbing in buildings in the 1930s.[2] His techniques were developed for potable and wastewater pipes in multi-family buildings. These studies are the foundation of modern hot water distribution system design. Unfortunately, they are dated and based on practices and materials not applicable to current construction. Residential building practices have changed dramatically since that time. Houses are larger, with more hot water end uses (bathrooms), occupied by fewer people.[3] The constellation of changes in plumbing practice has inadvertently caused performance issues.[4] The slower flows in longer, larger pipe is also leading to potential health hazards. The greater water age — the time since it was treated by a water utility — is increasing, due to the lower velocity of water in the pipes. In turn, this leads to increased biofilm growth and on-premise pathogens.[5]

In short:

1. Plumbing fixture flow rates, flush volume and appliance fill volumes have been reduced every decade since the 1950s.
2. Table 1 shows the reductions that have occurred since the 1980s. The smallest reduction is almost 50 percent, the largest is more than 90 percent. Reductions for hot water fixtures and appliances range from 49-86 percent.
3. Pipe sizing rules have not been revisited since they were written down in the 1940s.
4. The median square footage of a house is roughly 1.5 times larger than in was in 1970.

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[2] Hunter, Roy B. *Methods of Estimating Loads in Plumbing Systems*. US Department of Commerce, National Bureau of Standards, 1940.

[3] Lutz, J, and G Klein. *A Conceptual Framework for Understanding Residential Hot Water Systems, Poster.* ACEEE 1998 Summer Study on Energy Efficiency in Buildings, Asilomar, California, 1998.

[4] Klein, Gary. Hot Water Distribution Research. IAPMO Official, 2006, 39–44.

[5] Falkinham, Joseph, Amy Pruden, and Marc Edwards. *Opportunistic Premise Plumbing Pathogens: Increasingly Important Pathogens in Drinking Water*. Pathogens 4, no. 2 (June 9, 2015): 373–86.

5. The result:
    a. It takes much longer than it used to for hot water to arrive. For key hot water events such as showers and washing dishes, the wait for hot water is typically 30-60 seconds and is often much longer than that.
    b. More energy is lost when the pipes cool down.
    c. Dissatisfied occupants. For many events hot water never arrives, even though it left the water heater.
    d. Potentially unsafe conditions in the piping network. Lower flow rates mean for a given pipe size, it takes longer for the water to transit the piping network, both before it reaches the building and then again before it is discharged through a fixture. This means that there is more time for the disinfection chemicals provided by many municipalities to dissipate before the water is used. The potential for opportunistic pathogens to grow has increased.

Table 1: Flow Rate Changes of Plumbing Products and Appliances Since 1980

Water-using Fixture or Appliance	1980s Water Use (typical)	1990 Requirement (maximum)	EPAct 1992 Requirement (maximum)	2009 Baseline Plumbing Code (maximum)	"Green Code" Maximums (2017 CALGreen)	% Reduction in avg water use since 1980s
Residential Bathroom Lavatory Faucet	3.5+ gpm	2.5 gpm	2.2 gpm	2.2 gpm	1.2 gpm	66%
Showerhead	3.5+ gpm	3.5 gpm	2.5 gpm	2.5 gpm	1.8 gpm	49%
Residential ("private") Toilet	5.0+ gpf	3.5 gpf	1.6 gpf	1.6 gpf	1.28 gpf	74%
Commercial ("public") Toilet	5.0+ gpf	3.5 gpf	1.6 gpf	1.6 gpf	1.28 gpf	74%
Urinal	1.5 to 3.0+ gpf	1.5 to 3.0+ gpf	1.0 gpf	1.0 gpf	0.125 gpf	96%
Commercial Lavatory Faucet	3.5+ gpm	2.5 gpm	2.2 gpm	0.5 gpm	0.5 gpm	86%
Food Service Pre-Rinse Spray Valve	5.0+ gpm	No requirement	1.6 gpm *(EPAct 2005)*	No requirement	1.3 gpm	74%
Residential Clothes Washing Machine	51 gallons per load	No requirement	26 gallons per load *(2012 std)*	No requirement	12.6 gallons per load *(Energy Star)*	75%
Residential Dishwasher	14 gallons per cycle	No requirement	6.5 gallons per cycle *(2012 std)*	No requirement	3.5 gallons per cycle *(Energy Star)*	75%

Source: *The Drainline Transport of Solid Waste in Buildings*, Plumbing Efficiency Research Coalition, November 2012, page 10. (http://www.plumbingefficiencyresearchcoalition.org/wp-content/uploads/2012/12/Drainline-Transport-Study-PhaseOne.pdf)

Research Goals and Objectives

The goals of the study include:

1. Develop code change recommendations based on comprehensive assessment of technical, economic, and market feasibility improvement strategies that can significantly increase hot water distribution system efficiency in new construction and existing buildings.

2. Characterize the impact of low flow fixtures on distribution system performance and determine the theoretical lowest flow possible for hot water fixtures.

The objectives of the study include:

1. Identify system design and control strategies that can significantly increase the energy and water efficiency of hot water distribution systems in new construction and existing buildings.
2. Investigate the technical feasibility of distribution system improvement strategies that integrate both minimized pipe volume and low flow rates by applying them to a range of building designs and assess the impact of building architecture designs on pipe volume.
3. Develop a model to characterize transient hot water delivery processes in different types of pipes and use this model to further develop a performance analysis tool to assess hot water distribution system performance affected by piping layout, draw schedule, flow rate, and occupant behaviors in waiting for hot water.
4. Evaluate the performance, cost, and cost effectiveness of the improvement strategies. Assess market barriers to the adoption of each improvement strategy.
5. Use the transient hot water delivery model and distribution system design examples to characterize hot water delivery with low flow rates, identify performance factors that are sensitive to low flow rates, and assess the lowest acceptable flow rates that provide hot water usage performance requirements without degrading distribution efficiency.
6. Evaluate the performance of distribution systems using low flow fixtures and compared to systems without using low flow fixtures.
7. Develop recommendations to improve regulations, codes and standards based on the integrated assessment of distribution system improvement strategies and the utilization of low flow - high performance fixtures.

Literature Review and Stakeholder Interviews

What the research team learned from the literature review and interviews with stakeholders is that consumers care about two things regarding their residential hot water systems:

1. Hot water to arrive quickly at every plumbing fixture every time they turn on the tap.
2. To never run out of hot water in their shower.

In addition to these "wants", users expect the hot water system to be safe, reliable, relatively durable, low maintenance and be of a reasonable cost to purchase and operate. These desires are the same whether the user lives in a single family or multi-family dwelling. The expectations in multi-family are somewhat different, however, depending on whether they pay directly for hot water or it is included in their rent.

The main body of the California Plumbing Code does not limit the amount of water *in the supply pipe* between the source of hot water and the plumbing fixtures or appliances. Appendix L, Sustainable Practices, Section L502.7 does have such requirements, applying to all occupancies, but the use of the appendices in the plumbing code is optional.

Appendix A contains the detailed literature review and Appendix B contains the bibliography.

Overview of Hot-Water Distribution Systems

All piping systems contain trunks and branches. Branches are either connected to kitchens, bathrooms, laundry rooms, bars or pantries (wet rooms) or to individual plumbing fixtures and appliances (fixture branches). A fixture branch serves one plumbing fixture or appliance either hot or cold water,

There are several configurations of hot-water distribution systems including:

- Trunk and branch
- Circulation systems
- Electric heat trace systems
- Central home run systems
- Hybrid systems

These systems are discussed in detail in Chapter 2.

In hot water distribution systems, the first user starts the process of drawing hot water from the water heater to the fixture or appliance. Water pressure pushes cold water into the water heater. Hot water leaves the water heater and enters the hot-water piping, which is initially filled with building temperature water (cold).

Eventually, if you wait long enough, hot water will arrive. How long will this take, and how much water will run down the drain before the hot water arrives?

For a given volume in the pipe (X), research has shown that it takes roughly twice as much water (2X) before hot water (greater than or equal to 105F) comes out the other end. Within 15-45 minutes of the first use (depending how well the pipes are insulated), subsequent users can take advantage of the fact that at least some portion of the hot-water distribution system is hot, and they will get hot water more quickly.[6, 7, 8, 9]

There are various ways of designing a hot-water distribution system to deliver hot water more quickly. All of them revolve around reducing the volume of the hot-water piping between the source-of-hot-water and the use. This report examines some of these options in more detail.

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[6] Hiller, Carl. *Hot Water Distribution System Research–Phase I Final Report*. California Energy Commission, November 2005. http://www.energy.ca.gov/2005publications/CEC-500-2005-161/CEC-500-2005-161.PDF.

[7] Hiller, Carl. Hot Water Distribution System Piping Heat Loss Factors--Phase I: Test Results. ASHRAE Transactions 112, no. 1 (2006).

[8] Hiller, Carl C. Hot Water Distribution System Piping Heat Loss Factors, Both In Air and Buried-Phase II Test Results. ASHRAE Transactions 114, no. 2 (2008).

[9] Hiller, Carl C. Hot-Water Distribution System Piping Heat Loss Factors--Phase III: Test Results. ASHRAE Transactions 117, no. 1 (2011).

Appendix C: Primer on Plumbing provides more details of the design and installation of hot water distribution systems. The topics covered are as follows:

1. Common Piping Materials
2. Codes and Standards Relevant to Hot Water Distribution Systems in California
3. Appliance Standards for Faucets and Showers
4. California Code of Regulations Title 24, Part 5 California Plumbing Code (CPC)
5. California Code of Regulations Title 24, Part 6 California Energy Code (Title-24)
6. Potential Issues for Using Low-Flow or High-Efficiency Hot Water Fixtures

Appendix D: Hot Water Distribution System Provisions in the 2019 California Energy Code contains relevant items that have been extracted from the 2019 Revised Energy Code, the 2019 Draft Residential Compliance Manuals, and the 2019 Reference Appendices.

CHAPTER 2: Distribution Improvement Strategies

Characteristics of Architectural Designs and Fixture Locations

Buildings can be characterized by the relationship between the wet rooms and separately between the water heater and the wet rooms. Wet rooms include kitchens, bathrooms, laundry rooms, wet bars, pantries — rooms that have water distributed to them. In contrast, dry rooms are everything else, including bedrooms, dining rooms, living rooms hallways, closets, and offices. Although wet rooms and dry rooms can be found in any occupancy, the discussion and analysis in this report will be about wet rooms in residential occupancies.

The size of each wet room and the distance between them helps determine the size of the hot water distribution system. The further apart, the longer the piping. The longer the pipe, the greater the pressure-drop will be for any given diameter and flow rate. The greater the number of fixtures and appliances that share a common line, the larger the diameter of the shared portions will be. The greater the pressure drops due to elevation, length, fittings, valves and other restrictions, the larger the diameter needs to be. Length and diameter determine the volume of the water in the piping.

The area encompassed by the wet rooms can be bounded by a rectangle. The researchers chose this shape because most buildings in the United States are rectangles and because the plumbing generally resides within the interstitial spaces in a building, which are usually rectilinear in shape. These spaces are found between the walls and floors and in vertical risers from a basement to an attic. Where the piping rests on, is hung from, or is attached to a joist, truss, post or beam, it generally runs perpendicular or parallel to these framing members.

The area encompassed by the water heater and the wet rooms can also be bounded by a rectangle. It describes the hot water distribution system. As with the wet rooms, distance, number of fixtures and structural pressure drops affect the volume of water in the hot water piping. The logical worst-case hot water distribution system has the water heater located diagonally opposite the furthest plumbing fixture or appliance (collectively referred as fixtures in this report), including the number of stories. There are two kinds of waste in a hot water distribution system — structural and behavioral. Structural wastes — of energy, water and time — are proportional to the volume in the pipe between the source of hot water at the time of the hot water draw and the fixture being used. Behavioral wastes — what consumers do with what they learn about the structural waste — can be significantly larger than the structural waste. Wet rooms can be located back-to-back, stacked or spread throughout the building.

There are two ratios that are of interest: the percentage of the total floor area that surrounds the wet rooms and the percentage of the total floor area that is bounded by the hot water distribution system.

In the *logical* worst-case, the rectangle bounding the wet rooms would be 100 percent of the floor area of a 1-story building. If the water heater were located right next to this rectangle, the rectangle bounding the hot water distribution system would also be 100 percent of the floor area.

However, there is no requirement that the layout of the house be *logical* from the perspective of the hot water system. The plumber has no choice but to connect the water heater(s) to the fixtures, no matter where they are in the house. This makes it possible for the hot water distribution system to be worse than the *logical* worst-case. For example, the water heater could be located at the front of the garage instead of right next to the wall of the house. This adds roughly 25 feet to the hot water distribution system, the volume of which needs to be cleared out every time someone wants hot water. In another example, the hot water piping could go almost all the way around the building before ending at the "furthest" fixture, which turns out to be very close to the water heater. Creating a long, single zone hot water distribution system is a potential recipe for inefficient hot water delivery.

In summary, the *logical* worst-case proportions are:

- 1-story building, 100 percent
- 2-story building, 50 percent
- 3-story building, 33.3 percent

On the positive side, the wet rooms could be located back-to-back, and stacked above each other on a common plumbing wall and the water heater could be located within the wet-room rectangle. This concept of architectural compactness has the potential to dramatically reduce the structural wastes.

Summary of Collected Floor Plans

The team collected a sample of 1-and 2-story floor plans from the websites of builders located throughout California. There are nine 1-story and nine 2-story floor plans for single-family detached dwellings and nine 1-story floor plans for multi-family dwellings. One of the 2-story plans is from outside of California. It has been included because it is an example of how choices in the architecture can dramatically affect the compactness of the wet rooms and the hot water distribution system. All but the floor plan from outside California and the floor plans from Stockton Habitat for Humanity are model plans from subdivision builders; they represent many homes that will be built with the same characteristics. Appendix E Hot Water System Area versus Total Floor Area contains the complete sample.

According to the United States Census Bureau, the median size of homes built in the Western United States in 2017 was 2,398 square feet, slightly less than the median for the United States at 2,426 square feet. More than half of these were 1,800 to 2,999 square feet[10].

The sample has houses ranging in size from 1,223 to 4,820 square feet. Based on the research team's more than 25 years of experience evaluating hot water distribution systems, the sample is representative of single-family detached housing in the state. It is similar to what is found elsewhere in the United States.

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10 *(https://www.census.gov/construction/chars/pdf/squarefeet.pdf .* This document is found at *https://www.census.gov/construction/chars/completed.html* There are many useful documents available there in both XLS and PDF formats.)

The percentage of the hot-water distribution system area compared to the total floor area ranged from 4 percent to 155 percent in the 1-story houses. In the 2-story houses, the percentage ranged from 12 percent to 72 percent. In this sample, the wet room rectangles and the hot water distribution system rectangles were the same, so the two ratios were the same.

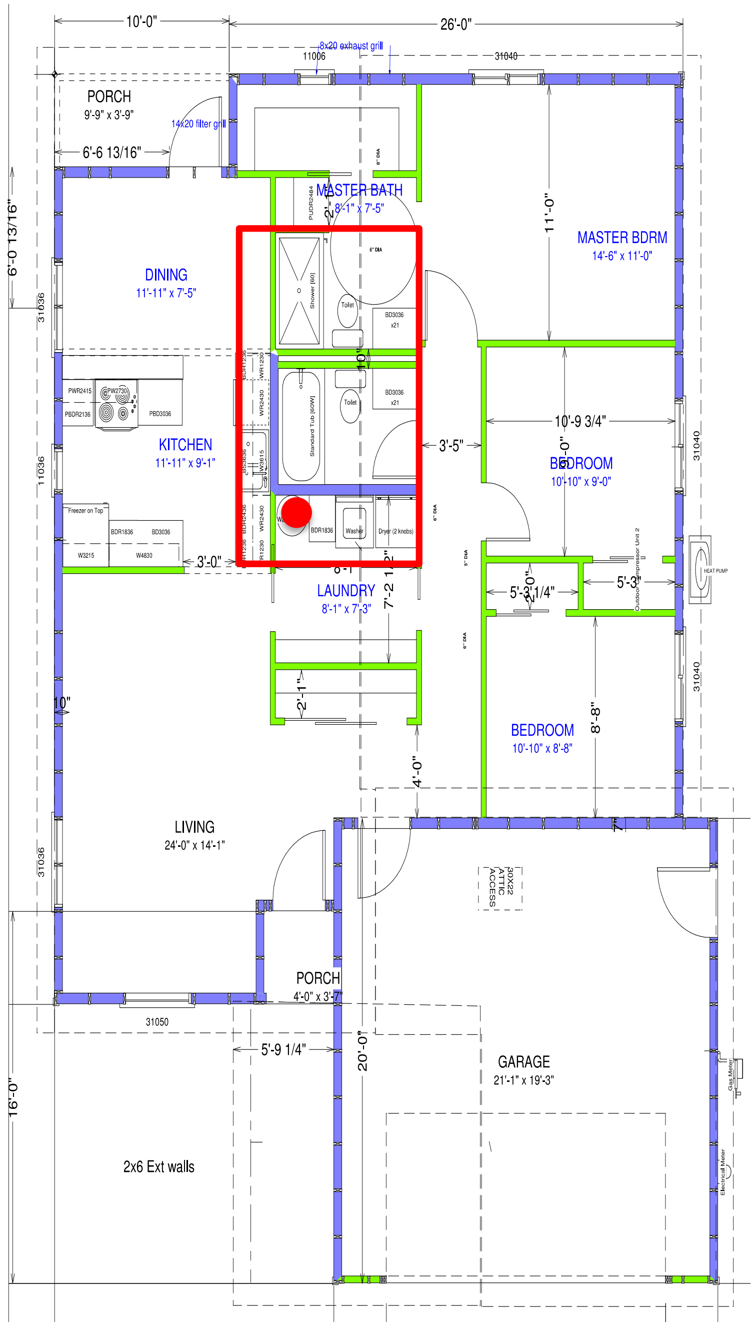
Two Exemplary Floor Plans

The Habitat for Humanity house in Stockton, California has the most compact wet room and hot water distribution system rectangles we have seen. It was built in 2016 as part of Pacific Gas and Electric Company's (PG&E) Zero-Net Energy Production Builder Demonstration. The hot water distribution system was only one of the many details they improved.

