047
Proponent Revision
Received 6/01/22

STATE OF WASHINGTON

STATE BUILDING CODE COUNCIL

Washington State Energy Code Development

Standard Energy Code Proposal Form

Code being amended: ☐ Commercial Provisions ☒ Residential Provisions

Code Section # ______R406.3_Option 5.6___________

Brief Description:

Compact Hot Water Distribution Systems for R406.3 additional energy credit.

For this proposal, utilizing the language in separately submitted "Short Water Volume Determination" proposal, our team expanded the analysis and performed LCC savings and Simple Paybacks. This proposal was found to have net positive savings for all scenarios with the 16-ounce or 1 pint language as proposed.

This analysis was done to introduce a new potential energy efficiency measure for section R406 and Table R406.3 that aligns with savings already included in section R405 for simulated performance.

This proposal recognizes that for this measure to be both effective and efficient, a useful hot water temperature of at least 105°F must be achieved in reasonable time at the tap. The analysis used savings estimates for this scenario.

Proposed code change text: (Copy the existing text from the Integrated Draft, linked above, and then use underline for new text and ~~strikeout~~ for text to be deleted.)

OPTION	DESCRIPTION	All Other	Group R-2
5.6	~~Not greater than 16 ounces of water volume shall be stored in the piping between the hot water source and any hot water fixture when calculated in accordance with Section R403.5.4.~~ ~~One of the following checks must be done to verify that the system meets the prescribed limit:~~ ~~1. At plan review, by referencing ounces of water per foot of tube on plans per Table R403.5.4.1.~~ ~~2. At rough in (plumbing), by referencing ounces of water per foot of tube installed per Table R403.5.4.1.~~ ~~3. At final inspection, in accordance with Department of Energy's Zero Energy Ready Home National Specification (Rev. 07 or higher) footnote on Hot water delivery systems.~~ For Compact Hot Water Distribution system credit, the volume shall store not more than 16 ounces of water between the nearest source of heated water and the termination of the fixture supply pipe where calculated using section	0.5	N/A

	R403.5.4 *Construction documents* shall indicate the ounces of water in piping between the hot water source and the termination of the fixture supply. When the hot water source is the nearest primed plumbing loop or trunk, this must be primed with an On Demand recirculation pump and must run a dedicated ambient return line from the furthest fixture or end of loop to the water heater.		

[note: remainder of table unchanged in this proposal]

Purpose of code change:

Inefficient hot water distribution systems have been recognized as a problem for many years as they result in energy and water waste, and result in long hot water delay times that are the cause of a considerable number of complaints by new home buyers. Recirculation systems are a solution to two of the three problems (water and wait time), but the thermal energy impact of different recirculation system options has already been addressed in section **R403.5.1.1 Circulation system.**[1]

In all non-recirculation distribution options, water heater energy consumption and hot water waste are correlated. A decrease in water heater energy consumption follows a reduction in wasted water; therefore, improving insulation and reducing the piping length and/or pipe diameter have equal benefits for energy and water waste. In recirculation systems, water heater energy consumption and wasted hot water are independent, and often have an inverse effect (when recirculation is not demand based).[2]

This distribution system problem exists for a variety of factors including:

- An outdated pipe sizing methodology in the plumbing code that results in oversized hot water distribution systems since the assumed fixture flow rates are much higher than current requirements.
- Municipalities with design recommendations that force plumbers and designers to assume low supply water pressure, resulting in larger distribution piping, which waste more water and energy.
- Increasing efforts to conserve water has resulted in the realization of water savings due to improvements in showerhead and lavatory maximum flow rates; however, reduced flow rates often result in increased wait times if the hot water distribution system is not designed to accommodate lower flows.
- Increasing popularity of gas instantaneous water heaters, which offer improved operating efficiency, but can result in increased water waste when starting from a “cold start up” situation.
- Inefficient plumbing installations that are not focused on minimizing pipe length or pipe diameters.

The WSEC-R has already addressed pipe insulation and Circulation systems in the 2018 WSEC-R prescriptive and Table 406.3 additional energy credits.

1Residential Compact Domestic Hot Water Distribution Design: Balancing Energy Savings, Water Savings, and Architectural Flexibility Farhad Farahmand, TRC Companies and Yanda Zhang, ZYD Energy

2 Evaluating Domestic Hot Water Distribution System Options With Validated Analysis Models E. Weitzel and M. Hoeschele, Alliance for Residential Building Innovation

Your amendment must meet one of the following criteria. Select at least one:

☐ Addresses a critical life/safety need.

☒ The amendment clarifies the intent or application of the code.

☐ Addresses a specific state policy or statute. (Note that energy conservation is a state policy)

☐ Consistency with state or federal regulations.

☐ Addresses a unique character of the state.

☐ Corrects errors and omissions.

Check the building types that would be impacted by your code change:

☒ Single family/duplex/townhome ☐ Multi-family 4 + stories ☐ Institutional

☒ Multi-family 1 – 3 stories ☐ Commercial / Retail ☐ Industrial

Your name	Dan Wildenhaus	Email address	dwildenhaus@trccompanies.com
Your organization	TRC, BetterBuiltNW	Phone number	772.932.4994

Other contact name Click here to enter text.

3Economic Impact Data Sheet

Is there an economic impact: ☒ Yes ☐ No

Briefly summarize your proposal's primary economic impacts and benefits to building owners, tenants, and businesses. If you answered "No" above, explain your reasoning.

The proposal states that this would neither increase nor decrease the cost of construction. Similar to bringing ducts inside the conditioned space, some research has estimated a net cost decrease after design changes due both to labor and materials reductions. For the analysis performed and used in the LCC, we did assume a slight $300 first cost increase to recognize that not scenarios will have the same cost reduction.

Provide your best estimate of the **construction cost** (or cost savings) of your code change proposal? (See OFM Life Cycle Cost **Analysis tool** and **Instructions;** use these **Inputs**. **Webinars on the tool can be found Here and Here**)

$0.14/square foot (CFA)(For residential projects, also provide **$300/ dwelling unit**)

Show calculations here, and list sources for costs/savings, or attach backup data pages

Incremental cost findings from the California Energy Commission's Energy Research and Development Division Final Project Report: Code Changes and Implications of Residential Low-Flow Hot Water Fixtures, September 2021, CEC-500-2021-043 indicate that there may be up to $1,500 cost savings for designing and installing a system with less materials and with greater work efficiency due to reduced plumbing layout. The Codes and Standards Enhancement (CASE) Initiative, Compact Hot Water Distribution – Final Report, Measure Number: 2019-RES-DHW1-F reported that incremental cost is highly scenario dependent, but overall determined that there would be little to no cost increase.

For the purposes of this analysis, we assumed that while incremental costs are likely to be neither higher, nor lower than standard plumbing designs, a small incremental cost of $300 would cover the bases for an increased number of potential scenarios.

Provide your best estimate of the **annual energy savings** (or additional energy use) for your code change proposal?

$0.05 KWH/ square foot (or) Click here to enter text.KBTU/ square foot

(For residential projects, also provide **111.2 KWH**/KBTU / dwelling unit)

Show calculations here, and list sources for energy savings estimates, or attach backup data pages

This analysis focused on kWh and Water Savings as it is estimated that over 80% of Residential New Construction Water Heaters installed are Heat Pump Water Heaters in Washington where many of the savings have already been accepted and analyzed.

SAVINGS

The two California assessments found slightly higher energy savings than did modeling in REM/Rate v16.0.6. For the purposes of this assessment, the more conservative REM/Rate values were used.

Climate Zone	Savings in kWh for 1 Pint	Savings in kWh for 1 Quart	Savings dollars 2021 Electric Rates for WA at 0.1007 $/kWh Pint	Savings dollars 2021 Electric Rates for WA at 0.1007 $/kWh Quart
4	117	83	11.78	8.36
5	130	92	13.09	9.26

Max Potential Savings as calculated in the Energy Research and Development Division, FINAL PROJECT REPORT, Code Changes and Implications of Residential Low-Flow Hot Water Fixtures September 2021 | CEC-500-2021-043 were found to be on average 322.3 kWh.

CZ/volume-based savings	1 pint savings in kWh/yr (translated from Therms/yr)	1 quart savings in kWh/yr (translated from Therms/yr)
CZ 3 through 5	556.7	322.3

Savings connected with maximum approach (1 pint in pipe + low-flow) and average approach (1.5 to 2 pint + federal minimum flow fixtures) and were analyzed in a 2,100 sq ft single story home and a 2,700 sq ft two-story home.

The Codes and Standards Enhancement (CASE) Initiative, 2019 California Building Energy Efficiency Standards, Compact Hot Water Distribution – Final Report, Measure Number: 2019-RES-DHW1-F found savings for a 1 Quart system to be approximately 117.2 kWh when converted from Therm savings.

First year weighted average residential energy savings (translated from Therms/yr to Mmbtu/yr) are estimated to be per Single Family Home: Climate Zone Savings in Therms Savings in Mmbtu[2] are estimated to be per Single Family Home:

Climate Zone	Savings in kWh (translated from Therm savings) 1 quart volume	Savings dollars 2021 EIA Washington electric rate of 0.1007 $/kWh
3c through 5	163.2	16.43

These estimates come from assumption of a 2,430 sq ft home with 3.5 bedrooms.

Considering these varying, but same order of magnitude savings numbers, a savings number has been generated for 1.5 pints or 24 ounces of water, across Washington to be: **106.5 kWh.**

Water Savings

Estimated impacts on water use are presented in the table below. Water use savings estimates are challenging given that hot water usage behaviors among individuals and households are highly variable and can depend strongly on the demographics of the household (Parker, D.; Fairey, P.; and Lutz, J.; 2015). In addition, the proposed compliance option approach ensures that compliant hot water distribution systems will be smaller than a conventional non-compact system but cannot precisely specify the design and configuration and hence the impacts on water waste. To provide a best approximation of water savings impacts, the Statewide CASE Team in California relied on detailed distribution simulation study completed under the U.S. Department of Energy's Building America program (Weitzel, E.; Hoeschele, M. 2014). In these estimates, it was assumed that all water savings occur indoors.

An average cost of $3/1000 gallons was used to estimate water savings.

Impacts on Water Use Table:

Title 24 CASE Report	**On-Site Indoor Water Savings (gal/yr)**
Per Dwelling Unit Impacts (single family)	962
Per Dwelling Unit Impacts (multifamily)	321

CEC Code Implications Report	**On-Site Indoor Water Savings (gal/yr)**
Per Dwelling Unit Impacts (single family)	1,750

Analysis	1 pint	1 quart	**$/year**

<u>Instructions</u>: Send this form as an email attachment, along with any other documentation available, to: sbcc@des.wa.gov. For further information, call the State Building Code Council at 360-407-9255.

All questions must be answered to be considered complete. Incomplete proposals will not be accepted.

CEC report	1750		(1750/1000)*3=5.25
CASE		962	(962/1000)*3=2.89

In lieu of attempting to convert water savings and costs for water from California to Washington, this analysis has chosen to utilize an embedded energy in wasted water that adds an **additional 4.7kWh/yr.**

Table : Impacts on Water Use

	Impacts on Water Use On-Site Indoor Water Savings (gal/yr)	Embedded Electricity Savings[a] (kWh/yr)
Per Dwelling Unit Impacts (single family)	962	4.7

a. Assumes embedded energy factor of 4,848 kWh per million gallons of water (CPUC 2015).

The choice to use a 4.7 kWh/yr adder to electricity savings produced a more conservative LCC calculation that did the option to individually subtract water savings costs independently.

LCC

Life-cycle costs were calculated using the IECC-Residential LCC Calculator.

A blended annual savings averaged across both climate zones in Washington and averaging savings between both 16- and 32-ounce cases led to the use of **111.2 kWh savings per year**.

Using these energy savings and a $300 first cost, the LCC shows Simple Payback of 17.15 years for LCC with social cost of carbon (SCC) included. The LCC without SCC showed a Simple Payback of 19.66 years.

Measure Incremental LCC in both scenarios were found to be as follows:

Blended Savings:

LCC Calculator - IECC Residential

Enter values into blue boxes

Proposal information

Proposal number	REPI-142-21	
CDP ID#		
Proponent	Wildenhaus, Dan; Rose, Kevin	
Climate zone(s) analyzed	4C, 5B,	Enter specific climate zone or zones included in the analysis below
Additional Notes	Averaged over 8 climate zones	

Methodology

Description of measure cost methodology	Utilized reporting and analysis from 3 sources. Title 24 CASE Report (2017), CEC Code Chage and Implications of Residential Low-Flow Hot Water Fixtures (2021), REM/Rate energy modeling (2022)
Description of savings calculation methodology. Include information about climate zones and fuel types where appropriate.	Compact desing practices with savings calculated in CBECC-Res for two CA reports, RESNET/IECC/ANSI 301 defaults vs CHWD in REM/Rate v16.0.6. Averaged savings across climate zones from 3

Inputs

Net measure cost	300	2020$, measure cost to consumer, including markup, less tax credits or other incentives
Measure electric savings	111.2	kWh/year
Measure natural gas savings		therms/year
Measure propane savings		gallons/year
If applicable:		
Change in maintenance or other non-energy operating costs	0	2020$/year (+ for increased cost, - for decreased cost)
Replacement cost		2020$
Year of first replacement		For measures with life <30 years, # of years from date of construction
Year of second replacement		For measures with life <30 years, # of years from date of construction

Results

	Discount Rate				
	3% nominal	3% real	7% real		
	DOE	OMB	OMB		
With SCC value					
Measure incremental LCC	$149.95	$107.41	$67.72		2020$ (+ for savings, - for increased cost)
Simple payback				17.15	Years
With SCC = $0					
Measure incremental LCC	$94.64	$52.11	$12.41		2020$ (+ for savings, - for increased cost)
Simple payback				19.66	Years

16-ounce or 1-pint scenario:

Results

	Discount Rate				
	3% nominal	3% real	7% real		
	DOE	OMB	OMB		
With SCC value					
Measure incremental LCC	$218.38	$159.77	$104.20		2020$ (+ for savings, - for increased cost)
Simple payback				14.90	Years
With SCC = $0					
Measure incremental LCC	$154.72	$96.11	$40.54		2020$ (+ for savings, - for increased cost)
Simple payback				17.08	Years

32-ounce or 1 quart scenario:

Results

	Discount Rate				
	3% nominal	3% real	7% real		
	DOE	OMB	OMB		
With SCC value					
Measure incremental LCC	$71.74	$47.57	$26.02		2020$ (+ for savings, - for increased cost)
Simple payback				20.73	Years
With SCC = $0					
Measure incremental LCC	$25.99	$1.82	($19.73)		2020$ (+ for savings, - for increased cost)
Simple payback				23.77	Years

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COST EFFECTIVENESS

As indicated in the LCC as seen above and using energy savings for 16-ounce (1 pint) and water savings for 32-ounce scenarios, the LCC shows Simple Payback of 17.15 years for LCC with social cost of carbon (SCC) included. The LCC without SCC showed a Simple Payback of 19.66 years.

CZ\Metric	Net Cost	Measure Savings	Discount 3% Real w/SCC	Discount 3% Real w/o SCC	Simple Payback w/ SCC	Simple Payback w/o SCC
4 and 5	$300	111.2 kWh	$107.41	$52.11	17.15	19.66

List any **code enforcement** time for additional plan review or inspections that your proposal will require, in hours per permit application:

If confirmed at time of both plan review and inspection, this may require up to 1/2 hour per application per floor plan and ¼ hour per site inspection per home.

Small Business Impact. Describe economic impacts to small businesses:

There is not anticipated to be any positive or negative impacts unique to small businesses.

Housing Affordability. Describe economic impacts on housing affordability:

Affordable housing typically has a smaller footprint, smaller house size, and is configured with "wet walls" or plumbing locations in close proximity to each other. This increases the likelihood that this credit could be taken by affordable housing projects.

Other. Describe other qualitative cost and benefits to owners, to occupants, to the public, to the environment, and to other stakeholders that have not yet been discussed:

REFERENCES

- *Residential Compact Domestic Hot Water Distribution Design: Balancing Energy Savings, Water Savings, and Architectural Flexibility* Farhad Farahmand, TRC Companies; Yanda Zhang, ZYD Energy
- *Evaluating Domestic Hot Water Distribution System Options With Validated Analysis Models* **E.** Weitzel and M. Hoeschele Alliance for Residential Building Innovation
- California Energy Codes & Standards Case Report for *Compact Hot Water Distribution;* Measure Number: 2019-RES-DHW1-F, Residential Plumbing
- Home Innovation Research Labs Annual Builder Practices Survey, 2021
- Department of Energy Zero Energy Ready Home National Program Requirements (Rev. 07) [footnote 15]
- Efficient hot water distribution system - USBGC **LEED** BD+C: Homes *v4*- **LEED** *v4*
- Residential Hot Water Distribution Systems: Roundtable Session; JD Lutz, Lawrence Berkely National Laboratory; G Klein, California Energy Commission; D Springer, Davis Energy Group; BO Howard, Building Environmental Science & Technology
- Code Changes and Implications of Residential Low-Flow Hot Water Fixtures – CEC-500-2021-043. Gary Klein, Jim Lutz, Yanda Zhang, John Koeller.

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- Time-to-Tap and Volume-until-Hot – Water, Energy, and Time Efficient Hot Water Systems. 2020 Educational Institute, March 2020, Gary Klein presentation.

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Hi all,

I wanted to thank everyone for the spirited discussion last week. I wanted to provide some additional information and an amended version of the 047 proposal to address some of the comments brought up. Kjell and Krista, please accept the attached Code Change Form as a friendly amendment based on the comments below and the general discussion during the previous TAG meeting.

Comment #1 – The code as written would violate IPC or UPCs. In particular, this was brought up in regards to 046 as new code language, to be referenced by Table R406.3 or any performance approach to codes, in order to ensure that measuring volume of water in the plumbing supply system will hold no more than a pint of water from the source of heat*

This is the table in proposal 046 (and is already in the WSEC-C):

OUNCES OF WATER PER FOOT OF TUBE

Nominal Size (inches)	Copper Type M	Copper Type L	Copper Type K	CPVC CTS SDR 11	CPVC SCH 40	CPVC SCH 80	PE-RT SDR 9	Composite ASTM F1281	PEX CTS SDR 9
3/8	1.06	0.97	0.84	N/A	1.17	—	0.64	0.63	0.64
1/2	1.69	1.55	1.45	1.25	1.89	1.46	1.18	1.31	1.18
3/4	3.43	3.22	2.90	2.67	3.38	2.74	2.35	3.39	2.35
1	5.81	5.49	5.17	4.43	5.53	4.57	3.91	5.56	3.91
1 1/4	8.70	8.36	8.09	6.61	9.66	8.24	5.81	8.49	5.81
1 1/2	12.18	11.83	11.45	9.22	13.20	11.38	8.09	13.88	8.09
2	21.08	20.58	20.04	15.79	21.88	19.11	13.86	21.48	13.86

For SI: 1 foot = 304.8 mm, 1 inch = 25.4 mm, 1 liquid ounce = 0.030 L, 1 oz/ft^2= 305.15 g/m^2.

N/A = Not Available.

This is what is in the 2018 UPC and IPCs:

2018 UPC

TABLE L 502.7
WATER VOLUME FOR DISTRIBUTION PIPING MATERIALS*

OUNCES OF WATER PER FOOT LENGTH OF PIPING													
NOMINAL SIZE (inch)	COPPER M	COPPER L	COPPER K	CPVC CTS SDR 11	CPVC SCH 40	PEX-AL- PEX	PE-AL- PE	CPVC SCH 80	PEX CTS SDR 9	PE-RT SDR 9	PP SDR 6	PP SDR 7.3	PP SDR 11
⅜	1.06	0.97	0.84	NA	1.17	0.63	0.63	NA	0.64	0.64	0.91	1.09	1.24
½	1.69	1.55	1.45	1.25	1.89	1.31	1.31	1.46	1.18	1.18	1.41	1.68	2.12
¾	3.43	3.22	2.90	2.67	3.38	3.39	3.39	2.74	2.35	2.35	2.23	2.62	3.37
1	5.81	5.49	5.17	4.43	5.53	5.56	5.56	4.57	3.91	3.91	3.64	4.36	5.56
1¼	8.70	8.36	8.09	6.61	9.66	8.49	8.49	8.24	5.81	5.81	5.73	6.81	8.60
1½	12.18	11.83	11.45	9.22	13.20	13.88	13.88	11.38	8.09	8.09	9.03	10.61	13.47
2	21.08	20.58	20.04	15.79	21.88	21.48	21.48	19.11	13.86	13.86	14.28	16.98	21.39

For SI units: 1 ounce = 29.573 mL
* NA: Not Applicable

2018 IPC

TABLE E202.1
INTERNAL VOLUME OF VARIOUS WATER DISTRIBUTION TUBING

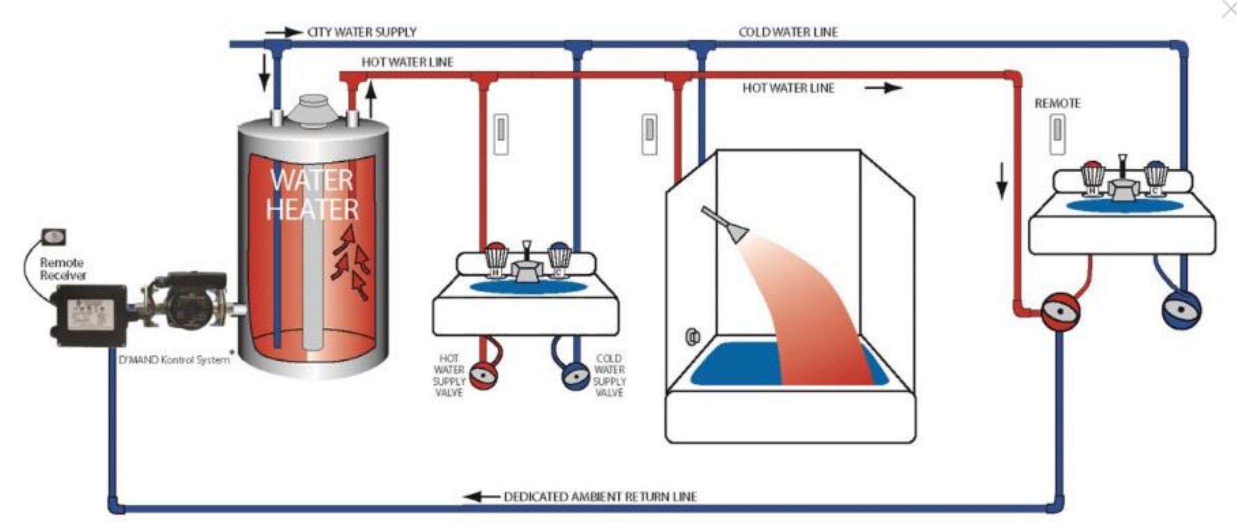
OUNCES OF WATER PER FOOT OF TUBE									
Size Nominal, Inch	Copper Type M	Copper Type L	Copper Type K	CPVC CTS SDR 11	CPVC SCH 40	CPVC SCH 80	PE-RT SDR 9	Composite ASTM F 1281	PEX CTS SDR 9
$^3/_8$	1.06	0.97	0.84	N/A	1.17	—	0.64	0.63	0.64
$^1/_2$	1.69	1.55	1.45	1.25	1.89	1.46	1.18	1.31	1.18
$^3/_4$	3.43	3.22	2.90	2.67	3.38	2.74	2.35	3.39	2.35
1	5.81	5.49	5.17	4.43	5.53	4.57	3.91	5.56	3.91
$1^1/_4$	8.70	8.36	8.09	6.61	9.66	8.24	5.81	8.49	5.81
$1^1/_2$	12.18	11.83	11.45	9.22	13.20	11.38	8.09	13.88	8.09
2	21.08	20.58	20.04	15.79	21.88	19.11	13.86	21.48	13.86

For SI: 1 ounce = 0.030 liter.

*Source of heat is either a water heater or the nearest portion of the plumbing distribution system as primed by a demand recirculation pump in the amended proposal.

Comment #2: On Demand recirculation systems typically use the cold-water line for the house.

This is true in existing homes, where re-designing the plumbing layout is not practical. In the Residential New Construction, this is the recommended design (which will now be referenced in the amended 047 proposal):



A demand plumbing layout uses a recirculation pump to speed delivery of hot water to plumbing fixtures.

Comment #3: We should put a floor or size limit of home that this could apply to (meaning not to be given credit in small homes as it's easier to do).

While this is easier in smaller homes, it is certainly not done regularly outside of Habitat for Humanity homes, and then, only in a few affiliated neighborhoods. It is our contention that there should NOT be a limitation on home size for this proposal as it is more common that smaller homes are also in the affordable housing sector and these homes should be given every opportunity meet the necessary credits.

Comment #4: There's not enough evidence that this can work in ranch homes or in general that this can be done regularly and well.

Attached is an ACEEE white paper and structured plumbing presentation, both shared with me by Gary Klein, who has studied this work for decades and has seen this done both in design and in the field, in residential new construction and in retrofits.

Comment #5: Are there any other codes that have already adopted or approved this?

Yes, California's Title 24 has this in the code, but with a 26-ounce limit (.2 gallons), but is looking to drop this to 16 ounces in the next cycle. In the IECC-R, both the prescriptive code language and the additional credit have been passed through the HVAC subcommittee, currently being reviewed for minor language recommendations from the SEHPCAC group. Once finalized, this will be voted on by the full IECC-R consensus committee for inclusion in the 2014 IECC. PNNL is currently doing modeling to determine the amount of points relative to other "Additional Energy" credits being proposed. Note, the WSEC-R will now specify in the amended language that any recirculation system in new construction must contain a dedicated ambient return line and all recirculation systems must be demand controlled (push button or motion sensor), not run continuously or on a timer. Effectively, the WSEC-R will be more restrictive.

Thank you again for all of the feedback and considerations put into this. I look forward to another robust and positive discussion at upcoming TAG meetings.

Cheers,

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BetterBuilt[NW]
Program of the Northwest Energy Efficiency Alliance (NEEA)
BetterBuiltNW.com

TRC is a contracted third party program implementer for NEEA

Slides for SF presentation

Gary Klein

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916-549-7080

Part 2 – Overview

A. *The CA vison for meeting California Green House Gas (GHG) goals*
B. *Overview of all-electric home market, EE programs and Code analysis*
C. *(Hot) Water System Design for single-family communities*

Do you know anyone who …

- Wants to reduce the first costs of construction by \$1,000 to \$2,000 – and ±40 hours of labor – per dwelling?
- Would like to improve customer satisfaction with their hot water system?
- Would like to “right-size” water supply systems based on current flow rates and modern piping materials and plumbing fixtures and appliances?
- Wondered why the “well-designed” plumbing system didn’t work as expected?
- Wants to increase their profit by \$1,000 to \$2,000 per dwelling?

Part of today's session is based on:

CEC Grant PIR-16-020
Code Changes and Implications of
Residential Low Flow Hot Water Fixtures
CEC Project Manager: Amir Ehyai

Project Team:

Gary Klein

Jim Lutz

Yanda Zhang

John Koeller

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Why This Research is Important?

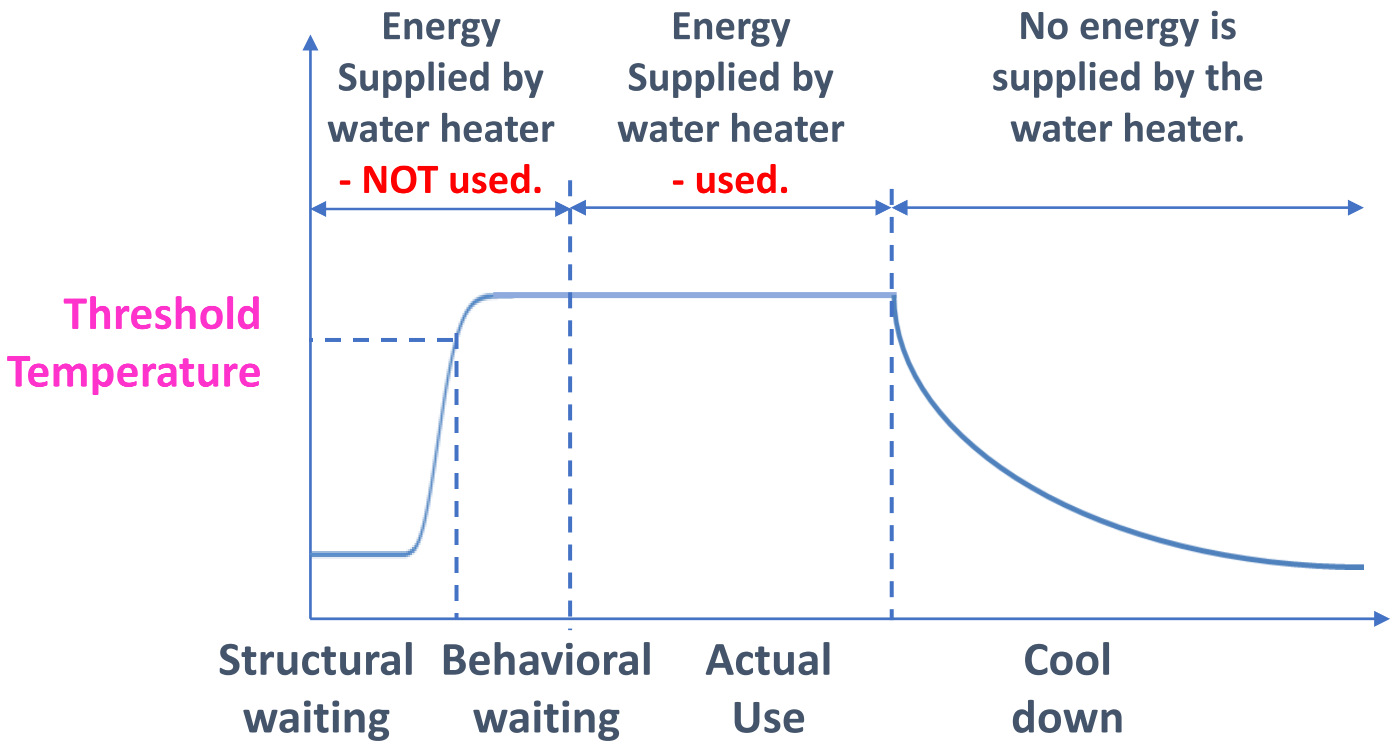
- Plumbing fixture flow rates, flush volumes and appliance fill volumes have been reduced every decade since the 1950s.
- Pipe sizing rules have not been revisited since written down in the 1940s.
- The median square footage of a house is roughly 1.5 times larger than it was in 1970.
- Result:
  - It takes much longer than it used to for hot water to arrive.
  - More energy is lost when the pipes cool down.
  - Dissatisfied occupants
  - Potentially unsafe conditions in the piping network

Why Hot Water is Critically Important to Builders and Owners

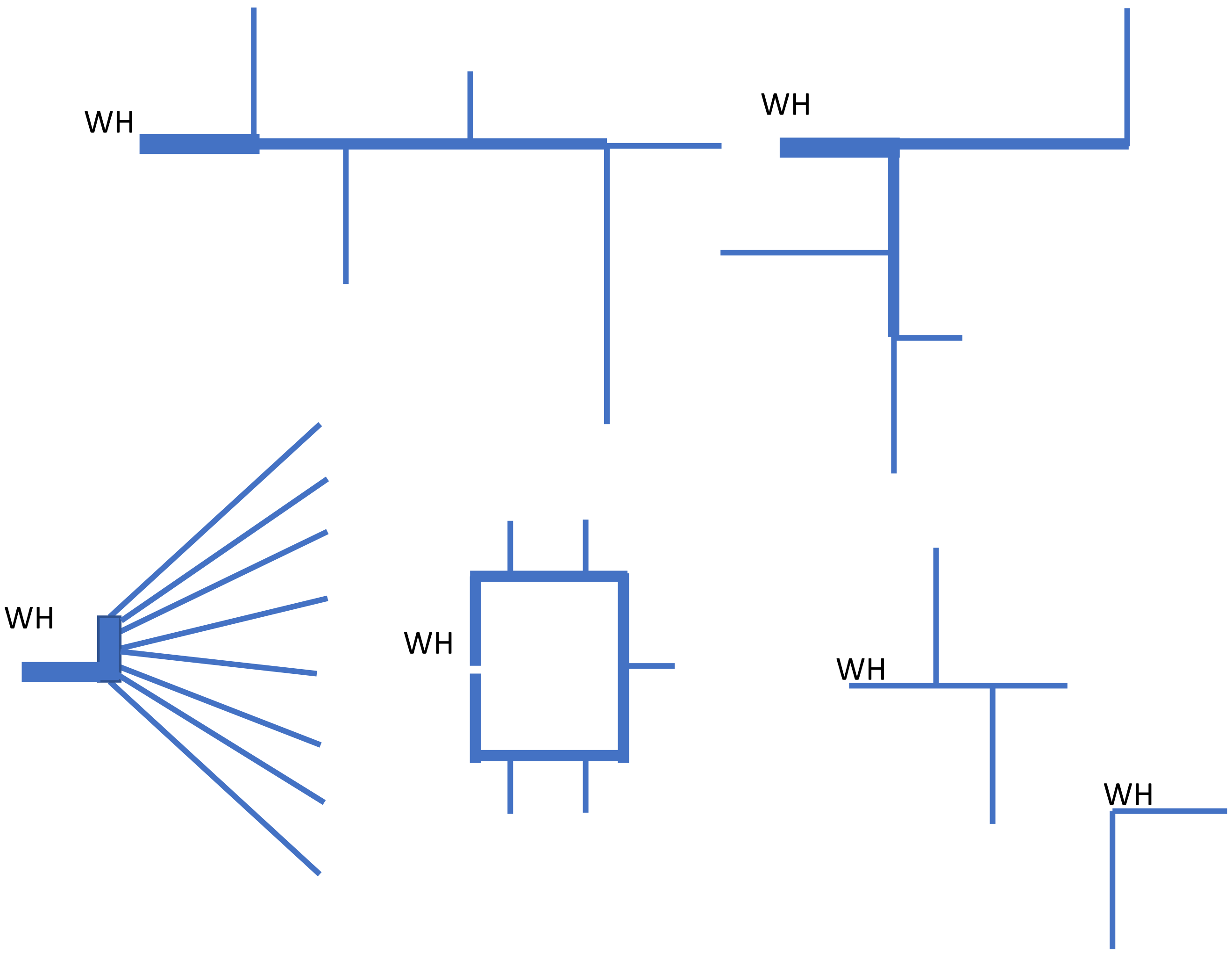
The hot water system is one of the:

1. More expensive components in construction
2. Costliest operational and maintenance items over the life of the building
3. Largest contributors to the building's operational carbon footprint
4. Least understood systems, especially the newest technology

A Typical Hot Water Use Event



Layout Methods for Hot Water Distribution



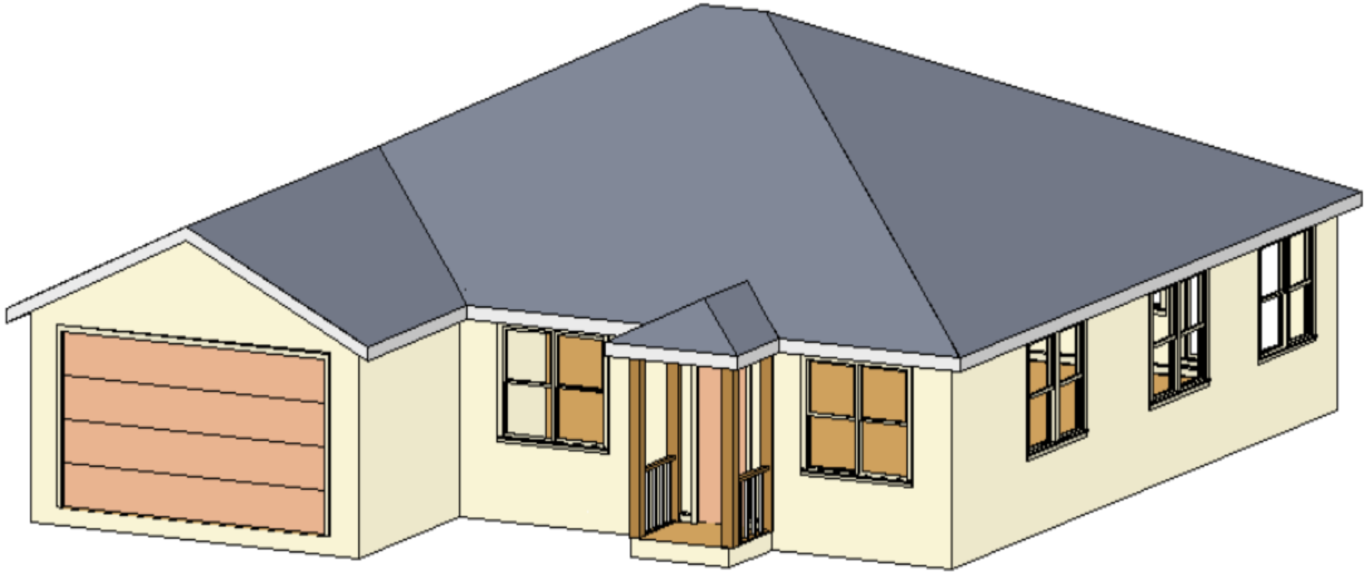
Low-Flow and High-Efficiency Fixtures

The current Federally required maximum flow rates are designated as "low-flow", whereas the lower volumes adopted by California and others are designated separately as "high-efficiency".