Figure 1 shows a 1-story 1,223 square foot house. There are three bedrooms and two bathrooms. The storage water heater is in the laundry room next to one of the bathrooms. The kitchen is to the west and the master bath is to the north of this bathroom. Three of the walls of the middle bathroom form a plumbing wall. All the hot water piping is within this wall. The plumbing configuration is a home run manifold system. The trunk goes from the water heater to the manifold, the manifold is the branch and fixture branches individually serve each fixture and appliance. The furthest fixtures from the water heater are the sinks in the two bathrooms. The distance is about 25 feet, most of which is 0.5-inch nominal piping. This is about 0.25 gallons. At 1 gpm, roughly 0.5 gallons will come out before hot water arrives in about 30 seconds. The laundry, the kitchen and the master bath form the boundary of the wet room rectangle. It represents 15 percent of the floor area. However, since all the fixtures and appliances are right next to the plumbing wall, the hot water distribution rectangle is significantly smaller at 49 square feet, or 4 percent of the floor area.

The National Institute of Standards and Technology (NIST) built a Net Zero Energy Residential Test Facility in Gaithersburg, Maryland in 2010 is another highly compact example. It is two stories above a full basement. As with the Habitat for Humanity house in Stockton, improving the hot water system was only one of the many topics they were studying. Figure 2 shows the 2-story 2,709 square foot house in Gaithersburg. There are four bedrooms and three bathrooms. The storage water heater is in the basement below the wall between the kitchen and the downstairs bathroom. The Master Bath is directly above the kitchen. The sink and the tub/shower combination in the other second floor bathroom are each roughly the same longest distance from the water heater. As with the Habitat for Humanity house, the plumbing configuration is a home run manifold. This made it much easier for the researchers to measure water and energy use for each fixture and appliance. The distance from the water heater to the furthest fixtures is about 50 feet of 0.5-inch nominal piping. This is about 0.5 gallons at 1 gpm, roughly 1 gallon will come out before hot water arrives in about 60 seconds. The downstairs bathroom and the laundry form the boundary of the wet room rectangle. It represents 12 percent of the floor area. If the basement included in the livable floor area, the ratio would drop to less than 8 percent.

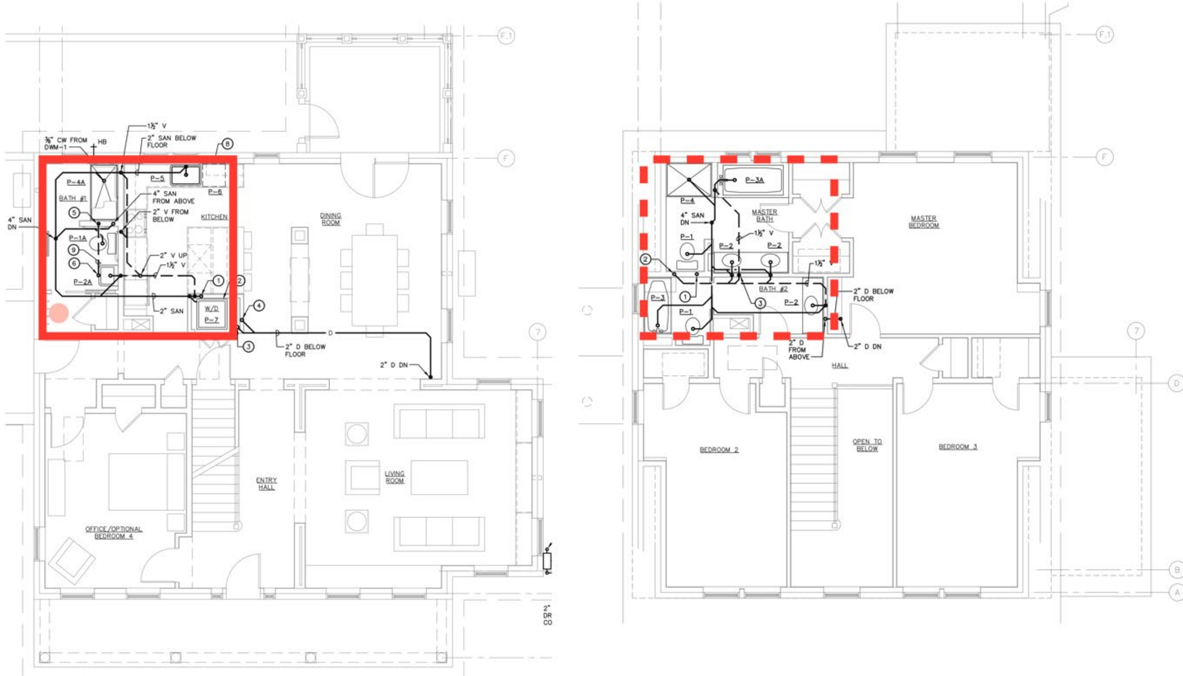
Figure 1: Exemplary Floor Plan: 1223 Square Foot House in Stockton, California



Source: Gary Klein and Associates, Inc.

Both of these houses demonstrate that it is possible to dramatically reduce the spread of the wet rooms and still have very livable floor plans. Both projects had architects who included hot water delivery system performance among the design constraints that had to be met as part of a successful design. Both are very close to the logical best-case hot water delivery systems for both 1- and 2- story dwellings.

Figure 2: Exemplary Floor Plan: 2709 Square Foot House in Gaithersburg, Maryland



Source: Gary Klein and Associates, Inc.

Distribution Improvement Strategies

The focus of this research project is on the first of the "wants" in all occupancies — getting hot water to arrive quickly after opening a tap. The keys to reducing the time waiting for hot water to arrive are to:

1. Reduce the volume in the pipe between the source and the use
2. Increase the flow rate, which increases the velocity

Cutting down the length, reducing the diameter, or doing both, are ways to reduce volume. Increasing the speed of delivery and then adjusting the flow rate to the amount needed for the task can also reduce the volume that runs down the drain while waiting. This ability already exists in buildings with combination tub/shower valves. The flow rate to fill the tub is 4-5 gpm while the showerhead is limited to a maximum of 1.8 gpm in California.

Sources of hot water include water heaters; the supply portion of a hot water circulation loop; and a supply pipe with electric heat trace attached. There can be more than one source and more than one plumbing configuration in a building's hot water system. The goal is to find the most water, energy and time efficient way to deliver the hot water.

Reducing the volume, whether due to shorter length or reduced diameter, saves energy during the wait, use, and cool-down phases of hot-water use events (see details in the next chapter).

Increasing the flow rate during the wait phase saves water and time. Energy savings may be achieved if behavioral waiting is reduced (see details in the next chapter). There are no benefits from increasing the flow rate during the use and cool down phases.

The study focused on improvement strategies to reduce pipe volume in single-family homes, where the source of hot water is a water heater. Development of improvement strategies addressed the following challenges:

- Is it possible to reduce pipe volumes to all fixtures, not just selected ones?
- Should the distribution design provide more shared flow paths to increase the interaction between draws from different fixtures, or should it provide the shortest flow path for each fixture without consideration of flow path sharing?

The research team investigated possible improvement strategies based on literature review, communication with stakeholders, and the team's extensive experience with hot-water systems. Table 2 provides the final list of distribution improvement strategies, in four groups, selected for performance assessment, with an indication of how each strategy may address the above challenges. These improvement strategies are independent of each other and can be used in combination to achieve enhanced improvements.

There are two design approaches to improve hot water delivery performance:

1) Reduce the volume from the water heater(s) to each hot water fixture, and
2) Increase flow path sharing among different hot water fixtures.

The first approach aims to independently improve hot water delivery performance for each fixture. The second approach aims to take advantage of the occasions where consecutive events are clustered close together in time and a portion of the path is already hot.

This study investigated the impact of these two design approaches by evaluating the performance of different pipe layout methods (shown in Table 2), which have different degrees of flow path overlapping. Using compact architectural design can alleviate conflicts between these two design approaches, because it is possible to locate the water heater(s) near all fixture they serve, so that pipe volumes to each fixture is relatively small.

Table 2: List of Distribution Improvement Strategies

Improvement Strategies	Characteristics
Pipe Layout Methods	Pipe layout methods can have a large impact on flow path sharing among fixtures.
Trunk and branch	All fixtures share a relatively long common flow path (trunk). Fixtures in the same area of the building may also share a secondary flow path (branch). Individual fixtures are connected to the trunk or branches through a tee via a relatively short fixture branch.
Home run (central manifold)	Each fixture is connected through a relatively long fixture branch to a manifold (branch), which is connected to the water heater with a common pipe (trunk). Fixtures have minimum flow path overlap.
Hybrid (distributed mini-manifolds)	Fixtures in the same area of the building are connected to a multi-port tee (mini-manifold). Each mini-manifold is connected to the trunk via a relatively long secondary flow path (branch). These secondary flow paths are connected to a relatively short trunk which is connected to the water heater
One-zone design	This configuration has only one main flow path (trunk) which is shared by all fixtures which are connected to the trunk via relatively short fixture branches. This system can easily be converted to a recirculation system.
Two water heaters	Fixtures in different areas of the building are connected to separate water heaters located relatively close to the fixtures they serve. Splitting the hot water system in two, allows for shorter and smaller diameter trunks and branches, reducing volume.
Water Heater (WH) Locations	These improvement strategies aim to reduce distance between the water heater and fixtures. However, pipe volumes may not be reduced for all fixtures.
Baseline design	The water heater is installed in the upper-left corner of the garage and is relatively far from the wet-room rectangle.
Relocate water heater in the garage	The water heater is installed in the garage and closer to the center line of the wet-room rectangle.
Water heater near the edge of the wet-room rectangle	The water heater is installed at a location, e.g., in a closet or attic, very close to the edge of the wet-room rectangle.
Water heater near the center of the wet-room rectangle	The water heater is installed at a location, e.g., in a closet or attic, near the center of the wet-room rectangle.
Unthinking (bad) practice	The water heater is installed far from the wet-room rectangle.
Architectural Design (Wet-room size)	This improvement strategy aims to reduce physical distance among fixtures so that pipe volumes to all fixtures might be reduced.

Improvement Strategies	Characteristics
Distributed wet rooms	This reflects normal architectural designs with wet rooms spread apart and fixtures having long distances from each other.
Compact wet rooms	Wet rooms are placed close to each other so that distances among corresponding fixtures are small.
Pipe Sizing (Reduce pipe size)	This group of improvement strategies reduce pipe volume to all fixtures without affecting flow path length and with little impact on flow path sharing.
½ inch → 3/8 inch	Use smaller pipes for fixture branches (branches connected directly to fixtures) by reducing pipe diameter from ½ inch to 3/8 inch.
1 inch → ¾ inch	Use smaller pipes for trunk and major branches by reducing pipe diameter from 1 inch to ¾ inch.
½ inch → 3/8 inch and 1 inch → ¾ inch	Use smaller pipes for fixture branches, trunk, and major branch.

Source: Gary Klein and Associates, Inc.

Prototype Floor Plans

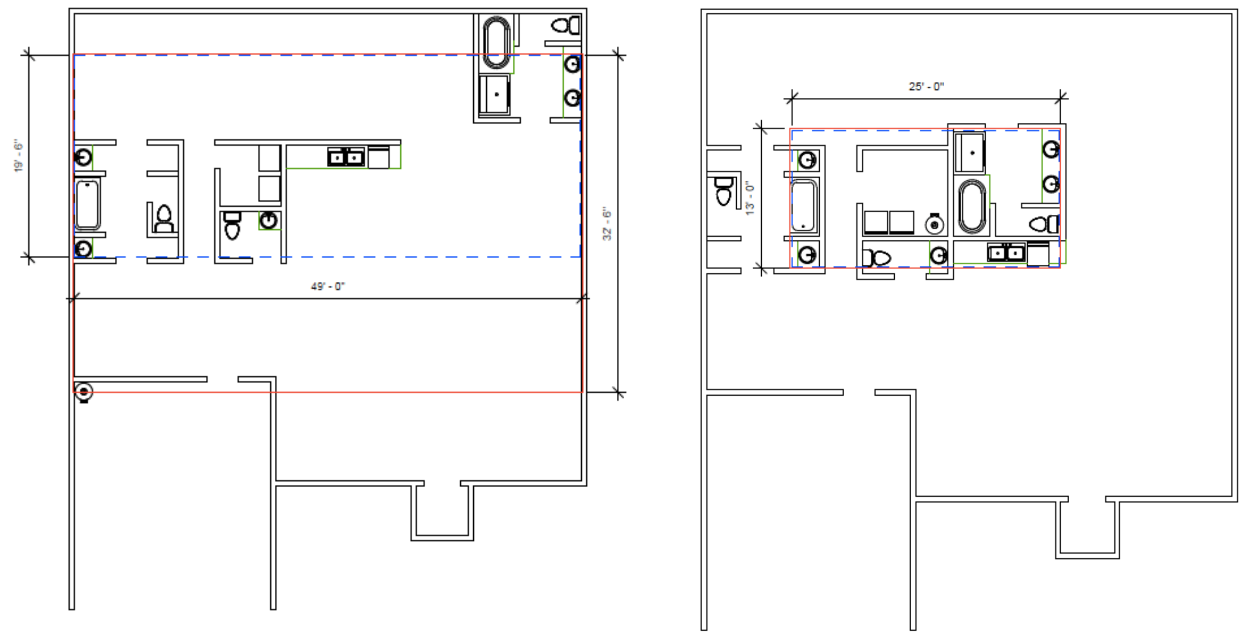
The California Energy Commission (CEC) has two prototype houses that are used as part of developing the Title 24 compliance calculations. The 1-story prototype is 2,100 square feet. It has 3 bedrooms. The 2-story prototype is 2,700 square feet. The 2-story prototype has 4 bedrooms. Neither floor plan contains any internal rooms. The location of the bedrooms is not specified in the prototypes. The water heater location is not defined. The research team focused its analysis on the 1-story prototype.

The 1-story prototype was given two-and-one-half bathrooms, a reasonable assumption for this size dwelling. The team also assigned wet room and water heater locations to analyze hot-water distribution system improvement strategies.

The left diagram in Figure 3 shows the wet room rectangle (blue dashed line) and the hot water system rectangle (red line) for the distributed wet room case in the 1-story prototype. The wet room rectangle includes only the hot water fixtures and appliances, not the entire wet room. This enables a more realistic assessment of where the hot water distribution piping needs to run. The hot water distribution rectangle includes the water heater location, which is in the northwest corner of the garage next to the interior wall of the house. The prototype has only one water heater, but it is possible to have more than one water heater and more than one set of rectangles. The wet room rectangle is 19.5 feet by 49 feet = 956 square feet, or 45.5 percent of the floor area. The hot water system rectangle is 32.5 feet by 49 feet = 1592 square feet, or 76 percent of the floor area. While the hot water system rectangle is typical of that found in much new construction, the wet room rectangle is smaller than what is typically found.

The right diagram in Figure 3 shows the wet room rectangle (blue dashed line) and the hot water system rectangle (red line) for the compact wet room case in the 1-story prototype. The water heater is located almost in the center of the wet room rectangle, in the southeast corner of the laundry room. The laundry room is larger than in the distributed wet room case so that it might be possible to include the rest of the mechanical equipment in the space. In addition, the layout of the hot water fixtures in Bath 2 is different than in the distributed wet room case. The wet room rectangle is 13 feet by 25 feet = 325 square feet, or 15.5 percent of the floor area. The hot water system rectangle is 13 feet by 25 feet = 325 square feet, or 15.5 percent of the floor area. Both of these rectangles are significantly smaller than what is typical.

Figure 3: Prototype Building Floor Plans



Left diagram: Distributed Wet-Room Design; Right diagram: Compact Wet-Room Design

Source: Gary Klein and Associates, Inc.

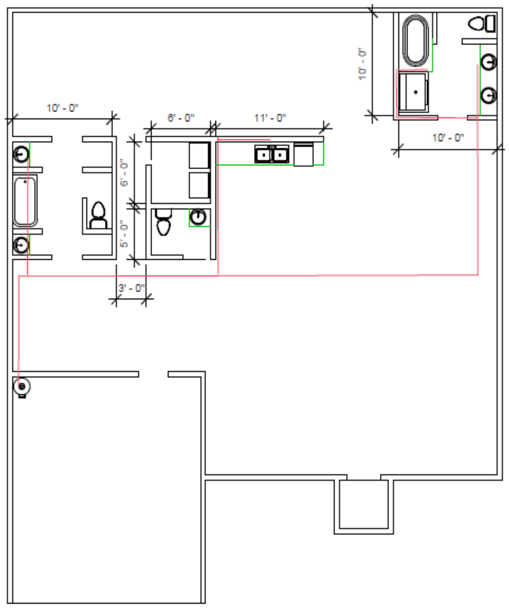
Baseline Hot Water Distribution Design

The baseline hot-water distribution configuration is a trunk and branch design with three branches serving the distributed wet rooms and normal flow-rate fixtures. Comparison with the baseline case indicates performance improvement. Figure 4 presents the baseline hot water distribution system configuration for the 1-story prototype with a *distributed wet-room rectangle*. This configuration was selected based on the team's experience and on discussions with plumbers and plumbing engineers in California before and during the first Technical Advisory Committee meeting.

The hot water distribution system configuration in the baseline case includes:

1. Water heater in the northwest corner of the garage
2. Long trunk: 1-inch pipe from the water heater to the tee for the 2nd branch; 0.75-inch pipe for the remainder of the trunk.
3. Three medium length branches: 0.75-inch pipe for each branch
4. Tees along the branches serving the fixtures and appliances:
   0.5-inch pipe for the fixture branches.

Figure 4: Baseline Case Hot Water System for Distributed Wet Room Rectangle

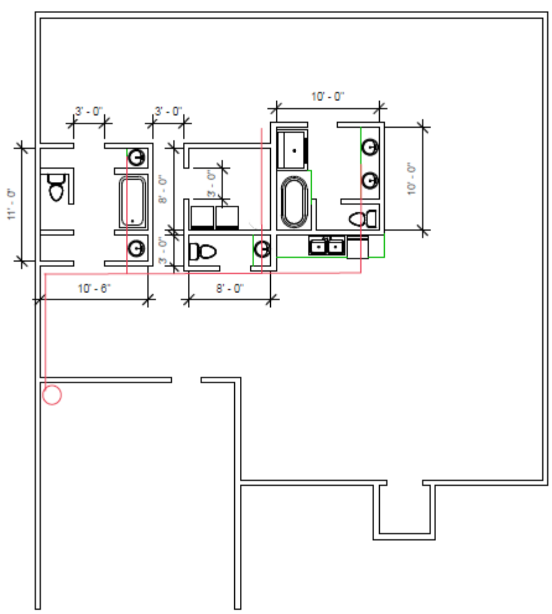


Source: Gary Klein and Associates, Inc.

Summary of Improved Distribution Designs

Figure 5 presents a trunk and branch hot-water distribution system configuration for the 1-story prototype with a *compact wet-room rectangle*. This configuration was selected based on the team's experience and on discussions with plumbers and plumbing engineers in California before and during the first technical advisory committee meeting.

Figure 5: Trunk and Branch Hot-Water System for Compact Wet-Room Rectangle



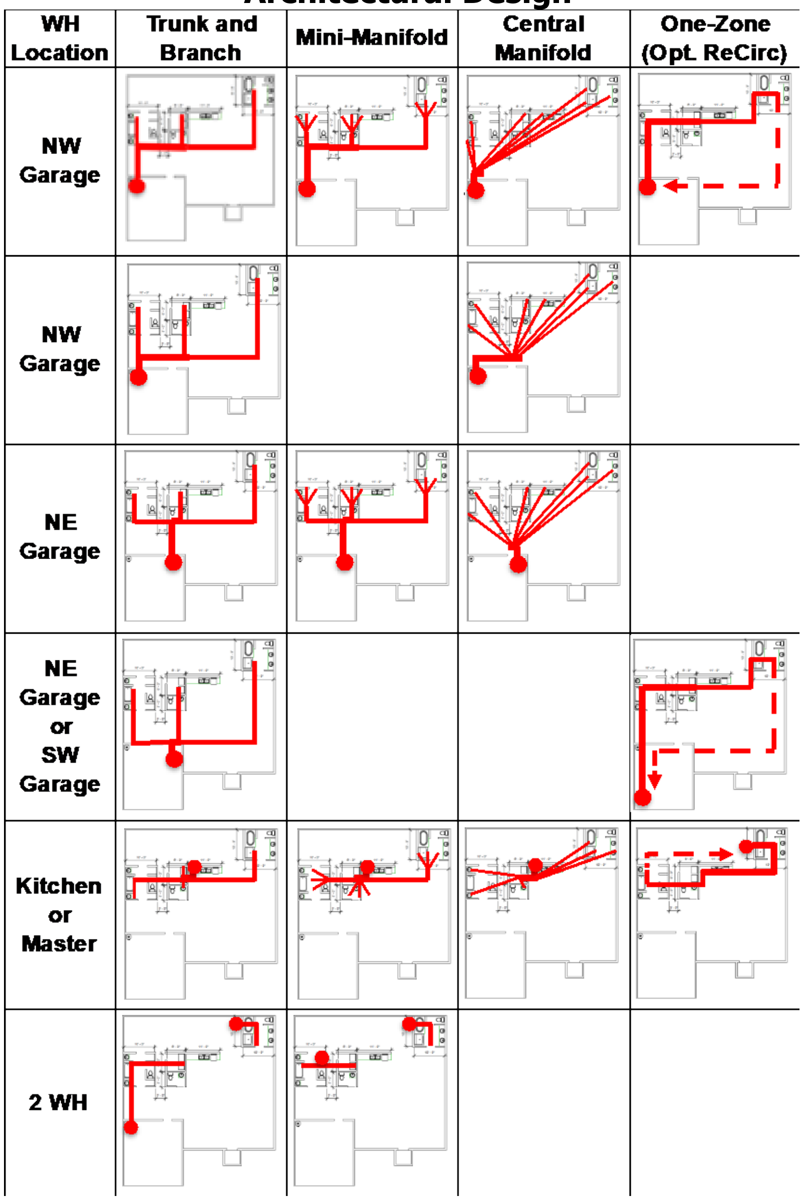
Source: Gary Klein and Associates, Inc.

Detailed configuration in the compact wet room case includes:

1. Water heater in the NW corner of the garage
2. Long trunk: 1-inch pipe from the water heater to the tee for the 2nd branch; 0.75-inch pipe for the remainder of the trunk.
3. Three medium length branches: 0.75-inch pipe for each branch
4. Tees along the branches serving the fixtures and appliances: 0.5-inch pipe for the fixture branches.

Figure 6 presents a schematic for the prototype with *distributed* wet rooms showing the different strategies that were evaluated for possible improvements in performance

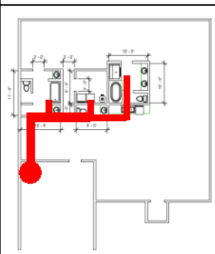
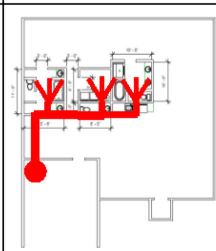
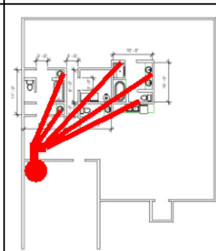
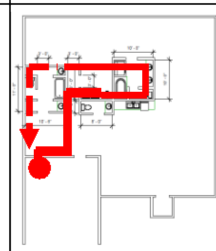
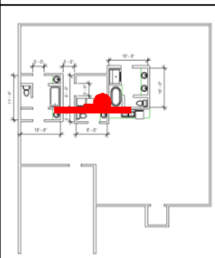
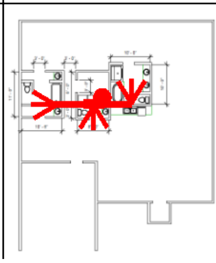
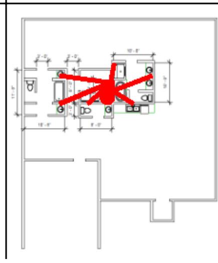
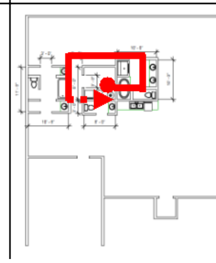
Figure 6: Improved Hot Water Distribution Designs - Distributed Architectural Design



Source: Gary Klein and Associates, Inc.

Error! Not a valid bookmark self-reference. presents a schematic showing the different strategies that were evaluated for possible improvements in performance for the prototype with *compact* wet rooms. Each figure has many small diagrams of the prototype house with hot water distribution systems superimposed on each diagram. The water heater is depicted with a circle. The diameter of the piping is depicted with lines of different widths. There are four different plumbing configurations: trunk and branch, mini-manifold, central manifold and 1-zone with optional circulation. Sometimes there are two water heaters.

Figure 7: Improved Hot Water Distribution Designs - Compact Architectural Design

WH Location	Trunk and Branch	Mini-Manifold	Central Manifold	One-Zone (Opt. ReCirc)
NW Garage				
SE Laundry				

Cost Effectiveness of Improvement Strategies

The process used to assess cost-effectiveness was straightforward.

1. Determine a plan for the hot water, cold water, drain lines for fixtures and condensate, vent stacks for piping and gas, gas piping and electrical line for the baseline case hot water distribution system (provided in Chapter 5).
2. Calculate the material and labor costs for each part of the system.
   - Materials are estimated primarily based on length, with an allowance for fittings.
   - Labor is estimated based primarily on the hours to complete the installation.
   - Material and labor costs are derived from the Plumbing Heating and Cooling Contractors (PHCC) cost estimator
   - Only those parts of the system that changed were included in the analysis. For example, the vertical drops from the branches to the fixtures and appliances did not change so they were not included in the cost analysis.
3. Evaluate the cost differences for those strategies that showed improvements in performance compared to the baseline case.

Cost of the Baseline Design — Distributed Wet Rooms

The research team reached out to a Sacramento-based engineering firm and a large residential new-construction plumbing contractor for assistance with this aspect of the project. Without their assistance, it would have been much more difficult to assess the costs of the different strategies. In particular, the team would have likely missed the nuances of real-world plumbing installations and either over or underestimated the actual costs.

The plumbing contractor suggested that the baseline hot water distribution system should be a trunk and branch configuration with the water heater located in the northwest corner of the garage. Common practice is to locate the trunk line relatively close to the southern edge of the wet rooms and run branches north to the fixture groupings. Tees, instead of mini-manifolds were used for the connections from the main branches to the fixture branches. A gas storage water heater was assumed in the analysis.

Establishing the parameters for the hot water distribution system, combined with the locations of the fixtures and appliances in the wet rooms made it possible to determine the layouts of the other systems that needed to be installed and priced.

The contractor used their job costing software to estimate the costs. The software estimates each component for the entire job, making it possible to disaggregate the totals into relevant parts. Labor hours are assigned by component, making it simpler to track costs. The hourly cost is the average hourly cost for a 3-person crew.

Table 3 shows the summary of the costs for the baseline case. The cost of materials is very small compared to the time it takes to install all the components. The costs are only for the components of the system that might change for this analysis. For example, the costs do not include the plumbing fixtures and appliances, which will be the same in each instance. Material costs are $1,046 and labor costs are $5,346, more than five times larger than the materials. All hot water piping is insulated with flexible tubular pipe insulation.

Table 3: Cost Summary of Baseline Design

Item	Materials		Labor		
	Quantity	Cost	Rate	Hours	Total
Supply Piping-PEX	297	$180.91	$43.45	15.0	$653.49
Supply Fittings-PEX	28	$162.45	$43.45	15.5	$672.17
Supply Joints-PEX	60	$25.00	$43.45	0.0	$0.00
Supply Hangers-PEX	137	$16.14	$43.45	35.6	$1,547.69
Drain Piping-ABS	182	$201.34	$43.45	19.5	$849.01
Drain Fittings-ABS	40	$120.05	$43.45	17.4	$756.46
Drain Excavation	60	$0.00	$43.45	0.0	$0.00
Steel Pipe	132	$146.08	$43.45	7.9	$341.95
Steel Fittings	14	$31.16	$43.45	8.9	$385.84
Miscellaneous Joints	122	$27.08	$43.45	0.0	$0.00
Pipe Insulation	111	$135.70	$43.45	3.2	$139.00
Subtotal		$1,046		123	$5,346
					$6,392
Sales Tax					$65
Subtotal					$6,457
Overhead			10%		$645.69
Profit			10%		$710
Total					$7,813

Source: Gary Klein and Associates, Inc.

Cost of the Improved Design — Compact Wet Rooms

While the team evaluated many improvement strategies, one case stands out in particular. This is the compact architectural design with the water heater located in the laundry room, which is central to the compact wet room rectangle. This section will begin by looking at this case.

Table 4 shows the summary of the costs for the compact architectural design — water heater in the laundry room case. The cost of materials is very small compared to the time it takes to install all the components. The costs are only for the components of the system that might change for this analysis. For example, the costs do not include the plumbing fixtures and appliances, which will be the same in each instance. Material costs are $866 and labor costs are $3,774, more than four times larger than the materials.

The compact architectural design saves $180 in materials and 37 hours in labor, which is almost 30 percent of the labor involved in the job. The big differences were in the feet of supply, drain and steel piping, pipe insulation and the labor associated with their installation. The single largest savings came from reducing the number of hangers needed to strap the supply pipe to the building; it represents almost 2/3 of the labor savings.

The compact architectural design costs significantly less to build; the savings are on the order of $1,000-$2,000 per dwelling including materials and labor. This range is based on varying labor costs from $30 to $50 per hour. The average cost savings is $1,500 per home.

Table 4: Cost Summary of Compact Architectural Design

Item	Materials		Labor		
	Quantity	Cost	Rate	Hours	Total
Supply Piping-PEX	170	$118.04	$43.45	8.8	$381.93
Supply Fittings-PEX	27	$171.55	$43.45	15.0	$652.18
Supply Joints-PEX	57	$25.00	$43.45	0.0	$0.00
Supply Hangers-PEX	46	$5.36	$43.45	12.0	$519.66
Drain Piping-ABS	150	$147.11	$43.45	15.1	$656.10
Drain Fittings-ABS	40	$119.42	$43.45	17.4	$756.46
Drain Excavation	60	$0.00	$43.45	0.0	$0.00
Steel Pipe	118	$152.15	$43.45	7.4	$321.53
Steel Fittings	16	$34.56	$43.45	8.9	$385.84
Miscellaneous Joints	128	$28.13	$43.45	0.0	$0.00
Pipe Insulation	56	$64.30	$43.45	1.6	$70.50
Subtotal		$866		86	$3,744
					$4,610
Sales Tax					$54
Subtotal					$4,664
Overhead			10%		$466
Profit			10%		$513
Total					$5,643

Source: Gary Klein and Associates, Inc.

These cost reductions accrue to the builder, allowing them to reduce the sales price and be more competitive or to increase their profitability. Most of the performance improvements in the distributed wet room case cost more to implement than building the baseline-plumbing configuration. However, implementing the compact core strategies generally cost less. The energy and water savings and performance improvements will accrue to the people living in the home. These will be discussed toward the end of Chapter 4.

CHAPTER 3: Performance Model Development

This chapter describes the method of distribution performance assessment.

Overall Performance Modeling Approach

Most hot water uses are transient, not steady-state events. Therefore, a distribution performance model needs to accurately account for transient hot water delivery processes to provide good assessment of energy, water and delivery time performance of distribution systems. Past studies investigated the transient delivery process but did not provide models for distribution performance assessment. For example, Carl Hiller's laboratory test study[11] provided many observations of flow patterns and temperature changes in different pipes with different temperature conditions but didn't provide models to quantify these observations. Davis Energy Group developed a distribution model[12] to examine annual energy impact but did not provide information on the detailed delivery processes to reveal how distribution performance was affected by piping designs and individual hot water draw conditions. It is not clear what flow and heat transfer assumptions are used in their model. In other studies, TRNSYS was used to model water heating systems, including hot water distribution systems.[13] Potentially, TRNSYS models may be built and calibrated to accurately reflect transient delivery processes. However, it is unclear if the assumptions embedded in TRNSYS can be easily modified for calibration. Even if it were possible, it would require significant effort to configure and calibrate a TRNSYS model for a particular distribution design. This study needed to evaluate a variety of distribution designs and, therefore did not use TRNSYS for performance analysis.

This study developed a distribution performance model that reflects detailed transient processes of hot water delivery in complicated distribution piping networks. First, the research team developed a model to accurately predict the performance of hot water delivery through a single pipe with a uniform initial temperature. Second, the team expanded the single-pipe model to cover hot water delivery through a flow path with multiple pipes with different initial temperatures. Last, the team further expanded the model to handle multiple hot water draws in distribution pipe networks with multiple hot water fixtures. The final model could deal with the interactions between two consecutive hot water draws from the same or different fixtures.

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[11] Hiller, Carl. *Hot Water Distribution System Research–Phase I Final Report*. California Energy Commission, November 2005. http://www.energy.ca.gov/2005publications/CEC-500-2005-161/CEC-500-2005-161.PDF.