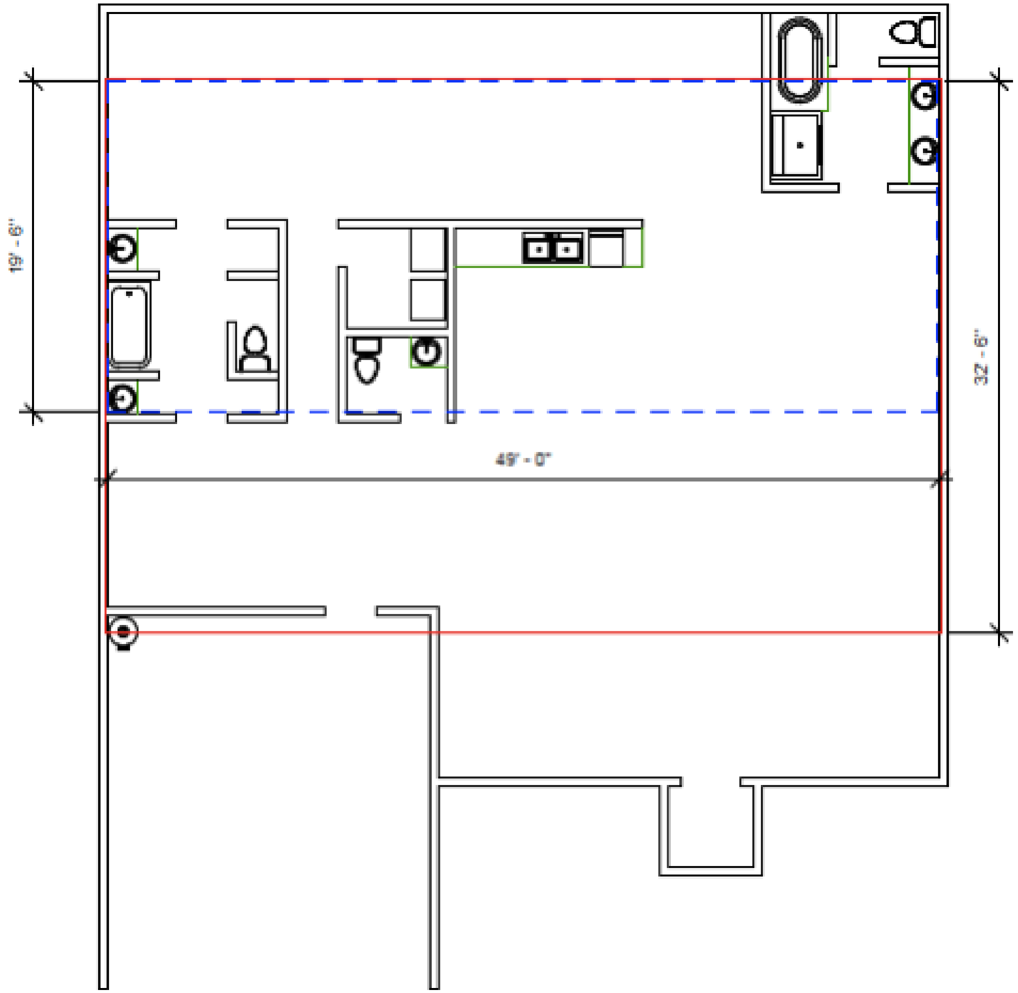
Hot water-using plumbing fixtures and fixture fittings	Maximum water consumption		
	Federal Standard	2016 CalGreen, Part 11 (mandatory)	Title 20, Article 4, Sections 1605.1 & 1605.3
Lavatory faucet-private	2.2 gpm	1.2 gpm	1.2 gpm
Lavatory faucet-public	2.2 gpm	0.5 gpm	0.5 gpm
Metering faucet-residential	0.25 gpc	0.25 gpc	0.25 gpc
Metering faucet-nonresidential		0.20 gpc	
Kitchen faucet	2.2 gpm	1.8 gpm	1.8 gpm
Showerheads	2.5 gpm	2.0 gpm	1.8 gpm

Analysis of Architectural Compactness

Title 24 Prototype Floor Plan



Distributed Core Case (Reference)



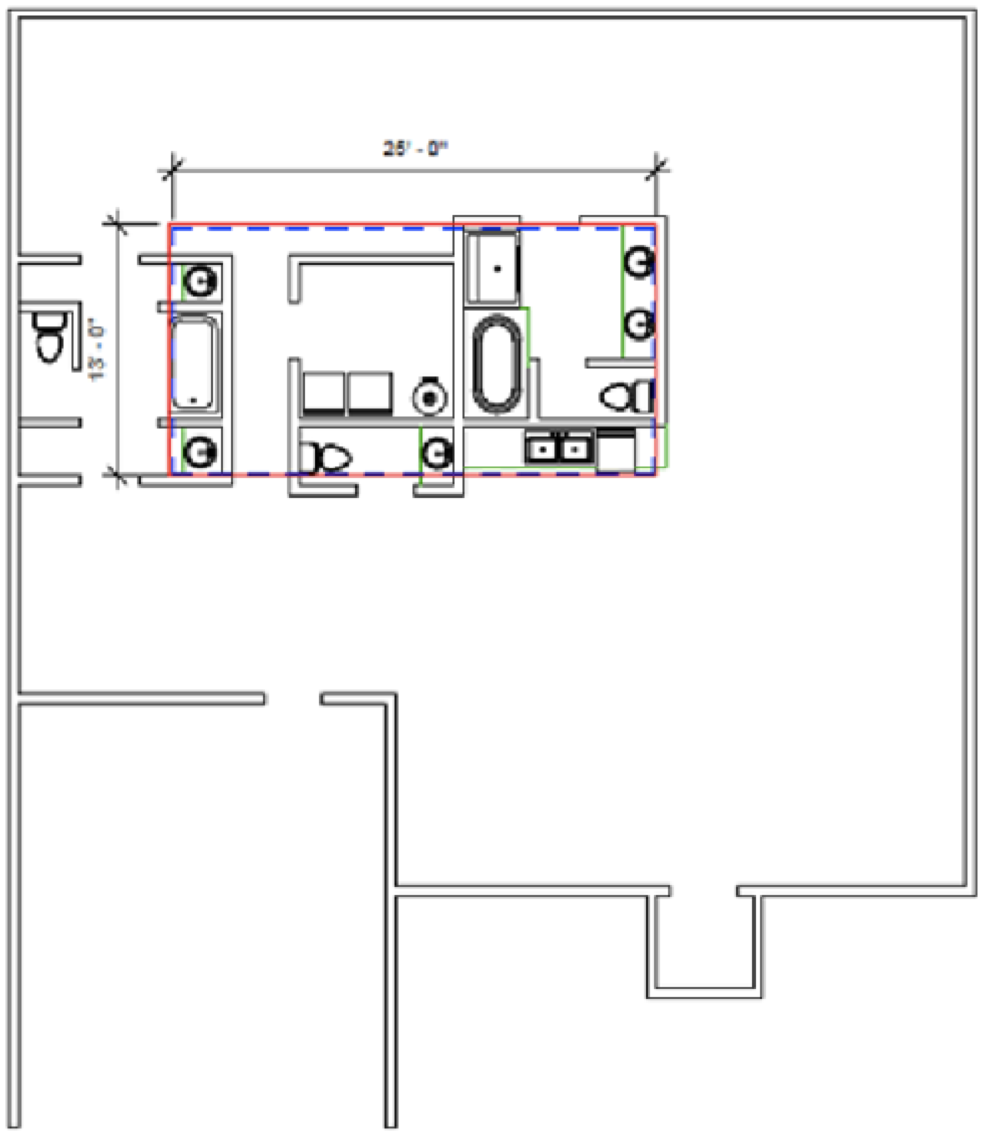
Wet Room Rectangle:

- 19.5 feet X 49 feet
- 956 square feet
- 45.5% of floor area

Hot Water System Rectangle

- 32.5 feet X 49 feet
- 1592 square feet
- 76% of floor area

Compact Core Case



Wet Room Rectangle:
- 13 feet X 25 feet
- 325 square feet
- 15.5% of floor area

Hot Water System Rectangle
- 13 feet X 25 feet
- 325 square feet
- 15.5% of floor area

Rating Performance
(it's not just the energy)

- **Which metrics to use?**
  - Energy
    - Energy used
    - Energy delivered but wasted
    - Energy not delivered
  - loads not met
    - compared to water heater set-point temperature
  - temperature delivered
    - wait time?
    - what temperature?
  - water wasted

New Single-Family Homes Completed in 2017

Median Home Size in Western United States
-2,398 sq ft

Average Home Size in Western United States
-2,548 sq ft

6% under 1,400
15% 1,400 to 1,799
29% 1,800 to 2,399
25% 2,400 to 2,999
17% 3,000 to ,3,999
8% 4,000 or more

(Source: United States Census Bureau)

New Multi-Family Units Completed in 2017

Median Unit Size in Western United States
-1,045 sq ft

Average Unit Size in Western United States
-1,088 sq ft

42% under 1,000
31% 1,000 to 1,199
15% 1,200 to 1,399
9% 1,400 to 1,799
4% 1,800 or more

(Source: United States Census Bureau)

= Wet Room Rectangle

Ratio in Percent: Hot Water System Rectangle/Floor Area x 100%

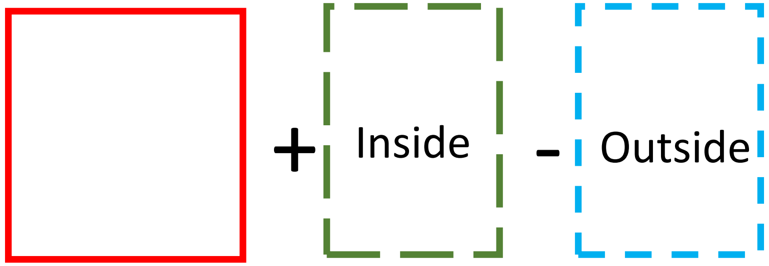
Use the dimensions available on the floor plan when available.
Otherwise, determine the areas based on the formula below.
The dimensions come from the drawing program.

+ Inside - Outside = Home Floor Area

= Hot Water System Rectangle

Ratio in Percent: Hot Water System Rectangle/Floor Area x 100%

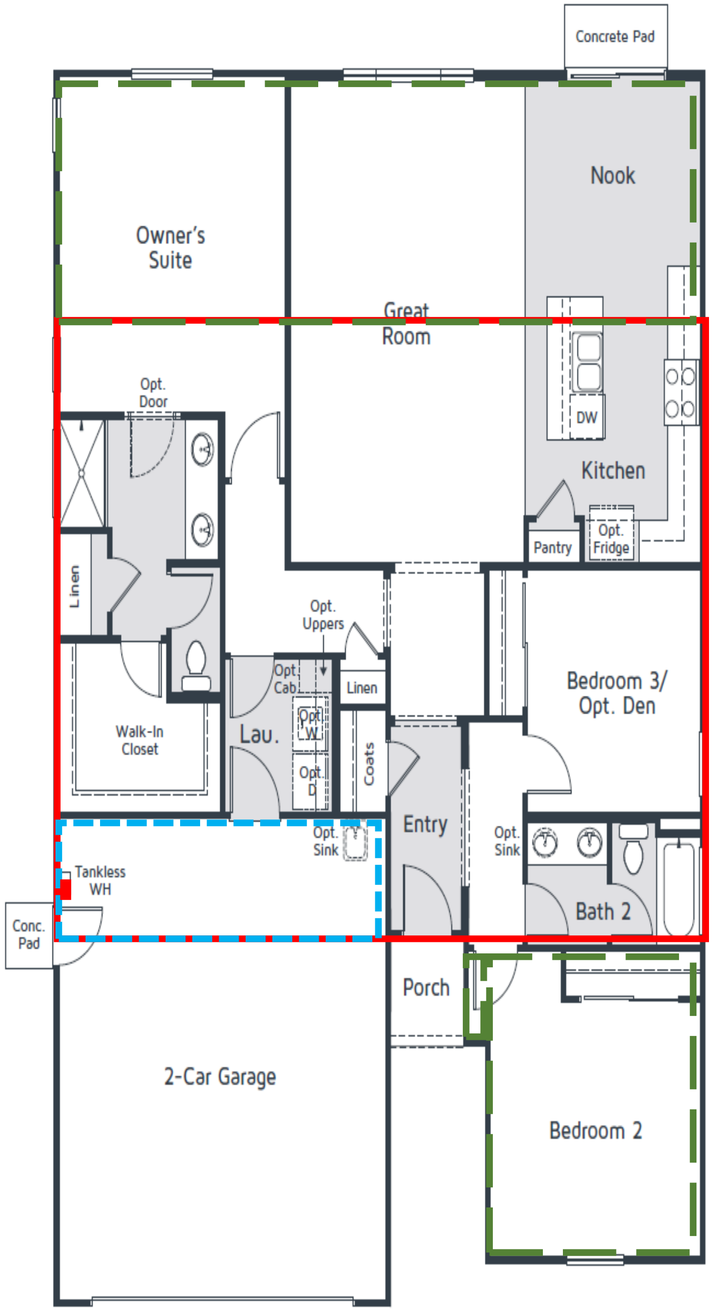
Use the dimensions available on the floor plan when available.
Otherwise, determine the areas based on the formula below.
The dimensions come from the drawing program.



= Home Floor Area

Example:

1 Story
3Br/2Ba
1,697 sq ft
Fresno, CA
~67% (1137 sq ft)



Relationship between the Hot Water System and the Floor Area – The Logical Worst Case

Number of Stories	Hot Water System/ Floor Area (%)
1-story	100%
2-story	50%
3-story	33.3%
4-story	25%
5-story	20%

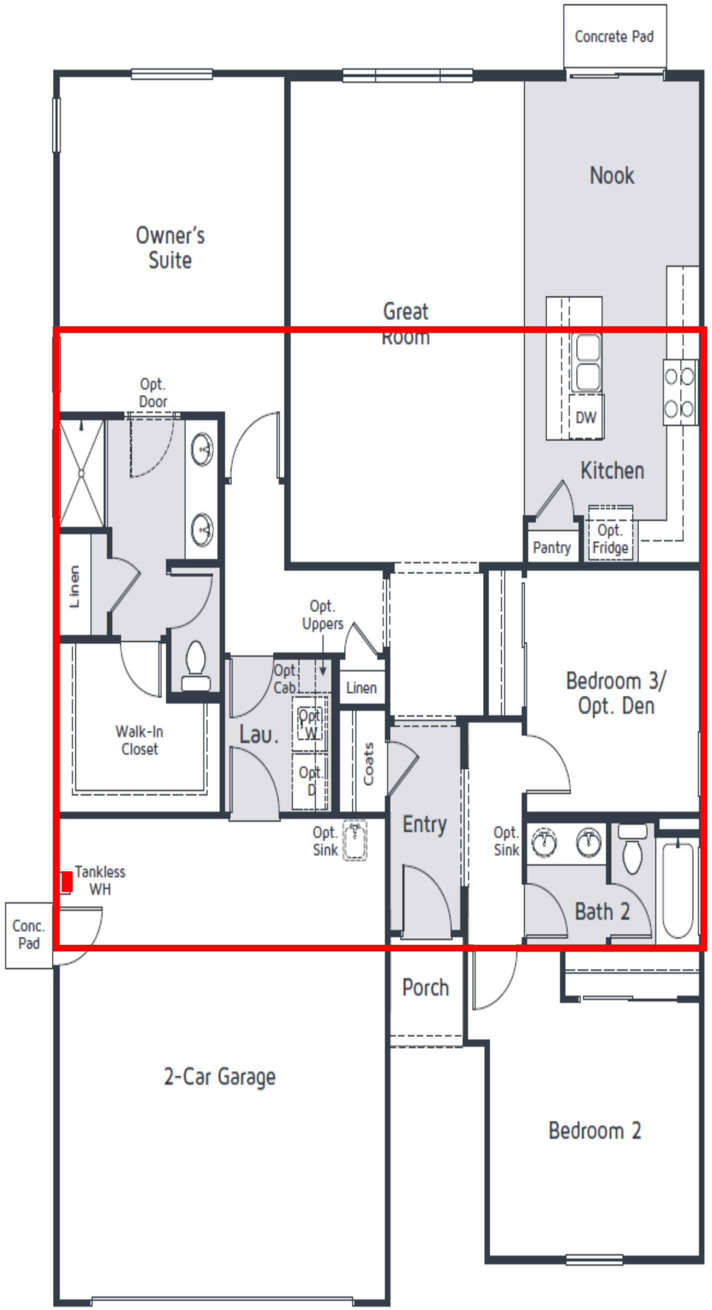
Basements count as stories if they contain wet rooms.

1-Story Floor Plans

- The wet room rectangle has the same area as the hot water system rectangle for all of the 1-story homes in this sample.

1 Story
3Br/2Ba
1,697 sq ft
Fresno, CA

~67%
(1,137 sq ft)

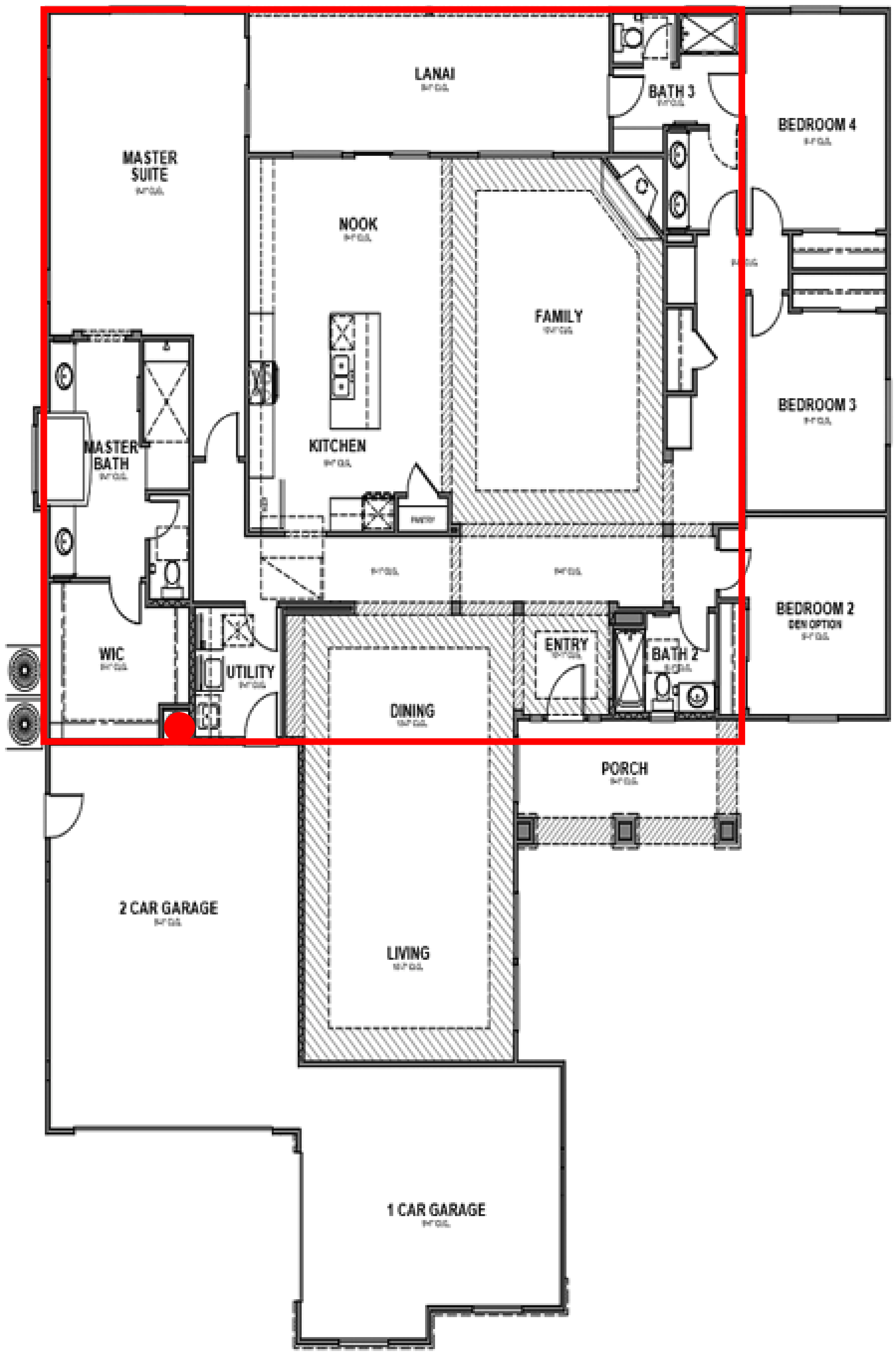


1 Story
3Br/2.5Ba
2,466 sq ft
Roseville, CA

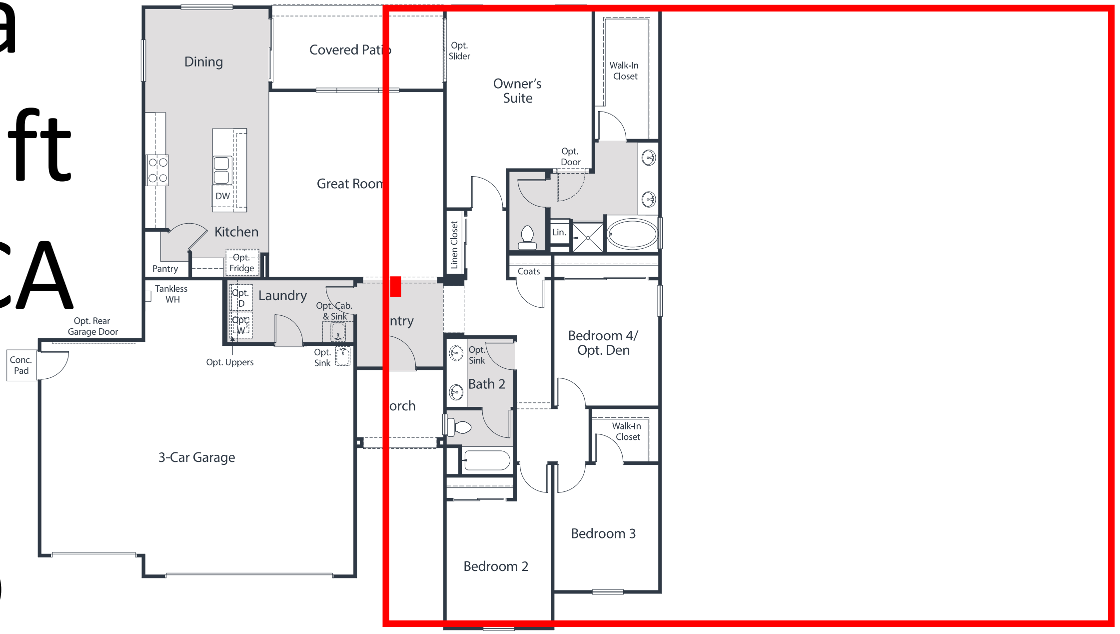
~75%
(1,835 sq ft)

1 Story
4Br/3Ba
3,073 sq ft
Chico, CA

~80%
(2,459 sq ft)



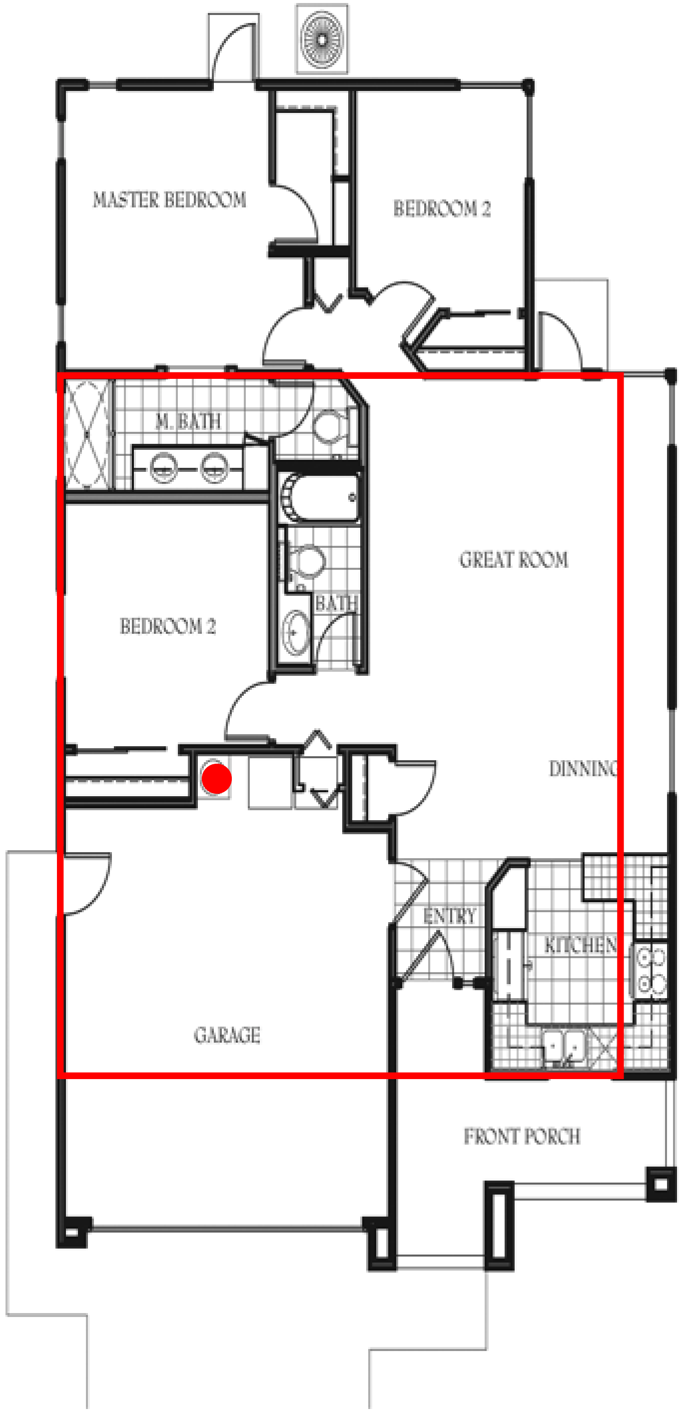
1 Story
4Br/2Ba
2,010 sq ft
Fresno, CA



~81%
(1,628 sq ft)

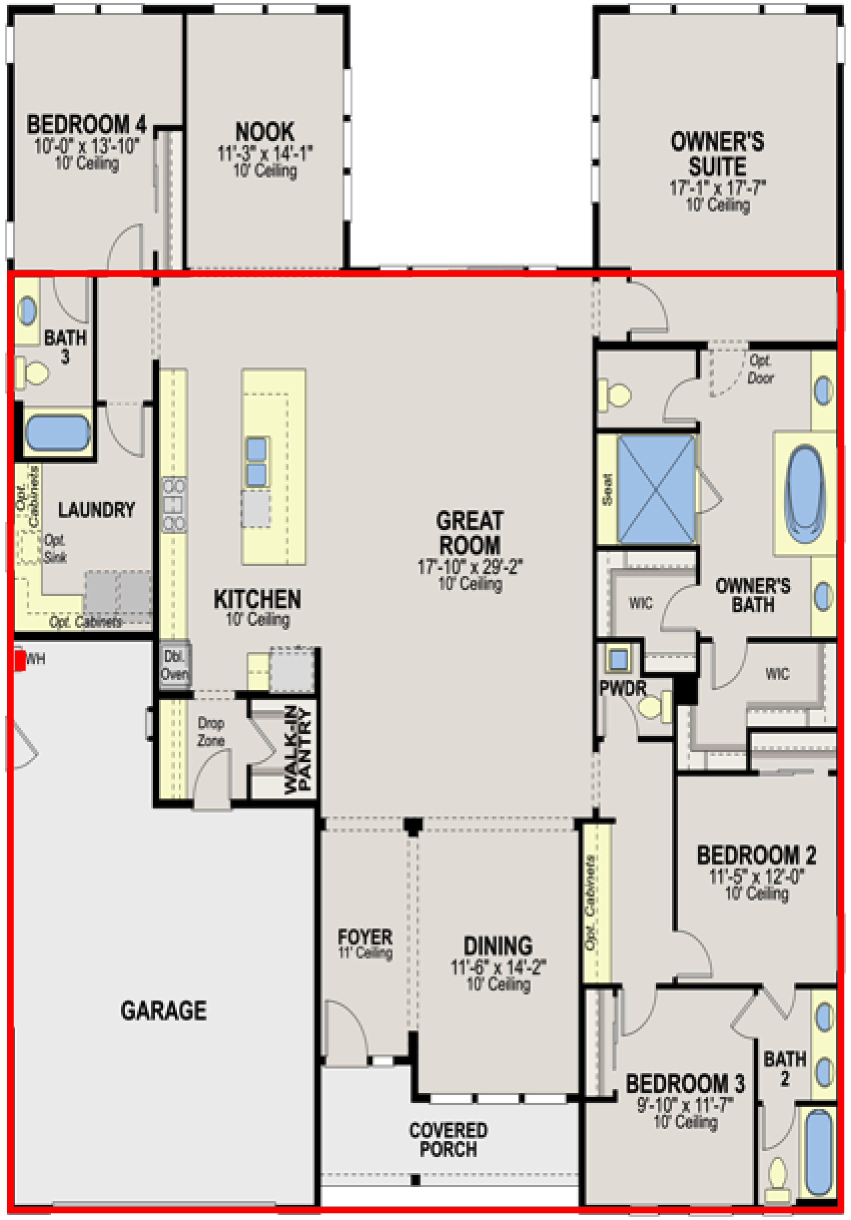
1 Story
2 Br/2 Ba
1,224 sq ft
Chico, CA

~88%
(1,077 sq ft)



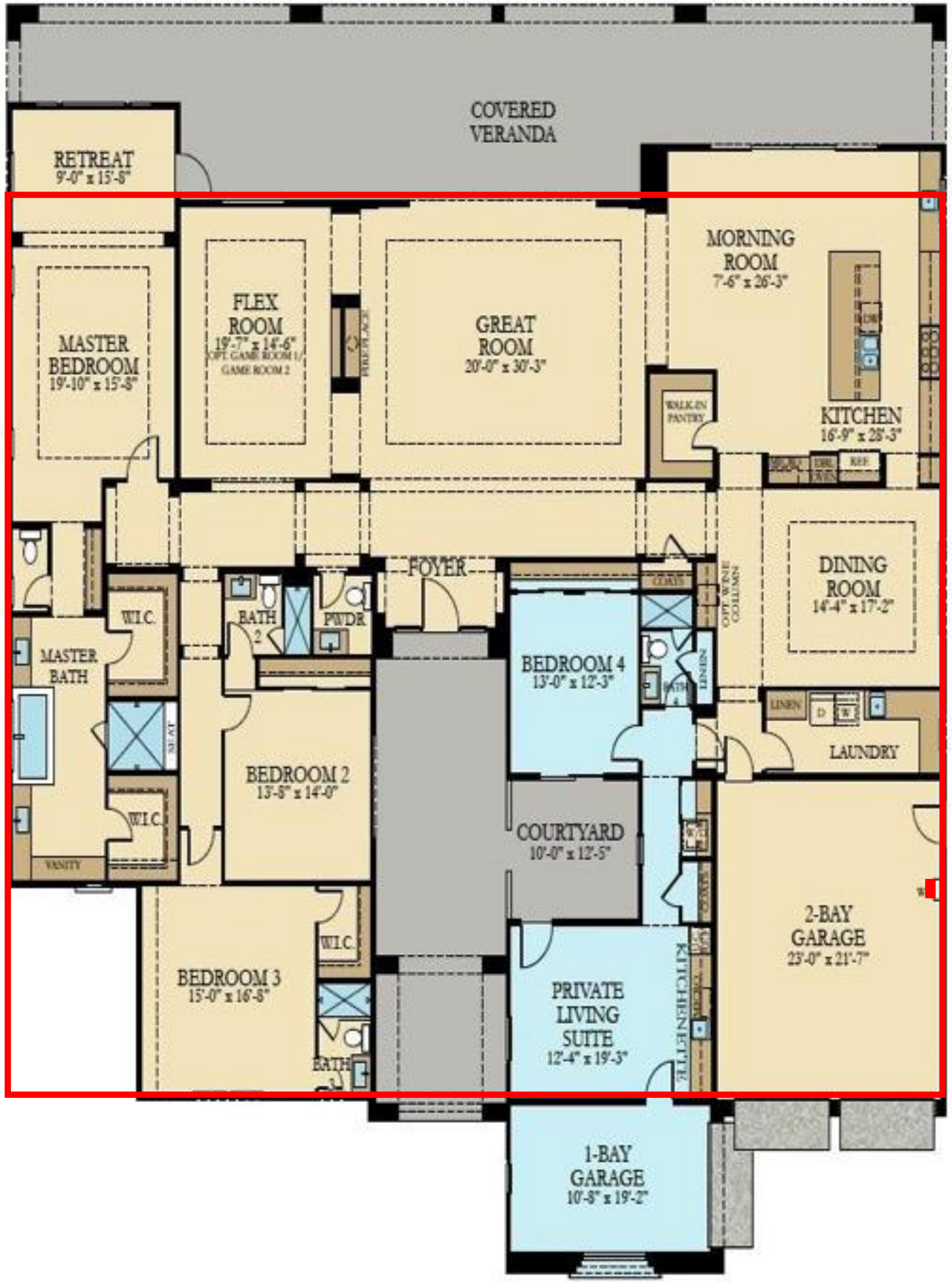
1 Story
4Br/3.5Ba
2,952 sq ft
Morgan Hill, CA

~105%
(3,100 sq ft)



1 Story
4 Br/4.5 Ba
4,820 sq ft
La Quinta, CA

~110%
(5,302 sq ft)



1 Story

5 Br/5.5Ba

4,467 sq ft

San Diego, CA

~155%

(6,924 sq ft)

Best 1-Story So Far…

In the beginning:

1 Story

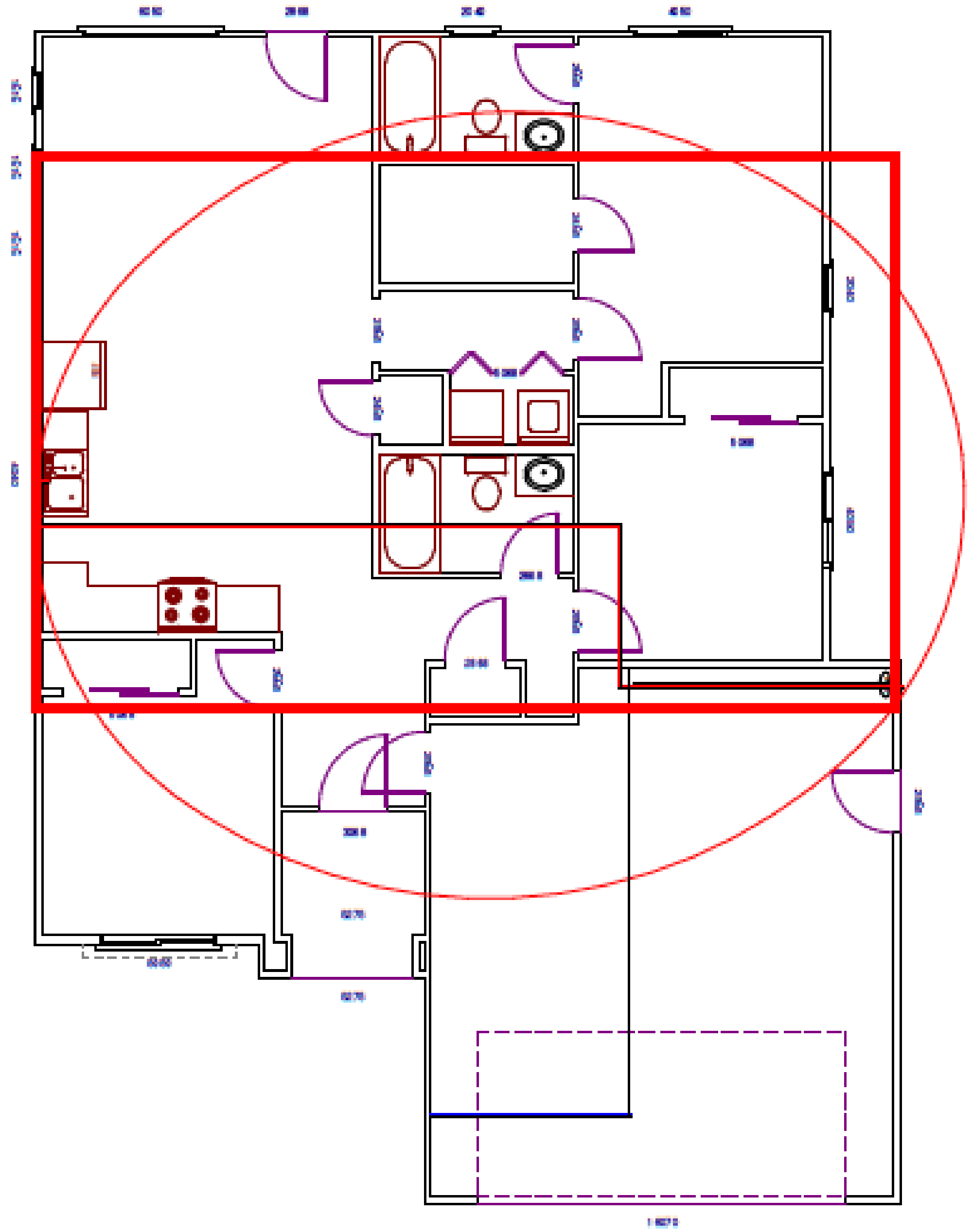
3 Br/2 Ba

1,619 sq ft

Stockton, CA

~79%

(1,279 sq ft)



1st iteration v1:

1 Story

3 Br/2 Ba

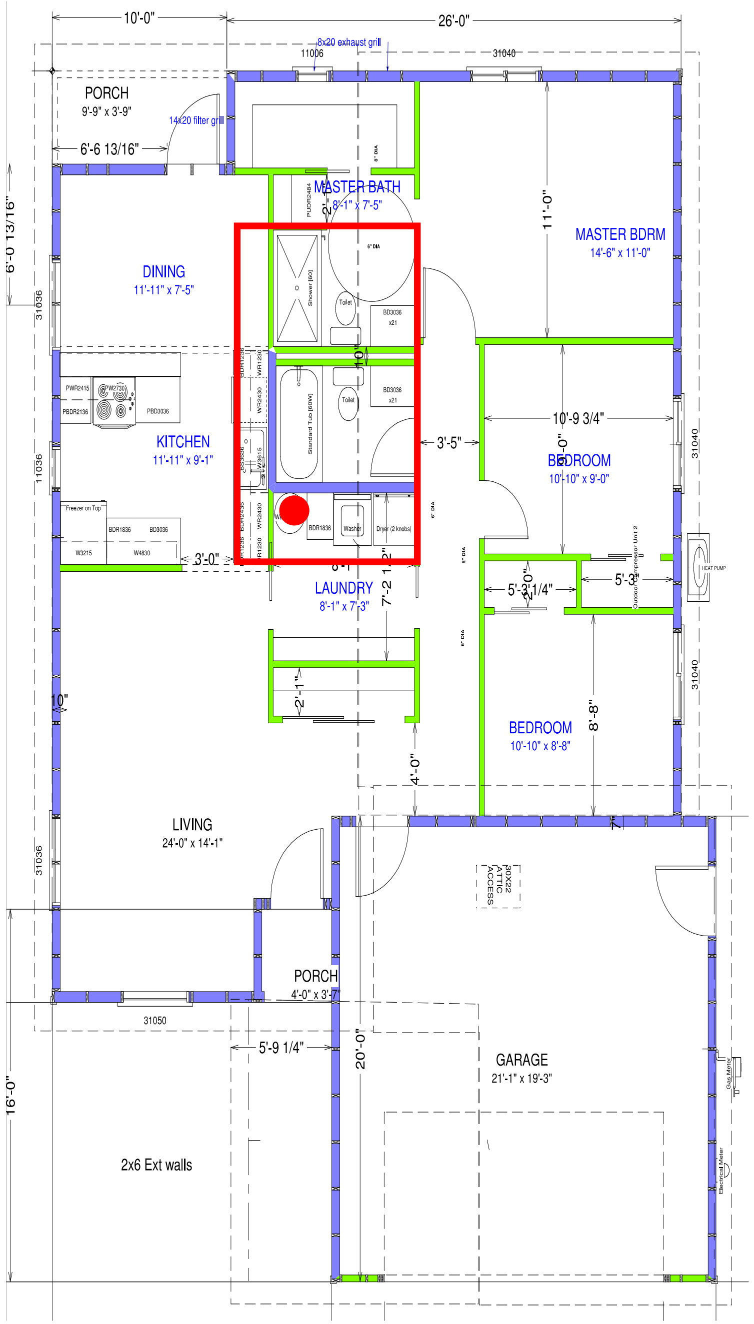
1,223 sq ft

Stockton, CA

~15%

(183 sq ft)

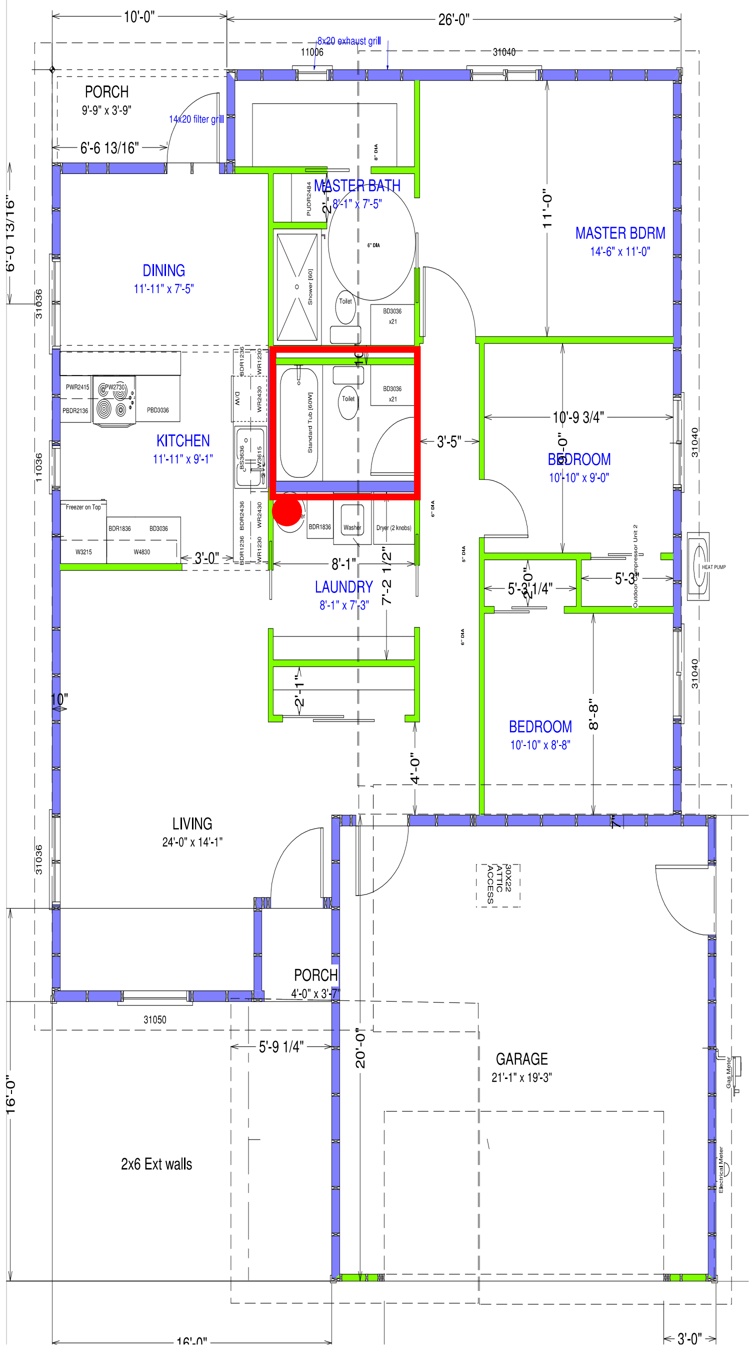
(when bounding the hot water plumbing fixtures and appliances)



<u>*1st iteration v2:*</u>

1 Story
3 Br/2 Ba
1,223 sq ft
Stockton, CA

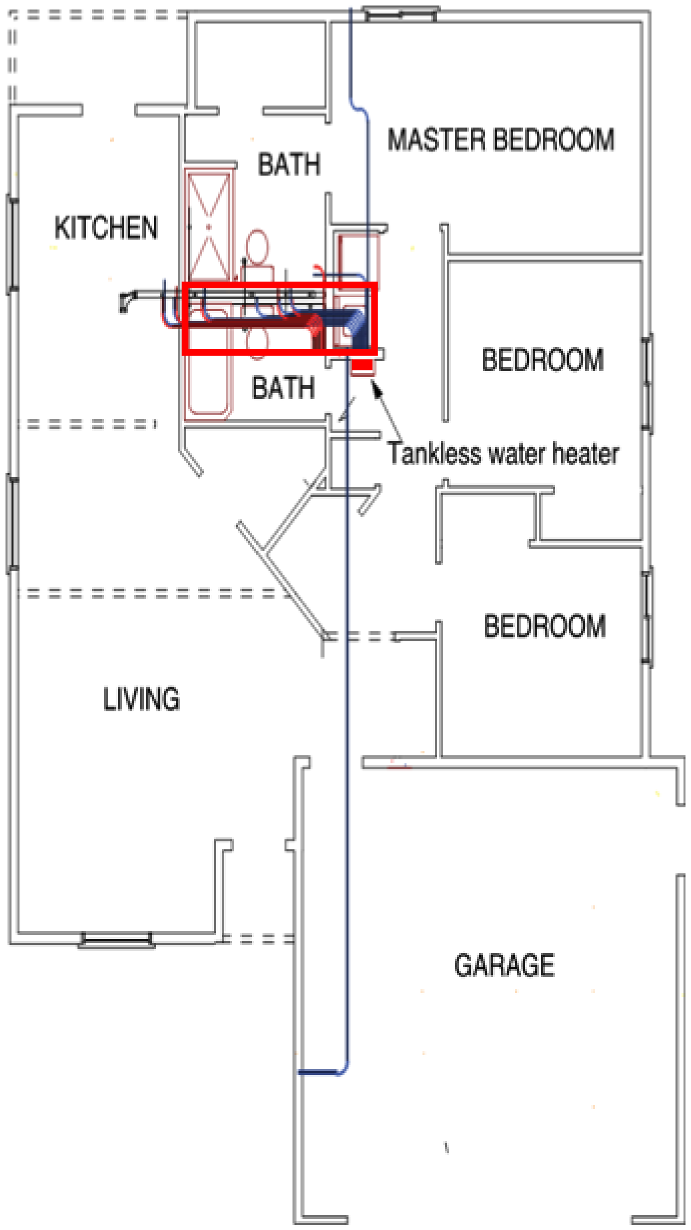
~4%
(49 sq ft)
(when bounding the plumbing walls)



2nd iteration:

1 Story
3 Br/2 Ba
1,223 sq ft
Stockton, CA

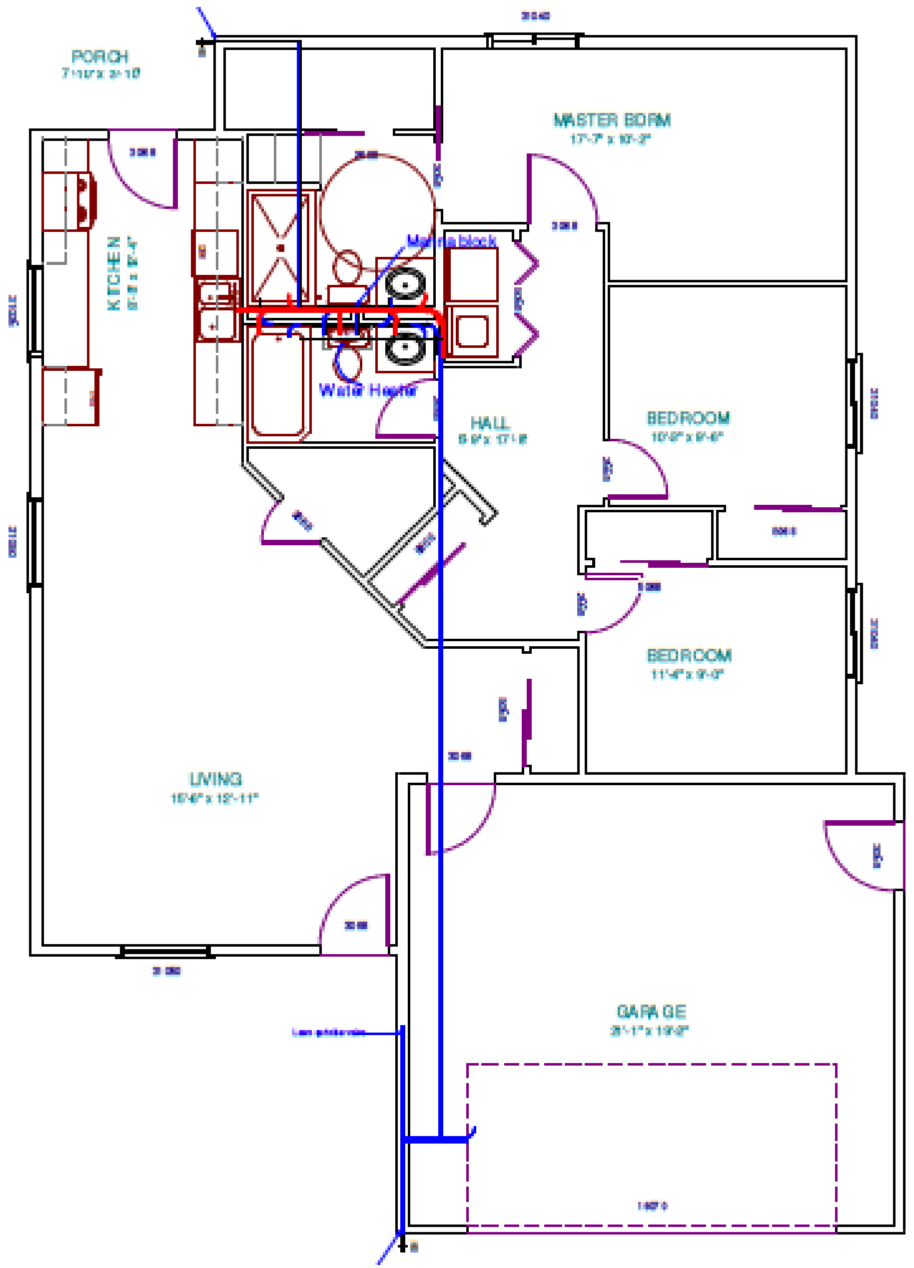
~2.5%
(30 sq ft)
(when bounding the plumbing walls)



<u>*3rd iteration:*</u>

1 Story
3 Br/2 Ba
1,245 sq ft
Stockton, CA

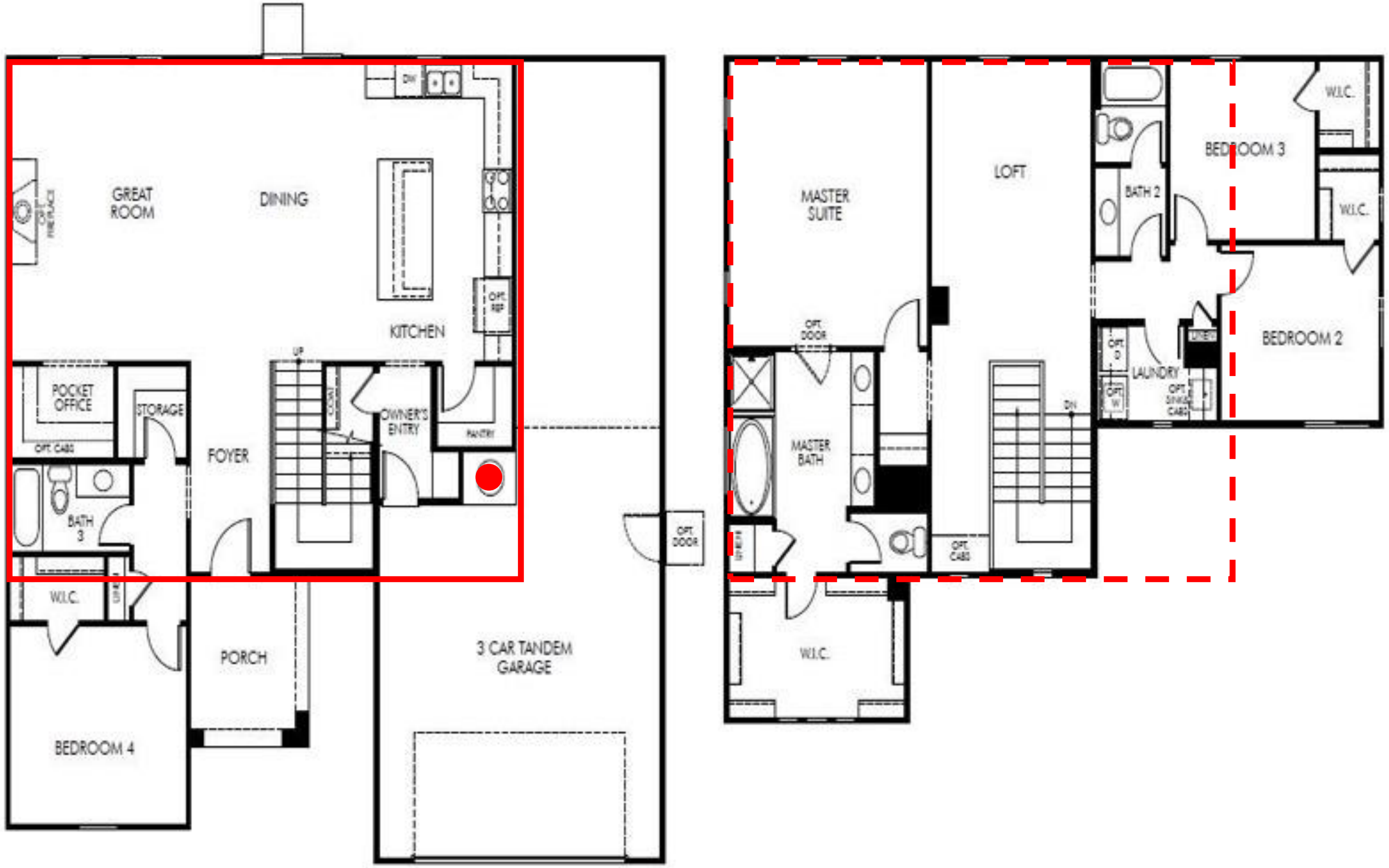
~0.8%
(< 10 sq ft)
(1 short
plumbing wall)



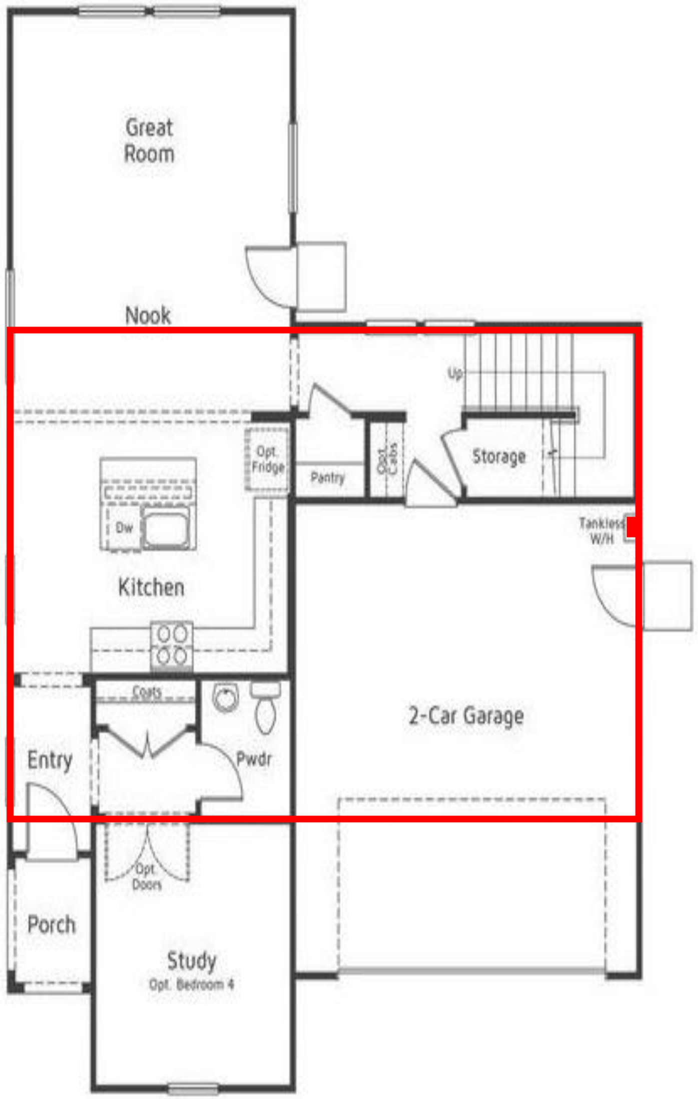
2-Story Floor Plans

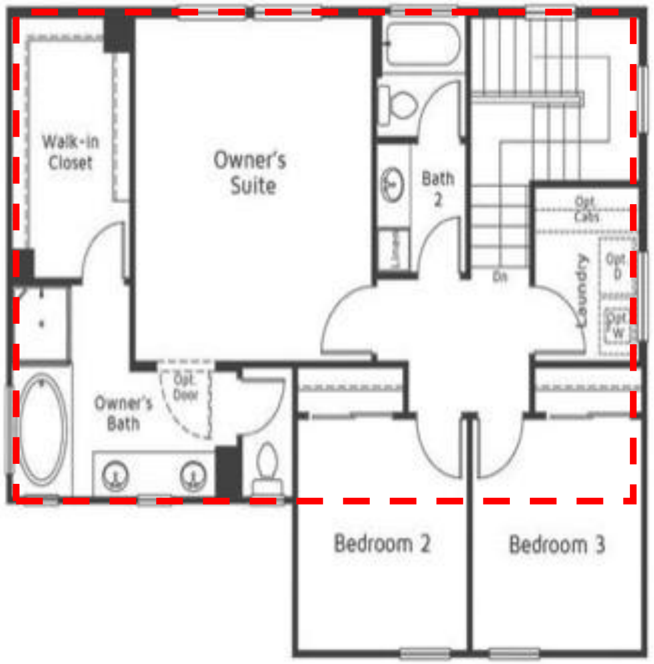
The wet room rectangle has the same area as the hot water system rectangle for all of the 2-story homes in this sample.

2 Story, 4 Br/3 Ba, 2,625 sq ft
Bakersfield, CA ~37% (962 sq ft)

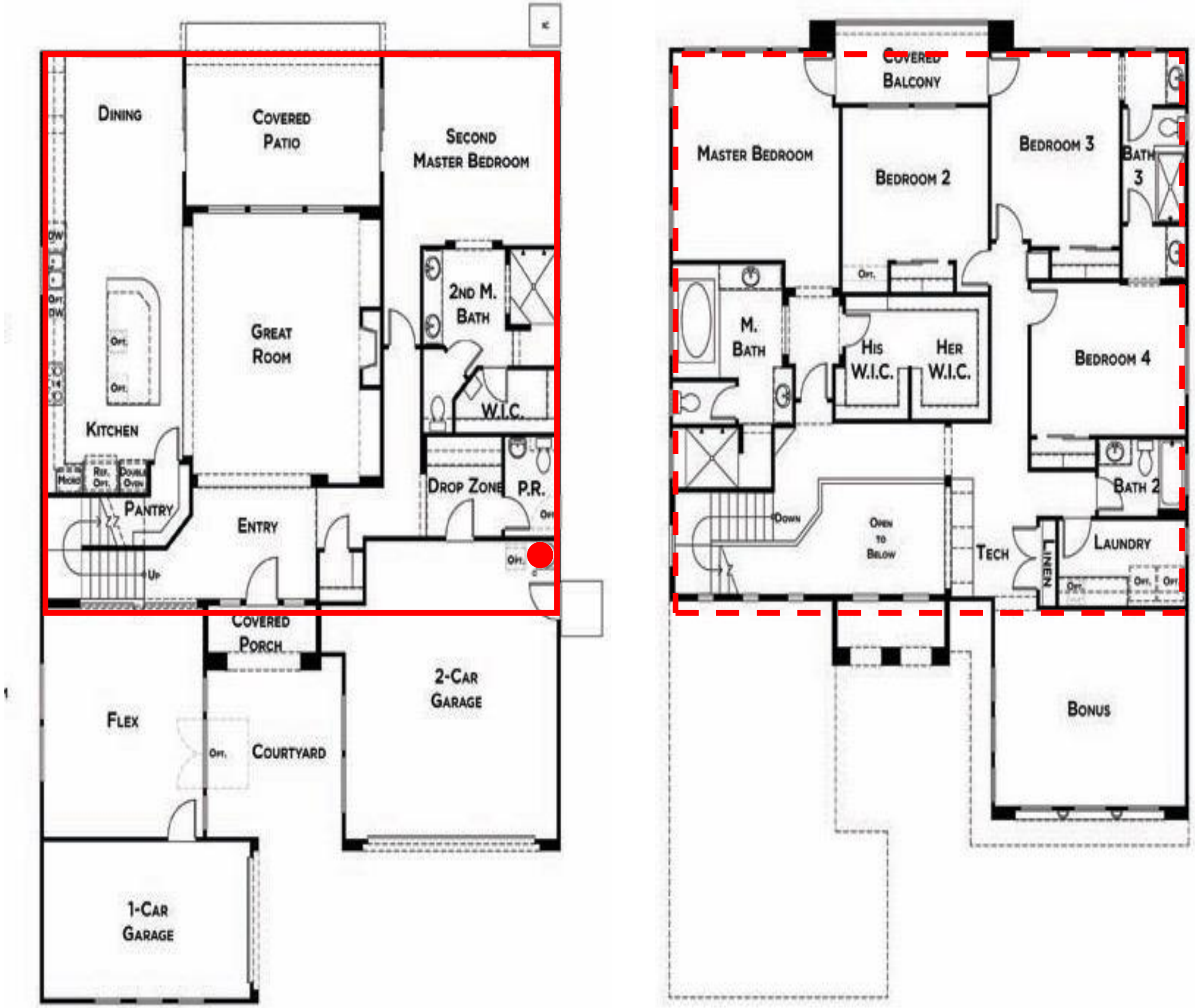


2 Story, 3 Br/2.5 Ba, 1,837 sq ft
Salinas, CA ~48% (882 sq ft)



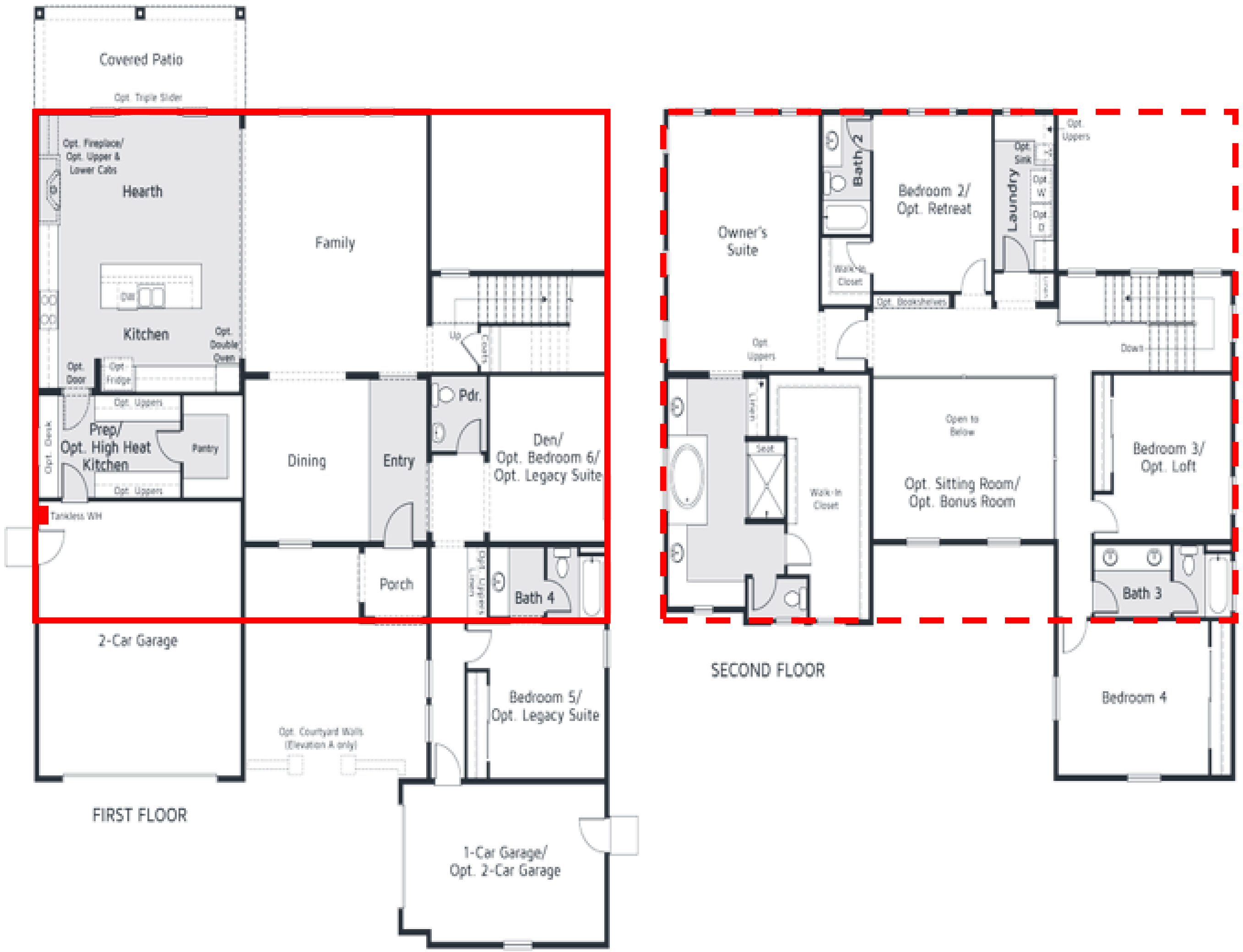


2 Story, 5 Br/4.5 Ba, 4,003 sq ft
Rocklin, CA ~51% (2,042 sq ft)

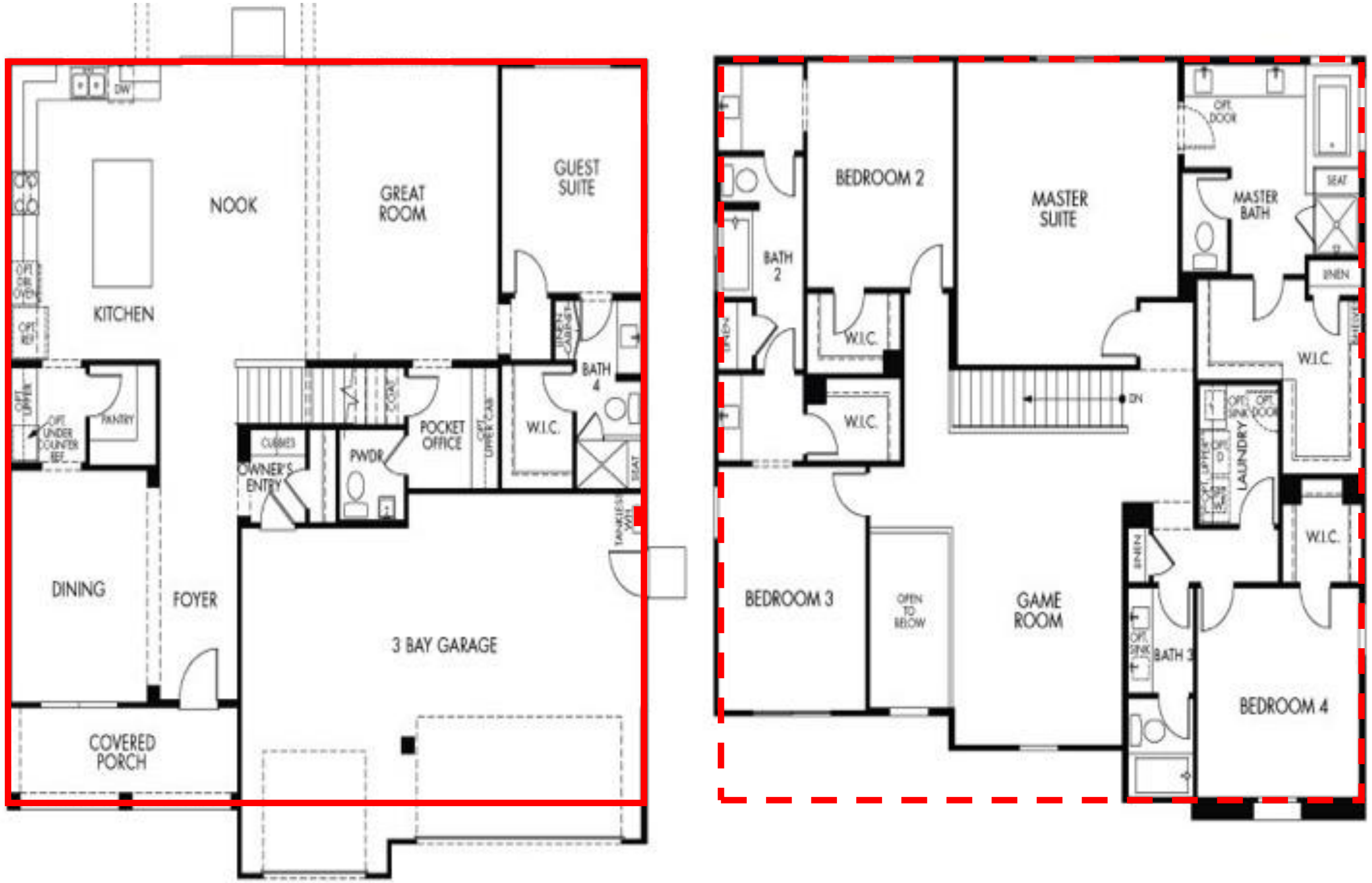


2 Story, 5 Br/5.5 Ba, 3,983 sq ft
Irvine, CA ~58% (2,310 sq ft)

2 Story, 5 Br/ 4.5 Ba, 4,301 sq ft
Rancho Cucamonga, CA ~62% (2,667 sq ft)

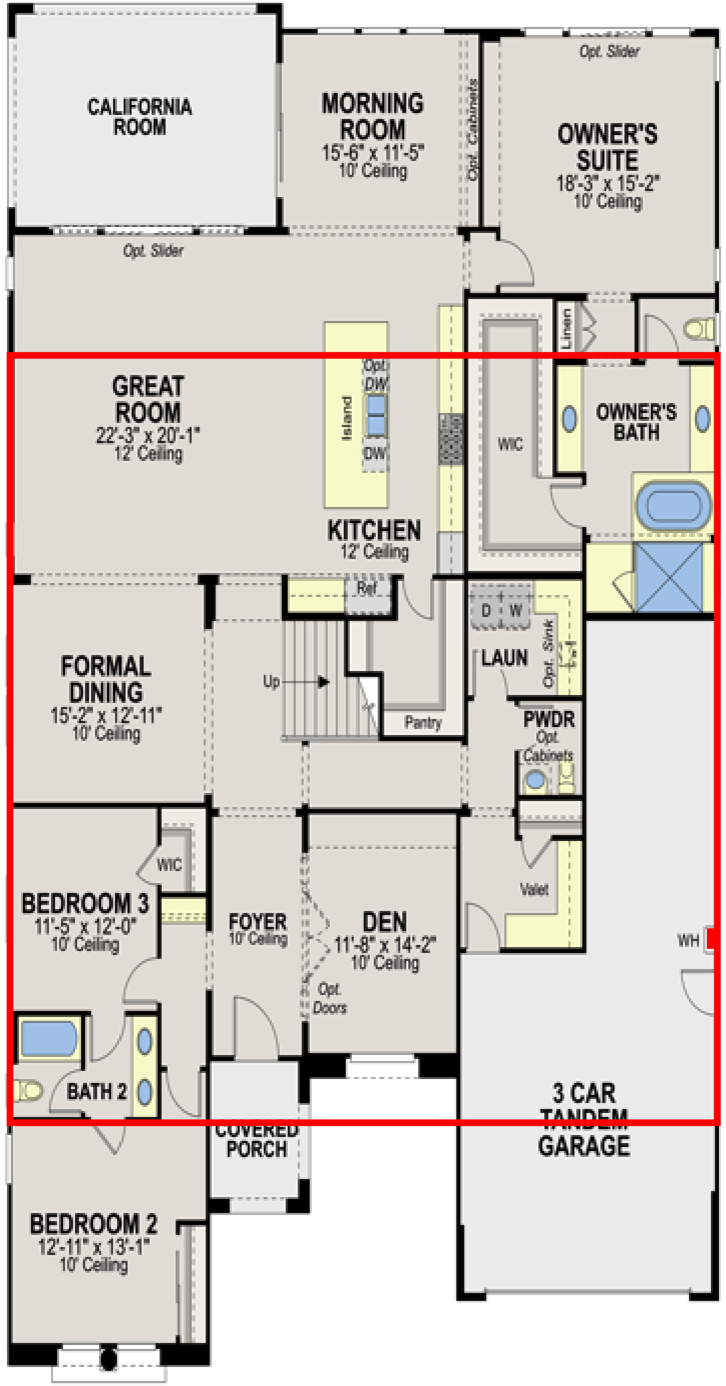


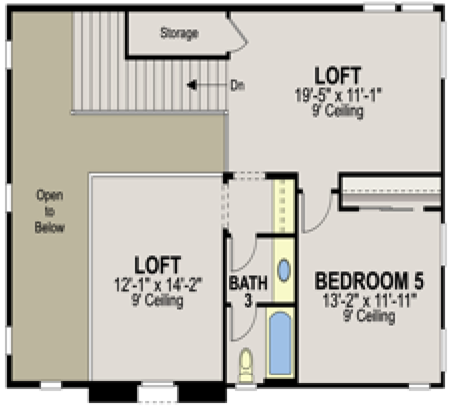
2 Story, 5 BR/4.5 Ba, 3,493 sq ft
Manteca, CA ~63% (3,493 sq ft)