[12] Weitzel, E., and M. Hoeschele. *Evaluating Domestic Hot Water Distribution System Options with Validated Analysis Models*, September 1, 2014. http://www.osti.gov/servlets/purl/1159372/.

[13] A TRaNsient SYstems Simulation Program, https://sel.me.wisc.edu/trnsys/

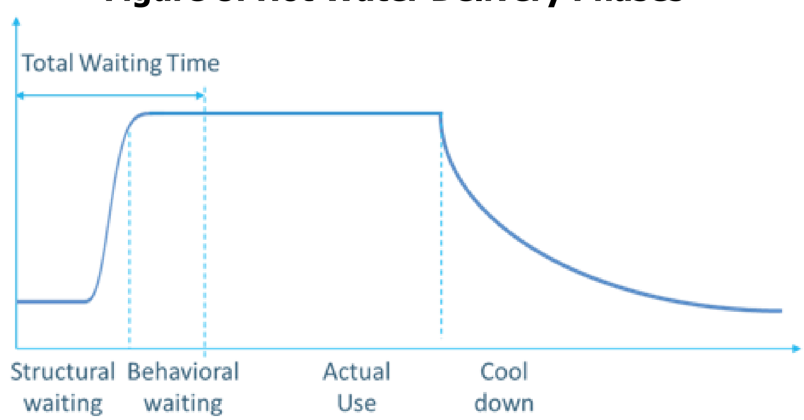
General Characteristics of Hot Water Draw Events

A typical hot water draw event can be considered to consist of three phases (Figure 8):

1. Waiting for hot water — Certain hot water services, e.g., showers, require the delivered water to reach a threshold to start the use. There are two types of waiting: structural waiting and behavioral waiting. The former is associated with waiting for clearing out the cold water in the pipes between the water heater and the fixture to receive hot water for use. The latter is associated with additional waiting that may happen because the user steps away from the fixture and is not back immediately after hot water reaches the fixture.
2. Actual use – the user begins to use hot water. Hot water consumption during this phase reflects the actual hot water demand of the user. If the user does not wait for the water to become hot before using it, this is considered an unmet hot water load.
3. Cool down – hot water flow stops after the user turns off the fixture. Hot water in the pipe gradually cools down to ambient temperature.

Not all hot water draws involve all three phases in their entirety. Some draws, such as rinsing hands or vegetables often do not include waiting. However, because of the way the faucet is activated, hot water will have been drawn into the distribution system. If the event is short, hot water will not reach the user. Conversely, some draws are followed by other draws before the shared pipes have completely cooled down. In this case, the amount of structural and behavioral waiting for the second draw will be reduced or eliminated.

Figure 8: Hot Water Delivery Phases



Source: Gary Klein and Associates, Inc.

At the beginning stage of the structural waiting, only cold water comes out the fixture. Hot water supplied by the water heater increases the temperature of the flow path. Energy supplied by the water heater is stored in the water, pipe and insulation materials along the flow path. It takes more than clearing the pipe volume for hot water to reach the fixture because some of the energy in the hot water is used to warm up the pipe and insulation materials along the flow path and some hot water is mixed with cold water already in the hot-water pipe. Pipe heat loss to ambient is low during the structural waiting phase because the pipe and insulation are cold. The lukewarm water delivered during the structural waiting phase may not be used and the associated energy and water are wasted. At the end of the structural waiting phase, water temperature at the fixture reaches the threshold level for use. During the behavioral waiting phase, hot water is delivered to the fixture but not used and, therefore, is wasted.

During the use phase, not all the thermal energy supplied by the water heater is delivered to the fixture. Some of the supplied thermal energy is lost to the ambient due to pipe heat loss. If at the beginning of the use phase, the delivered water has not reached steady-state temperature, additional energy may be used to further warm up the flow path to reach steady state. Many hot water events are so short that steady-state conditions are never reached. During the cool down process, the energy previously stored in the flow path will dissipate to ambient.

During the cool-down phase, the temperature of the water, pipe and insulation materials begins to drop until it reaches ambient temperature. During this phase the energy stored in the flow path is released to the ambient. If a subsequent hot water event occurs before the flow path completely cools down, the remaining stored energy helps to shorten the structural waiting.

To provide an in-depth understanding of hot water distribution system performance, the performance model assesses all involved energy components listed below:

- Energy supplied by the water heater
- Energy stored in water in the distribution pipes and dissipated during the cool-down phase
- Energy stored in piping and insulation materials and dissipated during the cool-down phase
- Heat loss through the pipe surface to ambient during the waiting and use phases
- Energy delivered to the fixture during the structural waiting phase
- Energy delivered to the fixture during the behavioral waiting phase
- Energy delivered to the fixture during the use phase

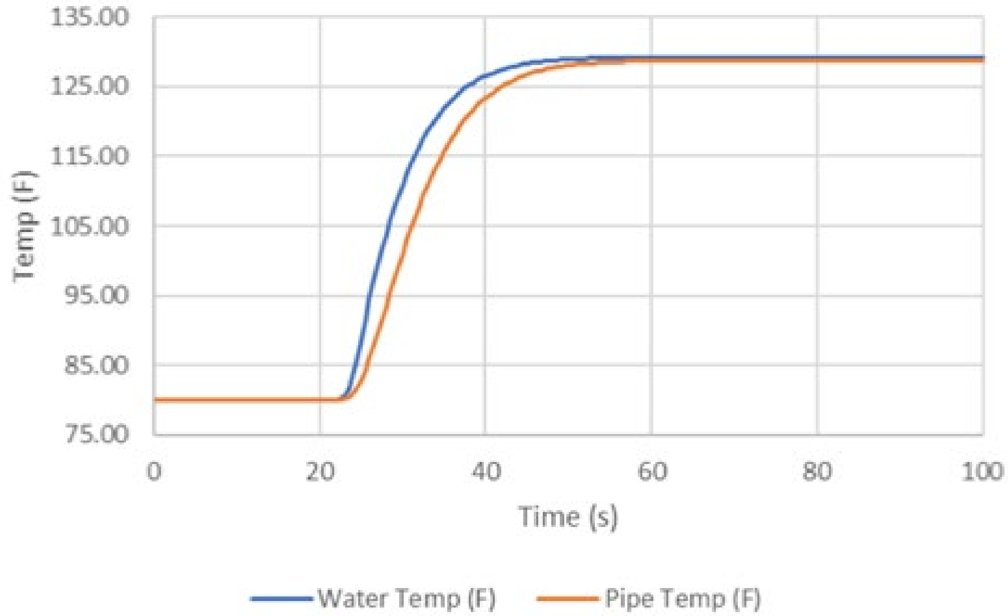
Transient Hot Water Delivery Model

Transient hot water delivery processes involve complicated fluid dynamic and heat transfer phenomena. Water flow in pipes can have several complicated patterns: laminar flow, turbulent flow, diffusion between cold and hot water, and mixing as the hot water penetrates into the cold water. Water temperature along the pipe changes during the delivery process and affects heat transfer between the water and the pipe. The project team explored different approaches to model the transient warm-up process to determine hot water deliver speed.

Physical Model

The research team developed a physical model to predict transient warm-up process. Following conventional heat transfer analysis method, the team developed a set of differential equations to model the heat transfer between the flowing water and the pipe and the mixing of hot and cold water. These differential equations were solved using a numerical method. The solutions, as shown in Figure 9 for a ¾ inch diameter pipe, looked reasonable but did not match well with the corresponding laboratory test results. The team was not able to adjust the numeric model assumptions to match the model results with laboratory test results. Therefore, it was determined that physical models based on basic heat and mass transfer analysis were not adequate to provide accurate performance results.

Figure 9: Numerical Solutions of Physical Model



Source: Gary Klein and Associates, Inc.

Empirical Model for a Single Pipe

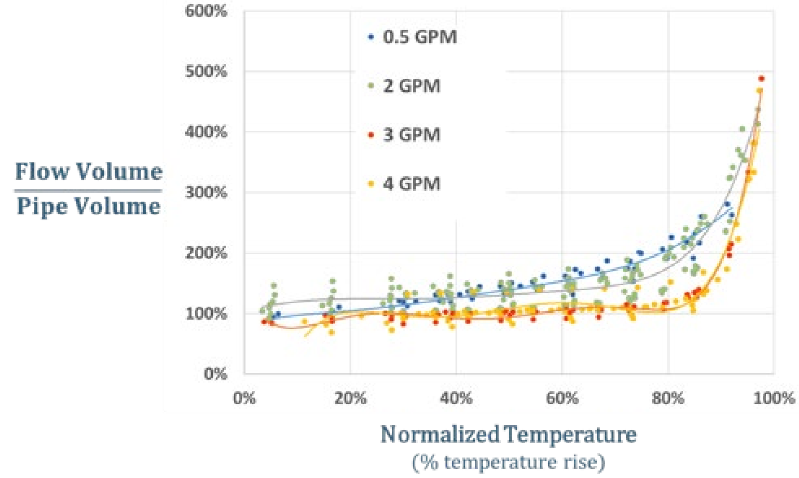
The research team then developed an empirical transient hot water delivery model based on laboratory test results obtained from the study by Carl Hiller.[14] In that study, Hiller investigated hot water delivery processes by measuring water temperature along pipes of the same diameter during the warm-up and cool down phases of a hot water event. He tested pipes of different materials, diameters, and insulation conditions and varied initial water temperatures and hot water flow rates. The team analyzed Hiller's data and found that a generic empirical formula could be used to describe water temperature changes during the warm-up process under different delivery conditions. This empirical formula is based on correlation between normalized temperature and normalized volume as defined below. Figure 10 illustrates the development of an empirical formula based on a large quantity of test data at different flow rates, and Source: Gary Klein and Associates, Inc.

Figure 11 illustrates the selected empirical formula based on data with 2 gpm flow.

Temperature reduction during cool-down phase follows an exponential trend. The rate of exponential temperature reduction is determined by heat loss rate and thermal mass of water, pipe, and insulation material. The research team analyzed the laboratory test data collected by Carl Hiller to obtain temperature cool-down rates for different pipe materials, sizes, and insulation conditions.

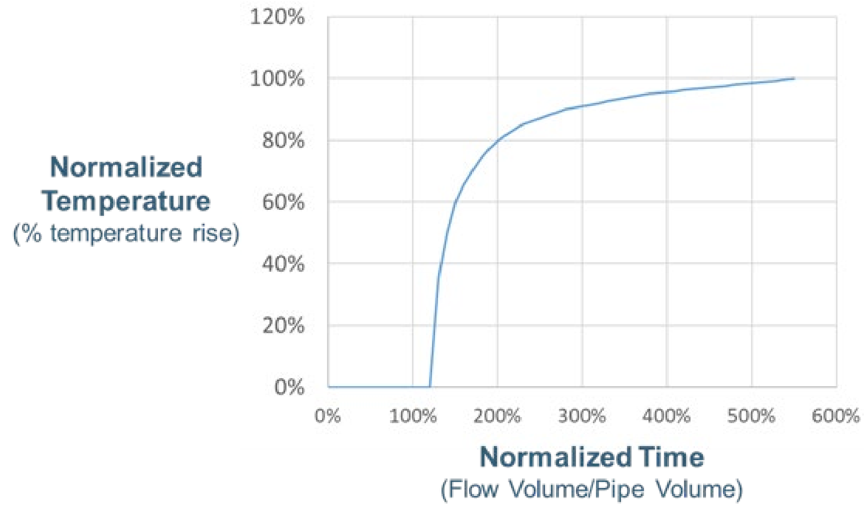
[14] Hiller. op.cit.

Figure 10: Correlation of Normalized Temperature and Volume (¾ Inch Insulated PEX Pipe)



Source: Gary Klein and Associates, Inc.

Figure 11: Empirical Transient Temperature Curve (¾ Inch Insulated PEX Pipe)



Source: Gary Klein and Associates, Inc.

Please note that normalized temperature reflects the fraction of the maximum possible temperature rise from the initial temperature to the hot water supply temperature. Normalized time reflects the actual time for hot water to arrive divided by the time that would have occurred with perfect plug flow in the pipe. Normalized volume reflects the actual volumetric flow divided by the physical pipe volume from the water heater to the measurement point. It turns out that normalized time and normalized volume are interchangeable; this report uses normalized volume. Because the empirical formula is based on laboratory test results, the modeling approach is inherently validated.

$$\textbf{Normalized Temperature} = \frac{Measured\ Temperature\ Rise\ from\ Initial\ Temperature}{Maximum\ Temperature\ Rise\ from\ Initial\ Temperature} = \frac{Measured\ Temperature - Initial\ water\ temperature}{Hot\ water\ Supply\ Temperature - Initial\ water\ temperature}$$

$$\textbf{Normalized Time} = \frac{Measurement\ time\ (from\ the\ beginning\ of\ the\ warmup\ process)}{Time\ needed\ for\ water\ to\ flow\ from\ the\ entrance\ to\ the\ measurement\ location\ (assuming\ plug\ flow}$$

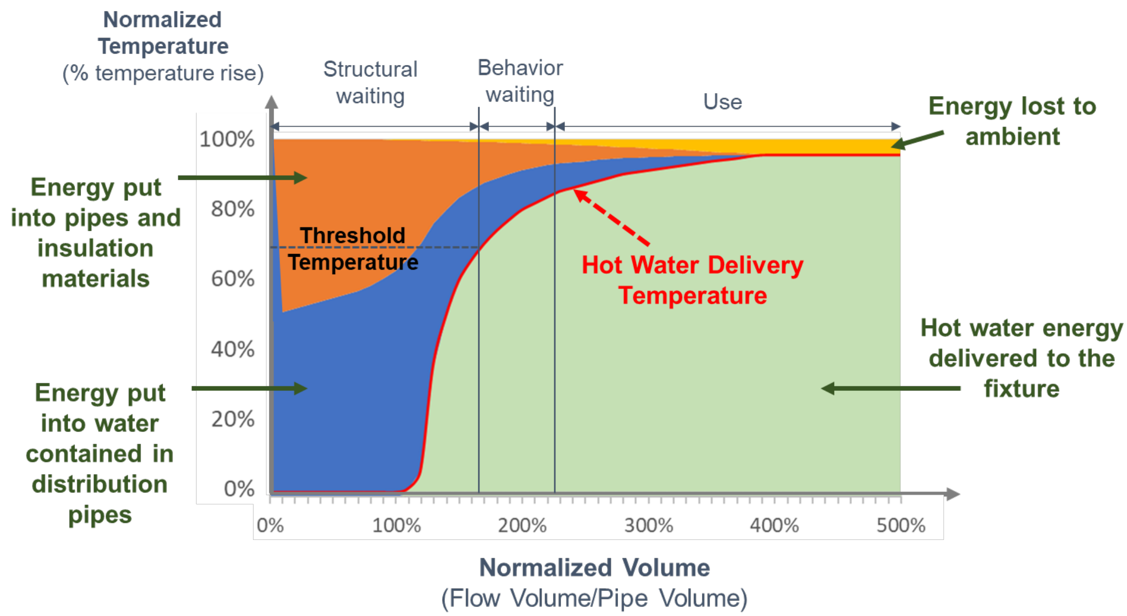
$$\textbf{Normalized Volume} = \frac{Flow\ volume\ passing\ the\ measurement\ location}{Pipe\ volume\ from\ the\ entrance\ of\ the\ pipe\ to\ the\ measurement\ point}$$

Energy Balance in Transient Delivery Process

The empirical temperature warm-up formula was used to predict the timing of the three phases of a hot water event, as shown in Figure 12.

The research team also developed a method to use the empirical temperature formula to assess different energy components involved in hot water delivery. This analysis method provides in-depth understanding of energy and water impacts of hot water distribution systems.

Figure 12: Illustration of Transient Hot Water Delivery Model



Source: Gary Klein and Associates, Inc.

Under the normal operational conditions in DHW systems, thermal energy of water is proportional to water temperature. Normalized volume is defined as actual flow volume divided by pipe volume and therefore, also represents the flow volume through the fixture. Therefore, the area under the empirical temperature curve reflects amount of thermal energy delivered to the fixture. The area under the horizontal line (at 100 percent) for the hot water supply temperature represents the thermal energy supplied by the water heater into the distribution system. Areas between the line for the hot water supply temperature and the line for the delivered temperature represents three energy components:

- Energy stored in the water in the pipe
- Energy stored in the pipe and insulation materials
- Energy lost to ambient through pipe heat loss

At the beginning of the hot water delivery process, the pipe has not been heated up and, therefore, heat loss to ambient is low. Most of the energy supplied by the water heater becomes stored energy in the water and in the pipe and insulation materials. No hot water is delivered to the fixture. As the pipe is heated up, pipe heat loss gradually increases, and some hot water energy begins to be delivered to the fixture. However, before the threshold temperature is reached or before behavioral waiting ends, if the hot water draw involves behavioral waiting, the delivered hot water energy is wasted. During the use-phase, hot water energy is delivered to, and used by the user. After steady state is achieved, potentially during the use phase, no additional energy is stored in the water and in the pipe and insulation materials; energy supplied by the water heater is balanced by energy delivered to the fixture and lost through pipe heat loss.

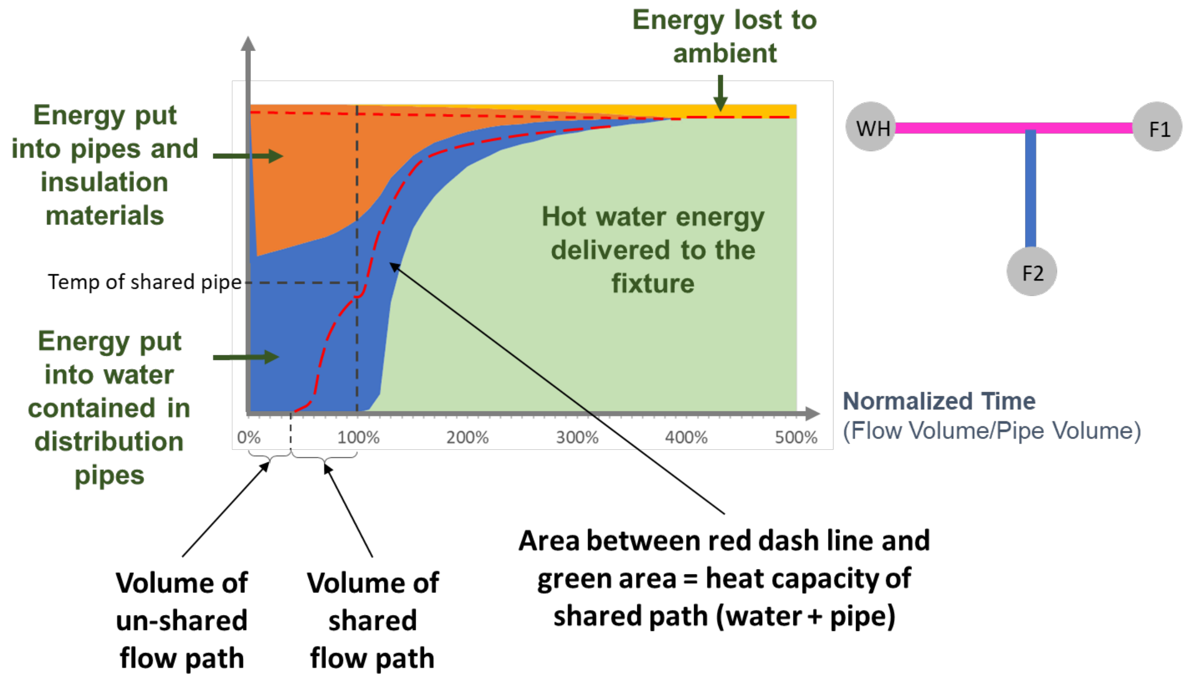
Empirical Temperature Formula for Complicated Delivery Conditions

Energy balance analysis in the last section shows that, in addition to the detailed heat and mass transfer processes, delivered water temperature is also related to the overall system heat balance. In particular, the estimated increase of stored energy in the flow path using the empirical temperature formula should be consistent with the estimate using flow path characteristics. The latter is obtained by summing up the increase of stored energy for each pipe section, i.e., the product of heat capacity of the pipe section and temperature increase after reaching steady state. This finding leads to a method of developing empirical temperature formula for flow paths with multiple sections of different pipe sizes. First, it was assumed that, with the same flow rate, the shape of the empirical temperature curve for a multi-pipe flow path is similar to that of a single pipe. Then, the empirical temperature formula for single pipe is modified in a way to ensure the predicted increase of stored energy is the same as that estimated using flow path characteristics.

The research team further developed a method to estimate the temperature change formula for a flow path with two different initial temperatures. For example, this happens when the trunk line has been filled with hot water by a previous draw at another fixture, while the branch pipe to the fixture for the next draw are still cold. Figure 13 illustrates how the temperature curve for the complicated flow path conditions (the red dashed line) is obtained.

In this approach, temperature change is considered to have two steps. In the first step, hot water flows from pipes with a relatively higher temperature, such as trunk pipe filled with hot water from a previous draw, to downstream pipes with lower temperatures, for example. cold branch pipes, to reach the fixture. The warm-up process in the downstream pipes can be modeled with the method described previously. In this case, the supply temperature is temperature of hot water in the upstream trunk pipes. In the second step, the warm-up process considers hot water from the water heater flow through the whole flow path. It is difficult to know the exact temperature change curve for the second step; the best approach is to assume curve is similar to the empirical temperature curve for delivery through a pipe with uniform initial temperature. The delivered temperature starts at the temperature obtained at the end of the first step and reaches the steady state temperature predicted by the empirical temperature formula for uniform initial temperature. Using a similar approach described above, the temperature curve is adjusted to ensure that the estimated increase of stored energy using the empirical temperature formula is consistent with that based on flow path characteristics.

Figure 13: Transient Hot Water Delivery Model for Interaction Between Two Draw Events



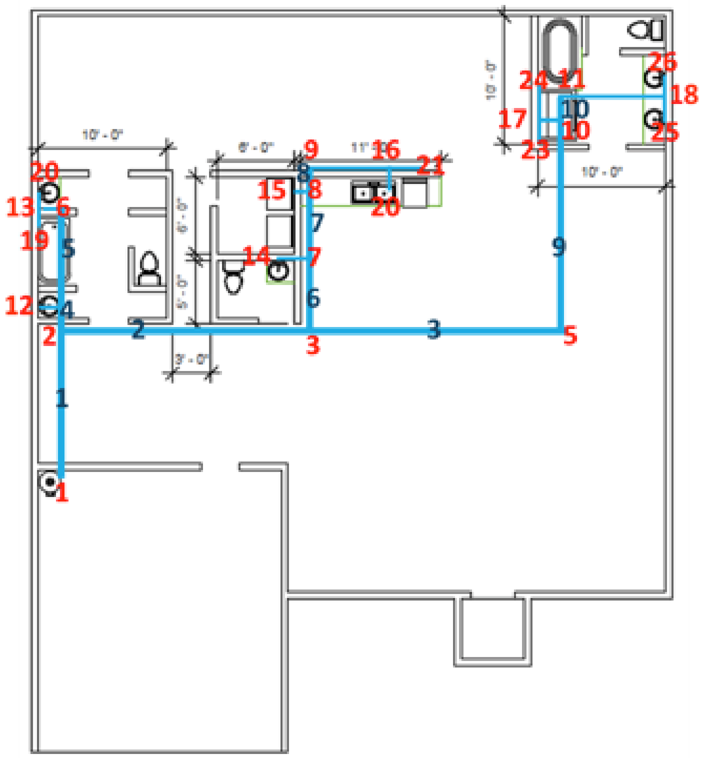
Source: Gary Klein and Associates, Inc.

Modeling Method for Distribution Designs

The research team developed a method to model distribution piping networks. The general approach was to separate the distribution-piping network into different pipe sections and use connection nodes to specify connections among pipe sections and locations of fixtures. For example, Figure 14 and Figure 15 show how the baseline trunk and branch distribution design was modeled. Figure 14 illustrates the physical piping design. Figure 15 shows the translation of the piping design into the inputs needed for the model. Red numbers in these two figures indicate the connection nodes and the fixtures; blue numbers identify the pipe sections. Each pipe section is defined by pipe properties, such as material, diameter, length, and insulation and environmental conditions, as well as beginning and ending nodes. Connection nodes include specifications of the pipe section numbers entering and leaving the node, respectively. If the node represents a fixture, a specific fixture type is provided.

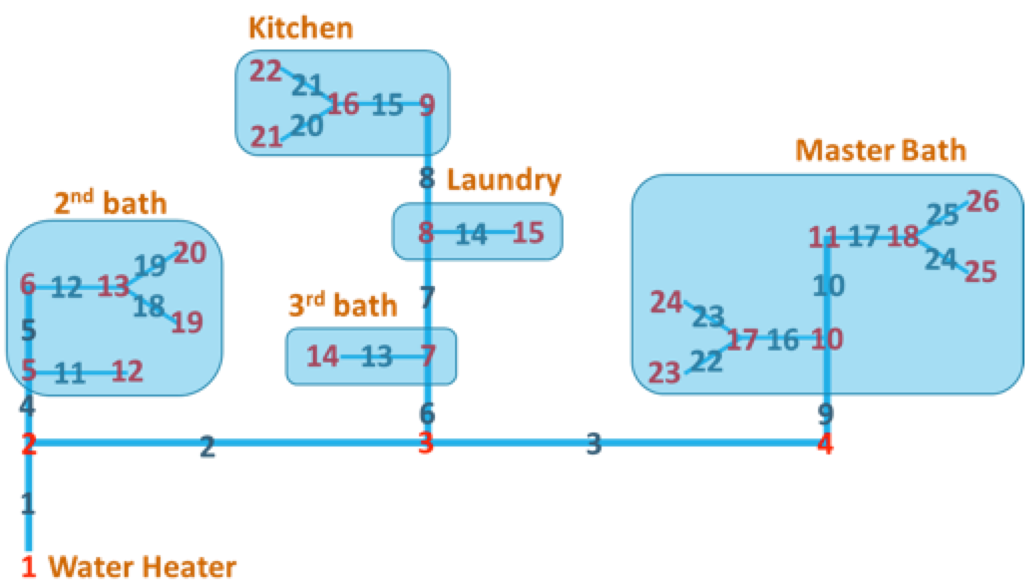
The model establishes the flow path for each fixture node by identifying the sequence of pipe sections from the water heater to the fixture. When a fixture has a hot water draw, the empirical temperature formula for the transient warm-up process is established based on the properties of the pipe sections along the flow path and the initial temperatures of each pipe section. For pipe sections without water flow, a cool-down calculation is performed.

Figure 14: Pipe Sections and Connection Nodes in a Trunk and Branch Design



Source: Gary Klein and Associates, Inc.

Figure 15: Schematic of Distribution Model for a Trunk and Branch Design

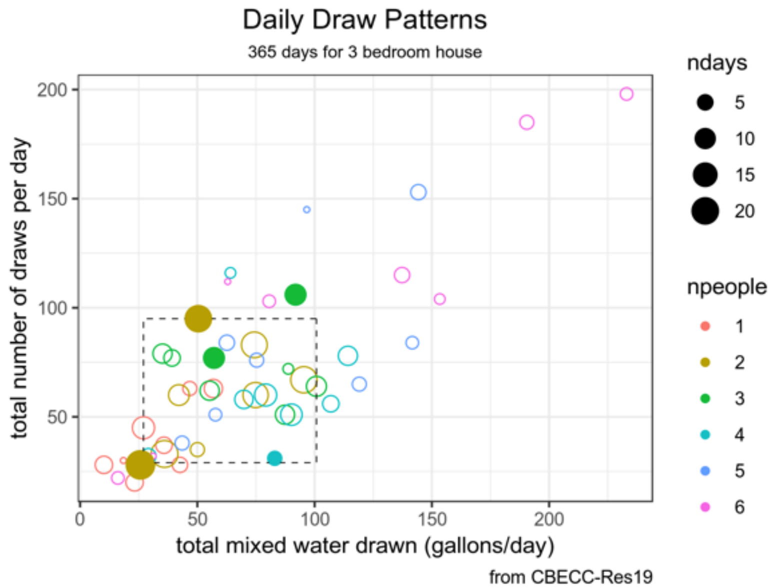


Source: Gary Klein and Associates, Inc.

Hot Water Draw Schedule

Hot water distribution performance depends on the hot water draw schedule. The hot water draw schedules used in this study to evaluate distribution performance were derived from the daily hot water use patterns found in CBECC-Res 2019 compliance software (CBECC-Res) for California Building Energy Standards. Figure 16 displays the 48 hot water use days included in CBECC-Res 2019 for a single-family home with three bedrooms. They are arranged by number of hot water draws per day and daily hot water (mixed hot and cold) use by all fixtures. The annual hot water draw pattern is formed by a combination of 365 of these 48 representative hot water use days. The size of the circles indicates how many times each hot water use day is included in the annual hot water draw pattern. The color of the circles indicates the occupancy level for that day.

Figure 16: Daily Hot Water Draw from CBECC-Res



Source: Gary Klein and Associates, Inc.

The dashed box includes hot water use days of middle range uses, in terms of number of draws per day and gallons per day. Days in this range represent 75 percent of the days in a year. The five (5) circles with solid colored indicate the hot water use days considered by this research project for performance assessment. Table 5 provides a summary of hot water use characteristics of these five hot water use patterns. These five draw patterns represent a middle range of daily hot water use with variations in number of draws per day and daily hot water use volume. Please note that daily volume of water is the total amount of water (mixture of hot and cold water) consumed by fixtures during the use phase without including water consumption during the waiting phase.

The daily draw pattern from Day 4 is in the middle of the ranges of total hot water use and total number of draws. It was ultimately chosen for the performance assessment. A closer look at this daily pattern shows that of the 77 events, only 7-10 of them (showers and long sink draws) were long enough in time or large enough in volume for the hot water to reach the fixtures in most of the plumbing configurations the researchers evaluated. This was even true in most of the cases with significantly reduced volumes.

Table 5: Daily Draw Patterns Used in the Analysis

Day	People	Day of Week	Daily Volume of Water (gal)	Daily Draws Total	Daily Draws Shower	Daily Draws Faucet	Daily Draws CW	Daily Draws DW	Daily Draws Bath
1	2	Wed	25.53	28	1	23	4	0	0
2	2	Sat	47.57	94	0	81	6	6	1
3	3	Thu	95.91	106	4	87	10	4	1
4	3	Thu	52.29	77	2	70	5	0	0
5	4	Mon	75.05	31	2	17	12	0	0

CW = Clothes Washer, DW = Dishwasher

Source: Gary Klein and Associates, Inc.

The CBECC-Res hot water draw patterns only indicate the type of fixture or appliance associated with each hot water draw, but not the location of the fixture in the home. To assess distribution design performance, every draw in each schedule was assigned to a specific fixture and appliance on the prototype floor plan based on the project team's best judgment. Flow rates were adjusted to ensure compliance with current Title-20 and CALGreen requirements. For example, flow rates for some shower draws are much less and some faucet flow rates are higher than allowed by Title-20. Flow rates less the allowable maximums were not changed. Appendix F Draw Schedule for Performance Assessment presents the complete draw pattern used in the analysis and the detailed adjustment process and results.

Performance Assessment Tool

The research team integrated the different modeling components into a distribution performance assessment tool using Excel. The tool provided detailed performance outputs for each hot water draw event. The data provided was used to analyze how the improvement strategies affected the three phases of each hot-water event, and how the combined affects impacted overall system performance.

Energy and water distribution efficiency of a draw event is calculated as follows:

$$\eta_{water} = \frac{Volume\ of\ water\ delivered\ during\ use\ phase}{Volume\ of\ water\ supplied\ by\ the\ water\ heater\ during\ the\ whole\ use\ event}$$

$$\eta_{energy} = \frac{Thermal\ energy\ delivered\ during\ use\ phase}{Thermal\ energy\ supplied\ by\ the\ water\ heater\ during\ the\ whole\ use\ event}$$

For hot water draws without waiting phases, e.g., dishwasher draws, clothes washer draws, and short faucet draws, water distribution efficiency is 100 percent efficiency. For these draws, the whole draw duration is in use phase. For short draws, barely any hot water may reach the fixture and energy distribution efficiency can be very low or even 0 percent.

Appendix G Additional Information on Distribution Performance Model provides detailed information on the performance assessment tool.

CHAPTER 4:
Performance Assessment Results

Performance by Fixture

This section provides detailed daily distribution performance by fixture for the baseline case hot-water system with a distributed wet-room rectangle. Results show how distribution performance varies among fixtures and how the performance of individual fixtures contributes to total system performance. The distribution performance model provided performance in four areas: energy, water, time, and service.

Table 6 presents the energy performance data for each fixture in the following categories:

- Energy Supplied by the Water Heater to the distribution system (Water heater supply energy)
- Energy Delivered To fixture – used (Energy used by fixtures)
- Energy Delivered To fixture – wasted (Energy wasted at fixtures)
- Energy Lost to Ambient During Delivery (Pipe heat loss during delivery)
- Energy Used to Warm up the Flow Path and Lost After Use (Energy wasted for warmup)

Water heater supply energy is either delivered to fixtures or wasted through distribution losses. The delivered hot water energy includes the energy wasted at fixtures (because the delivered water is not hot enough for use, or because behavioral waiting occurs) and the energy used at fixtures. Energy waste through distribution losses includes two components: pipe heat loss during delivery, and energy wasted due to system warm up.

Overall distribution energy efficiency — defined as the ratio of energy used by fixtures to water heater supply energy — was 60 percent. The rest (40 percent) of the energy provided by the water heater was lost in three ways: energy wasted during warmup (32 percent), energy wasted at the fixtures (6 percent), and pipe heat loss during delivery (2 percent).

In general, long, hot water use events have higher distribution efficiency than short ones. This is because the energy wasted during the warm-up phase does not increase once hot water is being used. As hot water use time increases, the proportion of the wastes to the energy leaving the water heater decreases and the event becomes more efficient. Average shower duration is usually much longer than average faucet duration. Therefore, as shown in Table 6, showers had higher distribution efficiency than draws from bathroom and kitchen sink faucets.