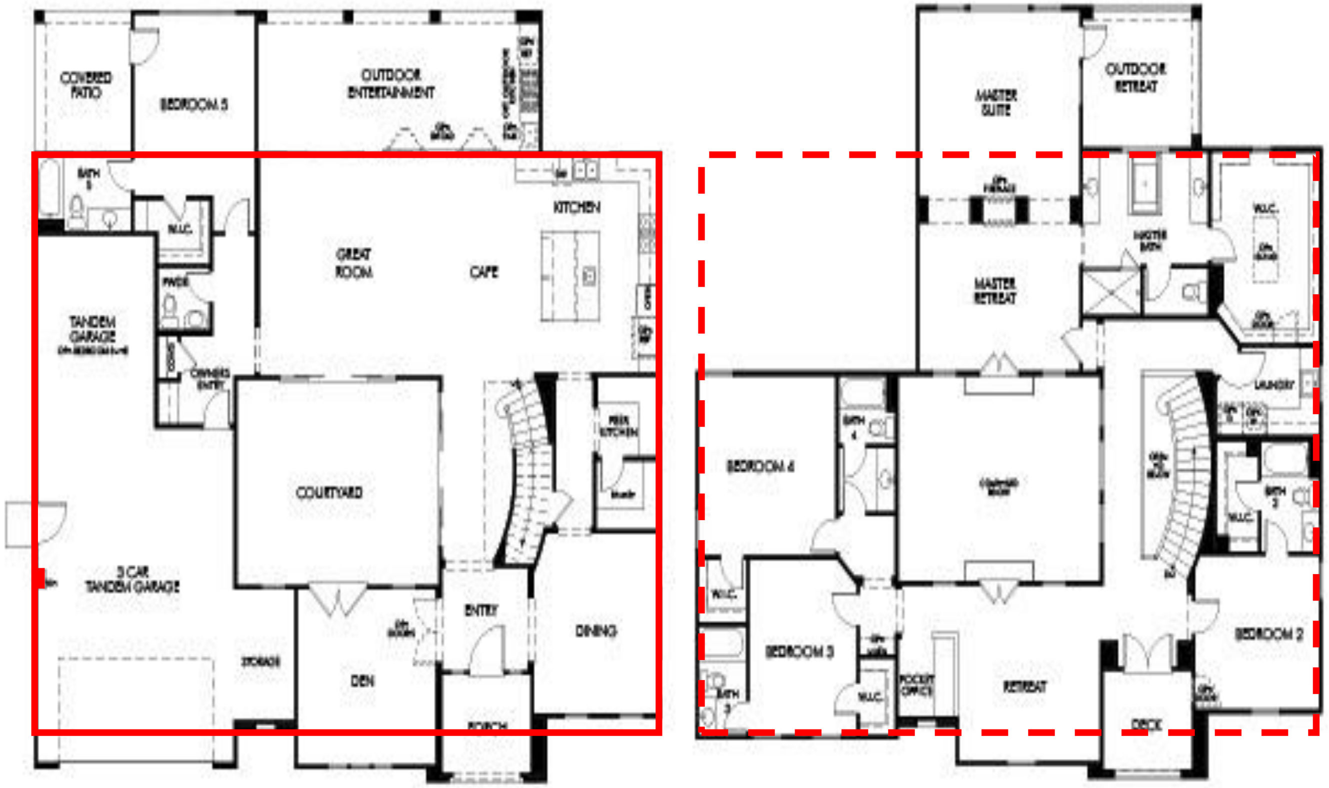
2 Story
4 Br/3.5 Ba
3,853 sq ft
Lincoln, CA

~71 %
(2,026 sq ft)



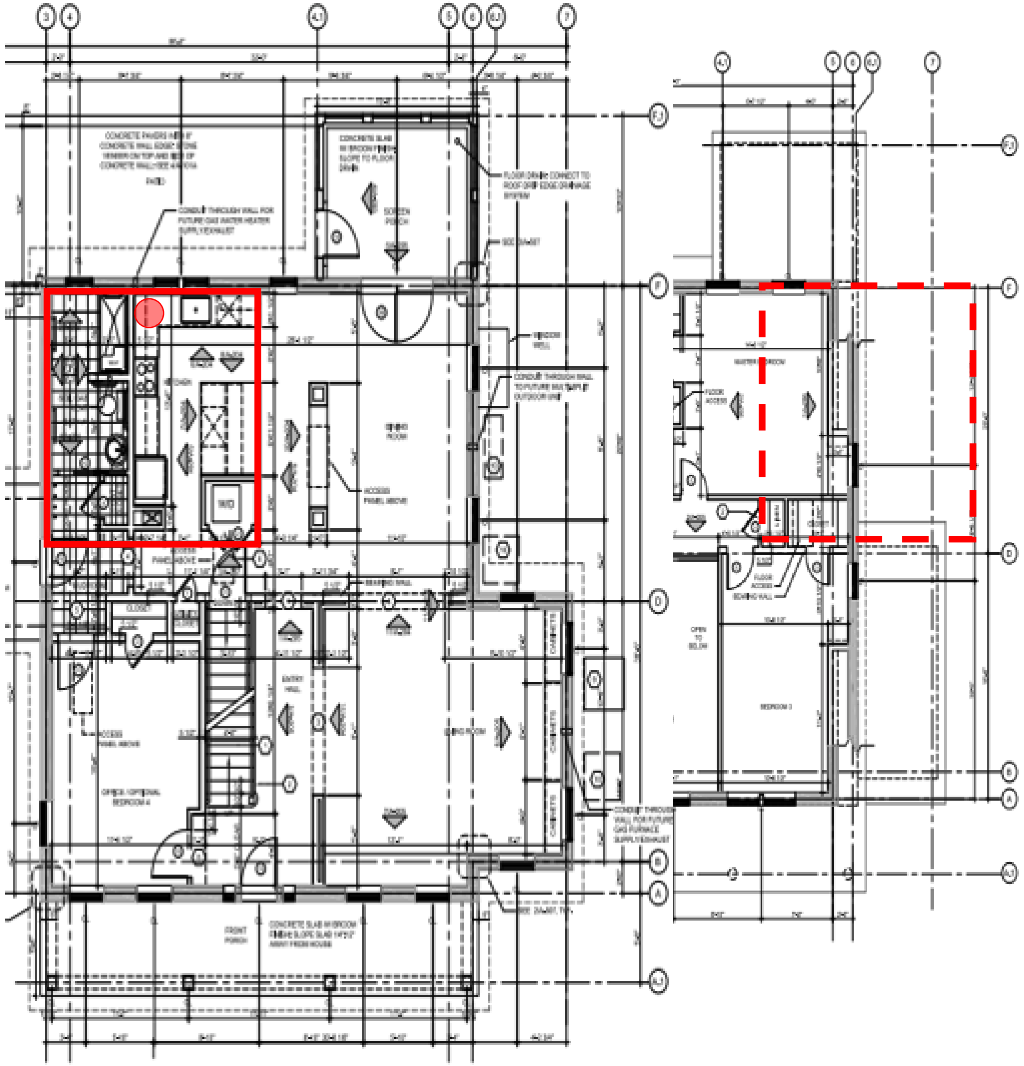


2 Story, 5 Br/5.5 Ba, 4,269 sq ft
La Verne, CA ~72% (3,074 sq ft)



Best 2-Story So Far…

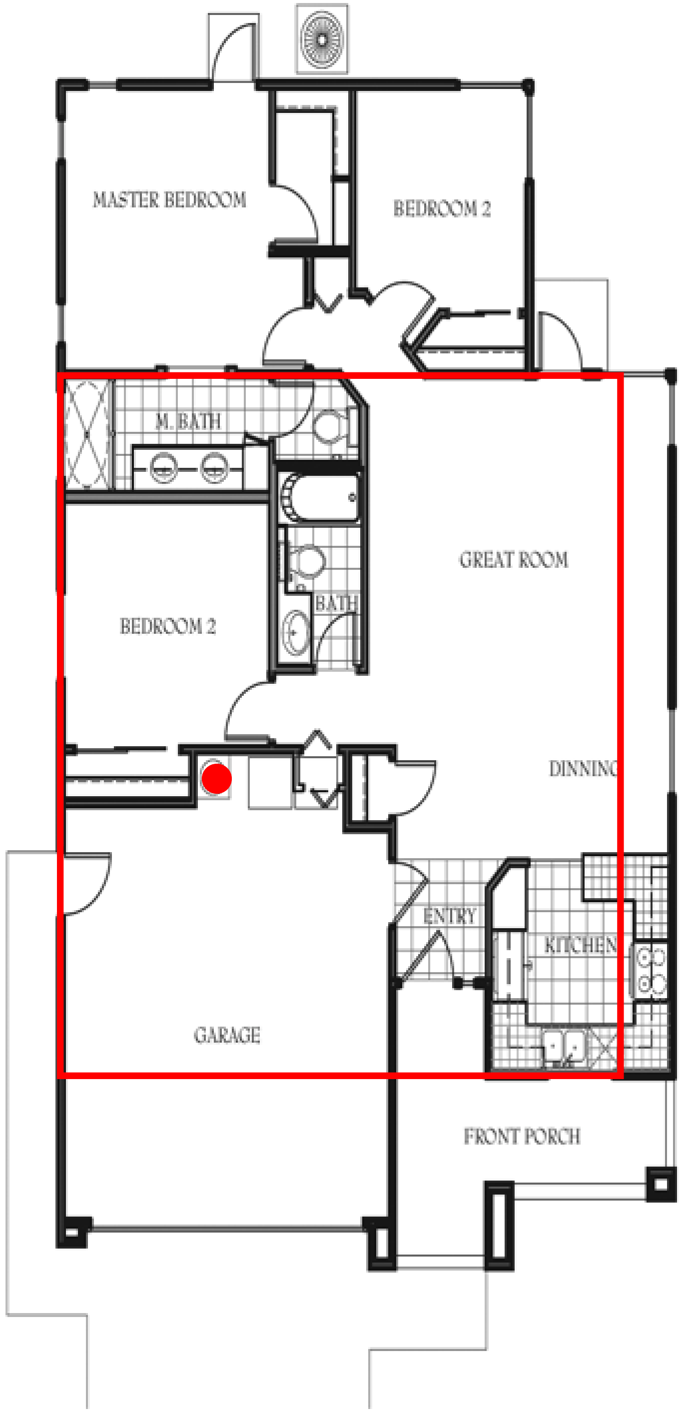
2 Story, 4Br / 3Ba, 2,709 sq ft
Gaithersburg, MD ~12% (325 sq ft)



Locating water heaters nearer to the fixtures…

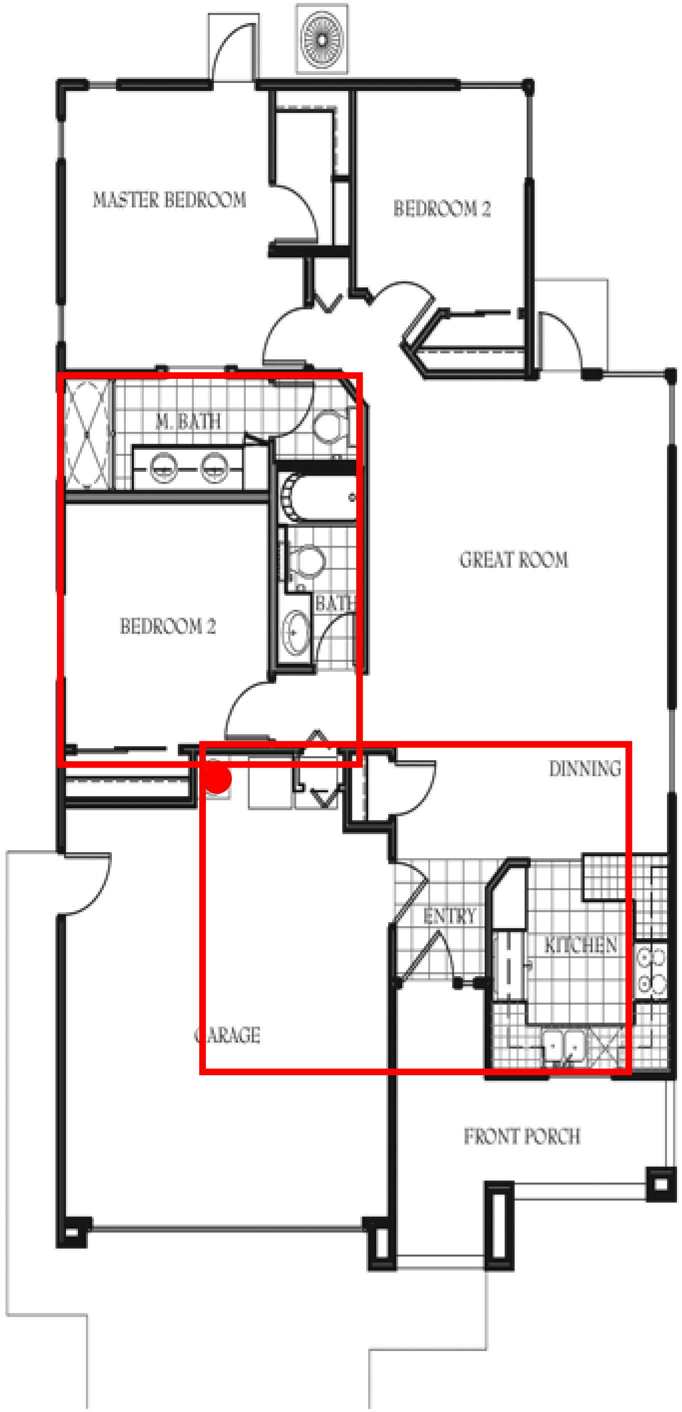
1 Story
2 Br/2 Ba
1,224 sq ft
Chico, CA

~88%
(1,077 sq ft)



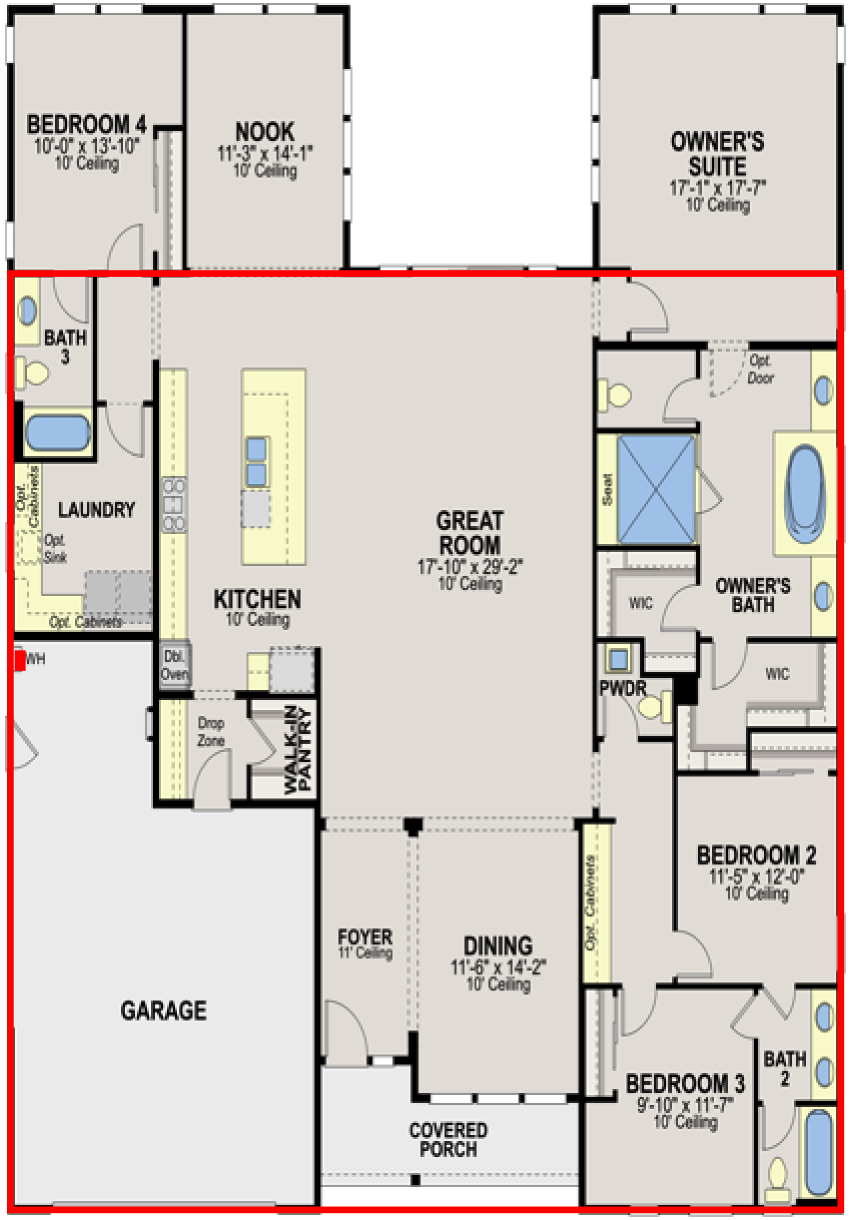
1 Story
2 Br/2 Ba
1,224 sq ft
Chico, CA

~58%
(710 sq ft)



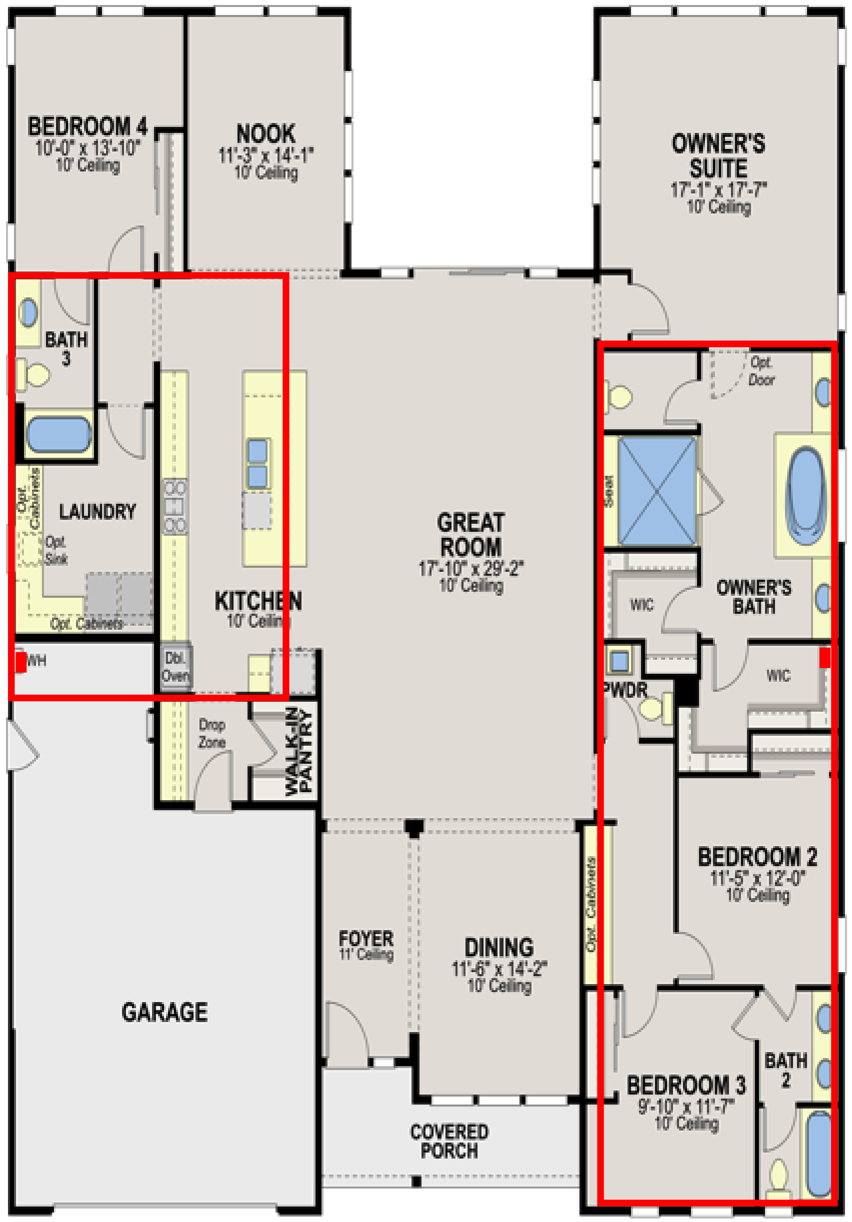
1 Story
4Br/3.5Ba
2,952 sq ft
Morgan Hill, CA

~105%
(3,100 sq ft)



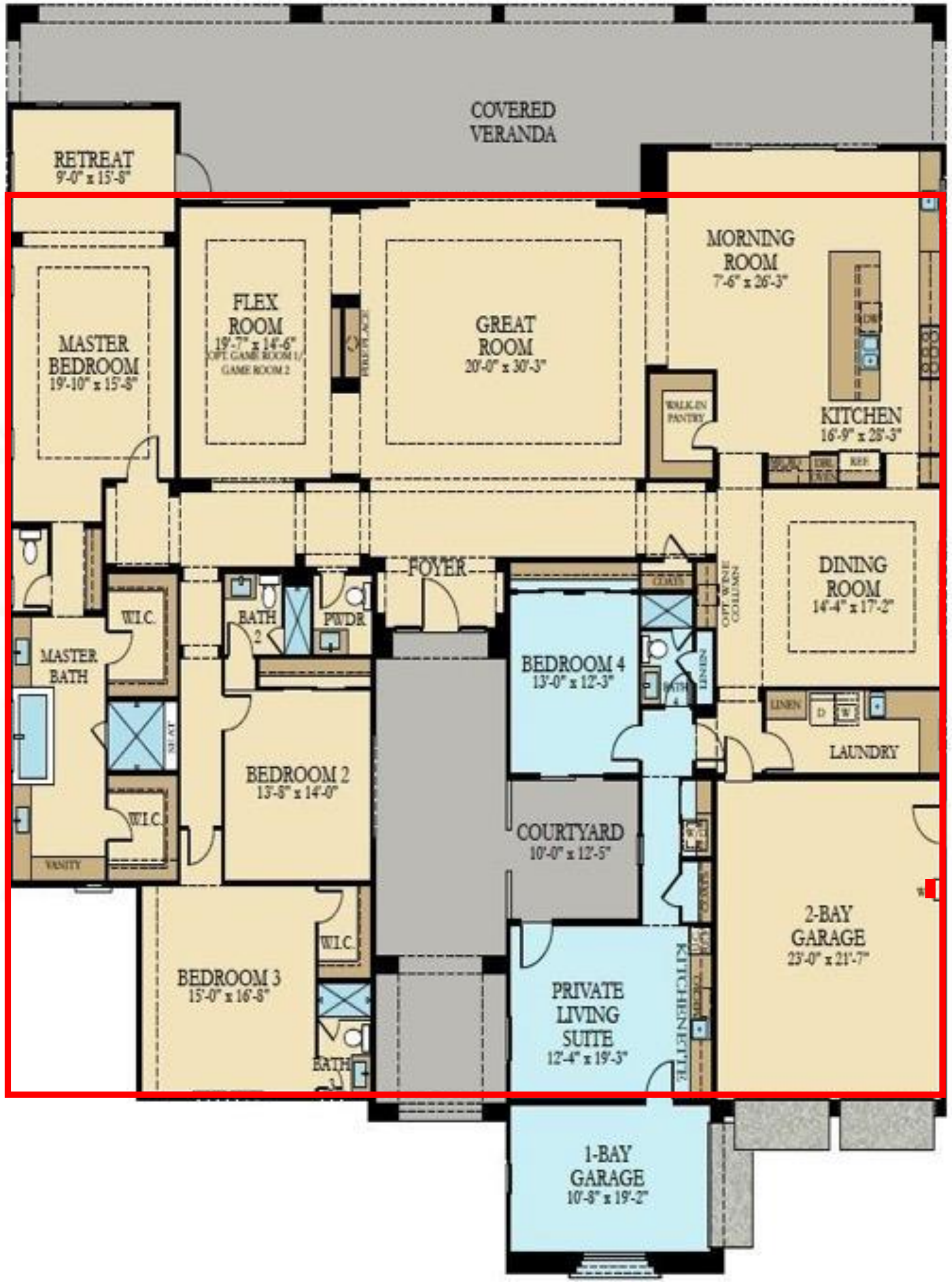
1 Story
4Br/3.5Ba
2,952 sq ft
Morgan Hill, CA

~43%
(1,269 sq ft)



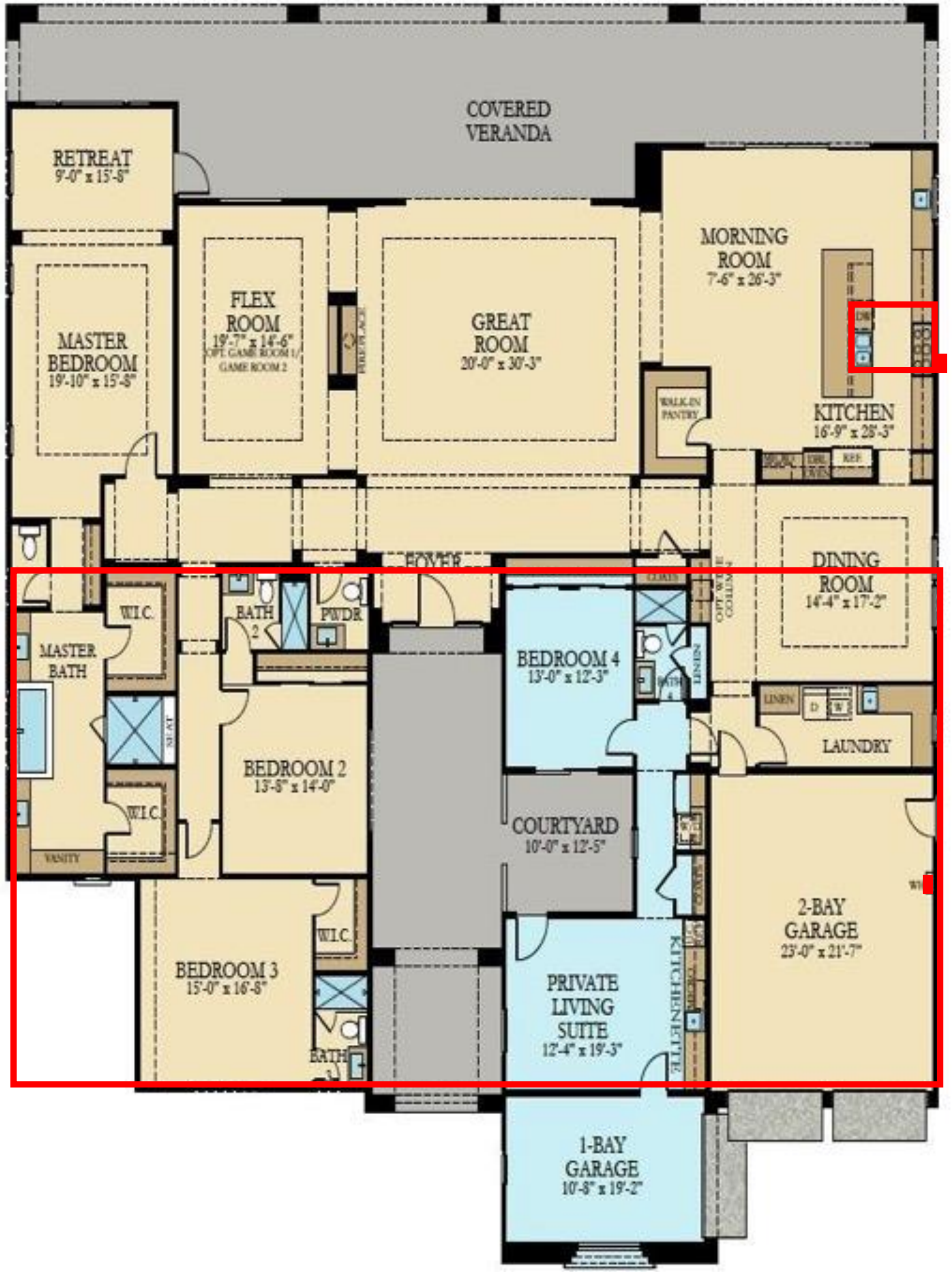
1 Story
4 Br/4.5 Ba
4,820 sq ft
La Quinta, CA

~110%
(5,302 sq ft)



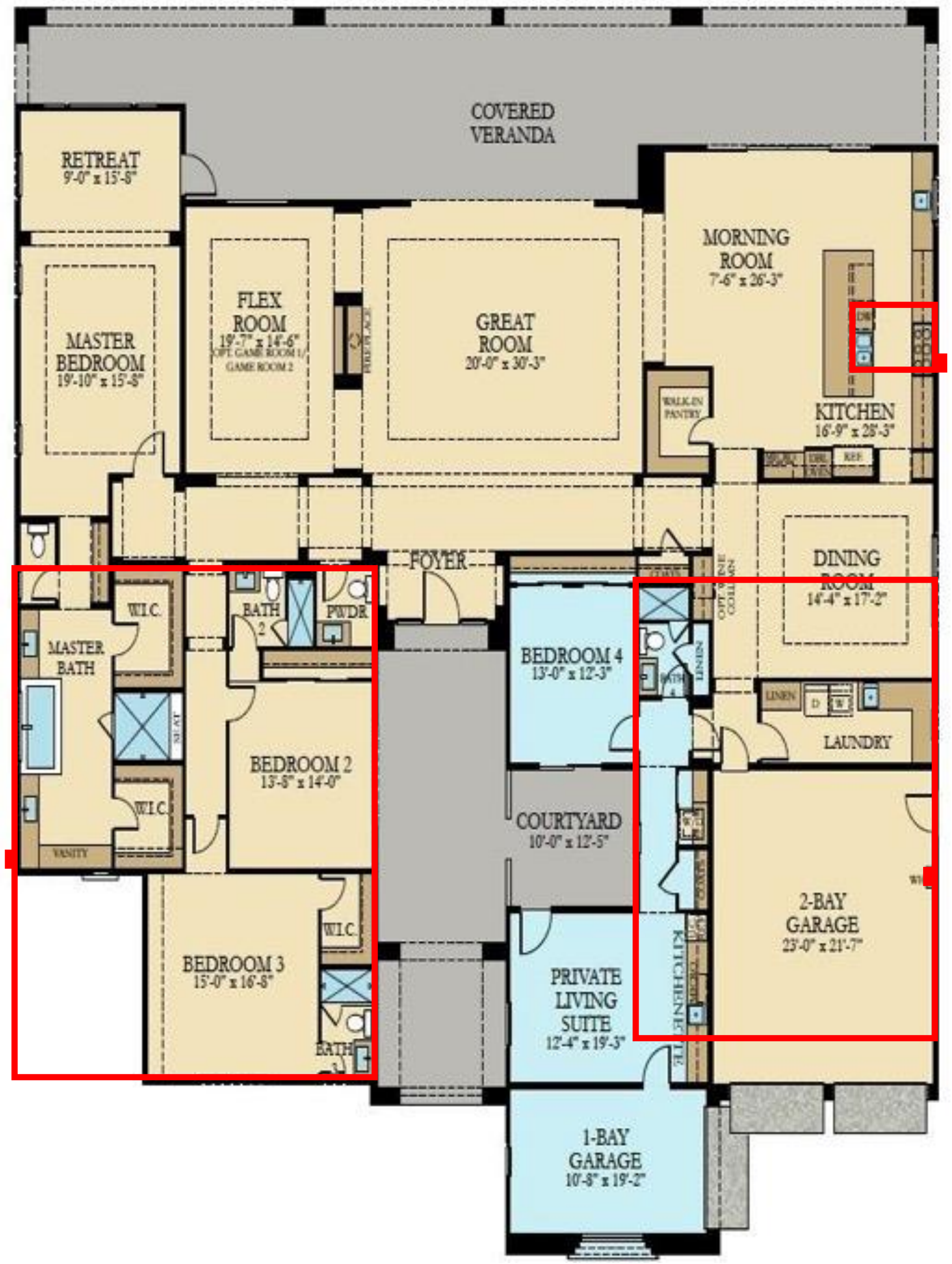
1 Story
4 Br/4.5 Ba
4,820 sq ft
La Quinta, CA

~64%
(3,085 sq ft)



1 Story
4 Br/4.5 Ba
4,820 sq ft
La Quinta, CA

~44%
(2,120 sq ft)