The hot-water draw schedule used in the analysis had relatively balanced draws from different fixtures. However, the sequence of hot water events also had a substantial impact on distribution performance. In the selected schedule, the research team allocated faucet draws to occur before shower draws in the same bathroom. The faucet draws warmed up practically the entire path before the shower draw began. As a result, the warm-up phase for the shower draws was relatively short and did not trigger behavioral waiting. If the shower draws had been first, then behavioral waiting would have been triggered.

The selected draw schedule provided a conservative estimate of distribution energy waste. Accordingly, the estimated energy and water savings potential for distribution improvement strategies, presented in the next section, are also conservative.

Table 6: Daily Energy Performance – Baseline Distribution Design

Fixture ID	Energy Supplied by the Water Heater (Btu)	Energy Delivered To fixture – used (Btu)	Energy Delivered To fixture – wasted (Btu)	Energy Lost to Ambient During Delivery (Btu)	Energy Used to Warm up the Flow Path and Lost After Use (Btu)	Distribution Energy Efficiency (%)
MB_SH	3,551	3,280	24	69	179	92%
MB_SK1	3,036	430	442	77	2,088	14%
MB_SK2	202	56	-	12	134	28%
MB_TB	-	-	-	-	-	-
K_SK	2,736	1,484	244	70	938	54%
K_DW	-	-	-	-	-	-
LN_WA	1,272	920	-	52	300	72%
B2_SH	2,383	2,094	24	23	241	88%
B2_SK1	937	515	24	25	373	55%
B2_SK2	817	217	128	6	466	27%
B2_TB	-	-	-	-	-	-
B3_SK	165	93	-	2	71	56%
Total	**15,100**	**9,089**	**886**	**337**	**4,789**	**60%**

Source: Gary Klein and Associates, Inc.

Table 7 presents water delivery performance by fixture. The overall water delivery efficiency is 76 percent. The time performance results for the baseline case are shown in Table 8. The overall time efficiency is 88 percent.

Table 7: Daily Water Delivery Performance – Baseline Distribution Design

Fixture ID	Fixture Details	Water Supplied by the Water Heater (Gallon)	Water - Used (Gallon)	Water - Wasted (Gallon)	Water Delivery Efficiency (%)
MB_SH	Master bathroom shower	7.8	7.6	0.2	98%
MB_SK1	Master bathroom sink faucet 1	6.6	2.1	4.5	32%
MB_SK2	Master bathroom sink faucet 2	0.4	0.4	-	100%
MB_TB	Master bathroom tub spout	-	-	-	-
K_SK	Kitchen sink faucet	6.0	4.5	1.5	75%
K_DW	Kitchen dishwasher	-	-	-	-
LN_WA	Laundry room clothes washer	2.8	2.8	-	100%
B2_SH	2nd bathroom shower	5.2	4.8	0.4	92%
B2_SK1	2nd bathroom sink faucet 1	2.1	1.8	0.2	90%
B2_SK2	2nd bathroom sink faucet 2	1.8	0.7	1.1	39%
B2_TB	2nd bathroom sink tub spout	-	-	-	-
B3_SK	3rd bathroom sink faucet	0.4	0.4	-	100%
Total		**33.0**	**25.2**	**7.8**	**76%**

Source: Gary Klein and Associates, Inc.

Table 8: Daily Time Performance – Baseline Distribution Design

Fixture ID	Structural Waiting (Seconds)	Behavior Waiting (Seconds)	Total Waiting (Seconds)	Use Duration (Seconds)	Time Efficiency (%)
MB_SH	7.8	-	7.8	390.0	98%
MB_SK1	224.8	-	224.8	310.1	58%
MB_SK2	-	-	-	100.0	100%
MB_TB	-	-	-	-	-
K_SK	49.0	-	49.0	600.1	92%
K_DW	-	-	-	-	-
LN_WA	-	-	-	600.0	100%
B2_SH	8.4	-	8.4	250.0	97%
B2_SK1	10.1	-	10.1	310.1	97%
B2_SK2	54.4	-	54.4	100.1	65%
B2_TB	-	-	-	-	-
B3_SK	-	-	-	40.0	100%
Total	**355**	**-**	**355**	**2,700**	**88%**

Source: Gary Klein and Associates, Inc.

Table 9 presents the results of service performance for the baseline case. Service performance indicates how much of the hot water at the desired temperature actually reached the fixtures. The researchers used the parameter of "Load not Met" (defined as the percentage of hot water demand, or apparent intended energy service, not met by the delivered hot water energy) to indicate service performance. The average daily load not met was 21 percent.

The apparent intended energy service is what the user of the system would have received if the system operated in an ideal manner and instantly delivered hot water at design temperatures to the end use. The total delivered energy service at the end use is the energy content of the delivered water.

For temperature critical hot water end uses (showers and long faucet draws) the apparent intended energy service is the energy content of just the use portion of the draw. In the case of baths, the apparent intended energy service is the energy content of all the water delivered to the tub.

For faucet draws, where hot enough water may not be delivered, the apparent intended energy service is the heat content of the total volume of water used heated from the cold-water inlet temperature that day to 105ºF. This will be larger than the heat content of the actual delivered water.

For appliance draws (clothes washers and dishwashers), the apparent intended energy service is the heat content of the total volume of hot water used heated from the cold-water inlet temperature that day to 125ºF, the assumed set point for the water heater.

Table 9: Daily Service Performance– Baseline Distribution Design

Fixture ID	Hot Water Load (Fixture Energy Demand) (Btu)	Hot Water Energy Delivered to Fixture and Used (Btu)	Load not Met (Hot Water Energy not Delivered to the Fixture) (Btu)	Load not Met (%)
MB_SH	3,476	3,280	196	6%
MB_SK1	981	430	551	56%
MB_SK2	202	56	146	72%
MB_TB	-	-	-	-
K_SK	2,065	1,484	580	28%
K_DW	-	-	-	-
LN_WA	1,272	920	352	28%
B2_SH	2,203	2,094	109	5%
B2_SK1	845	515	330	39%
B2_SK2	319	217	103	32%
B2_TB	-	-	-	-
B3_SK	165	93	73	44%
Total	**11,529**	**9,089**	**2,440**	**21%**

Source: Gary Klein and Associates, Inc.

Performance of Improvement Strategies

Common metrics must be used to compare the overall performance of different hot water distribution systems. The metrics should account for the different service provided (amount of hot water actually delivered) as well as the overall energy, water, and time efficiency.

For overall energy efficiency, researchers used the ratio of the energy in the water used at the fixture compared to the total thermal energy in the water entering the hot-water distribution system. The total thermal energy of hot water drawn at the water heater is the energy content of the water as it enters the hot-water distribution system.

In a perfect world, there would be no distribution losses between the source of hot water and the fixtures. The fixture is turned on and hot water at the desired temperature comes out. In this "ideal case" the water heater only needs to heat the actual loads.

- For temperature critical draws (showers and long faucet events), the intended energy service is equal to the energy content of the use portion of the draw. In the case of baths, the intended energy service is equal to the energy content of all the water delivered to the tub.
- For short faucet draws where temperature is not critical and where hot enough water may not be delivered, the intended energy service is equal to the heat content of the water heated to 105 ºF. The energy entering the hot-water distribution system will be larger than the energy delivered to the faucet.

- For appliance draws (clothes washers and dishwashers), the intended energy service is equal to the heat content of the water heated to 125 ºF (the assumed set point for the water heater).

For hot water draws without waiting phases, for example dishwasher draws, clothes washer draws, and short faucet draws, the distribution system water and time efficiencies are 100 percent — the entire event is in use phase.

If the draw duration is short, barely any hot water may reach the fixture and energy distribution efficiency can be very low or even 0 percent.

Researchers determined that water efficiency and time efficiency were not critical variables to be used in the comparisons of distribution strategies. Therefore, these results are not explicitly presented in the body of this report. (See Appendix H Detailed Modeling Results for details) In both cases, short events were very water and time efficient — the fixtures were turned on and the water was immediately used, regardless of the hot-water temperature. Only those events where hot-water temperature mattered did water or time efficiency decrease.

Performance with Normal Fixture Flow Rates

This section presents the performance assessment results for different distribution designs with normal fixture flow rates. Distribution performance is shown in terms of distribution energy waste and loads not met:

- Distribution energy waste, as percentage of fixture hot water energy demand, reflects the increase of system energy use due to distribution energy loss.
- Loads not met, as percent of fixture hot water energy demand, reflects the fraction of total hot water energy demand not delivered to fixtures.

Table 10 presents the performance assessment results for distribution designs with distributed wet rooms, *normal pipe sizes*, and normal fixture flow rates. The first row in this table shows that, compared to the "ideal case", the baseline case distribution design had distribution energy losses of 31 percent, and loads not met of 21 percent. All percentages shown in these two columns are based on comparisons to the ideal case. The last column, Distribution Energy Loss Reduction, compares the energy performance of each pipe layout method to the Baseline Case.

Table 10: Performance with Normal Fixture Flow Rates - Distributed Wet Rooms, Normal-Size Pipes

Pipe Layout Method	Water Heater Location	Pipe Size	Distribution Energy Loss (% of Fixture Demand)	Load not Met (% of Fixture Demand)	Distribution Energy Loss Reduction (Compare to Baseline)
Trunk & Branch	Garage, top left corner	Normal	31%	21%	**Baseline**
Trunk & Branch	Garage, top right corner	Normal	28%	21%	11%
Trunk & Branch	Near master bathroom	Normal	29%	18%	5%
Trunk & Branch	Near kitchen	Normal	27%	16%	12%
Trunk & Branch	Garage, bottom left (far) corner	Normal	33%	22%	-6%
Hybrid (Mini-Manifold)	Garage, top left corner	Normal	32%	22%	-4%
Hybrid (Mini-Manifold)	Garage, top right corner	Normal	29%	21%	7%
Hybrid (Mini-Manifold)	Near master bathroom	Normal	32%	20%	-4%
Hybrid (Mini-Manifold)	Near kitchen	Normal	36%	17%	-16%
Hybrid (Mini-Manifold)	Garage, bottom left (far) corner	Normal	34%	23%	-10%
Central Manifold	Garage, top left corner	Normal	32%	24%	-3%
Central Manifold	Garage, top right corner	Normal	39%	22%	-26%
Central Manifold	Near master bathroom	Normal	34%	22%	-10%
Central Manifold	Near kitchen	Normal	21%	19%	33%
Central Manifold	Garage, bottom left (far) corner	Normal	47%	25%	-51%
Two Heaters	Garage, top left corner / near master bathroom	Normal	14%	20%	54%
Two Heaters	Near 2nd bathroom / near master bathroom	Normal	12%	18%	60%
One Zone	Garage, top left corner	Normal	35%	20%	-14%
One Zone	Near master bathroom	Normal	41%	18%	-33%
One Zone	Garage, bottom left (far) corner	Normal	40%	22%	-30%

Source: Gary Klein and Associates, Inc.

Only three configurations showed reductions in distribution energy loss: central manifold with the water heater located near the kitchen and both layouts with two water heaters. While none of these configurations eliminated the distribution losses, the reductions in losses were significant; 33 percent, 54 percent and 60 percent. One of the reasons that using two water heaters showed such large improvement was that splitting the distribution system into two parts allowed the diameter of the trunk lines to be reduced from 1" to ¾ inch, reducing the internal volume roughly in half per foot. Table 10 also shows that in the case of distributed wet rooms, the individual strategy of locating one water heater within the wet room rectangle did not consistently result in reductions in distribution losses. It took a combination of strategies to show improvements.

The Load not Met column shows that none of the strategies resulted in significant improvement in meeting the loads, except where the water heater was located within the wet-room rectangle. This lack of improvement is likely because short draws dominated the number of daily hot water events. Even with changes in the distribution paths, short water draws rarely result in hot water arriving at the fixtures in time to be used.

Table 11 presents the performance assessment results for distribution designs with distributed wet rooms, *small pipe sizes*, and *normal fixture flow rates* with the only change being the diameter of the pipe. Based on the results presented in Table 10, the research team selected a smaller sample to evaluate with small pipes.

Table 11: Performance with Normal Fixture Flow Rates - Distributed Wet Rooms, Small Pipes

Pipe Layout Method	Water Heater Location	Pipe Size	**Distribution Energy Loss** (% of Fixture Demand)	**Load not Met** (% of Fixture Demand)	**Distribution Energy Loss Reduction** (Compare to Baseline)
Trunk & Branch	Garage, top left corner	Use 3/8" pipe	30%	20%	2%
Hybrid (Mini-Manifold)	Garage, top left corner	Use 3/8" pipe	29%	20%	7%
Central Manifold	Garage, top left corner	Use 3/8" pipe	20%	22%	35%
Two Heaters	Garage, top left corner / near master bathroom	Use 3/8" pipe	13%	20%	58%
One Zone	Garage, top left corner	Use 3/8" pipe	34%	19%	-11%
Trunk & Branch	Garage, top left corner	No 1" pipe	26%	20%	16%
Hybrid (Mini-Manifold)	Garage, top left corner	No 1" pipe	27%	21%	12%
Central Manifold	Garage, top left corner	No 1" pipe	30%	23%	2%
Two Heaters	Garage, top left corner / near master bathroom	No 1" pipe	N/A	N/A	N/A
One Zone	Garage, top left corner	No 1" pipe	27%	19%	12%
Trunk & Branch	Garage, top left corner	Use 3/8" pipe & no 1" pipe	25%	20%	18%
Hybrid (Mini-Manifold)	Garage, top left corner	Use 3/8" pipe & no 1" pipe	24%	20%	23%
Central Manifold	Garage, top left corner	Use 3/8" pipe & no 1" pipe	19%	21%	39%
Two Heaters	Garage, top left corner / near master bathroom	Use 3/8" pipe & no 1" pipe	N/A	N/A	N/A
One Zone	Garage, top left corner	Use 3/8" pipe & no 1" pipe	27%	18%	14%

Source: Gary Klein and Associates, Inc.

For designs using trunk and branch, hybrid, and one zone pipe layout methods, replacing 1” diameter pipes with ¾” diameter pipes showed greater savings than replacing the ½” pipe with 3/8” diameter pipe. The central manifold design benefited most from replacing ½” diameter with 3/8” diameter because the original central manifold design had long ½” diameter pipes and relatively short 1” diameter pipes. For designs with two water heaters, the distribution energy loss reduction improved a little bit due to the use of 3/8” pipe, but most of the reduction had already been realized.

All design cases had lower distribution energy losses than the baseline case, except the one-zone pipe layout with 3/8” diameter pipe. In the one-zone pipe layout, some unique interactions between consecutive hot water draws perform better with ½” diameter pipes compared to 3/8” diameter pipes, because the larger diameter keeps the water warm longer reducing the wait for subsequent draws.

The Load not Met column shows that none of the strategies resulted in significant improvement.

Table 12 presents the performance assessment results for distribution designs with *compact wet rooms,* normal pipe sizes, and normal fixture flow rates. The results indicate that using compact wet rooms without also locating the water heater closer to the fixtures did not provide much improvement in performance. Combining these two strategies — compact wet rooms and locating the water heater near the fixtures — significantly reduced distribution energy losses. One-Zone pipe layouts did not benefit from these combined strategies.

Table 12: Performance with Normal Fixture Flow Rates - Compact Wet Rooms, Normal-Size Pipes

Pipe Layout Method	Water Heater Location	Pipe Size	Distribution Energy Loss (% of Fixture Demand)	Load not Met (% of Fixture Demand)	Distribution Energy Loss Reduction (Compare to Baseline)
Trunk & Branch	Away from fixtures (Garage, top left corner)	Normal	30%	19%	2%
Trunk & Branch	Near fixtures (Near laundry room)	Normal	17%	15%	45%
Hybrid (Mini-Manifold)	Away from fixtures (Garage, top left corner)	Normal	36%	21%	-15%
Hybrid (Mini-Manifold)	Near fixtures (Near laundry room)	Normal	19%	17%	39%
Central Manifold	Away from fixtures (Garage, top left corner)	Normal	29%	23%	8%
Central Manifold	Near fixtures (Near laundry room)	Normal	17%	18%	46%
One Zone	Away from fixtures (Garage, top left corner)	Normal	33%	22%	-8%
One Zone	Near fixtures (Near laundry room)	Normal	30%	13%	4%

Source: Gary Klein and Associates, Inc.

The Load not Met column continues to show that most of these strategies did not result in significant improvement, except where the water heater was located within the wet-room rectangle (specifically in the laundry room).

Table 13 presents the performance assessment results for distribution designs with compact wet rooms, *small pipe sizes*, and *normal fixture flow rates*. Many of these designs showed very large distribution loss reductions. The central manifold design with the water heater close to fixtures and small pipes had the best performance — a 77 percent reduction compared to the baseline design.