Flow Rates for Faucets, Tubs and Showers

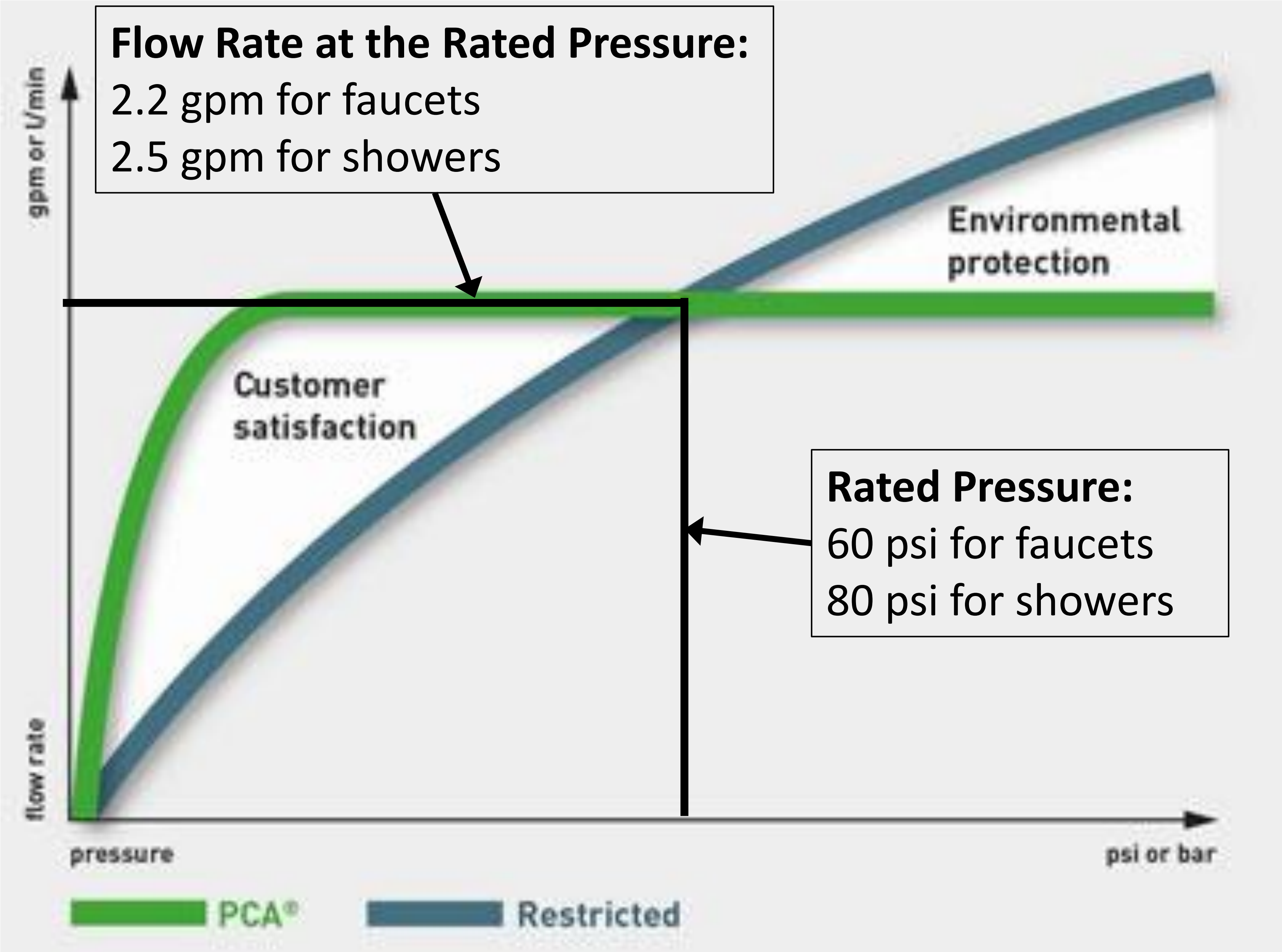
Fixture	Flow Rate-Rated (gpm)	Flow Rate- All Hot (gpm)
Shower- stand alone	2.0 [1.0-2.5]	1.4 [60%-80%]
Tub/shower combination	5.0 [4.0-6.0	3.5 [60%-80%]
Lavatory faucet	1.5 [0.5-2.2]	1.5 [100%]
Kitchen faucet	2.0 [1.5-2.2]	2.0 [100%]

Fixed vs. Variable Orifices

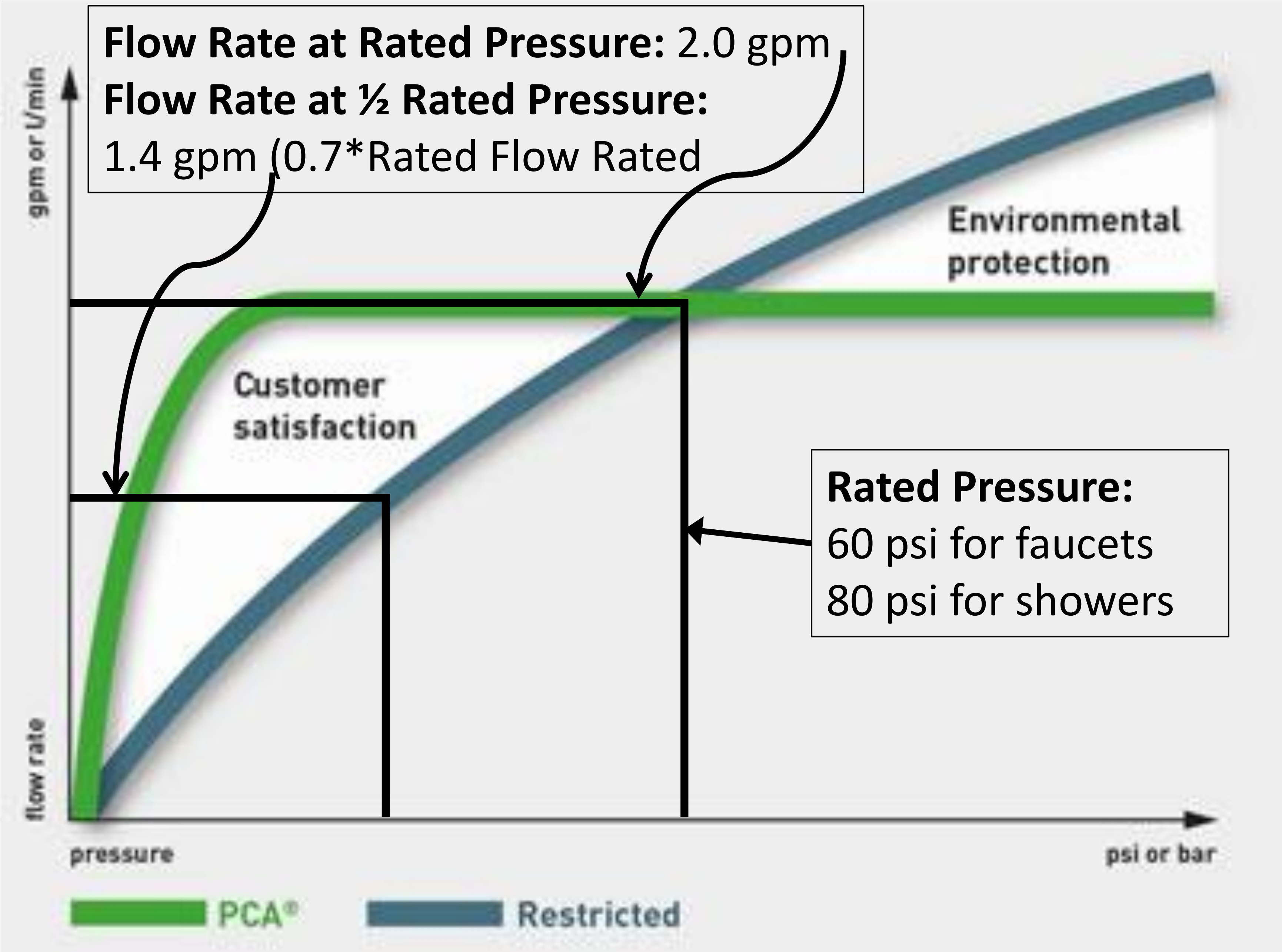
- **Fixed Orifice:**
  - High pressure: High flow rate
  - Low pressure: Low flow rate
  - Before 2000, practically all fixture fittings and appliances
- **Pressure Compensating Aerators**
  - Adjusts flow rate to compensate for available pressure
  - Almost the same flow rate for all pressures above 20-25 psi
  - Ramped up from 2000-2012 for showerheads
  - Today more than 90% and many faucet aerators

Pressure Compensating Aerators - 1

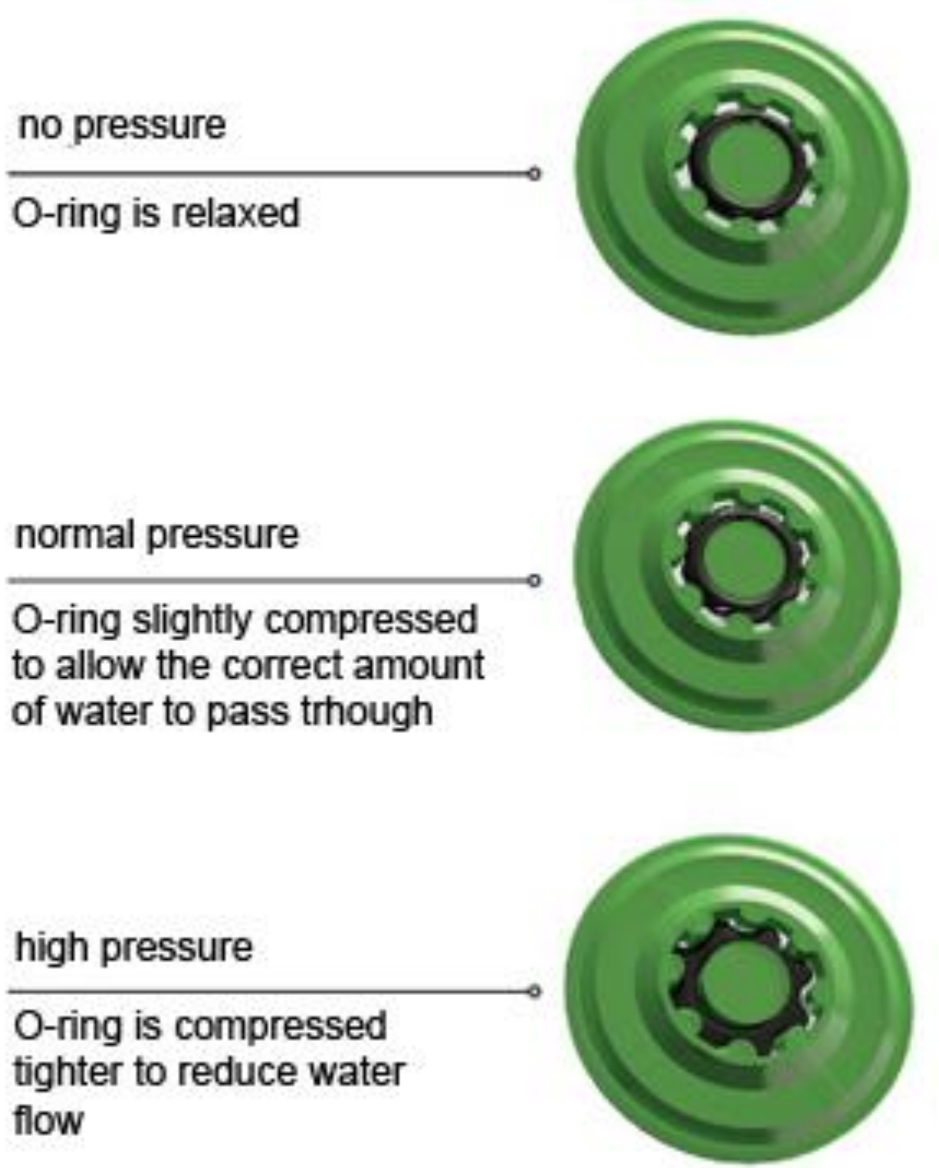
Pressure Compensating Aerators - 2



Pressure Compensating Aerators - 3



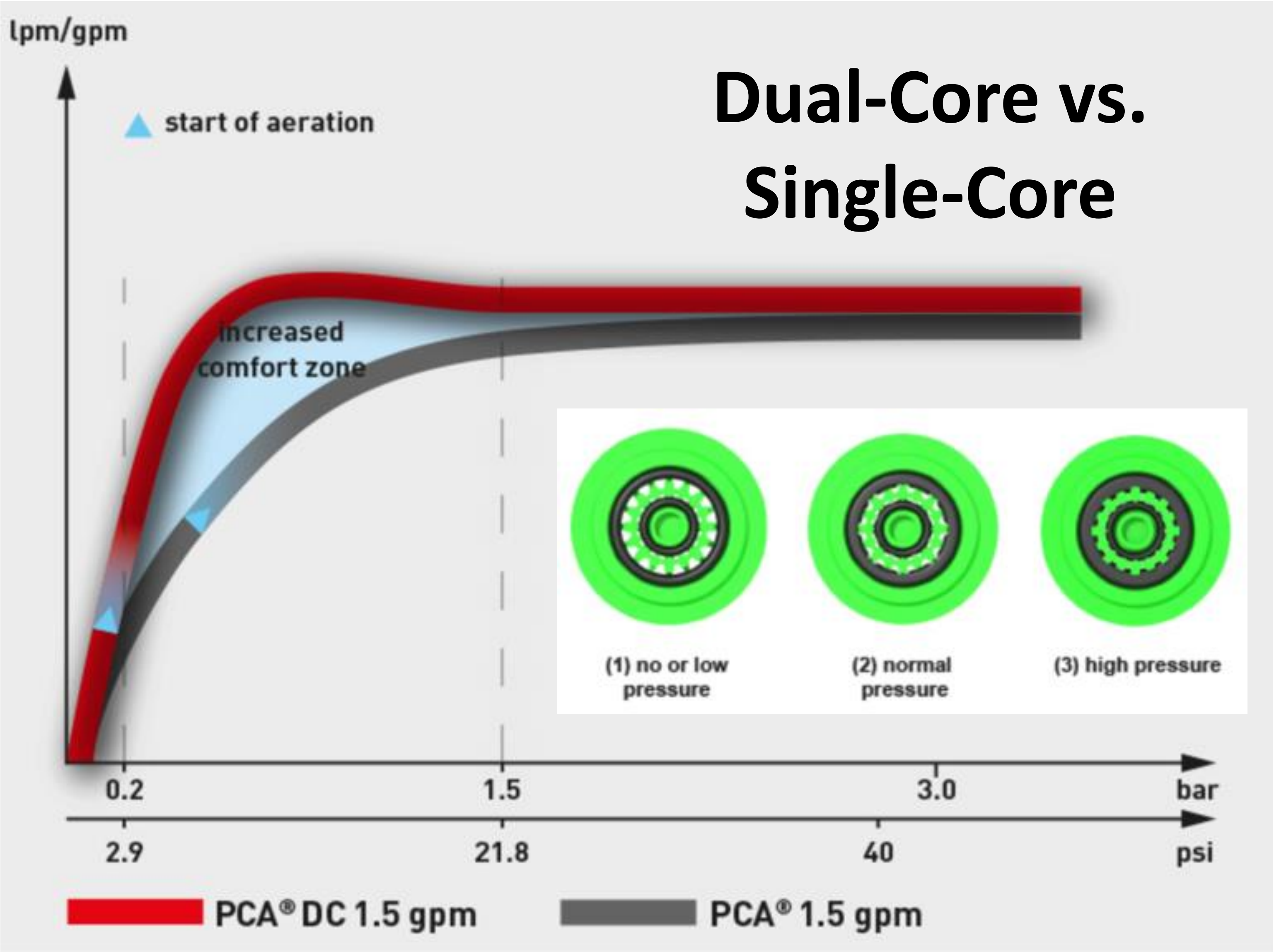
Pressure Compensating Aerators - 4



A pressure compensating flow regulator maintains a constant flow regardless of variations in line pressure thereby optimizing system performance and comfort of use at all pressures.

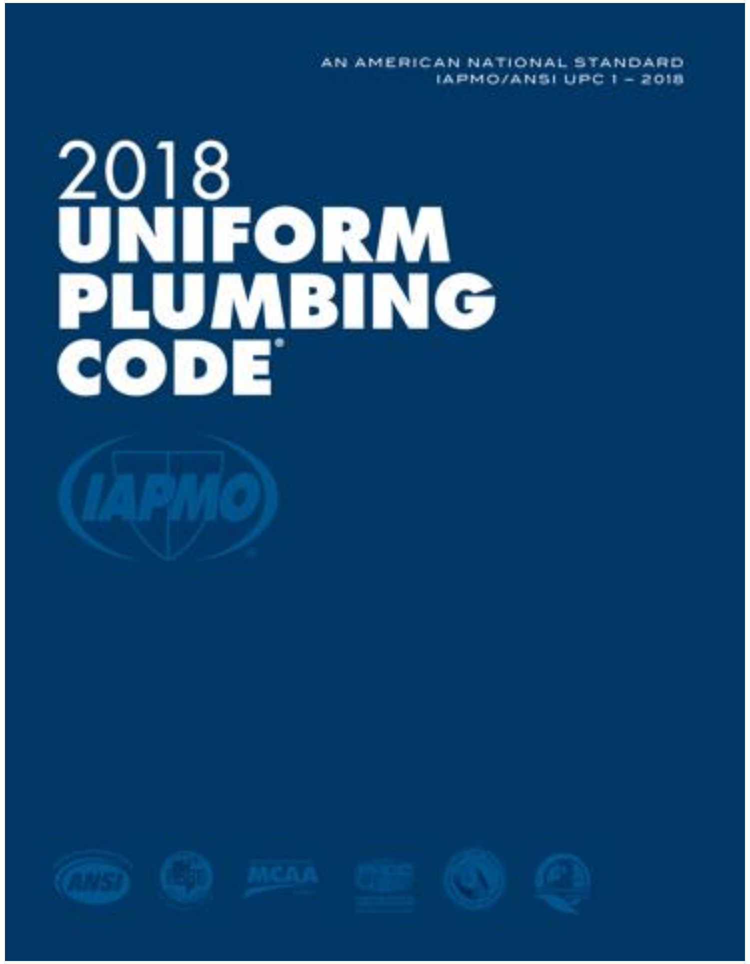
Source: Neoperl's website for this and the pressure-flow diagrams

Pressure Compensating Aerators - 5



Pipe Sizing for Peak Flows

Standard Method



Appendix M: Water Demand Calculator

↓ Select Units ↓

Tuesday, July 24, 2018 11:04 PM

PROJECT NAME : XXX-XXX

GPM | LPM | LPS

FIXTURE GROUPS		[A] FIXTURE	[B] ENTER NUMBER OF FIXTURES	[C] PROBABILITY OF USE (%)	[D] ENTER FIXTURE FLOW RATE (GPM)	[E] MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
Bathroom Fixtures	1	Bathtub (no Shower)	0	1.0	5.5	5.5
	2	Bidet	0	1.0	2.0	2.0
	3	Combination Bath/Shower	0	5.5	5.5	5.5
	4	Faucet, Lavatory	0	2.0	1.5	1.5
	5	Shower, per head (no Bathtub)	0	4.5	2.0	2.0
	6	Water Closet, 1.28 GPF Gravity Tank	0	1.0	3.0	3.0
Kitchen Fixtures	7	Dishwasher	0	0.5	1.3	1.3
	8	Faucet, Kitchen Sink	0	2.0	2.2	2.2
Laundry Room Fixtures	9	Clothes Washer	0	5.5	3.5	3.5
	10	Faucet, Laundry	0	2.0	2.0	2.0
Bar/Prep Fixtures	11	Faucet, Bar Sink	0	2.0	1.5	1.5
Other Fixtures	12	Fixture 1	0	0.0	0.0	6.0
	13	Fixture 2	0	0.0	0.0	6.0
	14	Fixture 3	0	0.0	0.0	6.0

Total Number of Fixtures 0

99th PERCENTILE DEMAND FLOW = GPM

RESET

RUN WATER DEMAND CALCULATOR

↑ CLICK BUTTON ↑

http://www.iapmo.org/Pages/WaterDemandCalculator.aspx

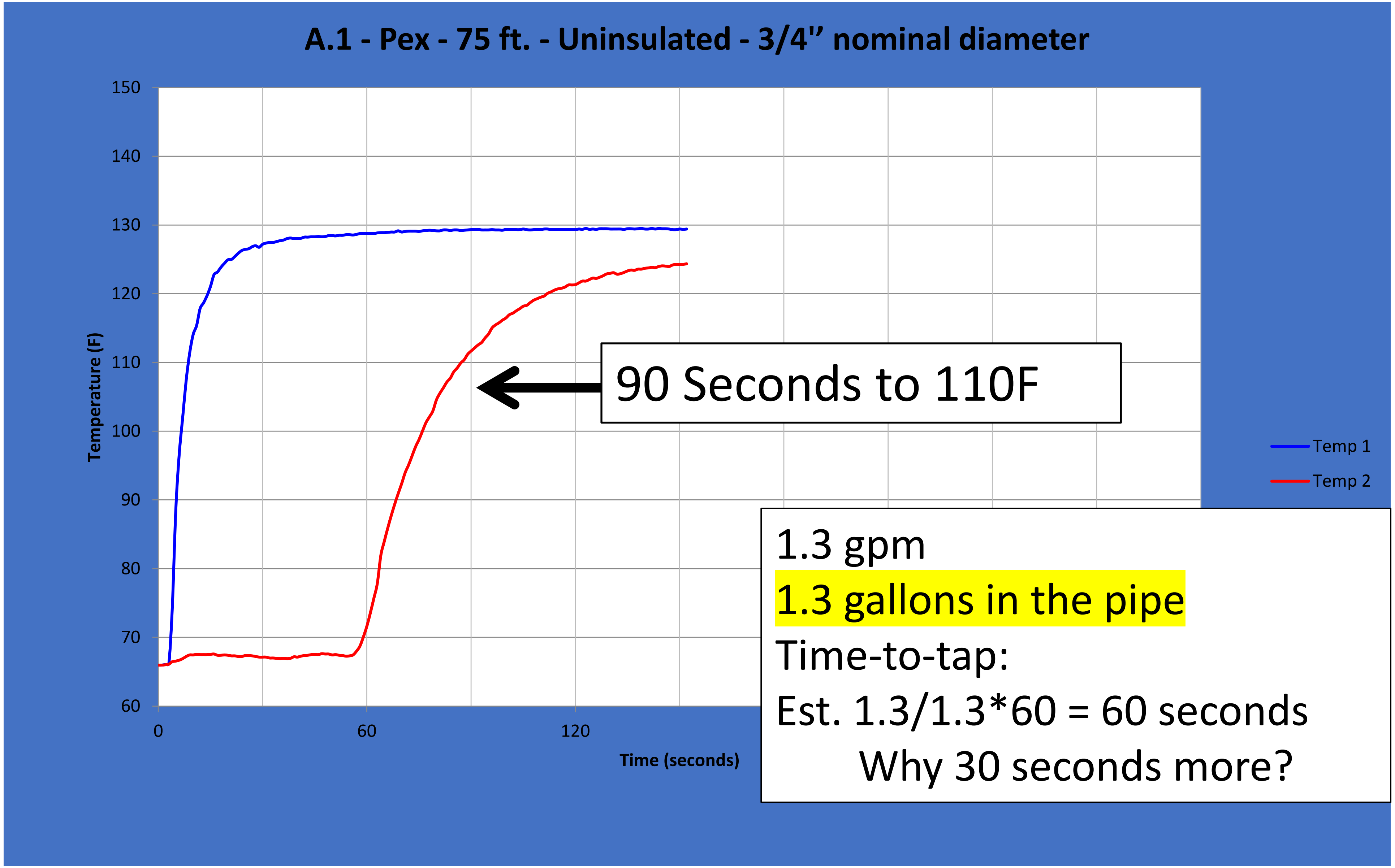
Appendix M

1. Provides a method to estimate the demand load for the building water supply and principal branches
   - For single and multi-family dwellings
   - With water conserving plumbing fixtures, fixture fittings and appliances
2. The method used in the Peak Water Demand Calculator is based on probabilities of simultaneous use from residential water use surveys and actual fixture flow rates
3. A useful tool for “right-sizing” pipe.

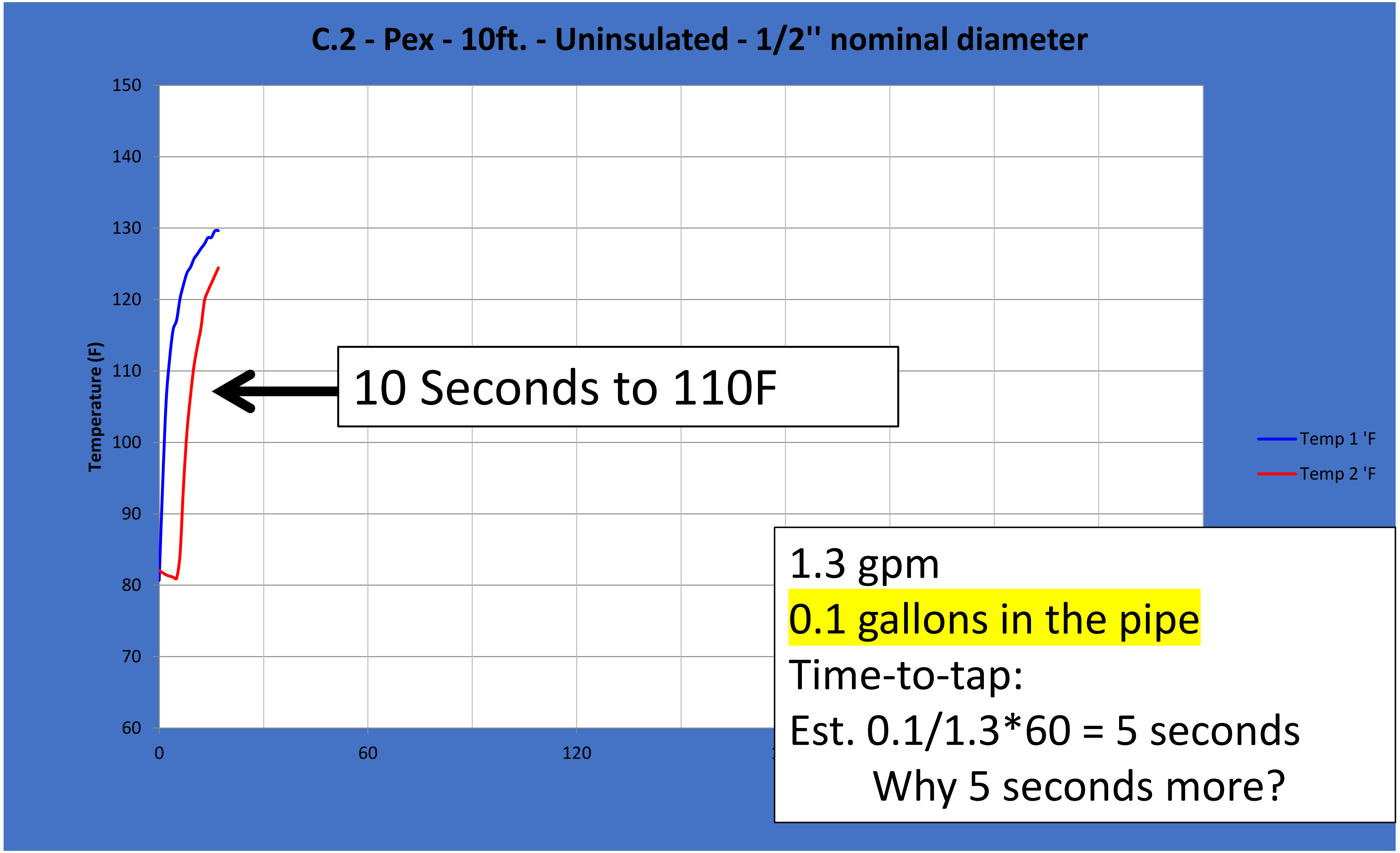
How Close Can We Get?

- Unless the heater is <u>in the fixture or appliance</u>, there will always be some volume in the pipe between the source and the use.
- It takes roughly twice the volume in the pipe for hot water to come out the other end.
  - See the next 2 slides for examples of this extra volume for two different pipe volumes.
- We need to decide what is an “acceptable” time-to-tap or volume-until-hot and work backwards to determine the maximum allowable in the pipe between the source and the use.
  - Plumbing up from below needs about 5 feet of pipe.
  - Plumbing down from above needs about 10 feet of pipe

Demonstrating Performance-1



Demonstrating Performance-2



How Long Should We Wait?

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

Cut the pipe volume in half to get these times

ASPE Time-to-Tap Performance Criteria

	Acceptable Performance	1 – 10 seconds
	Marginal Performance	11 – 30 seconds
	Unacceptable Performance	31+ seconds

Source: Domestic Water Heating Design Manual – 2nd Edition, ASPE, 2003, page 234

How Long Should We Wait?

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

Cut the pipe volume in half to get these times

ASPE Time-to-Tap Performance Criteria

	Acceptable Performance	1 – 10 seconds
	Marginal Performance	11 – 30 seconds
	Unacceptable Performance	31+ seconds

Source: Domestic Water Heating Design Manual – 2nd Edition, ASPE, 2003, page 234

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TABLE L 502.7
WATER VOLUME FOR DISTRIBUTION PIPING MATERIALS*

OUNCES OF WATER PER FOOT LENGTH OF PIPING													
NOMINAL SIZE (inch)	COPPER M	COPPER L	COPPER K	CPVC CTS SDR 11	CPVC SCH 40	PEX-AL- PEX	PE-AL- PE	CPVC SCH 80	PEX CTS SDR 9	PE-RT SDR 9	PP SDR 6	PP SDR 7.3	PP SDR 11
⅜	1.06	0.97	0.84	NA	1.17	0.63	0.63	NA	0.64	0.64	0.91	1.09	1.24
½	1.69	1.55	1.45	1.25	1.89	1.31	1.31	1.46	1.18	1.18	1.41	1.68	2.12
¾	3.43	3.22	2.90	2.67	3.38	3.39	3.39	2.74	2.35	2.35	2.23	2.62	3.37
1	5.81	5.49	5.17	4.43	5.53	5.56	5.56	4.57	3.91	3.91	3.64	4.36	5.56
1¼	8.70	8.36	8.09	6.61	9.66	8.49	8.49	8.24	5.81	5.81	5.73	6.81	8.60
1½	12.18	11.83	11.45	9.22	13.20	13.88	13.88	11.38	8.09	8.09	9.03	10.61	13.47
2	21.08	20.58	20.04	15.79	21.88	21.48	21.48	19.11	13.86	13.86	14.28	16.98	21.39

For SI units: 1 ounce = 29.573 mL
* NA: Not Applicable

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TABLE E202.1
INTERNAL VOLUME OF VARIOUS WATER DISTRIBUTION TUBING

OUNCES OF WATER PER FOOT OF TUBE									
Size Nominal, Inch	Copper Type M	Copper Type L	Copper Type K	CPVC CTS SDR 11	CPVC SCH 40	CPVC SCH 80	PE-RT SDR 9	Composite ASTM F 1281	PEX CTS SDR 9
$^{3}/_{8}$	1.06	0.97	0.84	N/A	1.17	—	0.64	0.63	0.64
$^{1}/_{2}$	1.69	1.55	1.45	1.25	1.89	1.46	1.18	1.31	1.18
$^{3}/_{4}$	3.43	3.22	2.90	2.67	3.38	2.74	2.35	3.39	2.35
1	5.81	5.49	5.17	4.43	5.53	4.57	3.91	5.56	3.91
$1^{1}/_{4}$	8.70	8.36	8.09	6.61	9.66	8.24	5.81	8.49	5.81
$1^{1}/_{2}$	12.18	11.83	11.45	9.22	13.20	11.38	8.09	13.88	8.09
2	21.08	20.58	20.04	15.79	21.88	19.11	13.86	21.48	13.86

For SI: 1 ounce = 0.030 liter.

Calculating Time-to-Tap and Volume-to-Hot

Time-to-tap = Feet * (Ounces/foot) *(1 gallon/128 ounces) / gpm * 1 minute/60 seconds

$$= \frac{\text{Feet} * 1\text{ oz} * 1\text{ gallon} * 1\text{ minute} * 60\text{ seconds}}{1\text{ foot} * 128\text{ oz} * 1\text{ gallon} * 1\text{ minute}}$$

= 0.46875 * Feet * ounces/foot * gallons per minute

Volume-to-Hot $= \frac{\text{Feet} * 1\text{ oz} * 1\text{ gallon}}{1\text{ foot} * 128\text{ oz}}$ = gallons in the pipe

Adjustment = Range of extra volume or time until hot is 1.5-2.5

≅ 2 * time in seconds based on pipe volume

≅ 2 * gallons in the pipe

Time-to-Tap, Volume-until-Hot – 5 ft. of Pipe

Pipe Material	Pipe Diameter (nominal, inches)				
	0.25	0.375	0.5	0.75	1
Gallons to Hot: 5 Feet of Pipe					
Copper-Type L	0.04	0.08	0.12	0.25	0.43
CPVC	NA	NA	0.10	0.21	0.35
PEX	0.03	0.05	0.09	0.18	0.31
Time to Hot @ 0.5.gpm: 5 Feet of Pipe (seconds)					
Copper-Type L	5	9	15	30	51
CPVC	NA	NA	12	25	42
PEX	3	6	11	22	37
Time to Hot @ 1.0 gpm: 5 Feet of Pipe (seconds)					
Copper-Type L	2	5	7	15	26
CPVC	NA	NA	6	13	21
PEX	2	3	6	11	18

This table includes the factor of 2 adjustment

Time-to-Tap, Volume-until-Hot – 10 ft. of Pipe

Pipe Material	Pipe Diameter (nominal, inches)				
	0.25	0.375	0.5	0.75	1
Gallons to Hot: 10 Feet of Pipe					
Copper-Type L	0.08	0.15	0.24	0.50	0.86
CPVC	NA	NA	0.20	0.42	0.69
PEX	0.05	0.10	0.18	0.37	0.61
Time to Hot @ 0.5.gpm: 10 Feet of Pipe (seconds)					
Copper-Type L	10	18	29	60	103
CPVC	NA	NA	23	50	83
PEX	6	12	22	44	73
Time to Hot @ 1.0 gpm: 10 Feet of Pipe (seconds)					
Copper-Type L	5	9	15	30	51
CPVC	NA	NA	12	25	42
PEX	3	6	11	22	37

This table includes the factor of 2 adjustment

How Low Can We Go? How Close Can We Get?

- The shorter the pipe, the less time it takes.
- The lower the flow rate, the longer it takes.
- How long is too long?
  - 5 seconds?
  - 10 seconds?
  - Longer? Shorter?

Water, energy and time efficient hot water systems start with deciding how long we want people to wait.

The decision on the location of the wet-room(s) and the mechanical room(s) is made by the architect.

Better floor plans can lead to better hot water system performance.

Residential Compact Domestic Hot Water Distribution Design: Balancing Energy Savings, Water Savings, and Architectural Flexibility

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Yanda Zhang, ZYD Energy[1]

ABSTRACT

The goal of the study is to develop compact domestic hot water (DHW) distribution strategies in single family homes to save both energy and water, and to reduce hot water waiting time. The study developed compact design measures that can be implemented through voluntary programs or building energy efficiency standards. Laboratory testing is planned to validate performance model development, and a field study is underway to assess installed performance and demonstrate measure feasibility.

The project team performed a literature review, stakeholder engagement, and analysis to determine the impact of compact designs on water waste and time-to-tap. Stakeholder engagement indicated that time savings, energy savings, and cost effectiveness are the highest priorities for stakeholders. Analysis yielded that installing a water heater close to fixtures can result in significant water savings and time savings. Conventional demand recirculation, while delivering excellent time-to-tap and water savings, has not been shown to save energy due to larger heat losses from the distribution loop piping.

The project team selected three preliminary compact DHW measures for further testing. The measures intend to eliminate behavioral waste by delivering hot water to all showers within 5 seconds, and to all other fixtures within 10 seconds. The measures require builders to install water heaters close to fixtures, limit the total length of trunk piping installed, and introduce pump priming for fixtures that still have long time-to-tap wait times after the first two measures are implemented.

Study Background

This study was commissioned by Pacific Gas and Electric Company to develop compact design solutions for single family DHW distribution systems that can be incorporated California's building energy efficiency standards (Title 24 Standards), incentive programs, and design guidelines.

Most single family DHW distribution systems are poorly designed, or not based on design. Hastily routed indirect pipe paths are often taken by field installers even when plumbing designs may exist. In most homes, people experience long hot water delivery times from a cold start (hot water has not been used for a long time and water in the hot water pipe is cold). A significant amount of water must be drained before hot water arrives at the fixture, leading to both energy and water waste.

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[1] The authors would like to thank other project team members Gary Klein, Marc Hoeschele, and Peter Grant for the contributions to the project and this paper.

For example, a field survey looking at 97 new construction homes throughout California found that distribution systems were designed and installed on site by plumbers, and often avoids direct paths from the water heater to the fixtures (DEG 2012). This study also found that average pipe volume between water heater and use points was fairly consistent with a 2006 sixty home California field survey, about one gallon of water for a 2000 ft^2 house, suggesting that there was little improvement in single family DHW distribution systems during the period between the two studies. A recent study found that based on 283 individual shower events, average bathroom total warm-up waste was 1.8 gallons, with 0.7 gallons categorized as structural waste (time to get water to adequate temperature) and 1.1 gallons categorized as behavioral waste (Sherman 2014).[2, 3] Behavioral waste refers to the situation when building occupants leave the hot water fixture turned on to do other things because the hot water waiting time is too long, even after hot water has arrived to the fixture.

Title 24 Standards have tried to promote compact designs by providing compliance credits to compact design options and penalties to inefficient distribution systems. The 2013 Title 24 Standard defines a compact design option by prescribing maximally allowed pipe length from the water heater to hot water fixture shown in Table 1. However, this option has made very limited impacts on industry practice on distribution system design as evidenced by the studies discussed above. One reason is that there is a lack of documentation and inspection processes for distribution plumbing systems. Another reason is that the Title 24 compact design requirements are not supported with any design guidelines, which also means that the practicality of meeting these requirements, and opportunities for further improving them, are unknown.

Table 1. Title 24 compact DHW criteria

Floor area served by the water heater (ft^2)	**< 1000**	**1001 – 1600**	**1601 – 2200**	**2201 – 2800**	**> 2800**
Maximum measured distance from water heater to use point (ft)	28	43	53	62	68

The US Environmental Protection Agency (EPA) defines compact hot water delivery system in its WaterSense® New Home Specifications as having no more than 0.5 gallons of water volume between the fixture and hot water source. In addition, no more than 0.6 gallons can leave the fixture before the temperature has risen 10°F above the ambient water temperature (EPA 2014). The hot water source can be either a water heater or recirculation loop. It is very difficult to meet this specification when using the water heater as the hot water source, and the EPA does not provide any guidance on how to do so. It is very easy to meet this specification using recirculation loop as the hot water source, but, as discussed below, recirculation systems usually have higher energy use than non-recirculation systems.

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[2] The structural waste number is a blended number that includes cold starts (the entire hot water line had cooled off and the total volume of the line would need to be purged prior to hot water arrival) as well as clustered events (the line already had hot water in it to some degree).
[3] The author of this study has generally concluded that there is ~1 minute of behavioral waste for every shower taken. A set time of behavioral waste will lead to various wasted volume for showerheads with various flowrates.

This study aims to develop compact distribution measures based on practical design strategies addressing variations in home architectural designs. The goal is to improve both energy and water efficiency by significant reducing pipe volumes and avoiding occupant behavior related waste.

Development Approach

Development of compact design measures faces the following major challenges:

- Hot water fixtures can be placed at different locations in homes due to variations in architectural designs. To achieve compact distribution, compact design strategies should be able to accommodate a variety of home designs and avoid imposing architectural barriers, which will also help the strategies be more acceptable to the building industry.
- There are several pipe layout methods (discussed below in Compact Design Options) and many options in pipe routing to consider in search for optimal solutions.
- Hot water draw schedules are uncertain due to their dependence on occupant behavior. Some designs may work well for certain draw patterns, but not others. Therefore, it is difficult to determine the performance of a design, and compare performance among different design solutions.
- Potential conflicts exist between energy and water savings. Recirculation design is considered by many practitioners the only solution that is able to bring the hot water source close enough to all fixtures to significantly reduce hot water waiting time and water waste. However, studies have shown that recirculation designs consume more hot water energy than other designs even when advanced controls are used (Henderson 2015, and Weitzel and Hoeschele 2014). So, are there practical design options that can provide high performance in both energy and water efficiency?

The project team addressed the above challenges through technical analysis in the four following areas: characterization of fixture layout compactness, compact design option assessment, and piping layout performance analysis. The project team also conducted a stakeholder workshop and interviewed industry practitioners to seek input improve methodologies and refine preliminary compact design measures.

Fixture Layout Compactness

Homes have different sizes and fixtures can be placed at all possible locations in homes. The project team developed a unique method, called the fixture layout polygon method, to effectively compare fixture layout compactness among different homes. For a given home floor plan, a polygon can be formed by using straight lines to connect fixtures. The area of the polygon is then divided by the home footprint, excluding garage areas, to obtain a normalized polygon size as the indicator of fixture layout compactness. In the example shown in Figure 1, the polygon area is 1200 ft^2, compared to a conditioned floor area of 3300 ft^2, resulting in a normalized polygon size of 36%.

The project team randomly sampled fourteen floor plans and obtained their normalized fixture layout polygon sizes, which range from 10% to 50%, as shown in Figure 2. Results roughly reflect the range of fixture layout compactness in the market. Sampling more floor plans to provide more polygon size data will increase the accuracy of findings. This finding was used to determine the pipe length limit discussed in a following section.

The polygon analysis also clearly shows the importance of have the water heater placed near or within the fixture polygon. If the water heat is placed away from the fixture polygon, usually in the garage, additional piping is needed for the space between the water heater and the polygon and large diameter pipes must be used to serve multiple downstream fixtures.

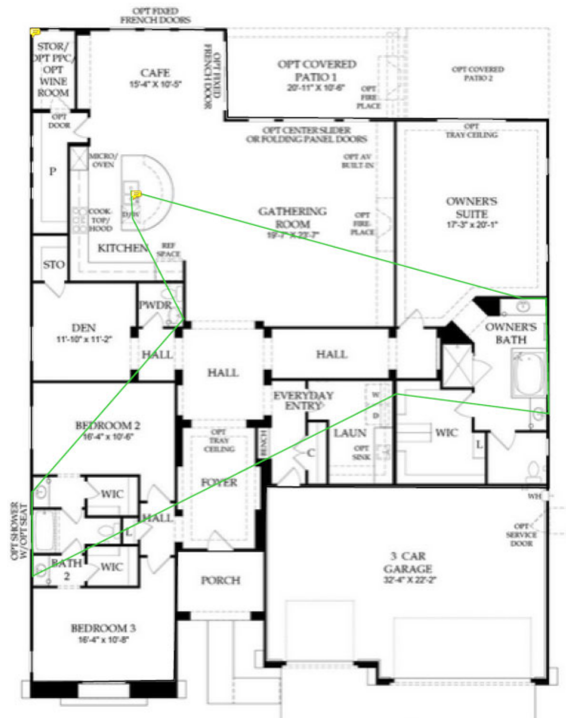

Figure 1. Example of the polygon drawn to characterize fixture compactness.

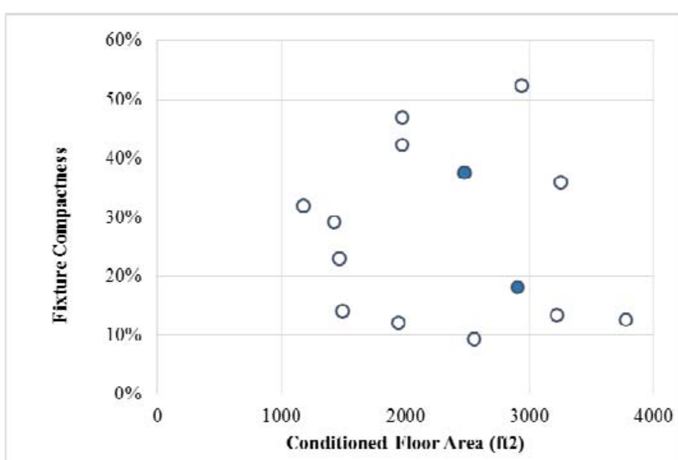

Figure 2. Fixture compactness compared to floor area.

Compact Design Options

The project team investigated various water heater locations and pipe layout methods as potential compact design strategies. The fixture layout polygon analysis clearly shows that it is important to place the water heater close to fixtures. Therefore, as the first step of design option analysis, the project team compared the following water heater locations:

- Water heater away from the polygon, in the garage
- Water heater near the polygon, e.g. on the side wall of the kitchen
- Water heater inside the polygon, e.g. in attic.

The team then considered the following four common pipe layout methods:

- Trunk and Branch – The most commonly used distribution design scheme, this method has the benefit of sharing pipes among different fixtures. After one fixture receives hot water, other fixtures connected to the same trunk and branch pipes can receive hot water quickly, reducing water and energy waste in instances of clustered hot water draws.
- Home Run – This method dedicates a pipe path for each fixture and appliance originating from a manifold in close proximity to the water heater. This approach allows a small pipe volume from the manifold to each individual fixture, reducing water and energy waste due to shared pipes in instances of sporadic hot water draws.
- Hybrid – This method combines the design concepts used in the trunk and branch and home run in order to take advantage of the benefits of each. There are several ways to mix the use of trunk and branch and the home run piping layouts.
- Recirculation – This method uses one loop of pipe that goes near each fixture to reduce branch length and returns to the water heater. By circulating hot water around the loop, this design can drastically reduce hot water wait times and water waste.

The project team selected two floor plans to investigate the impact of the design options discussed above on system performance. The two sample floor plans, a one-story and a two-story as highlighted in dark blue in Figure 2, have similar floor areas but large differences in normalized polygon size, and adequately cover the range of sample variation. Table 2 provides a summary of design options considered for the two floor plans.

Table 2. Design Option (water heater location and pipe layout method) for Two Floor Plans

Design Options	Floor Plan 1 (1-story)	Floor Plan 2 (2-stories)
Base case: Water heater away from polygon (in garage), trunk & branch	√	√
Water heater near polygon (near corner of garage), trunk & branch	√	
Water heater inside polygon (in attic), trunk & branch	√	
Water heater inside polygon (in pantry), trunk & branch	√	√
Water heater inside polygon (two water heaters), trunk & branch		√
Water heater inside polygon (in attic), home run	√	
Water heater inside polygon (in pantry), home run	√	√
Recirculation (water heater in garage)	√	√
Recirculation (water heater in garage), two zones		√

Preliminary Performance Analysis

To investigate compact design, the project team needed an easy-to-use performance analysis tool to quickly estimate the impacts of several design options. The performance analysis at this stage focused on understanding relative hot water wait times and water waste among various strategies, rather than accurately estimating annual energy use.

The project team developed a spreadsheet-based model instead of using existing simulation software, such as TRNSYS or HWSIM, to have full control over analysis assumptions. The model takes detailed pipe layout inputs, such as pipe diameter, length, and connections between different pipe sections, to estimate of pipe volume, hot water waiting time, and water waste. The model uses a set of hot water draw events from the most frequently used fixtures, including the kitchen faucet, master shower, master bath faucet, and second bath shower, to estimate the overall distribution performance. The initial fixture draw was from a cold start, and the remaining fixture draws assume that the hot water has filled the trunk and branches leading to the initial fixture, thus capturing the impact of clustered events.

Findings

The results shown in Table 3 indicate that moving the water heater more centrally (near or inside fixture layout polygon) can result in significant water savings and time savings. For trunk and branch and home run systems, water and time savings are indicative of the potential for energy savings (25-38%). Furthermore, a conventional trunk and branch system is capable of delivering hot water to many high use fixtures in an average of under 25 seconds if the water heater location is centralized. Home run systems may show even better performance than trunk and branch. Recirculation systems clearly show the best results for reducing water and time waste, though, as mentioned earlier, are unlikely to deliver energy savings.

Table 3. Results from varying piping layouts and water heater locations for two floor plans

Description	Wasted Gallons/Day	% of Base Case	Avg Wait Time (sec)	% of Base Case
Base case	4.9	100%	38	100%
Trunk & branch, WH near/inside polygon	3.7	75%	25	67%
Home run, WH near/inside polygon	3.0	62%	15	39%
Recirculation	0.6	12%	4	9%

Stakeholder Engagement

The project team organized a workshop held in Gold River, CA in October 2015 to obtain industry input and vet the analysis methodologies and results. Seventeen people attended including builders, plumbing engineers, policymakers, and the project team. Recurring themes voiced by attendees include:

- Reducing water, energy, and time wasted is an important issue to all stakeholders, and provides value to homebuyers. 15 seconds time-to-tap may be marketable, which is near to the American Society of Plumbing Engineers (ASPE) 10-second criteria for acceptable performance (ASPE 2013).
- Barriers to relocating water heaters closer to fixtures (rather than in the garage) include dealing with potential leaks, a slight increase in labor costs, and the possible repurposing of valuable conditioned floor area to accommodate the water heater.
- Compact design needs to be easily assessed and enforceable by builders and the building department, so that plumbing is installed according to design.
- Revising floor plans is likely the most economical method for compact DHW distribution, though the least palatable from a builder standpoint.

As a result of feedback received during the workshop, the project team sought to gain a broader understanding of strategies most acceptable to California builders, gather best practices, and collect cost data. Interviews with seven builders and two plumbers showed that:

- Builders commonly receive wait time complaints. Two builders indicated that they often pre-plumb homes to be compatible with demand recirculation, except for the final point of connection to the water heater, in case of complaints.
- Builders would rather install a demand recirculation system than a pipe priming system, because the recirculation system is more likely to reduce hot water wait times to all fixtures.
- Respondents indicated that locating water heaters closer to fixtures and designing homes more compactly would be their most preferred methods of compact DHW distribution.

Compact Design Strategies

In developing comprehensive compact design strategies, the project team considered all related issues summarized in Table 4. It is important to note:

- Energy savings and waiting time reduction are the highest priorities
- Cost and cost effectiveness is a priority for all perspectives. Builders and plumbers want to satisfy homeowners in the least costly way possible, while Title 24 requires life cycle cost effective energy savings.
- Water savings are not the top priority. However, as the California is facing a long-term drought condition, saving water is very important.

Table 4. Priorities from perspectives impacted by a compact DHW measure

Perspective	Priority #1	Priority #2	Priority #3	Priority #4
Homeowner	Waiting time reduction and convenience	Reliability	Low incremental cost	Water savings
Builder	Minimize homeowner complaints	High value (i.e., Title 24 credits) compared to incremental cost	Reliability (low maintenance)	-
Plumber	Minimize homeowner complaints & callback	Low installation cost, easy implementation	-	-
Title 24	Energy savings	Cost effectiveness	Water Savings	Reliability

The project team developed the following compact design strategies based on technical analysis results and stakeholder feedback. Table 5 presents performance characteristics of the compact strategies based on technical analysis conducted by the project team and stakeholder feedback:

- **Proximate Water Heater –** Locating the water heater near high use fixtures can significantly reduce the volume of entrained water in the distribution system, regardless of the distribution system type. The water heater can be located in an attic or a closet near the kitchen or master bathroom, which contain the fixtures with the most hot water usage. The project team suggests implementing this strategy first.
- **Minimize Pipe Lengths –** Once the water heater in properly located, the pipe volume can be further reduced through a streamlined pipe layout. In particular, it is beneficial to have only one or two plumbing zones and use a trunk line to serve each zone. This strategy would limit the allowed lengths of large pipe diameters, reducing pipe volume, energy loss, and time-to-tap. While the floorplan, including water heater location and fixture locations, determines the overall plumbing layout, direct requirements for floorplans that are architecturally compact (i.e., group fixtures close to each other and locate them close to the water heater) are unfavorable to builders. This measure sets limits on pipe lengths, rather than floorplan layout, to allow for flexibility in architectural design.
- **Pipe Priming –** Even with the above two strategies in place, hot water wait time may still not be short enough to avoid behavior waste. A pump can be installed specifically to

serve a fixture far away from a water heater. When turned on by an occupant, the pump will prime the trunk and branches leading to the fixture with hot water before the fixture is used. Until hot water arrives at the fixture, the purged cold water can be diverted into the cold water line or returned to the water heater. This strategy should only be used after the first two to ensure overall pipe volume is small. When properly implemented, this strategy yields the water and waiting time reduction as conventional demand recirculation without the high heat losses, thus also saving energy.

- **Multiple Water Heaters –** The project team also considered using multiple water heaters in a home. Each water heater serves nearby fixtures to reduce the distance to the furthest fixture and entrained pipe volume.

Table 5. Characteristics of Compact Distribution Design Strategies

Compact Design Strategies	**Wait Time Savings**	**Energy Savings**	**Cost**	**Reliability**	**Water Savings**
Proximate Water Heater	Medium	High	Medium	Medium	Medium
Minimize Pipe Lengths with Proper Zoning	Medium	Medium	Low to none	High; same as status quo	High
Trunk Pipe Priming	Medium	Medium	Medium	Medium	Medium
Installing Multiple Water Heaters	Medium	Medium; penalty with storage	High	Medium; more maintenance	Medium

Preliminary Compact Design Measures

While compact design *strategies* are general approaches, compact design *measures* aim to specify design goals. These measure specifications are intended to inform future incentive program and building standards development. However, they need to be further refined before consideration for adoption. The project team used the first three design strategies in Table 6 to develop compact design specifications. Installing multiple water heaters is also a viable compact design solution, but is deemed as the least likely measure to be cost effective and not recommended for further evaluation.

Specifically, measures aim to reduce hot water waiting time to a level where behavioral waste can be avoided. According to ASPE criteria, the acceptable hot water waiting time should be no more than 10 seconds, though this may still be too long to avoid behavioral waste. Showers are only used after hot water is available, so the hot water waiting time for showers should be even shorter. Thus, the preliminary measures aim to achieve a wait time of less than 5 seconds for showers, and less than 10 seconds for all other fixtures. Each of the measures achieve the EPA water sense criteria of a pipe volume of <0.5 gallons to each fixture (a volume of 0.5 gallons is approximately equal to a wait time of 15-20 seconds, depending on the flow rate of the fixture).

While the preliminary measures do not exclude any pipe layout methods, they may be more difficult to achieve with some pipe layout methods.

Measure 1 - Proximate Water Heater

This measure requires that the water heater be located close to hot water fixtures with the most hot water use, namely the master bath shower and the kitchen faucet. Volume performance analysis suggested that distribution pipe volume can be significantly reduced by moving the water heater closer to these fixtures.

Pipe length estimates are developed based on the two most feasible locations for keeping the water heater close to the master shower and the kitchen faucet: on a home exterior wall (with or without a water heater closet), and the attic. The lengths associated with pipe volumes are calculated using PEX pipe characteristics. The measure requirements are specified in pipe volume so that builders can implement with a variety of pipe sizes.

Measure Specification. The water heater must be located close to the kitchen faucet or the master bath shower to meet one of the following specifications.

1. Pipe volume from the water heater to the kitchen faucet shall be ≤ 0.20 gallons (the volume of 1 foot of 1” pipe + 3 feet of 3/4" pipe + 11 feet of 1/2” pipe);
2. Pipe volume from the water heater to the kitchen faucet on a kitchen island shall be ≤ 0.25 gallons (the volume of 1 foot of 1” pipe + 3 feet of 3/4" pipe + 16 feet of 1/2” pipe);
3. Pipe volume from the water heater to the master bath shower shall be ≤ 0.20 gallons (the volume of 1 foot of 1” pipe + 3 feet of 3/4” pipe + 11 feet of 1/2” pipe).

Measure 2 – Minimize Pipe Lengths

This measure reduces entrained volume by specifying different length limits for different pipe diameters. Pipes greater than ½” typically form the trunks and recirculation loop supply lines, and small diameter pipes (equal or less than 1/2”) are used as branch pipes. The length limit formula was developed based on polygon analysis, a conceptual two-zone design concept, straight pipe runs, and pipe runs between floors in two-story buildings. Preliminary polygon analysis yielded that the maximum fixture compactness ratio (FCR, polygon area divided by the conditioned floor area) was 52% for a one-story home, and 32% for a two-story home. These values are used to determine maximum pipe lengths per home.

Measure Specification. Pipe installations must meet all of the following specifications:

1. Total pipe length for pipes > 1/2" in diameter shall not exceed the following length:

    Total Pipe Length = √((Conditioned Floor Area × FCR)/(Length to width ratio))×(1+Length to width ratio)
    where, FCR = 52% for one-story homes and 32% for two-story homes,
    Length to width ratio for homes is assumed to be 1.2

2. Pipes > 3/4" inch shall be ≤ 3 feet. This length of pipe is enough to connect several branches of 3/4” diameter pipe near the water heater.

3. For each fixture, pipes ≤ 1/2" shall be ≤ 15 feet total, or the total pipe length to the water heater is ≤ 30 feet.

Examples of the formula output based on conditioned floor area are provided in Table 10 below.

Table 7. Examples of Maximum >1/2” Diameter Pipe Lengths

Home Area (ft^2)	One-Story Home Max Pipe Length (ft)	Two-Story Home Max Pipe Length (ft)
1200	50	39
2400	71	56
3600	87	68

Note that this measure does not currently account for recirculation or pipe priming return pipe requirements. The project team is considering how to refine the measure to address these pipes.

Measure 3 – Trunk Pipe Priming

The pipe volume performance achieved through the prior two measures will not be able to satisfy the hot water waiting time goal for all fixtures. Therefore, using circulation pumps to prime the distribution system with hot water can help to meet the waiting time performance target of 10 seconds (or 5 seconds for showers). This can be essential for showers and the kitchen faucet because of their frequent uses and related behavioral waste.

Measure Specification. Pipe Priming may only be implemented in conjunction with the Proximate Water Heater and Minimize Pipe Lengths measures. Pipe Priming shall be implemented in all of the following ways:

1. For fixtures with a pipe volume to the water heater of more than 0.2 gallons, implement pipe priming to ensure the pipe volume from the fixture to the primed pipe is less than 0.2 gallons.
2. For showers and kitchen faucets with a pipe volume of more than 0.1 gallons, implement pipe priming to ensure the pipe volume from the fixture to the primed pipe is less than 0.1 gallons (approximately 5 seconds or 10 feet of 1/2" pipe),
3. Pumps must be manually turned on via demand switches. Pumps will automatically turn off once hot water arrives at the fixture.

Next Steps

The project team has recruited California builders to install all these measures in some of their new construction single family homes. The team will document the entrained volume and time for hot water to reach the fixture for homes with the measure installed, and identical homes with conventional plumbing installation. Laboratory tests will develop data on the flow and heat loss characteristics of PEX pipe, and energy savings estimates will be developed through a dynamic performance model validated by the lab data. Estimated increases in wait time will be developed based on potential future low-flow fixture flow rates.

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Evaluating Domestic Hot Water Distribution System Options With Validated Analysis Models

E. Weitzel and M. Hoeschele
Alliance for Residential Building Innovation

September 2014

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Evaluating Domestic Hot Water Distribution System Options With Validated Analysis Models

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Unless otherwise noted, all figures were created by the ARBI team.

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Unless otherwise noted, all tables were created by the ARBI team.

Definitions

ARBI	Alliance for Residential Building Innovation
BEopt	Building Energy Optimization model
DHW	Domestic Hot Water
DHWESG	Domestic Hot Water Event Schedule Generator
HWSIM	Hot Water Simulation software
LBNL	Lawrence Berkeley National Laboratory
NAHB	National Association of Home Builders
NREL	National Renewable Energy Laboratory
PEX	Cross-Linked Polyethylene
TRNSYS	TRaNsient System Simulation program

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Executive Summary

While water heater performance is well characterized, DHW distribution system impacts on energy loss and water waste have only recently been studied in detail. A developing body of work is forming that provides for more data on DHW consumption, water use behaviors, and energy efficiency of various distribution systems. Concurrent models in HWSIM (Hot Water Simulation Program, Davis Energy Group) and TRNSYS (Transient System Simulation Program, TESS) have been developed to analyze distribution system performance. These high fidelity pipe models have been validated using both laboratory and field data. More recently a full distribution system developed in TRNSYS has been validated using field monitoring data and then exercised in a number of climates to understand climate impact on distribution performance. This study builds upon previous distribution model work to evaluate differing distribution systems and the sensitivities of water heating energy and water use efficiency to variations of climate, load, distribution type, insulation, and compact plumbing practices.

Overall 124 different TRNSYS models were simulated and results compiled. The base case, an uninsulated trunk and branch system is best improved in terms of annual energy consumption by insulating and locating the water heater central to the use points. Demand recirculation systems are not projected to provide significant energy savings and in some cases increase system energy consumption. Water use is most efficient with demand recirculation systems, followed by the insulated trunk and branch system with a centrally located water heater. Compact plumbing practices and insulation levels have the most impact on energy consumption (energy savings of 2%–6% for insulation and 3%–4% per 10 gal of enclosed volume reduced). Of the configurations evaluated, distribution losses account for 13%–29% of the total water heating energy use, with compact, insulated low-load systems having the least distribution losses. Water use efficiency ranges from 11%–22%, with uninsulated home run systems and noncompact plumbing practices accounting for the most water waste.

The results of this work are useful in informing future development of water heating best practices guides as well as more accurate (and simulation time efficient) distribution models for annual whole-house simulation programs. Future work is needed to better characterize many of the inputs to these models (plumbing configurations and layouts, usage patterns, impact of high efficiency hot water fixtures and appliances), as all these factors can have a significant impact on water heating energy use and water waste.

1 Introduction

Domestic hot water (DHW) systems have four areas of energy transfer: water heater inefficiency, water heater standby losses, distribution system losses, and energy consumed at the end use point. The losses at the water heater, including standby energy consumption, efficiency of the heating source, and delivery have been well studied and characterized. The distribution systems have only recently been studied and evaluations include the losses attributed to piping elements and useful hot water thresholds, which combine to what is called structural waste. There have also been several recent studies into the behavioral patterns of hot water usage (Lutz and Melody 2012; Sherman 2014); however, the behavioral and structural wastes have been difficult to decouple. This study aims at determining the impact of differing distribution system parameters on structural component of waste, to provide insight into how distribution systems affect total water heating energy and water use efficiency.

1.1 Background and Motivation

In recent years, many studies have been conducted to better understand the performance of DHW distribution systems. In 2008, Davis Energy Group released an updated Hot Water SIMulation software (HWSIM) to analyze DHW system performance at a higher resolution than previous hourly analysis models (Springer et al. 2008). The original HWSIM allowed for an input of seven distinct daily water heater draw schedules per month, applied pipe heat capacitance and material-dependent convective and radiant terms to the heat transfer model, and utilized a simple tank water heater with a user-specified energy factor to supply the distribution system. In 2011, HWSIM was further updated with high resolution, multinodal atmospheric gas storage and gas tankless water heating models. HWSIM reduced the input draw schedules to one representative day per season to expedite simulation performance with the higher fidelity water heating models (Kosar et al. 2012). HWSIM was validated with laboratory data collected by Carl Hiller from Applied Energy Technology (Hiller 2006) testing various piping materials under different flow rates and environmental conditions.

On a parallel track to the HWSIM enhancements, the National Renewable Energy Laboratory (NREL) was evaluating a typical trunk and branch distribution model for the Building America benchmark home using TRNSYS (Maguire et al. 2011). TRNSYS is a time-based discrete simulation software that analyzes models assembled from individual modeling elements. The pipe element model used in the NREL analysis used a fixed pipe heat transfer coefficient and did not account for the heat capacity effects that affect cold-start conditions and relaxation between draws. The results from the study were implemented in the Building Energy Optimization Model (BEopt™), with the exception that correction factors are applied to the daily hot water volume, house internal heat gain (from pipe losses), additional pumping energy, and the change in recovery load of the water heater (Wilson et al 2014) based on different distribution systems. The correction factors were determined from runs generated by the original HWSIM that evaluated different distribution systems in different climates (DEG 2006).

In 2011 TRNSYS updated a pipe model with dynamic exterior surface convective and radiant heat transfer based on material properties, fluid properties, and environmental conditions. In a 2013 Building America study (Backman and Hoeschele 2013), Davis Energy Group used the 2006 Hiller lab data to validate the new TRNSYS pipe model. The distribution system from the Maguire NREL study was enhanced with the new pipe element model and adjusted to match the distribution layout in an NREL monitored project (Solar Row in Boulder, Colorado), where detailed distribution system flow and temperature measurements were completed (Backman and Hoeschele 2013). The model was then validated with the Solar Row data to drive the TRNSYS model and was shown to be very robust in terms of observed distribution losses and energy consumption relative to monitored data over a several month period when monitoring data were available.

With all these successive enhancements to distribution system models, the next step is to analyze various distribution systems and determine the range of performance on a set of varying factors. Driving these models are annual draw schedules generated by a spreadsheet utility, domestic hot water event schedule generator (DHWESG) developed in 2010 by NREL (Hendron and Burch 2008).

The DHWESG utility was developed using data from two studies conducted by Aquacraft (Aquacraft 2008; Mayer and DeOreo 1999), one from a large study that measured whole-house water usage and the other measured discrete water draw events in a sample of 20 households. Lawrence Berkeley National Laboratory (LBNL) (Lutz and Melody 2012) compiled detailed high-resolution hot water usage data from numerous studies, suggesting that there is a wide variation in usage and draw patterns, both between households and within households from day to day. The high variability in usage patterns presents a particularly difficult challenge in trying to compare alternative distribution system types without completing thousands of simulation runs. In an effort to better understand use patterns, LBNL developed a database where researchers can input disaggregated end use data from various monitoring efforts.

A more recent study conducted by Advanced Residential Integrated Energy Solutions (Henderson and Wade 2014) monitored five homes near Syracuse, New York, where thermocouples were applied to each plumbing run-out line to disaggregate flow in a more nonintrusive and economical manner. In another monitoring study of disaggregated uses in 19 homes conducted by LBNL and evaluated by ShowerStart, analysis was performed to separate behavioral waste from structural waste. The study found behavioral waste to be between 38 and 56 seconds after the temperature has been reached (Sherman 2014).[1] These data, along with the data collected by LBNL, will ultimately help refine assumptions of hot water usage patterns.

The Alliance for Residential Building Innovation (ARBI) team worked with the National Association of Home Builders (NAHB) Home Innovation Research Labs to obtain a snapshot of current regional and national plumbing practice based on new homes built during 2011. Based on information provided on more than 9,000 homes built in the United States, the data suggest that currently 60% of single-family homes use cross-linked polyethylene (PEX) for distribution plumbing, while ~25% use chlorinated polyvinyl chloride and the rest use copper. Of the homes using PEX, nearly 40% are plumbed as trunk and branch systems, 17% in a home run configuration, and ~5% as zone or hybrid (combining a trunk feeder line with remote manifolds). (In ~40% of the homes, the exact plumbing system type was not represented.)

From these findings in the NAHB data, PEX was assumed for all distribution systems modeled and a representative single-family home is used for constructing different plumbing layout

[1] Identified by the time after hot water was reached and the observed throttling back flow to the desired temperature.

configurations. This type of data is valuable in identifying regional and national construction practices. More refined data on actual documented plumbing layouts (Kosar et al. 2012; Lutz 2008) are critically needed to characterize actual installed plumbing systems. Foundation data from NAHB were also used to inform the typical house construction analyzed in various climates in terms of water heater location (basement or garage).

1.2 Research Questions

The primary objective of this project is to expand upon the previously validated TRNSYS DHW distribution system model by evaluating the impacts on energy and water use for different distribution system layouts, climates, and loads. This parametric study, although limited in scope, will assess sensitivity of varying factors of the distribution system to overall hot water usage and contribute to the developing body of knowledge that will ultimately inform a comprehensive hot water design guide.

The research questions that will be addressed are:

1. What is the expected range in distribution losses (as a fraction of water heater recovery load) as a function of distribution system configuration, climate, and hot water usage pattern?
2. What are the realistic savings that can be realized through measures such as insulating all piping or improving distribution system design?
3. What are the projected water use/waste implications of the various scenarios simulated?
4. Where are better data needed to improve the characterization of the "hot water system" based on the observed sensitivities in the modeling study?

2 Methodology

In this study, systems were evaluated in a sample of representative climates and states of high growth according to information presented on U.S. Census Bureau website in 2013. All locations evaluated are listed in the 10 fastest growing states, and cover cold (Chicago, Illinois, and Denver, Colorado), mixed-humid (Atlanta, Georgia), hot-humid (Houston, Texas) and hot-dry (Phoenix, Arizona) climates.

While the plumbing materials were not varied in this study, the location of the system was varied by climate in a decision informed by data supplied from the NAHB on current practices. According to the NAHB, the majority of single-family homes in locations encompassing Chicago and Denver are being constructed with full basements, while locations encompassing Atlanta, Houston and Phoenix are constructed on slab foundations. It is assumed for homes with full basements, that the water heater would be located in the basement, with the distribution system routing beneath the floor of the living areas. For homes constructed on slab, it is assumed the water heater would be located in the garage, with the distribution system extending into the attic and down through the interior walls to service the fixtures.

The model used as a starting point for this study was constructed using a representative benchmark home described in the NREL study (Maguire et al. 2011) and is shown in Figure 1. The home was modeled in BEopt with the options of a full basement or slab foundation with garage, and simulated in the various climates to gather garage, basement, attic, and interior temperatures with which to simulate the distribution systems. The original trunk and branch layout was used to determine locations and lengths of plumbing needed to reach the fixtures. The layouts were modified for homes with basements in that the plumbing would span beneath the floor and basement while the original garage model had the plumbing routed through the attic. As an example, original line diagram is shown in Figure 2. Diagrams for the other distribution options, as well as a table listing of the differences in distribution options are provided in Appendix B.

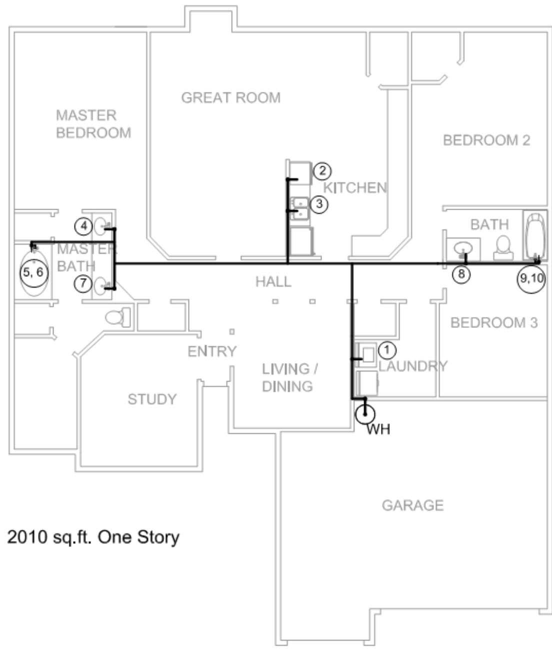


Figure 1. Sample home layout

Source: Backman and Hoeschele 2013

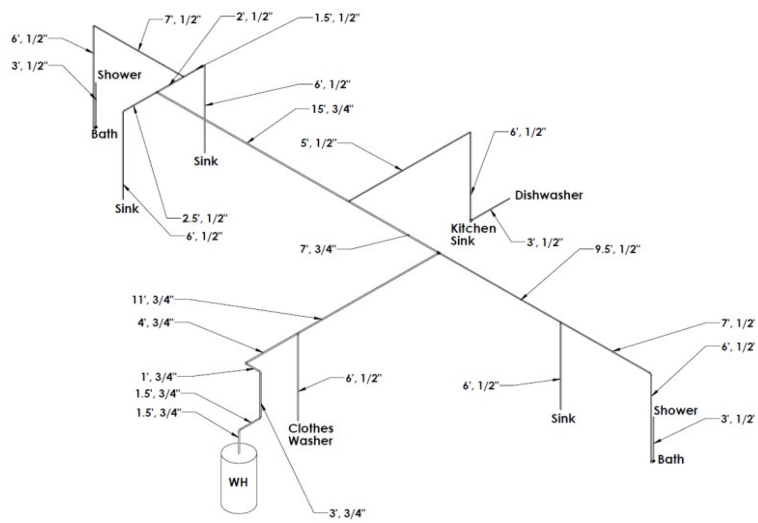


Figure 2. Sample distribution layout

Source: Maguire et al. 2011

In each distribution system evaluated, the plumbing configuration and insulation level were adjusted to represent a best- and worst-case scenario. In trunk and branch systems, the worst case involves a water heater mounted near the far corner of the garage or basement, with a resulting long main trunk feeding the uninsulated distribution piping. The best trunk and branch case layout is a centrally located water heater, a shortened main line, and all pipes insulated to R4.7.

In home run systems it is assumed from field experience the worst-case scenario involves a 15-ft, 1-in. diameter main line between the water heater and the manifold, with ½-in. lines supplying all use points from the manifold. Our experience is that it is typical practice to insulate the 1-in. main line; therefore, in the worst-case ("uninsulated") system the main line is the only insulated pipe. The optimal home run configuration reduces the main line to a significantly reduced length of 3 ft of ¾-in. line, and also assumes lines to the sinks and dishwasher are reduced to ⅜ in.

Finally, in hybrid systems, the worst-case scenario involves a 15-ft, 1-in. diameter main line, with ½-in. lines to all the use points. The line between the water heater and the first distribution manifold is insulated, while the supply lines to the use points remain uninsulated. In the optimal case, all lines are insulated, runs to sinks and the dishwasher are reduced to ⅜ in. and the main line is both shortened in length and reduced to ¾ in.