Table 13: Performance with Normal Fixture Flow Rates - Compact Wet Rooms, Small Pipe

Pipe Layout Method	Water Heater Location	Pipe Size	Distribution Energy Loss (% of Fixture Demand)	Load not Met (% of Fixture Demand)	Distribution Energy Loss Reduction (Compare to Baseline)
Trunk & Branch	Away from fixtures (Garage, top left corner)	Use 3/8" pipe	30%	18%	5%
Trunk & Branch	Near fixtures (Near laundry room)	Use 3/8" pipe	12%	15%	60%
Hybrid (Mini-Manifold)	Away from fixtures (Garage, top left corner)	Use 3/8" pipe	34%	20%	-9%
Hybrid (Mini-Manifold)	Near fixtures (Near laundry room)	Use 3/8" pipe	13%	16%	57%
Central Manifold	Away from fixtures (Garage, top left corner)	Use 3/8" pipe	19%	22%	40%
Central Manifold	Near fixtures (Near laundry room)	Use 3/8" pipe	8%	17%	74%
One Zone	Away from fixtures (Garage, top left corner)	Use 3/8" pipe	33%	21%	-5%
One Zone	Near fixtures (Near laundry room)	Use 3/8" pipe	29%	12%	6%
Trunk & Branch	Away from fixtures (Garage, top left corner)	No 1" pipe	26%	18%	16%
Trunk & Branch	Near fixtures (Near laundry room)	No 1" pipe	15%	14%	52%
Hybrid (Mini-Manifold)	Away from fixtures (Garage, top left corner)	No 1" pipe	30%	20%	2%
Hybrid (Mini-Manifold)	Near fixtures (Near laundry room)	No 1" pipe	18%	17%	43%
Central Manifold	Away from fixtures (Garage, top left corner)	No 1" pipe	27%	22%	12%
Central Manifold	Near fixtures (Near laundry room)	No 1" pipe	16%	18%	48%
One Zone	Away from fixtures (Garage, top left corner)	No 1" pipe	23%	21%	25%
One Zone	Near fixtures (Near laundry room)	No 1" pipe	28%	13%	9%
Trunk & Branch	Away from fixtures (Garage, top left corner)	Use 3/8" pipe & no 1" pipe	25%	17%	19%
Trunk & Branch	Near fixtures (Near laundry room)	Use 3/8" pipe & no 1" pipe	10%	14%	66%
Hybrid (Mini-Manifold)	Away from fixtures (Garage, top left corner)	Use 3/8" pipe & no 1" pipe	29%	19%	8%
Hybrid (Mini-Manifold)	Near fixtures (Near laundry room)	Use 3/8" pipe & no 1" pipe	13%	16%	59%
Central Manifold	Away from fixtures (Garage, top left corner)	Use 3/8" pipe & no 1" pipe	17%	21%	44%
Central Manifold	Near fixtures (Near laundry room)	Use 3/8" pipe & no 1" pipe	7%	16%	77%
One Zone	Away from fixtures (Garage, top left corner)	Use 3/8" pipe & no 1" pipe	22%	20%	28%
One Zone	Near fixtures (Near laundry room)	Use 3/8" pipe & no 1" pipe	27%	12%	11%

Source: Gary Klein and Associates, Inc.

This is the first time where the Loads not Met results show some improvement for many of the cases. This is likely due to noticeable reductions in the volume of the piping to the temperature critical uses, such as showers and long sink draws as well as to the reduced volume to the faucets in general. Moving the water heater to within the wet-room rectangle showed the greatest improvement.

Performance With Flow Rates Lower Than Title-20

Table 14 and Table 15 compare the performance between very low and high-efficiency fixture flow rates for distribution designs with *distributed* and *compact* wet-rooms (respectively) and normal pipe sizes. For high efficiency fixture flow rates, the maximum flow rates for showerheads and bathroom sink faucets were set to 1.8 and 1.2 gallon per minute (GPM), respectively, based on California's Appliance Efficiency Regulations (Title-20) adopted in 2015. For very low fixture flow rates, maximum flow rates for showerheads and bathroom sink faucets were set to 1.5 and 0.5 GPM, respectively.

Table 14: Impact of Very Low Fixture Flow Rates - Distributed Wet Rooms, Normal-Size Pipes

			Distribution Energy Loss (% of Baseline Fixture Demand)		Energy Demand from the Water Heater (% of Baseline)	
Pipe Layout Method	**Water Heater Location**	**Pipe Size**	**Low Flow**	**Normal Flow**	**Low Flow**	**Normal Flow**
Trunk & Branch	Garage, top left corner	Normal	31.3%	31.0%	88%	100%
Trunk & Branch	Garage, top right corner	Normal	27.60%	27.58%	85%	97%
Trunk & Branch	Near master bathroom	Normal	30.0%	29.5%	87%	99%
Trunk & Branch	Near kitchen	Normal	27.6%	27.3%	85%	97%
Trunk & Branch	Garage, bottom left (far) corner	Normal	33.3%	32.8%	89%	101%
Hybrid (Mini-Manifold)	Garage, top left corner	Normal	32.5%	32.3%	89%	101%
Hybrid (Mini-Manifold)	Garage, top right corner	Normal	28.97%	28.96%	86%	98%
Hybrid (Mini-Manifold)	Near master bathroom	Normal	33.0%	32.3%	89%	101%
Hybrid (Mini-Manifold)	Near kitchen	Normal	36.2%	36.0%	92%	104%
Hybrid (Mini-Manifold)	Garage, bottom left (far) corner	Normal	34.4%	34.0%	90%	102%
Central Manifold	Garage, top left corner	Normal	32.1%	31.9%	88%	101%
Central Manifold	Garage, top right corner	Normal	39.5%	39.2%	94%	106%
Central Manifold	Near master bathroom	Normal	34.6%	33.9%	90%	102%
Central Manifold	Near kitchen	Normal	21.5%	20.8%	80%	92%
Central Manifold	Garage, bottom left (far) corner	Normal	46.95%	46.93%	100%	112%
Two Heaters	Garage, top left corner / near master bathroom	Normal	15.0%	14.3%	75%	87%
Two Heaters	Near 2nd bathroom / near master bathroom	Normal	12.8%	12.3%	74%	86%
One Zone	Garage, top left corner	Normal	36.4%	35.3%	92%	103%
One Zone	Near master bathroom	Normal	41.8%	41.2%	96%	108%
One Zone	Garage, bottom left (far) corner	Normal	40.4%	40.3%	95%	107%

Source: Gary Klein and Associates, Inc.

Table 15: Impact of Very Low Fixture Flow Rates - Compact Wet Rooms, Normal-Size Pipes

Pipe Layout Method	Water Heater Location	Pipe Size	Distribution Energy Loss (% of Baseline Fixture Demand)		Energy Demand from the Water Heater (% of Baseline)	
			Low Flow	Normal Flow	Low Flow	Normal Flow
Trunk & Branch	Away from fixtures (Garage, top left corner)	Normal	30.9%	30.4%	87%	100%
Trunk & Branch	Near fixtures (Near laundry room)	Normal	17.7%	17.1%	77%	89%
Hybrid (Mini-Manifold)	Away from fixtures (Garage, top left corner)	Normal	36.2%	35.7%	92%	104%
Hybrid (Mini-Manifold)	Near fixtures (Near laundry room)	Normal	19.4%	18.9%	79%	91%
Central Manifold	Away from fixtures (Garage, top left corner)	Normal	29.1%	28.7%	86%	98%
Central Manifold	Near fixtures (Near laundry room)	Normal	17.4%	16.7%	77%	89%
One Zone	Away from fixtures (Garage, top left corner)	Normal	33.5%	33.3%	89%	102%
One Zone	Near fixtures (Near laundry room)	Normal	30.4%	29.7%	87%	99%

Source: Gary Klein and Associates, Inc.

The results show that using low-flow fixtures *increased* distribution energy loss, albeit by a small amount when compared to the baseline fixture use. In many cases, the increase was hardly noticeable. On the other hand, using low-flow fixtures decreased the energy demand from the water heater.

Only six of the cases (three in each table) showed significant reductions in distribution losses. In Table 14 the designs with two water heaters showed the largest reductions. In Table 15 the designs with the water heater located within the compact wet-room rectangle performed almost as well, but with only one water heater.

How Low Can We Go?

This study only looked at the inefficiencies associated with hot water distribution system design. It assumed that when a hot water event occurred, that hot water immediately entered the distribution system. If a tankless water heater is used, there will be additional losses during the ramp-up stage, which generally takes from 15-45 seconds for gas tankless water heaters and losses during the cool-down stage. Similarly, the standby loss from one or more storage water heaters was not included in the research. Standby, ramp-up and cool-down losses need to be accounted for to properly determine the hot water system impacts.

Table 16 presents energy and water savings for hot water distribution designs achieving more than 10 percent improvement from the baseline. The *simplified* annual energy savings estimates were calculated by dividing the reduction of daily hot water supply energy by an assumed water heater thermal efficiency of 75 percent and multiplying by 365. The estimated annual water savings were calculated by multiplying the reduction of daily hot water consumption by 365. These energy and water savings do not reflect the wide range of hot water use days in the CBECC-Res simulation model. These results only account for one of many possible ways to allocate hot water uses to fixtures.

Table 16: Hot Water Distribution Designs Providing High Energy and Water Savings

Architectural Design	Pipe Layout Method	Water Heater Location	Pipe Size	Energy/Water Use Reduction from Baseline: Normal Flow	Energy/Water Use Reduction from Baseline: Low Flow	Annual Energy Savings (Therm/Year): Normal Flow	Annual Energy Savings (Therm/Year): Low Flow	Annual Water Savings (Gallon/Year): Normal Flow	Annual Water Savings (Gallon/Year): Low Flow
Compact	Trunk & Branch	Near fixtures (Near laundry room)	Use 3/8" pipe	14%	26%	10.4	19.2	1,700	3,150
Compact	Hybrid (Mini-Manifold)	Near fixtures (Near laundry room)	Use 3/8" pipe	13%	26%	9.9	18.8	1,630	3,080
Compact	Central Manifold	Near fixtures (Near laundry room)	Use 3/8" pipe	18%	30%	12.9	21.8	2,110	3,580
Compact	Trunk & Branch	Near fixtures (Near laundry room)	No 1" pipe	12%	24%	9.1	17.8	1,500	2,920
Compact	Central Manifold	Near fixtures (Near laundry room)	No 1" pipe	11%	24%	8.4	17.3	1,380	2,840
Compact	Trunk & Branch	Near fixtures (Near laundry room)	Use 3/8" pipe & no 1" pipe	16%	27%	11.5	19.9	1,890	3,260
Compact	Hybrid (Mini-Manifold)	Near fixtures (Near laundry room)	Use 3/8" pipe & no 1" pipe	14%	26%	10.2	19.1	1,670	3,130
Compact	Central Manifold	Near fixtures (Near laundry room)	Use 3/8" pipe & no 1" pipe	18%	30%	13.3	22.2	2,190	3,650
Distributed	Two Heaters	Garage, top left corner / near master bathroom	Use 3/8" pipe	14%	25%	10.0	18.6	1,650	3,050
			Average	**14%**	**26%**	**11**	**19**	**1,750**	**3,180**

Source: Gary Klein and Associates, Inc.

Most of these high-impact designs are based on a compact architectural design with the water heater installed near fixtures. For distributed architectural designs, the researchers found that using two water heaters could achieve high energy and water savings.

Using these simplified annual calculations, for distribution designs using *normal fixture flow rates*, the average improvement from the baseline is 14 percent, the estimated annual energy savings are 11 therms and the estimated annual water savings are 1,750 gallons. To put these energy savings in perspective, this is roughly six percent of 173 therms based on the 2009 Residential Appliance Saturation Survey (RASS) for all homes with gas water heating.[15] Assuming 45 gallons of hot water per household per day, the water savings are roughly 11 percent. *With very low-flow rate fixtures*, the average improvement from the baseline is 26 percent, the estimated annual energy savings are 19 therms, (11 percent) and the estimated annual water savings are 3,180 gallons (19 percent).

Benefits to California

If new homes were built incorporating the results of this study several benefits would accrue to Californian ratepayers. Average long-term annual construction of single-family homes in California is about 100,000 units per year.

Table 17 presents the savings in natural gas, water, green-house gas emissions, nitrous oxides and first costs. Savings of natural gas and water are based on the results shown in Table 16. Green-house gas and nitrous oxide reductions are based on the savings in natural gas. The

[15] According to Figure ES-6, water heating is 49 percent of annual household gas consumption of 354 therms. Executive Summary, *2009 California Residential Appliance Saturation Study*, https://ww2.energy.ca.gov/2010publications/CEC-200-2010-004/CEC-200-2010-004-ES.PDF

first cost reduction of compact architectural design was estimated based on average cost savings of $1,500/home provided in Chapter 2. Methods of obtaining these benefits are discussed in Conclusions and Recommendations.

Table 17: Estimated Benefits to California

	Natural Gas (Therms)	**Water** (Gallons)	**GHG** (Tons CO_2e)	**NOx** (pounds)	**First cost for Compact Architectural Design** ($)
First-year Savings from One Home					
Distribution Improvement Only	11	1,750	0.056	0.026	1,500
Distribution Improvement and Low-flow Fixtures	19	3,180	0.103	0.046	1,500
First-year Savings from Annual New Construction of 100,000 Homes					
Distribution Improvement Only	1.1	0.175	5.6	1.3	0.15
Distribution Improvement and Low-flow Fixtures	1.9	0.318	10.3	2.3	0.15
Cumulative Savings in 10 years					
Distribution Improvement Only	59	9.6	310	71	8.3
Distribution Improvement and Low-flow Fixtures	107	17.5	565	129	8.3

Source: Gary Klein and Associates, Inc.

Technology/Knowledge Transfer

In addition to obtaining the environmental and economic benefits that come from implementing the results of this research, the team shared the interim and final results with plumbing and energy professionals in California and elsewhere in the nation.

The project team participated in conferences both as organizers and presenters to inform the audiences about the knowledge gained from the research and to obtain feedback from them on any concerns they had. These included the 2017 ASHRAE Summer meeting, the 2018 ASHRAE Winter Meeting, the 2018 ASHRAE Summer meeting, the 2018 ACEEE Hot Water Forum, and the 2018 Emerging Water Technology Symposium. The team also participated in sharing the results with CEC staff working on the 2021 changes to Title 24. They also submitted code change proposals to the 2021 Uniform Plumbing Code (UPC) and the 2021 International Energy Conservation Code (IECC). The research team intends to continue the knowledge transfer activities after the project is complete.

The approach to understanding the location of the hot water fixtures to each other and to the source of hot water that serves them has been generally well-received. The fact that there are many hot water draws that are too short to reach the fixture (mostly faucets), even in dwellings with a compact wet-room architecture surprised the participants; particularly since the industry has long thought that bringing the sources of hot water closer to the uses (by reducing the length or diameter or both) would make a significant impact on hot water distribution system efficiency. See Appendix I Technology/Knowledge Transfer Report for details of these activities.

CHAPTER 5: Conclusions and Recommendations

Two Unexpected Findings

The research identified two surprising and related issues:

1. A very large percentage of hot water draws are too short in duration and too small in volume for hot water to reach the fixtures. This problem occurs most frequently with rinsing events at a faucet. It can also occur with dishwashers and water-efficient washing machines. In these cases, the hot water leaves the water heater, goes some distance along the pipe at which point the draw ends. The water coming out of the fixture was used, at whatever temperature it came out, but the hot water was left stranded, and its energy dissipated to the building. If the volume of the draw is 0.5 gallons the hot water will only move about 0.25 gallons along the hot water pipe. In this case, even if the pipe only contains 0.25 gallons, no useful hot water will arrive before the event is over. To reduce the volume one can either move the fixtures close to a single water heater or move the source(s) of hot water closer to the fixtures. Moving the source(s) of hot water is generally easier to do. The research team examined both compact architectural designs and smaller diameter fixture branch lines. Even in the cases where the volume was very small, there were still a significant number of events when hot water would not arrive. While both researched options provide a higher level of service, which consumers seem to want, the energy stranded in the piping is on the order of 15 percent of the daily hot water energy use.
2. Models used to evaluate hot water energy use, including Title-24 energy budget calculations, assume that all water heated by a water heater is considered to be delivered at a useful hot water temperature. However, as discussed above, a large percentage of hot water events do not deliver hot water to the user. For the baseline case evaluated by this study, 21 percent of the desired hot water demands were not met. If the idea is to provide hot water as desired by consumers, then the mathematics needs to evaluate the same level of service for all hot water distribution system options. The relevant service for hot water distribution systems is the time-to-tap or volume-until-hot. The research team developed the "ideal case" to establish the amount of energy needed to heat the water, assuming a "perfect" hot water distribution system. Unless the source of hot water is in the fixture, there will always be some lag in time and volume. It is necessary to select a specific number in seconds or volume to add to this ideal case so that the energy consequences of each method of delivering hot water are evaluated while providing the same level of service. It needs to be recognized that some percentage of "hot" draws will not arrive, even with shorter pipes. These become "loads not met". Like the requirement in the energy modeling for HVAC systems that the thermostat setting be maintained for a high percentage of time throughout the year, there needs to be a similar requirement for the timeliness of hot water delivery.

Conclusions

Distribution Performance Assessment Method

This study analyzed transient hot water delivery processes using laboratory test data obtained by a prior PIER research project. The analysis showed that energy used to warm up the delivery flow path, which is dissipated to the ambient after the hot water use, is much more than pipe heat loss during the hot water draw. This is because normal hot water draws in residential buildings are short and, before these draws end, distribution pipes are not fully warmed up or only warmed up for too brief a period to have significant pipe heat loss. Therefore, accurate assessment of flow path warm-up time is more important than accurate assessment of pipe heat loss in analyzing hot water distribution performance. In addition, water efficiency of hot water delivery processes is determined by flow path warm-up characteristics.