Demand recirculation technology was also modeled because it represents a preferred approach for applications where recirculation is desired. By minimizing the operation of the recirculation pump to only when needed at the start of a draw, recirculation loop heat loss and pumping energy are significantly reduced relative to conventional recirculation strategies. Proponents of the technology suggest that it not only saves water, but energy as well when compared to conventional nonrecirculating strategies. For this evaluation, two demand recirculation plumbing configurations were analyzed. Water heater researcher Gary Klein has conveyed in personal communications that an optimal system requires all use points be less than 15 ft from the recirculation loop. In this "short run-out configuration," the recirculation loop was brought to within 15 ft of pipe from the master bath and bath two showers, ensuring all use points were within range. In the "long run-out configuration," the recirculation loop was shortened (decreased in total length by 32 ft), extending the furthest shower to 23 ft from the recirculation line.

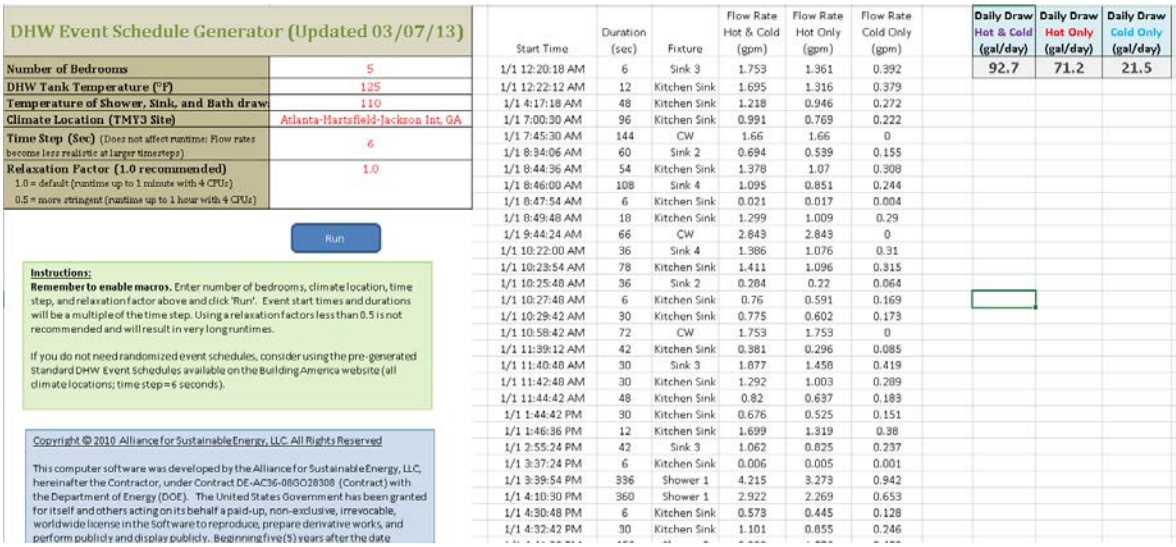
In total, 124 models were analyzed with the list of parameters evaluated shown in Table 1.

Table 1. Evaluation Parameters

Parameter	Options	Contingent
Occupancy	2-, 4-person household	
Climates	Houston, Denver, Phoenix, Chicago, Atlanta	
House Types	Basement, garage	Typical for climate
Distribution Types	Trunk and branch, home run, hybrid	
Water Heater Location and Plumbing Practices	Wasteful case with water heater nearest exterior wall, Compact case with central water heater	
Insulation	None, 1 in.	
Recirculation	Long and short run-outs Demand control with push button at sink/shower	Occupancy, Climate

2.1 Building America Domestic Hot Water Event Schedule Generator

The models were evaluated using draw schedules supplied by the DHWESG shown in Figure 3. The generator was developed from two studies conducted by Aquacraft (Aquacraft 2008; Mayer and DeOreo 1999). One study gave insight into discrete water draw events by monitoring the disaggregated uses in 20 homes. The other study involved 1,200 homes in which only total water consumption was monitored. The DHWESG includes assumptions for structural and behavioral waste in the draw events, driven by a fixed useful hot water set point (e.g., 110°F) for nonappliance loads. As the TRNSYS model evaluates distribution system contribution to waste, it was necessary to reduce the nonappliance loads in the draw schedule so that waste wouldn't be accounted for twice. As some draws were only a single time-step, the flow rates were reduced. In the study that validated the distribution system, the water waste was nearly climate independent at 20%–22% of total hot water use. For this evaluation, the sink, shower and bath loads in the generated schedules were reduced by 22% before being supplied to the model.


DHW Event Schedule Generator (Updated 03/07/13)

Number of Bedrooms	5
DHW Tank Temperature (°F)	125
Temperature of Shower, Sink, and Bath draw	110
Climate Location (TMY3 Site)	Atlanta-Hartsfield-Jackson Int, GA
Time Step (Sec) (Does not affect runtime: Flow rates become less realistic at larger timesteps)	6
Relaxation Factor (1.0 recommended) 1.0 = default (runtime up to 1 minute with 4 CPUs) 0.5 = more stringent (runtime up to 1 hour with 4 CPUs)	1.0

Run

Instructions:
Remember to enable macros. Enter number of bedrooms, climate location, time step, and relaxation factor above and click 'Run'. Event start times and durations will be a multiple of the time step. Using a relaxation factors less than 0.5 is not recommended and will result in very long runtimes.

If you do not need randomized event schedules, consider using the pre-generated Standard DHW Event Schedules available on the Building America website (all climate locations; time step = 6 seconds).

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Start Time	Duration (sec)	Fixture	Flow Rate Hot & Cold (gpm)	Flow Rate Hot Only (gpm)	Flow Rate Cold Only (gpm)
1/1 12:20:18 AM	6	Sink 3	1.753	1.361	0.392
1/1 12:22:12 AM	12	Kitchen Sink	1.695	1.316	0.379
1/1 4:17:18 AM	48	Kitchen Sink	1.218	0.946	0.272
1/1 7:00:30 AM	96	Kitchen Sink	0.991	0.769	0.222
1/1 7:45:30 AM	144	CW	1.66	1.66	0
1/1 8:34:06 AM	60	Sink 2	0.694	0.539	0.155
1/1 8:44:36 AM	54	Kitchen Sink	1.378	1.07	0.308
1/1 8:46:00 AM	108	Sink 4	1.095	0.851	0.244
1/1 8:47:54 AM	6	Kitchen Sink	0.021	0.017	0.004
1/1 8:49:48 AM	18	Kitchen Sink	1.299	1.009	0.29
1/1 9:44:24 AM	66	CW	2.843	2.843	0
1/1 10:22:00 AM	36	Sink 4	1.386	1.076	0.31
1/1 10:23:54 AM	78	Kitchen Sink	1.411	1.096	0.315
1/1 10:25:48 AM	36	Sink 2	0.284	0.22	0.064
1/1 10:27:48 AM	6	Kitchen Sink	0.76	0.591	0.169
1/1 10:29:42 AM	30	Kitchen Sink	0.775	0.602	0.173
1/1 10:58:42 AM	72	CW	1.753	1.753	0
1/1 11:39:12 AM	42	Kitchen Sink	0.381	0.296	0.085
1/1 11:40:48 AM	30	Sink 3	1.877	1.458	0.419
1/1 11:42:48 AM	30	Kitchen Sink	1.292	1.003	0.289
1/1 11:44:42 AM	48	Kitchen Sink	0.82	0.637	0.183
1/1 1:44:42 PM	30	Kitchen Sink	0.676	0.525	0.151
1/1 1:46:36 PM	12	Kitchen Sink	1.699	1.319	0.38
1/1 2:55:24 PM	42	Sink 3	1.062	0.825	0.237
1/1 3:37:24 PM	6	Kitchen Sink	0.006	0.005	0.001
1/1 3:39:54 PM	336	Shower 1	4.215	3.273	0.942
1/1 4:10:30 PM	360	Shower 1	2.922	2.269	0.653
1/1 4:30:48 PM	6	Kitchen Sink	0.573	0.445	0.128
1/1 4:32:42 PM	30	Kitchen Sink	1.101	0.855	0.246

Daily Draw Hot & Cold (gal/day)	Daily Draw Hot Only (gal/day)	Daily Draw Cold Only (gal/day)
92.7	71.2	21.5

Figure 3. DHWESG output

Source: NREL DHWESG

The DHWESG output format consists of a date and time stamp, draw event duration and discrete flow rates. As the TRNSYS model requires input files to be at a discrete time step, a python script was developed to take a fixed, user-supplied time step and generate individual files for cold and hot water draws by fixture. The TRNSYS model simulates at a 6-second time step as the minimum draw duration specified by the DHWESG, therefore the draw schedule files contain a full year of 6-second records.

2.2 TRNSYS Distribution Model Description

TRNSYS is a widely adopted simulation tool that is flexible in using any combination of models, including user-specified models, to analyze equipment and building system performance. HWSIM is a narrowly focused simulation tool for analyzing DHW systems and is only newly enhanced with high fidelity water heating and control models.

Where HWSIM has its advantage is that distribution systems may be quickly laid out and analyzed in a matter of minutes with simple water heater system models. HWSIM comes integrated with several recirculation control options and individual use points may be easily and individually configured to operate either as a tub draw (fixed final energy condition), minimum required supply temperature, or fixed volume flow (appliances). HWSIM is also publicly available and the results are easily generated in either discrete, tabular, or refined summary reports. HWSIM lacks the ability to model simultaneous (i.e., overlapping) draws, and in order to expedite simulation speeds with high fidelity water heating models, the input draw schedules were reduced to three representative seasonal days (winter, summer, and spring/fall).

Where TRNSYS has its advantage is with the flexibility of analyzing a variation of conditions, including buried pipes, concurrent draw events, and a full year of hourly temperatures and draw schedules. TRNSYS takes significantly more effort to develop and input a model, with large systems consisting of individual pipe elements that require multiple conditions and inputs. In addition, each individual branch requires a discrete control element to direct the flow to the corresponding use point. Outputs are manually formatted and reported in user-specified delimited files, and full annual simulations at a 6-second time step take approximately 5 hours to complete. TRNSYS is not capable of easily adjusted parametric evaluations, therefore an individual model and input file is needed to evaluate each option, climate, and draw schedule.

While HWSIM has some benefits, TRNSYS is much more widely used, and in an effort to build upon our prior validation work, it was decided to use TRNSYS to evaluate the various distribution systems. The validated model shown in Figure 4 consists of an electric storage water heater (Type 534 set at 120°F),[2] individual piping elements (Type 604a), diverters (Type 11), Typical Meteorological Year 3 weather file and individual file readers for hourly zone (attic, basement, garage, indoor) temperatures generated by BEopt and the six second draw schedule file. The diverters are controlled by inline calculators that determine the fraction of flow through each branch from the draw schedule. In each distribution system evaluated, the calculators had to be rewritten as needed to accommodate the change in routing. The original validated model was driven by the combined hot and cold flow rates generated by the DHWESG, and controlled output temperature with a series of valves to maintain non-appliance loads at the desired temperature. The model's useful energy delivered varied across climates as the useful hot water volumes correlated with pipe heat loss. This makes it difficult to accurately evaluate the impact of climate and plumbing configurations on distribution loss. The validated model also did not evaluate demand recirculation as there is no existing TRNSYS model available. In order to accurately model useful energy delivered and recirculation systems, component models needed to be written to control the water supply.

[2] Nationally gas water heating is slightly more common that electric water heating. Because the focus of the study was on the distribution system, we decided not to make water heater type an added parametric case. The recovery load (energy leaving the water heater) would be similar in either case.

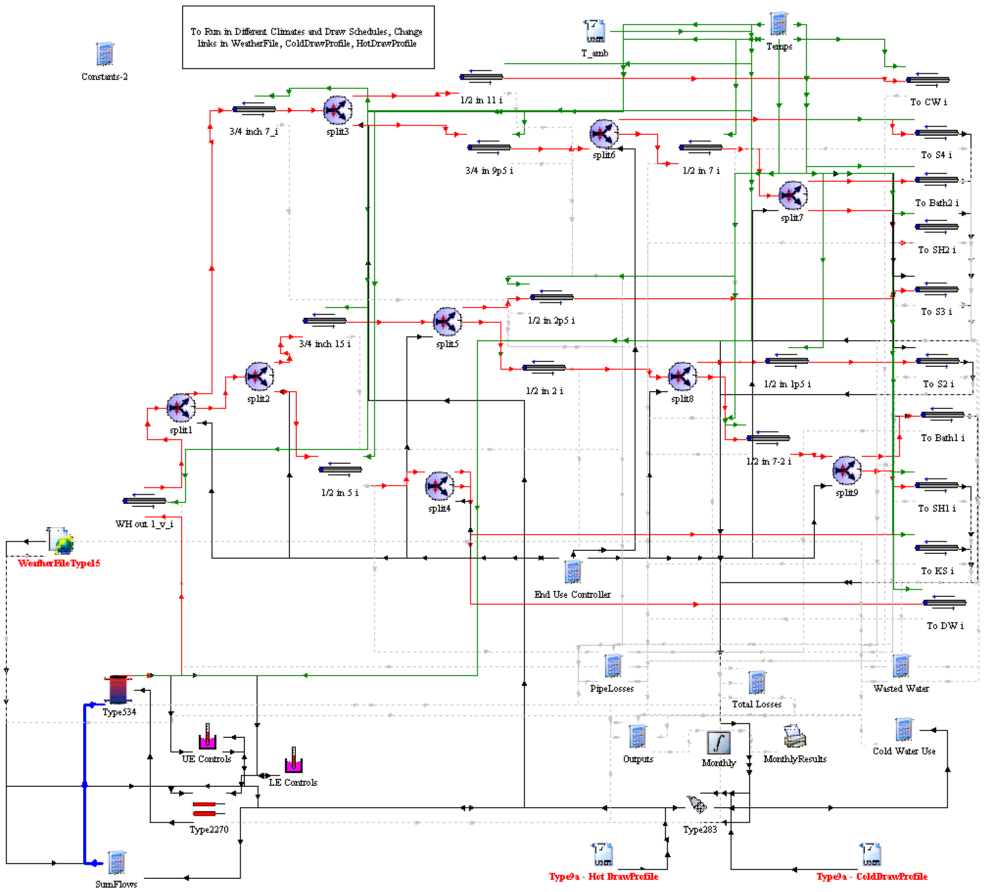

Figure 4. Representation of TRNSYS model configuration

2.3 Delivered Hot Water Control Model

The draw schedule supplied from the DHWESG takes into account non-appliance mixed flow temperature setting and a basic assumption for water waste. The flow rates are fixed throughout the draw event and the prior TRNSYS model used the mixed flow schedule to drive the simulation. A component model was created in FORTRAN and compiled for use in TRNSYS that takes into account the separate hot and cold water schedules and use point temperatures to control the hot and cold water flows. The control model observes the fixture temperature and throttles the hot and cold flow rates to deliver specified tempered water to the use point. The draw schedule is considered to be a schedule of desired useful hot water volumes, therefore insufficiently hot flows are accumulated as water waste and the draw is extended until the desired volume of useful hot water is reached.

2.4 Demand Recirculation Model

In addition to the delivered hot water control model, a demand recirculation model required development. The demand recirculation control model makes use of the hot water control model to meet the desired fixture useful hot water volume and applies an additional control delay for recirculation time. The model takes a user-specified control location in the distribution system in which to monitor temperature and outputs a binary signal for pump runtime, which then could be used to estimate pumping energy and drive recirculation flow rates. Research is still being conducted on behavioral use of demand recirculation systems. In most models (including

HWSIM), it is assumed that demand recirculation is initiated prior to each draw, and once the control point temperature is reached, the pump shuts off and the draw commences. For this demand control model, a user-specified fixed time delay is applied before a draw. If the control point temperature is not yet reached, the pump continues to operate along with the draw until the control point temperature is reached. The flows are modulated to deliver the desired useful hot water volume and hot water that is insufficiently hotis accumulated as waste. The control, as modeled, represents optimized demand recirculation control, both in terms of perfect initiation for all draws, and immediate subsequent hot water use. An alternative occupancy sensor based control strategy would demonstrate degraded performance as it is prone to prime the recirculation loop at times when hot water draws do not necessarily follow the pump activation. A prior single home study that Davis Energy Group completed under the CARB team in 2003, suggested that 70% of occupancy sensor pump signals were not followed by a hot water use event (DEG 2003).

3 Results

In conducting the evaluations a set of parameters were varied to determine the sensitivity of the results. TRNSYS is not capable of Monte Carlo simulations, and each variation requires a separate model, resulting in the 124 models prescribed. Simulating the model over a full year at a 6-second time step, the average runtimes were 5 hours each, excessively long for direct integration with annual whole-building simulations. By analyzing the sensitivity of the outputs, assumptions may be made that will integrate better into whole-building simulations. The key outputs are distribution losses, water consumption, and water waste. The parameters evaluated that influence these results are occupancy, climate, building types, distribution types, typical plumbing, and insulation practices. With six parameters varied, it is necessary to hold some parameters constant or averaged, to inspect the independent influence on results. In the results expressed in the following section, we begin by looking at the system results averaged over climate and occupancy. Distribution losses, water heater energy consumption, hot water use, and waste are examined separately to determine significance of climate, plumbing practice, and insulation influence. Further inspection can be made with additional parameters varied, such as water heating type and different recirculation strategies, but are beyond scope of this analysis and are suggested for further research.

In all nonrecirculation distribution options, water heater energy consumption and hot water waste are correlated. A decrease in water heater energy consumption follows a reduction in wasted water; therefore, improving insulation and reducing the piping length and/or pipe diameter have equal benefits for energy and water waste. In recirculation systems, water heater energy consumption and wasted hot water are independent, and often have an inverse effect. Averaging across climates, Figure 5 and Figure 6 show the ranking of various distribution options by average annual energy consumption for the two- and four-person households, respectively, with the most energy efficient configuration shown at the left-hand side. In all climates this rank was the same, with the insulated, central heater, trunk and branch system using the least amount of energy and the short-run recirculation system wasting the least amount of hot water. Highlighted in yellow are uninsulated trunk and branch systems that are typical plumbing practices in existing single-family homes and reference as the base case.

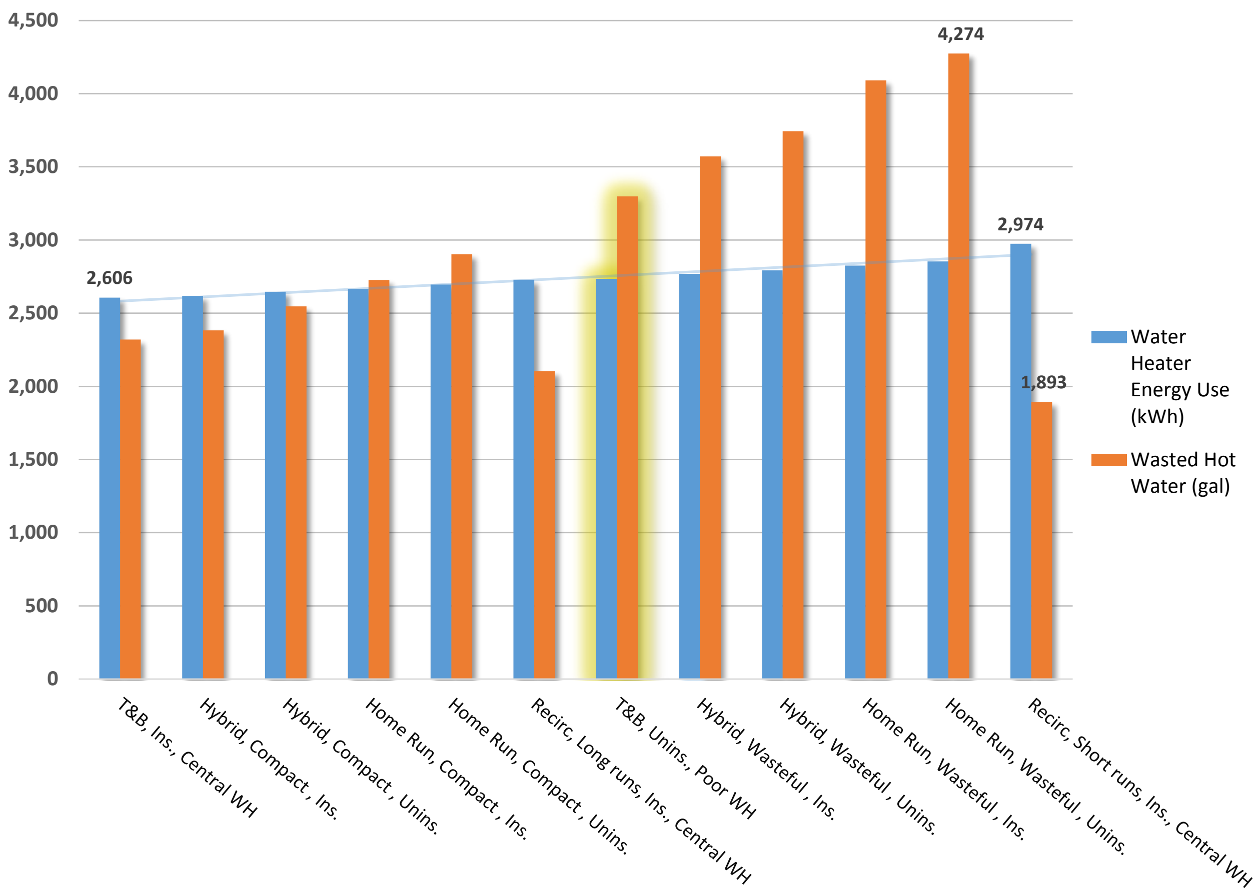

Figure 5. System ranking by annual water heater energy use and waste (2 person)

For a two-person household, the greatest projected reduction in annual water heater energy use is 128 kWh from the base case, which is achieved by insulating and locating the water heater centrally to the distribution system. For the same case, the water waste improvement is 978 gal/year (30% reduction). For short run recirculation systems, a reduction in hot water waste of 1,405 gal (36% reduction) comes at a cost of 240 kWh annually. By lengthening the run-outs and shortening the recirculation loop, there is an improvement in energy savings (6 kWh/year) and wasted hot water (1,194 gal/year) and over the base case, however the site energy savings are not enough to cover the cost of the recirculation pump.[3]

[3] Factoring in the embedded energy in municipal water nationally (Copeland 2014), the energy savings with the reduction in water waste is at best an additional 4.8 kWh/year. While the energy varies significantly nationally, even in southern California (Klein 2005), the energy savings are only 17.4 kWh/year. Factoring in the embedded water use in electricity generation (Wilson et al. 2012), the most energy-efficient option saves an additional 5,325 gal/year.

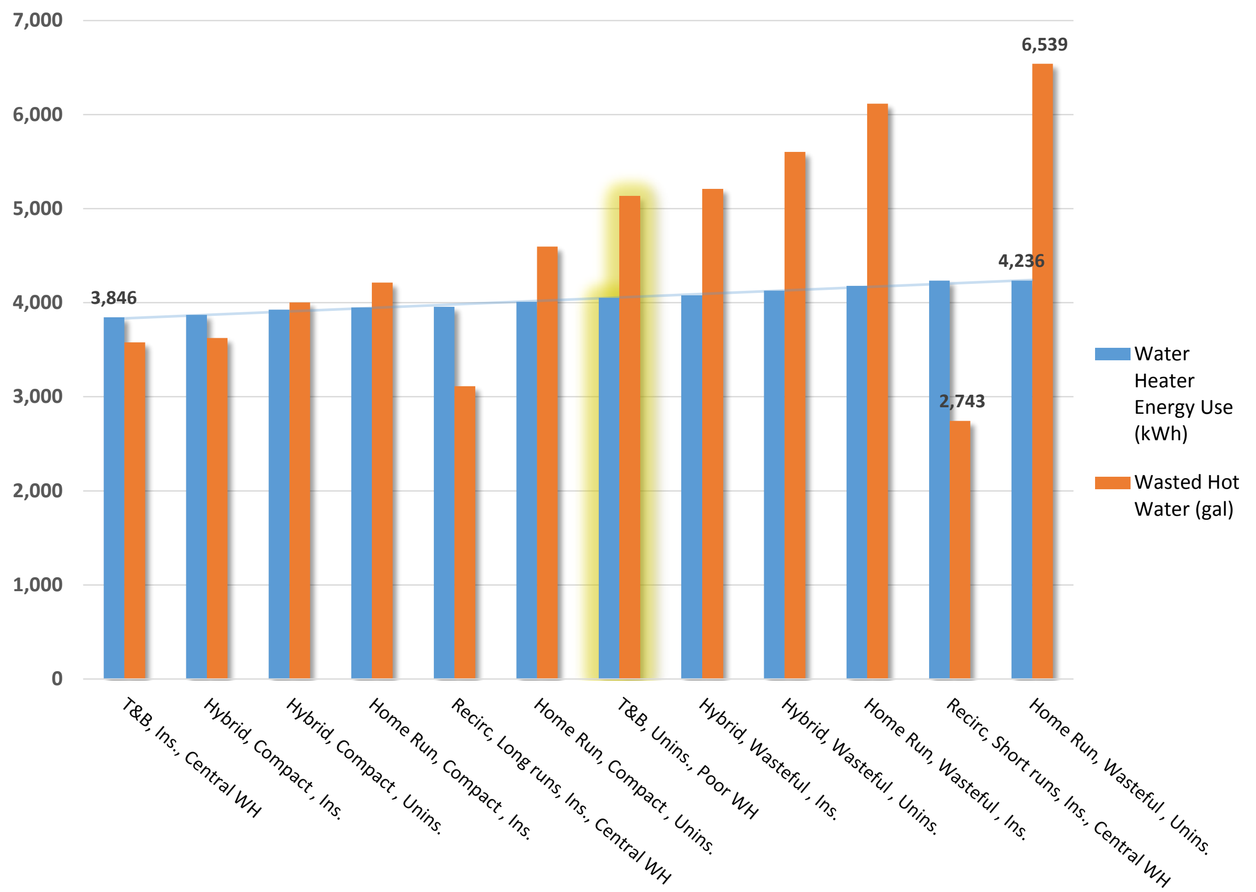

Figure 6. System ranking by annual water heater energy use and waste (4 person)

For a four-person household, the greatest projected reduction in annual water heater energy use is 203 kWh from the base case. For the same case (insulated trunk and branch with central water heater) the water waste improvement is 1,555 gal/year. At this higher hot water consumption level, home run systems are projected to be the worst energy performer; however, only by a small margin (2 kWh/year) from the short run recirculation system. Again, for short run recirculation systems, a reduction in hot water waste of 2,391 gal comes at a cost of 185 kWh annually. Shortening the recirculation loop and lengthening the run-outs save 93 kWh/year and 2,021 gal/year; however, the compact hybrid and trunk and branch systems provide additional energy savings.

3.1 Distribution Losses

Distribution losses are defined as both pipe losses during the draw and the wasted energy associated with wasted hot water. The latter term includes behavioral effects that are not easily modeled or quantified. Table 2 shows the fraction of total projected water heater energy use that is lost through the distribution system as determined for the differing climates. From the draw schedules generated, it can be expected that for any system, the distribution losses represent 13%–29% of water heater energy use. Lower loads in more efficient distribution systems result in the lower distribution loss fraction, while higher loads in less efficient systems result in higher distribution loss fraction. Breaking out the distribution types shows only a slightly narrower range of distribution losses, indicating that other factors, including insulation and pipe lengths, have a larger impact on distribution losses than climate and type. It is important to note that demand recirculation has higher distribution losses due to the increase in the volume of water flowing through the (larger diameter) recirculation plumbing. Cold climates have slightly better recirculation system performance, due in part to the location of the distribution system being between the basement and the subfloors, whereas the other climates piping is routed through the attic space.

Table 2. Range of Distribution Losses as a Percentage of Total Water Heater Annual Energy Use

Climate	Trunk and Branch	Home Run	Hybrid	Recirculation
Hot-Humid (Houston)	13%–20%	15%–23%	13%–20%	20%–29%
Cold (Denver)	14%–20%	16%–23%	13%–20%	18%–26%
Hot-Dry (Phoenix)	14%–19%	15%–23%	13%–20%	19%–28%
Cold (Chicago)	14%–20%	15%–23%	13%–20%	18%–26%
Mixed-Humid (Atlanta)	14%–20%	15%–23%	14%–21%	19%–28%

Averaging across the climates, the various cases were ranked again in terms of the fraction of annual energy consumption represented by the distribution system. The base case of uninsulated trunk and branch is highlighted in yellow for reference. Insulated hybrid systems, compact home run, and the combination of insulating and centrally locating the water heater on a trunk and branch system all have less distribution losses than the base case. The short run recirculation system has the highest distribution losses due to the large recirculation run. All recirculation systems have higher distribution losses than the base case for this reason. The hybrid and home run systems marked as wasteful have an extended length of pipe between the water heater and the manifold, as is typically seen with PEX systems.

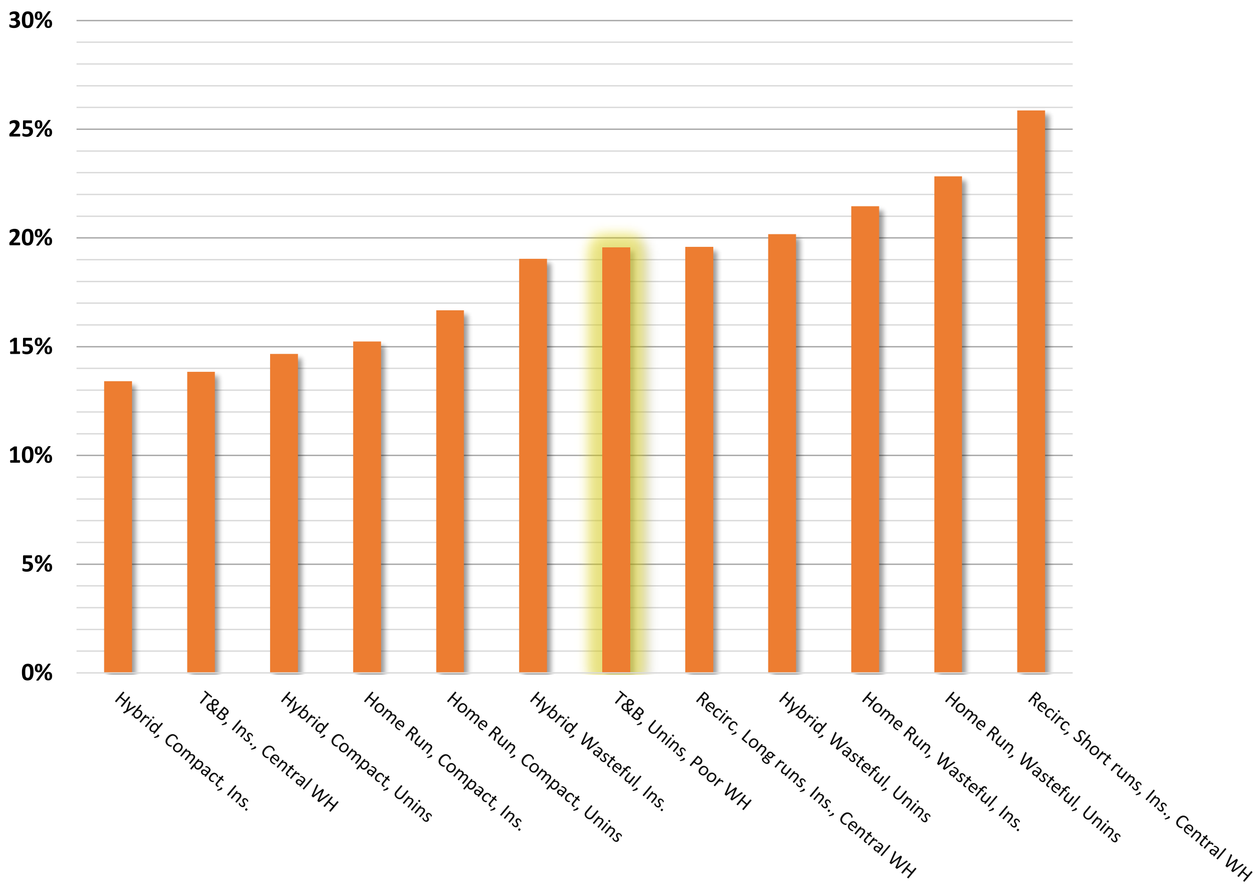

Figure 7. System ranking by percent distribution loss of total water heater energy use

Both piping lengths and pipe diameter have strong influence on distribution losses. Even with recirculation systems, the total enclosed volume of water between the water heater and the use point impacts the percentage of energy use that is lost to the distribution system. In all the cases evaluated, for every 10 gal of water volume reduced by compact plumbing practices, there is a reduction of 2.6%–4% of water heater energy losses. For instance in home run systems, by reducing the main pipe between the water heater and the manifold, and reducing the pipe diameter of sink and dishwasher runs to ⅜ in., 24 gallons of enclosed water and 6% of water heater energy are saved.

Likewise, insulation has an impact on pipe heat loss. In Figure 8, distribution losses as a fraction of water heating energy use are shown for the various plumbing types with and without insulation. Recirculation systems show the largest benefit from insulation, due to the larger pipe diameters and lengths (i.e., enclosed volume). The cost effectiveness of pipe insulation, especially in piping < ¾ in. diameter, is diluted by the reduced available "savings per foot," and the reduced transit time of hot water in smaller pipes.

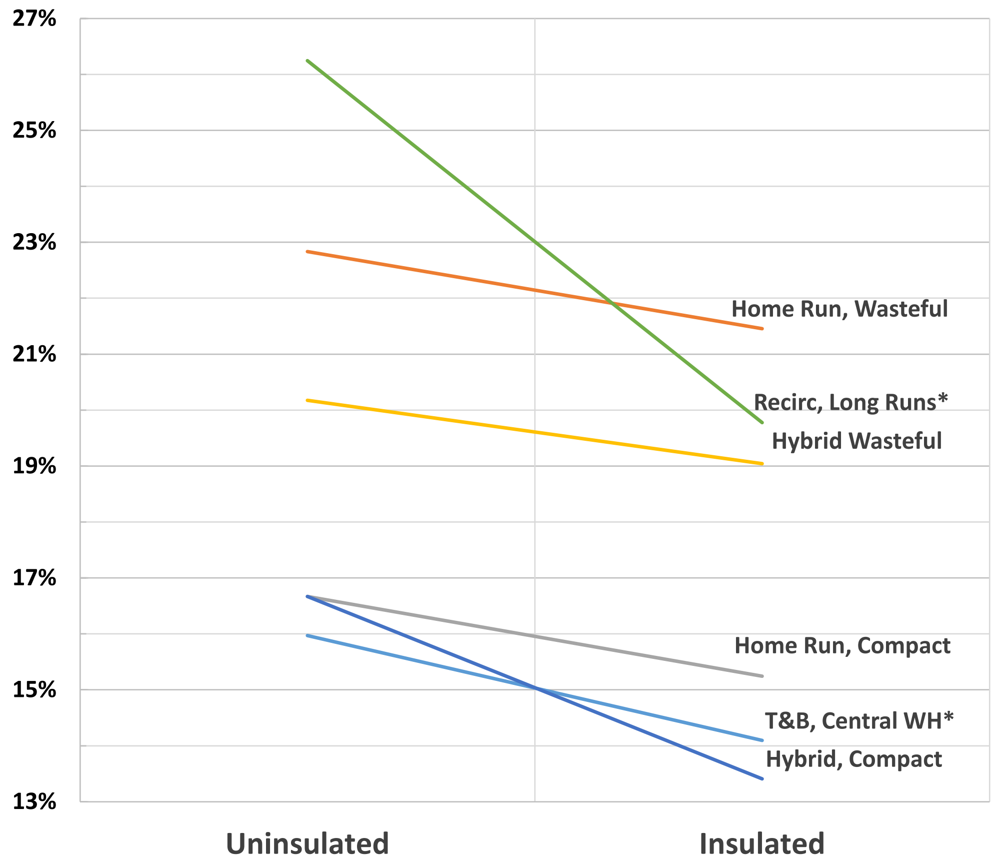

Figure 8. Insulation impact on distribution loss percent of annual water heater energy use

* These are shown for Atlanta only.[4]

3.2 Projected Energy and Water Savings

The energy and water savings of each distribution type and option compared with the base case are presented in Table 3. Uninsulated trunk and branch systems are typical plumbing practices, while home run and hybrid systems are gaining traction. Recirculation loops are often proposed for larger houses and plumbing systems with long distances between use points. Uninsulated trunk and branch systems are projected to consume 1,190 kWh per person per year, with distribution losses accounting for approximately 20% of the water heating energy. The water waste accounts for approximately 18% of the total water use. By simply relocating the water heater to a central location and insulating the pipes, the enhanced system saves nearly 5% of the water heater energy consumed in the base case, with the next best option being an insulated compact hybrid system. Both the insulated compact trunk and branch and hybrid systems save more than 30% in distribution losses.