Real-time distribution system performance is also affected by interactions between hot water draws, specifically how a hot water draw may partially or completely warm up the flow path of the succeeding hot water draw and, therefore, reduce its hot water delivery delay. Assessment of interactions between hot water draws needs to address two issues: one is how fast warmed pipes cools down and the other is how the flow path of two consecutive hot water draws overlap with each other.

This study provides a breakthrough in distribution system performance assessment by developing a distribution performance model to implement the analysis of transient process of individual hot water draws and interactions among hot water draws from fixtures connected through complicated pipe networks. The study developed the transient hot water delivery model based on laboratory test results and energy balance principles to ensure accurate assessment of flow path warmup and cool down processes. The distribution performance model also provides a streamlined approach to define complicated distribution piping and fixture configurations to enable the analysis of interactions among hot water draws.

Using realistic hot water draw patterns developed based on those used in Title 24 compliance software, the study analyzed the performance of a wide range of distribution designs reflecting different distribution improvement strategies. Findings regarding these improvement strategies are presented in following sections. Analysis of system performance shows that, with interactions among hot water draws, total energy used to warm up the delivery flow paths for different draws and dissipated to the ambient after the draws, is also much more than pipe heat loss during all hot water draws. For example, for the base case distribution design, of the total hot water energy supplied by the water heater, 32 percent is used to warm up flow paths before draws and dissipated into ambient after draws, 2 percent is lost through pipe heat loss during hot water draws, 6 percent is delivered to fixtures but not used, and the remaining 60 percent is delivered to fixtures. Energy used to warm up flow paths before draws and dissipated into ambient after draws accounts for 80 percent of the energy waste. Meanwhile 21 percent of the hot water loads at the end uses are not met. In short, it is inefficient and doesn’t work very well.

Performance of Distribution Improvement Strategies

The study investigated the impact of a range of distribution improvement strategies. The study found that distribution system performance is very sensitive to hot water draw schedule of individual fixtures in the system. For example, a hot water draw schedule with showers mostly from the second bathroom could only identify improvement to the pipe connection to the second bathroom. To avoid this type of bias, the study used a hot water draw schedule with relatively balanced hot water draws from all fixtures.

The study found that the distribution loss in the baseline design increased system energy use by 31 percent without meeting all hot water end use loads. In other words, 24 percent of DHW energy use was associated with distribution loss. Please note that this study aimed to find significant energy and water savings beyond simple distribution design and installation improvements. Therefore, the selected baseline represents a well-designed and installed distribution system. Typical distribution systems found in the field usually have much higher distribution losses and higher loads not met due to poor design and installation.

The study found that home run and hybrid pipe layout designs had a similar performance as the baseline. The one-zone pipe layout design, which emphasizes pipe sharing, had a higher distribution energy loss, about 14 percent higher than the baseline.

For the trunk-and-branch pipe layout method, moving the water heater to be nearer the fixtures improved distribution efficiency. When the water heater was moved to the edge of the wet-room rectangle, represented by the design case of installing the water heater near the master bathroom (such as in a closet), distribution loss decreased from 31 percent to 29 percent. Relocating the water heater to the right corner of the garage, closer to the centerline of the wet rooms decreased distribution loss to 28 percent. When the water heater was moved to the center of the wet-room rectangle, represented by the design case where the water heater was near the kitchen, distribution loss decreased to 27 percent. Therefore, moving the water heater closer to the fixtures reduces distribution losses, although not by very much.

Using two water heaters allowed the fixtures to be further close to hot water sources and, therefore, provided much higher distribution loss reduction. By placing the two water heaters close to different clusters of fixtures, the distribution loss was reduced by 60 percent compared to the baseline. However, it should be noted that this study did not consider additional standby loss associated with the second water heater.

For trunk-and-branch pipe layout method, replacing 1-inch diameter trunk pipes with ¾-inch diameter pipes had a much large impact on distribution performance than replacing 1/2-inch diameter branch pipes with 3/8-inch diameter pipes. However, for home-run pipe layout method, the opposite was true.

The study found that using compact architectural design could significantly reduce distribution loss only when the water heater was also moved to be very close to the fixtures. For trunk-and-branch pipe layout method, reducing the wet-room size while keeping the water heater in the garage only slightly reduced distribution loss. As the water heater was moved to be near the kitchen, distribution energy loss was reduced to 17 percent compared to 31 percent in the baseline. However, it is challenging to implement compact wet-room designs because they impose limitations on architecture designs. Requiring the water heater to be installed near hot water fixtures increases architectural design constraints. This is best addressed by changing compliance calculations to correctly reflect energy budget consequences of these types of architectural decisions.

Investigation of detailed hot water delivery processes revealed that there were three possible outcomes of flow path volume reduction:

- For short faucet draws, hot water may not reach the fixture before the draw ends. Distribution performance for these short draws may not be improved unless the pipe volume is significantly reduced.
- For draws that do not need to wait for hot water, reducing the flow path volume increased the amount of hot water delivered to the fixture. However, there was no impact on hot water energy consumption. There will be an impact on indirect energy use by dishwashers as they heat water that wasn't hot enough when delivered.
- Shower draws and some faucet draws require hot water to be delivered to the fixture before use. For these draws, reducing flow path volume can reduce both energy and water waste.

Distribution system performance is affected by the combined effects of the above three types of draws and further affected by interaction between consecutive hot water draws. In the draw schedule used by the study, draws from the master bathroom shower are preceded by short draws from master bathroom sinks. The short sink draws were not affected by pipe volume reduction, as the water was used without waiting for it to get hot. Based on the selected draw schedule, bathroom sink draws warmed up most of the flow path for the subsequent shower draws, so that these had minimal waiting time. As a result, reducing pipe volume had no impact on neither sink draws nor shower draws in this case. If the shower draw occurred before the sink, then the situation would be reversed. This example shows how the effectiveness of improvement strategies can be affected by hot water draw schedules.

In summary, the study learned the following about different distribution improvement strategies:

- There are no significant performance differences among trunk and branch, home run, and hybrid pipe layout methods, if they are properly designed. Long, large diameter one-zone trunk and branch layouts have higher distribution losses than normal (multiple-zone) trunk and branch designs. However, they also meet a higher percentage of the desired hot water service.
- For trunk and branch and hybrid pipe layout methods, replacing 1-inch diameter pipes with ¾ inch diameter pipes provides higher distribution loss reduction (12-16 percent) than does reducing fixture branch diameter from ½ inch to 3/8 inch (2-7 percent). However, for home run pipe layout, the latter provide much higher distribution loss reduction (35 percent) than the former (2 percent).
- With distributed architectural design, placing the water heater within the wet-room rectangle can achieve moderate reductions in distribution losses, about 7-9 percent.
- Compact architectural design can achieve 60-80 percent distribution loss reduction if the water heater is located very close to or within the wet-room rectangle. This strategy also performs best at meeting hot water loads. In addition, this strategy can significantly reduce labor costs and construction time for distribution system installation.

- For homes with distributed wet rooms (common design), using two water heaters, with each installed close to different clusters of fixtures, provides about 60 percent reduction in distribution losses.

Performance with Very Low-Flow Fixtures

The study assessed the impact of very low-flow fixtures by setting the maximum flow rate for showers to 1.5 gpm (17 percent reduction from the current California standard of 1.8 gpm) and the maximum flow rate for bathroom sink faucet to be 0.5 gpm (58 percent reduction from the current California standard of 1.2 gpm). These flow rate limits were recommended by project TAC members, even though lower flow rates are possible. The study found that using very low-flow fixtures slightly *increased* distribution losses. On the other hand, very low flow rates resulted in reduced overall energy consumption compared to the baseline. Most of the reduction is due to the reduced volume of the showering events.

Many bathroom and kitchen faucet draws are too short to allow hot water to be delivered to the faucet before the draw ends. It is likely that many of these draws were never intended to receive hot water; presumably hot water is drawn because a single-lever faucet is used and turned on with a default position to draw mixed water. Using a very low-flow faucet increases the number of draws not receiving hot water. Lowering the shower flow rate does not cause this type of problem because users usually wait for hot water to arrive before starting the shower.

How Low Can We Go?

The study assessed the maximum improvement by applying all three improvement strategies: using small pipes, using compact architectural design, and installing the water heater near fixtures. The trunk and branch, hybrid, and home run pipe layout methods achieved 66 percent, 59 percent, and 77 percent distribution loss reduction from baseline, respectively. Accordingly, energy use for these three pipe layout methods was reduced by 16 percent, 14 percent, and 18 percent from baseline, respectively. Using two water heaters achieved a similar level of improvement: a 60 percent distribution loss or 14 percent energy reduction from the baseline. Using low-flow fixtures achieved an addition 12 percent reduction in system energy use for all these design cases. For these three improvement strategies, the loads not met are reduced to 12 percent, 14 percent, and 15 percent.

Recommendations

Based on study findings, this study provides the following recommendations regarding codes and standards development to improve hot water distribution systems:

1. The CEC should consider including in the Title 24 baseline energy budget calculations a consistent value for the time-to-tap and volume-until-hot so that all hot water distribution system options can be evaluated against providing the same level of service. At the same time, it should establish a maximum number of events or percentage of daily hot water volume that is allowed to not arrive within a given time or volume; this value should be the same for all systems. This becomes the allowable "Loads Not Met".
2. The hot water draw schedule used by Title 24 for compliance calculations needs to be improved, particularly if it is going to be used to evaluate hot water distribution system

alternatives. As detailed in Appendix F, the research team made many decisions in order to use the CBECC-Res draw schedules in this study. Each of these choices need to be standardized so that different energy consultants get the same results when evaluating the same layout. Even if the draw schedule is only used to estimated hot water energy use, the flow rates need to be constrained to those allowed by Title-20 and CALGreen.

3. The Title 24 building energy efficiency standard may set appropriate requirements to prevent the use of 1-inch diameter pipe in single-family DHW distribution systems, or within individual units in multi-family dwellings. The requirement may be developed based on pipe sizing analysis using the water demand calculator in Appendix M of the Uniform Plumbing Code (UPC). It is advisable to collaborate closely with the Department of Housing and Community Development and IAPMO in the development of these requirements. The pipe sizing analysis can also identify factors that limit the use of ¾-inch diameter pipe for main trunk lines. For example, the high flow rate of bathtub spouts may be a possible limiting factor. Laboratory tests should be conducted to examine the issue and seek distribution design solutions.
4. Compact architectural designs can lead to significant reduction of distribution losses if the water heater is installed close to hot water fixtures. Title 24 building standards currently provide compliance credit (Point-of-Use and Compact Design) to encourage this type of building and distribution system design. The level of these credits should be evaluated to see if they need to be adjusted based on the findings of this study.
5. The strategy of using two or more water heaters can provide large improvements in distribution system performance. Compared to the strategy of compact architectural design, this strategy has fewer implementation barriers because it imposes almost no constraints on building architecture designs. The Point-of Use credit already included in Title-24 is a way to obtain the benefits of this strategy. However, the additional installation costs and energy penalties of multiple water heaters may limit its inclusion in the standards. For single family buildings with large floor areas or large wet-room areas, prescriptive requirements for hot water systems could be based on an expanded version of the Point-of-Use credit. To support further revisions to Title 24 standard development, the algorithms to accurately model distribution system losses should be incorporated into the model to understand the potential impact of the standby loss associated with multiple water heaters and to assess preferred approach to implement this strategy in terms of water heater type and installation locations.
6. Title 24 building standards need to discourage the use of long, large diameter one-zone pipe layouts. Particularly since they are often installed as a pre-cursor to the installation of a circulation loop after the Certificate of Occupancy has been issued. The study showed that a one-zone layout was less energy efficient than the baseline when the distance (volume) from the one-zone trunk to the fixtures was large. However, the one-zone layout often had the fewest loads-not-met, even more so when the distance (volume) from the one-zone trunk to the fixtures was small. Some builders provide all pipe connections needed to form a recirculation loop to allow homeowners to enable recirculation operation by simply install a recirculation pump. If the volume in the branch lines to the fixtures is kept as small as practical, the consumer will have more of their demands for hot water met. However, depending on the pump control strategy,

circulation loops can significantly increase distribution energy use, for example, continuous circulation takes more energy than that needed for the daily hot water use. Existing Title 24 requirements discourage recirculation systems, especially uncontrolled recirculation systems. However, these requirements are not adequate to prevent conversion of long, large diameter one-zone designs to recirculation systems after new homes are occupied. One approach to prevent one-zone design is to limit the total pipe length (or volume) between fixtures and the water heater.

The study has the following recommendations on future research and development activities:

1. Explore innovative system designs: This study comprehensively investigated conventional distribution improvement strategies. Strategies of preventing 1-inch pipe and one-zone design provide improvement opportunities for wide market adoption, as recommended in the prior section for Title 24 adoption. However, as shown in Table 16, significant distribution improvement can only be achieved by using (1) compact architecture designs with one water heater installed close to the fixtures or (2) distributed architectural designs, with two (or more) water heaters installed close to the fixtures. Both strategies are technically feasible, as demonstrated by design examples evaluated in the study. Compact architectural designs constrain the location of the wet rooms and the water heater; and multiple-heater designs may not be cost-effective. To help transform the market to achieve deep reductions in distribution losses, future research efforts need to go beyond conventional design methods and promote the development of innovative system designs, components, and control methods. It should also be noted that builders and consumers are willing to pay for good delivery performance, for example recirculation systems are used despite additional installation cost and higher energy cost. Therefore, the research team recommends future research be conducted into innovative hot water system designs, and related components and controls, which bring hot water sources very close to fixtures to achieve very fast hot water delivery and very low distribution losses. New hot water system designs should have reasonable incremental cost compared to conventional systems and be easy to install in both new and existing homes.
2. Improve draw patterns: The hot water draw schedule used by Title 24 for compliance calculations needs to be improved, particularly if it is going to be used to evaluate hot water distribution system alternatives. As detailed in Appendix F, the research team made many decisions on how to apply the CBECC-Res draw schedules for this study. Each of these choices need to be standardized so that different energy consultants get the same results when evaluating the same layout. Even if the draw schedule is only used to estimated hot water energy use, the flow rates need to be constrained to those allowed by Title-20 and CALGreen. To support future distribution performance assessment, including codes and standards development, full-year draw schedules need to be developed, with fixtures assigned for each draw event, for both single-family and multi-family buildings.
3. Improve and validate the distribution performance model: This study developed a distribution performance model based on laboratory test results of hot water delivery process in single pipes. It would be valuable to further improve the model through validation using test results of hot water delivery in more complex piping configurations, reflecting realistic distribution systems. Detailed model algorithms of the improved

model should be documented to support future research and standard development efforts. The model validation method could be based on ASHRAE 140 specifications. Model improvement and validation should also cover recirculation and electric heat trace systems under various control schemes.

4. Improve pipe sizing methods: The UPC/CPC pipe sizing method can be further improved by investigating peak flow characteristics in homes and pipe friction loss characteristics of modern fittings. The friction losses as a function of Reynold's number (Moody chart) embedded in the pipe sizing calculations can be revised based on more recent data[16]. Also, pressure drop characteristics of pipe fittings need to be further investigated to inform pipe sizing method improvement. Also, the current pipe sizing methods are dominated by the flow rates of bathtubs and washing machines, neither of which are flow-rate critical. For draws requiring a certain volume of hot water, not a certain flow rate, such as bath filling, clothes washer filling, or dishwasher filling, further flow rate reduction is acceptable. This could potentially lead to the reduction of peak flow rates and, therefore, distribution pipe sizes.
5. Cold-start faucets: Given the practical limits of delivering hot water very quickly, encourage the development of single handle faucets that default to cold water at the start of each draw.

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LIST OF ACRONYMS

Term	Definition
BTU	British Thermal Unit
CASE	Codes and Standards Enhancement
CBECC-Res	California Building Energy Code Compliance – Residential
CPC	California Code of Regulations, Title 24, Part 5 California Plumbing Code
DHW	Domestic Hot Water
GPM	Gallons per minute
IAPMO	International Association of Plumbing and Mechanical Officials
IECC	International Energy Conservation Code
NIST	National Institute of Standards and Technology
PG&E	Pacific Gas and Electric Company
PIER	Public Interest Energy Research
PHCC	Plumbing, Heating and Cooling Contractors Association
RASS	Residential Appliance Saturation Survey
TAC	Technical Advisory Committee
Title-20	California Code of Regulations, Title 20, Article 4, Appliance Efficiency Regulations
Title-24	California Code of Regulations, Title 24, Part 6 California Energy Code
UPC	Uniform Plumbing Code

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APPENDICES

The following appendices are available under separate cover (Publication Number CEC-500-2021-043-APA-I).

- Appendix A: Literature Review
- Appendix B: Bibliography
- Appendix C: Primer on Plumbing
- Appendix D: Hot Water Distribution System Provisions in the 2019 California Energy Code
- Appendix E: Hot water system area versus total floor area
- Appendix F: Draw Schedule For Performance Assessment
- Appendix G: Additional Information on the Distribution Performance Model
- Appendix H: Detailed Modeling Results
- Appendix I: Technology/Knowledge Transfer Report