Plumbing practices such as extending runs to avoid the use of elbows and larger than required supply lines should be avoided as they both increase energy consumption and water consumption.

[4] The uninsulated case was run in one sample climate to reduce the number of parametric runs. The comparison to insulated is shown for Atlanta only.

In nonrecirculation systems, the distribution loss savings of the improved systems are slightly higher than the water heater energy savings. This is due to the fact that some of the draws with the improved systems are satisfied by the enclosed water in the distribution system that is barely above an acceptable minimum use condition. The lower delivery temperatures require an increased hot water flow rate needed to satisfy the draw, until the line is flushed with hot water from the water heater. In recirculation systems, the inverse is true, the higher temperatures from the nearby recirculation loop mean more hot water is delivered than is wasted.

Table 3. Distribution Systems Savings in Energy, Distribution Loss, Water Use, and Water Waste Relative to Base Case, Averaged Over Climates and Occupancy Levels

Distribution Type	Annual Water Heater Use (kWh/ person)	Distribution Losses (kWh/ person)	Total Hot Water Use (gal/ person-day)	Wasted Hot Water (gal/ person-day)
Base Case: Trunk and Branch, Uninsulated, Typical WH Location	1,190	233	22.7	4.0
Trunk and Branch, Insulated, Central WH Location	4.8%	32.7%	5.5%	29.9%
Home Run, Wasteful Plumbing, Uninsulated	(4.5%)	(21.9%)	(4.9%)	(28.6%)
Home Run, Wasteful Plumbing, Insulated	(3.3%)	(13.2%)	(3.5%)	(21.9%)
Home Run, Compact Plumbing, Uninsulated	1.2%	15.9%	1.6%	11.3%
Home Run, Compact Plumbing, Insulated	2.5%	24.1%	3.0%	17.6%
Hybrid, Wasteful Plumbing, Uninsulated	(2.1%)	(5.2%)	(2.2%)	(11.6%)
Hybrid, Wasteful Plumbing, Insulated	(1.0%)	1.8%	(0.9%)	(5.3%)
Hybrid, Compact Plumbing, Uninsulated	3.1%	27.4%	3.6%	22.5%
Hybrid, Compact Plumbing, Insulated	4.3%	34.4%	5.0%	28.5%
Recirculation Loop, Long Run-outs, Insulated, Central WH Location	1.1%	1.1%	10.0%	37.6%
Recirculation Loop, Short Run-outs, Insulated, Central WH Location	(7.0%)	(41.4%)	10.4%	44.3%

Recirculation systems are designed to reduce water waste by shortening the length between available hot water and the use point, and do so effectively. Demand recirculation systems offer the added benefit of minimizing pump runtimes and therefore reducing losses relative to continually operating recirculation systems. They do experience heat loss during flow, as the energy input needed to bring the loop up to temperature at the start of subsequent pump cycles. The latter can be significant based on the size of the loop and hot water usage patterns, which will dictate how many heat up/cool down cycles exist during a day. A balance exists between getting hot water quickly to all use points (and also minimizing water waste) and the energy penalty associated with a larger recirculation loop. There is a point at which the loop length and water savings can be maximized, but it appears to be in systems with shorter recirculation loops and longer run-outs. Simply the reduction in distribution losses must balance out with the recirculation losses to maximize energy savings. Demand recirculation systems are not projected to provide energy savings relative to an already centrally located water heater with insulated lines for trunk and branch systems. Even by extending the run-outs and shortening the recirculation loop there are marginal water heater energy savings with demand recirculation.

In writing an additional TRNSYS control model that performs a wait for useful hot water and extending the draw so the entire volume of water is satisfied, the useful energy delivered is fairly consistent across distribution systems. In order to compare the various distribution system losses, the distribution loss is expressed as a fraction of useful energy delivered, providing a normalized view of the losses. In Figure 9, the distribution losses are compared for each type across each climate. The base case for each type is the uninsulated, distantly located water heater and wasteful plumbing practice, while the improved system is the compilation of these measures. The improved recirculation system is the system with the short run-outs and long recirculation loop, as suggested. In terms of distribution loss, they do not add any improvement over the smaller recirculation loop. In all climates, the improved hybrid system shows the least amount of distribution loss.

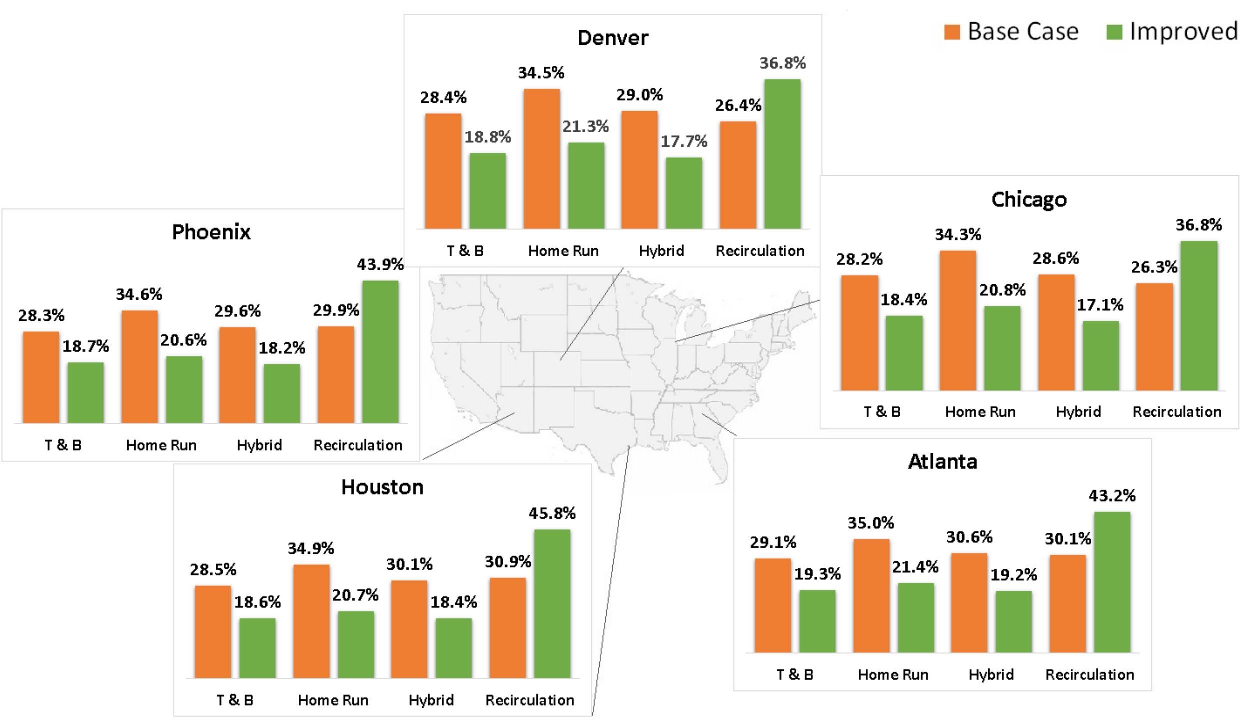

Figure 9. Variation in distribution loss percent of useful energy delivered by climate and installation quality

3.3 Water Use and Waste

The average daily hot water use (combined useful and waste) is presented in Figure 10. Recirculation systems require the least amount of delivered hot water to satisfy the load, with very little improvement with the short run-out configuration. Cold climates typically use more hot water per day than warmer climates (due primarily to mixing with colder water), as well as seeing a larger variation in water use by distribution configuration. Home run systems consume the most amount of water, yet by improving the plumbing configuration and insulation they make the most improvement in water usage relative to the base home run systems. In all climates, the recirculation systems consume the least amount of water, followed by the improved trunk and branch systems.

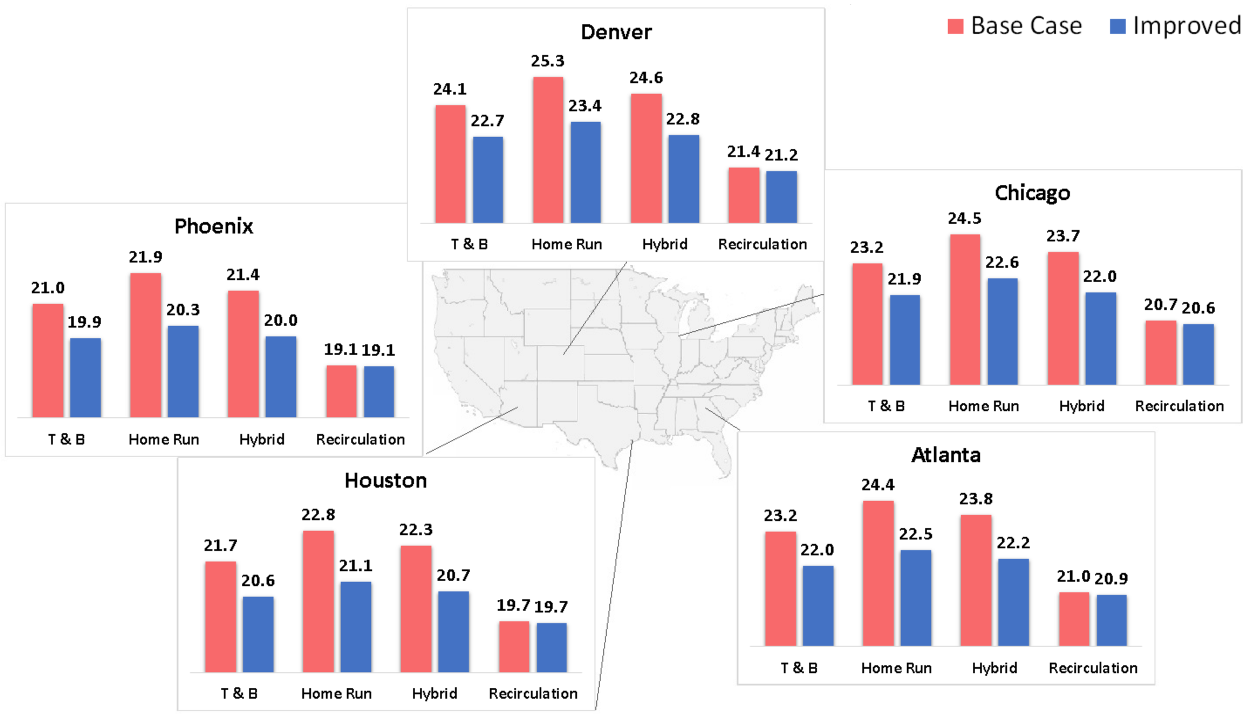

Figure 10. Hot water use (per person, per day) by climate and distribution type

To normalize water waste across the different distribution types, waste is expressed as a fraction of useful hot water delivered, which remains consistent among all cases. In Figure 11, the water waste is compared for the uninsulated wasteful plumbing (base case) and improved systems for each distribution type (green). Again, the recirculation systems show the least water waste, 12%–15%. The base case home run system double the water waste, and even improved home run systems waste more water than improved trunk and branch systems. In cold climates, water waste can be as much as 30% of the total water delivered, 5% higher than the waste in hot-dry climates.

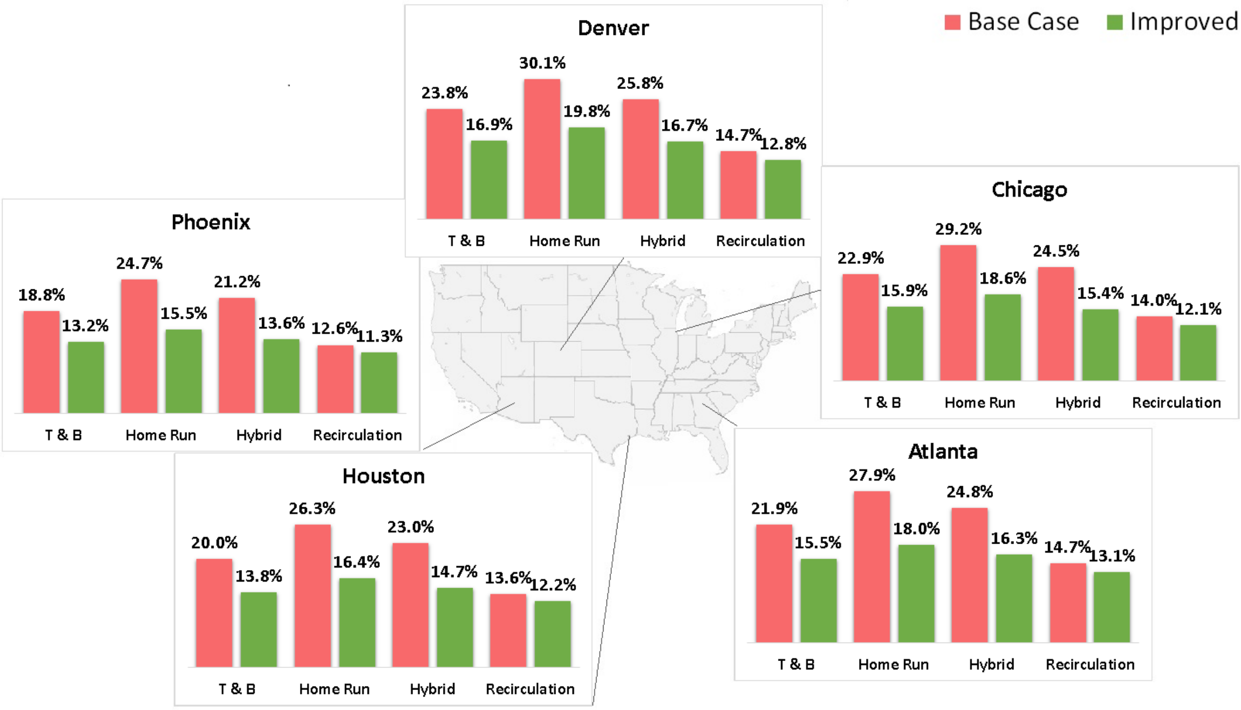

Figure 11. Water waste (as a fraction of useful water delivered) by climate and distribution type

4 Conclusions

The purpose of the project is to provide a deeper understanding of typical energy and water impacts by various distribution system configurations under different load and climate assumptions. While these data give better insight into the sensitivities of distribution performance from several parameters, it is important to highlight that there are wide variances in house architecture, distribution layouts, occupancy levels, and usage patterns. Use point locations do not necessarily dictate distribution layouts and house size is not always correlated with occupancy levels. The results of this research represent a first step in developing a better understanding of the typical parameters to inform a best practices guide to DHW distribution systems. A more thorough Monte Carlo based evaluation strategy is needed to fully characterize the variability of energy and water use. Within the constraints of this study (124 detailed simulations), the authors find that insulated trunk and branch systems with a centrally located water heater provide the most site energy savings (4.8%), while the short-run recirculation systems provide the most site water savings (10.4%).

The project has addressed the following research questions:

1. **What is the expected range in distribution losses (as a fraction of water heater recovery load) as a function of distribution system configuration, climate, and hot water usage pattern?**

In general, distribution losses are 13%–29% of the annual electric water heater energy use. Compact insulated systems with low loads have the lowest distribution losses. While climate does influence the total load on the system and the distribution losses, it has little effect on the range of distribution losses between the systems studied. Cold climates experience slightly better recirculation performance compared with warmer climates. Insulated compact hybrid and central trunk and branch systems have the lowest distribution losses. Nearly all "improved" nonrecirculation distribution systems are more energy efficient than the base-case trunk and branch system. Demand recirculation systems with short run-outs consume 7% more energy than the base trunk and branch system, while the long run-out system provides a marginal 1% energy savings.

2. **What are the realistic savings that can be realized through measures such as insulating all piping or improving distribution system design?**

For the systems evaluated, insulating all lines saves 1.2% (14.3kWh/person) in water heater energy for the home run and hybrid systems, and nearly 6% (71.4kWh/person) for demand recirculation systems. The fraction of energy savings is due to insulation changes with insulation levels and plumbing lengths. Enclosed volume has a direct influence on energy savings (2.6%–4% per 10 gal of enclosed pipe volume reduced); therefore, careful consideration to reduce plumbing lengths is important to maximize energy savings. In nonrecirculation systems, improving distribution losses is not directly equal to water heater energy savings, due to the fact that draws are satisfied with thermally "relaxed," or slightly cooled enclosed water, and higher hot water flow rates are initially needed to satisfy the draw, while for recirculation systems, the higher temperatures from the loop result in more water delivered than wasted. In order for recirculation systems to provide savings over the base distribution system, the recirculation losses must be balanced out with savings in distribution losses.

3. **What are the projected water use/waste implications of the various scenarios simulated?**

The average daily hot water use is lowest in the recirculation systems as waste is minimized by delivering hot water closer to the use points. By insulating and compacting the plumbing on home run systems, water use and waste are the most improved from the base home run system. The insulated trunk and branch system with a centrally located water heater consumes only slightly more water and produces slightly more waste than either of the recirculation systems. The cost to install recirculation pumps and components are typically $1,000 and the savings with the long run-out system do not show much more water waste improvement over centrally located water heating systems.

4. **Where are better data needed to improve the characterization of the "hot water system" based on the observed sensitivities in the modeling study?**

While this study evaluated only demand recirculation control strategies, it is expected that losses would only increase with continual, timer, and occupancy sensor-based control. What is not known are behavioral impacts on demand recirculation, how long users wait after pressing the control before using the fixture, and at what locations are they most likely to use the controls. Tankless systems were not evaluated in this study, as the behavioral wastes with tankless systems have not been fully characterized and are needed to understand the impact of water use and waste with the "cold water sandwich" effect.[5]

4.1 Next Steps

Modeling hot water distribution systems requires a validated model, accurate characterization of the hot water distribution system, and high-resolution input data related to hot water flows and use point characteristics. Efforts to increase the quality of these data feeding into models are important in improving the understanding of distribution systems and the interactions with the overall hot water system. Improved data are needed to better understand plumbing practices as they exist regionally for both base case system performance and evaluating alternative options.

Further related research is needed to better understand how occupants interact with their hot water system and to what extent behavior impacts system performance projections. The advent of wireless sensing technologies should improve the ability to collect high resolution data at a lower cost. Emerging technologies such as gas tankless, heat pump water heater, and other new technologies will likely influence behaviors to some degree. Theoretically, behavioral assumptions could then be implemented as another control model into the TRNSYS simulation model to evaluate potential behavioral impacts.

Ongoing work in this research area should be reviewed to determine what elements can be incorporated in future versions of BEopt. Given the need for very short time step modeling of hot water events, it is unlikely that a full-scale hot water model can be effectively implemented in BEopt, but some components or features may improve the ability of the software to model hot water systems.

[5] Cold water sandwich effect happens when multiple draw events occur close together. With each tank firing there is a burner firing delay after the start of flow, allowing an initial slug of cold water to pass through the exchanger. At the use point the user will experience hot water that was in the lines from the previous draw, followed by a cooled or cold volume, before hot water arrives.

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Appendix A: TRNSYS Model Results

Included in Table 4 are the compiled annual results for the 124 selected model cases.

Table 4. Compiled Annual Results

Parametric Options for Run ID:	1	2	3	4	5
Climate	Chicago	Chicago	Denver	Denver	Chicago
Occupants	2	4	2	4	2
Distribution Type	Trunk & Branch	Trunk & Branch	Trunk & Branch	Trunk & Branch	Trunk & Branch
Recirculation Type					
Insulation	None	None	None	None	Ins
Plumbing Practice	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Compact
Annual Results:					
Water Heater Energy Use (kWh)	3,365	4,889	3,343	4,932	3,201
Hot Water Draw (gal)	19,160	29,437	19,843	30,607	18,071
Total Water Use (gal)	20,851	32,070	21,605	33,375	19,917
Energy Delivered (kWh)	2,946	4,472	2,927	4,518	2,782
Tank Losses (kWh)	415.5	414.1	412.6	410.7	415.8
Use Point Wasted Energy (kWh)	330.5	507.7	330.4	518.0	252.7
Wasted Hot Water (gal)	3,590	5,470	3,871	5,801	2,509
Pipe Loss, All (kWh)	325.1	466.4	328.6	466.5	190.0
Recirc Losses (kWh)					
Total Distribution Losses (kWh)	655.6	974.2	659.0	984.5	442.8
Total Useful Energy (kWh)	2,294	3,501	2,271	3,537	2,343
Useful Energy (% of water heater energy use)	68.2%	71.6%	67.9%	71.7%	73.2%
Pipe Losses (% of water heater energy use)	9.7%	9.5%	9.8%	9.5%	5.9%
Wasted Energy (% of water heater energy use)	9.8%	10.4%	9.9%	10.5%	7.9%
Water Heater Losses (% of water heater energy use)	12.3%	8.5%	12.3%	8.3%	13.0%
Water Waste (% of total hot water)	18.7%	18.6%	19.5%	19.0%	13.9%
Wasted Water (% of useful water delivered)	23.1%	22.8%	24.2%	23.4%	16.1%
Distribution Losses (% of water heater energy use)	19.5%	19.9%	19.7%	20.0%	13.8%
Distribution Losses (% of useful energy delivered)	28.6%	27.8%	29.0%	27.8%	18.9%

6	7	8	9	10	11	12	13	14
Chicago	Denver	Denver	Chicago	Chicago	Denver	Denver	Chicago	Chicago
4	2	4	2	4	2	4	2	4
Trunk & Branch	Trunk & Branch	Trunk & Branch	Demand Recirc	Demand Recirc	Demand Recirc	Demand Recirc	Demand Recirc	Demand Recirc
			Long run-outs	Long run-outs	Long run-outs	Long run-outs	Short run-outs	Short run-outs
Ins	Ins	Ins	Ins	Ins	Ins	Ins	Ins	Ins
Compact	Compact	Compact	Compact	Compact	Compact	Compact	Compact	Compact
4,630	3,181	4,676	3,314	4,731	3,278	4,752	3,585	5,032
27,703	18,740	28,850	17,144	26,291	17,577	27,269	17,032	26,087
30,578	20,659	31,869	18,907	29,130	19,425	30,207	18,714	28,798
4,212	2,765	4,261	2,893	4,310	2,860	4,333	3,164	4,611
414.6	412.9	411.2	417.1	417.5	414.2	414.5	417.0	417.5
373.3	256.7	386.7	225.0	302.0	215.6	312.6	209.6	269.8
3,754	2,784	4,071	2,235	3,016	2,360	3,341	1,988	2,569
267.9	193.0	268.7	421.8	530.4	423.7	528.4	711.3	863.9
			101.1	104.2	99.3	103.7	248.2	262.6
641.2	449.7	655.4	646.8	832.4	639.4	841.0	920.9	1,133.7
3,575	2,318	3,609	2,250	3,481	2,224	3,496	2,247	3,481
77.2%	72.9%	77.2%	67.9%	73.6%	67.9%	73.6%	62.7%	69.2%
5.8%	6.1%	5.7%	12.7%	11.2%	12.9%	11.1%	19.8%	17.2%
8.1%	8.1%	8.3%	6.8%	6.4%	6.6%	6.6%	5.8%	5.4%
9.0%	13.0%	8.8%	12.6%	8.8%	12.6%	8.7%	11.6%	8.3%
13.6%	14.9%	14.1%	13.0%	11.5%	13.4%	12.3%	11.7%	9.8%
15.7%	17.5%	16.4%	15.0%	13.0%	15.5%	14.0%	13.2%	10.9%
13.8%	14.1%	14.0%	19.5%	17.6%	19.5%	17.7%	25.7%	22.5%
17.9%	19.4%	18.2%	28.7%	23.9%	28.7%	24.1%	41.0%	32.6%

15	16	17	18	19	20	21	22	23
Denver	Denver	Chicago	Chicago	Denver	Denver	Chicago	Chicago	Denver
2	4	2	4	2	4	2	4	2
Demand Recirc	Demand Recirc	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run
Short run-outs	Short run-outs							
Ins	Ins	None	None	None	None	Ins	Ins	Ins
Compact	Compact	Compact	Compact	Compact	Compact	Compact	Compact	Compact
3,545	5,052	3,323	4,850	3,294	4,887	3,287	4,777	3,257
17,450	27,062	18,857	29,137	19,470	30,252	18,613	28,644	19,218
19,215	29,877	20,655	31,936	21,342	33,191	20,495	31,569	21,175
3,127	4,634	2,904	4,432	2,877	4,472	2,868	4,359	2,841
414.2	414.4	415.7	414.4	412.9	411.0	415.7	414.5	413.0
199.1	281.9	293.7	450.6	296.2	461.3	279.9	419.1	283.4
2,096	2,893	3,156	4,862	3,433	5,217	2,964	4,442	3,237
711.1	859.1	253.4	381.7	256.2	384.0	221.0	323.1	222.8
243.2	257.7							
910.2	1,141.0	547.1	832.3	552.4	845.3	500.9	742.1	506.2
2,220	3,496	2,360	3,604	2,328	3,630	2,370	3,620	2,338
62.6%	69.2%	71.0%	74.3%	70.7%	74.3%	72.1%	75.8%	71.8%
20.1%	17.0%	7.6%	7.9%	7.8%	7.9%	6.7%	6.8%	6.8%
5.6%	5.6%	8.8%	9.3%	9.0%	9.4%	8.5%	8.8%	8.7%
11.7%	8.2%	12.5%	8.5%	12.5%	8.4%	12.6%	8.7%	12.7%
12.0%	10.7%	16.7%	16.7%	17.6%	17.2%	15.9%	15.5%	16.8%
13.6%	12.0%	20.1%	20.0%	21.4%	20.8%	18.9%	18.4%	20.3%
25.7%	22.6%	16.5%	17.2%	16.8%	17.3%	15.2%	15.5%	15.5%
41.0%	32.6%	23.2%	23.1%	23.7%	23.3%	21.1%	20.5%	21.7%

24	25	26	27	28	29	30	31	32
Denver	Chicago	Chicago	Denver	Denver	Chicago	Chicago	Denver	Denver
4	2	4	2	4	2	4	2	4
Home Run	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run
Ins	None	None	None	None	Ins	Ins	Ins	Ins
Compact	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)
4,818	3,523	5,140	3,494	5,162	3,490	5,070	3,461	5,098
29,781	20,177	31,052	20,836	32,115	19,950	30,575	20,606	31,669
32,852	21,869	33,701	22,602	34,906	21,732	33,353	22,461	34,591
4,403	3,104	4,723	3,078	4,748	3,071	4,653	3,045	4,683
411.1	415.3	413.8	412.5	410.5	415.4	414.0	412.6	410.6
436.0	377.5	587.0	382.4	584.4	371.3	570.0	377.4	574.2
4,832	4,595	6,954	4,943	7,255	4,403	6,512	4,747	6,858
324.7	422.8	609.9	426.0	608.3	381.5	532.6	383.3	531.0
760.7	800.3	1,196.9	808.4	1,192.7	752.8	1,102.6	760.7	1,105.1
3,646	2,307	3,529	2,273	3,559	2,322	3,554	2,288	3,582
75.7%	65.5%	68.7%	65.1%	68.9%	66.5%	70.1%	66.1%	70.3%
6.7%	12.0%	11.9%	12.2%	11.8%	10.9%	10.5%	11.1%	10.4%
9.0%	10.7%	11.4%	10.9%	11.3%	10.6%	11.2%	10.9%	11.3%
8.5%	11.8%	8.1%	11.8%	8.0%	11.9%	8.2%	11.9%	8.1%
16.2%	22.8%	22.4%	23.7%	22.6%	22.1%	21.3%	23.0%	21.7%
19.4%	29.5%	28.9%	31.1%	29.2%	28.3%	27.1%	29.9%	27.6%
15.8%	22.7%	23.3%	23.1%	23.1%	21.6%	21.7%	22.0%	21.7%
20.9%	34.7%	33.9%	35.6%	33.5%	32.4%	31.0%	33.2%	30.9%

33	34	35	36	37	38	39	40	41
Chicago	Chicago	Denver	Denver	Chicago	Chicago	Denver	Denver	Chicago
2	4	2	4	2	4	2	4	2
Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
None	None	None	None	Ins	Ins	Ins	Ins	None
Compact	Compact	Compact	Compact	Compact	Compact	Compact	Compact	Typical (Waste)
3,241	4,719	3,216	4,756	3,210	4,653	3,187	4,694	3,435
18,335	28,295	18,967	29,389	18,126	27,843	18,775	28,954	19,603
20,184	31,187	20,894	32,420	20,038	30,829	20,764	32,088	21,339
2,822	4,301	2,799	4,342	2,791	4,235	2,771	4,279	3,016
415.7	414.4	412.9	411.1	415.8	414.6	412.9	411.2	415.4
256.1	390.2	262.7	401.4	245.4	360.7	255.0	377.0	357.6
2,626	4,026	2,926	4,354	2,465	3,636	2,786	3,990	3,945
197.0	292.2	200.1	294.2	171.6	245.6	174.3	246.5	327.2
453.0	682.4	462.8	695.6	417.0	606.3	429.4	623.5	684.9
2,372	3,622	2,340	3,649	2,377	3,632	2,345	3,659	2,335
73.2%	76.8%	72.8%	76.7%	74.1%	78.1%	73.6%	78.0%	68.0%
6.1%	6.2%	6.2%	6.2%	5.3%	5.3%	5.5%	5.3%	9.5%
7.9%	8.3%	8.2%	8.4%	7.6%	7.8%	8.0%	8.0%	10.4%
12.8%	8.8%	12.8%	8.6%	13.0%	8.9%	13.0%	8.8%	12.1%
14.3%	14.2%	15.4%	14.8%	13.6%	13.1%	14.8%	13.8%	20.1%
16.7%	16.6%	18.2%	17.4%	15.7%	15.0%	17.4%	16.0%	25.2%
14.0%	14.5%	14.4%	14.6%	13.0%	13.0%	13.5%	13.3%	19.9%
19.1%	18.8%	19.8%	19.1%	17.5%	16.7%	18.3%	17.0%	29.3%

42	43	44	45	46	47	48	49	50
Chicago	Denver	Denver	Chicago	Chicago	Denver	Denver	Phoenix	Phoenix
4	2	4	2	4	2	4	2	4
Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Trunk & Branch	Trunk & Branch
None	None	None	Ins	Ins	Ins	Ins	None	None
Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)
4,982	3,409	5,017	3,405	4,923	3,381	4,956	1,928	2,950
30,024	20,278	31,166	19,407	29,617	20,077	30,730	16,975	27,407
32,734	22,086	34,015	21,199	32,422	21,949	33,677	20,370	32,825
4,564	2,993	4,603	2,986	4,505	2,965	4,542	1,628	2,650
414.0	412.6	410.6	415.5	414.2	412.7	410.8	296.5	296.2
537.1	365.1	548.1	348.7	518.8	357.9	527.0	106.7	191.2
5,786	4,300	6,172	3,775	5,429	4,129	5,778	2,740	4,250
456.2	330.1	456.1	299.3	404.7	301.7	403.4	259.7	384.0
993.4	695.2	1,004.2	648.0	923.4	659.6	930.5	366.3	575.2
3,574	2,301	3,602	2,342	3,585	2,309	3,615	1,265	2,078
71.7%	67.5%	71.8%	68.8%	72.8%	68.3%	72.9%	65.6%	70.5%
9.2%	9.7%	9.1%	8.8%	8.2%	8.9%	8.1%	13.5%	13.0%
10.8%	10.7%	10.9%	10.2%	10.5%	10.6%	10.6%	5.5%	6.5%
8.3%	12.1%	8.2%	12.2%	8.4%	12.2%	8.3%	15.4%	10.0%
19.3%	21.2%	19.8%	19.4%	18.3%	20.6%	18.8%	16.1%	15.5%
23.9%	26.9%	24.7%	24.1%	22.4%	25.9%	23.2%	19.3%	18.4%
19.9%	20.4%	20.0%	19.0%	18.8%	19.5%	18.8%	19.0%	19.5%
27.8%	30.2%	27.9%	27.7%	25.8%	28.6%	25.7%	29.0%	27.7%

51	52	53	54	55	56	57	58	59
Houston	Houston	Atlanta	Atlanta	Phoenix	Phoenix	Houston	Houston	Atlanta
2	4	2	4	2	4	2	4	2
Trunk & Branch	Trunk & Branch	Trunk & Branch	Trunk & Branch	Trunk & Branch	Trunk & Branch	Trunk & Branch	Trunk & Branch	Trunk & Branch
None	None	None	None	Ins	Ins	Ins	Ins	Ins
Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Compact	Compact	Compact	Compact	Compact
2,257	3,309	2,776	4,167	1,843	2,811	2,155	3,148	2,650
17,856	27,774	18,822	30,196	16,107	26,012	16,887	26,256	17,801
20,451	31,944	21,007	33,659	19,726	31,777	19,691	30,743	20,181
1,900	2,952	2,362	3,754	1,542	2,512	1,798	2,792	2,236
353.4	353.1	410.5	409.3	296.6	296.3	353.5	353.3	410.6
130.2	219.9	198.9	367.7	85.8	149.8	104.0	170.8	158.7
3,004	4,585	3,283	5,563	1,935	2,956	2,078	3,147	2,295
297.5	428.5	333.4	481.4	163.8	235.7	183.3	259.9	203.2
427.7	648.4	532.3	849.1	249.6	385.5	287.3	430.7	361.9
1,476	2,308	1,833	2,909	1,297	2,130	1,514	2,364	1,878
65.4%	69.7%	66.0%	69.8%	70.4%	75.7%	70.3%	75.1%	70.8%
13.2%	12.9%	12.0%	11.6%	8.9%	8.4%	8.5%	8.3%	7.7%
5.8%	6.6%	7.2%	8.8%	4.7%	5.3%	4.8%	5.4%	6.0%
15.7%	10.7%	14.8%	9.8%	16.1%	10.5%	16.4%	11.2%	15.5%
16.8%	16.5%	17.4%	18.4%	12.0%	11.4%	12.3%	12.0%	12.9%
20.2%	19.8%	21.1%	22.6%	13.7%	12.8%	14.0%	13.6%	14.8%
19.0%	19.6%	19.2%	20.4%	13.5%	13.7%	13.3%	13.7%	13.7%
29.0%	28.1%	29.0%	29.2%	19.2%	18.1%	19.0%	18.2%	19.3%

60	61	62	63	64	65	66	67	68
Atlanta	Phoenix	Phoenix	Houston	Houston	Atlanta	Atlanta	Phoenix	Phoenix
4	2	4	2	4	2	4	2	4
Trunk & Branch	Demand Recirc	Demand Recirc	Demand Recirc	Demand Recirc	Demand Recirc	Demand Recirc	Demand Recirc	Demand Recirc
	Long run-outs	Long run-outs	Long run-outs	Long run-outs	Long run-outs	Long run-outs	Short run-outs	Short run-outs
Ins	Ins	Ins	Ins	Ins	Ins	Ins	Ins	Ins
Compact	Compact	Compact	Compact	Compact	Compact	Compact	Compact	Compact
3,964	1,954	2,916	2,293	3,287	2,800	4,093	2,146	3,138
28,557	15,414	25,016	16,140	25,309	17,033	27,276	15,401	24,935
32,329	18,934	30,755	18,826	29,637	19,289	30,918	18,762	30,457
3,551	1,654	2,616	1,936	2,930	2,386	3,678	1,847	2,838
409.6	295.8	296.4	353.1	353.6	410.9	411.2	295.8	296.5
290.2	81.3	128.6	103.5	163.7	153.0	253.2	79.5	122.8
3,968	1,787	2,716	1,955	2,988	2,181	3,506	1,633	2,427
286.0	329.1	427.6	382.8	485.4	432.2	544.9	531.9	667.5
	61.1	63.6	80.9	84.2	94.9	99.5	152.9	161.9
576.3	410.4	556.2	486.4	649.1	585.1	798.1	611.4	790.3
2,978	1,247	2,064	1,453	2,285	1,804	2,884	1,239	2,052
75.1%	63.9%	70.8%	63.4%	69.5%	64.4%	70.5%	57.7%	65.4%
7.2%	16.8%	14.7%	16.7%	14.8%	15.4%	13.3%	24.8%	21.3%
7.3%	4.2%	4.4%	4.5%	5.0%	5.5%	6.2%	3.7%	3.9%
10.3%	15.1%	10.2%	15.4%	10.8%	14.7%	10.0%	13.8%	9.4%
13.9%	11.6%	10.9%	12.1%	11.8%	12.8%	12.9%	10.6%	9.7%
16.1%	13.1%	12.2%	13.8%	13.4%	14.7%	14.7%	11.9%	10.8%
14.5%	21.0%	19.1%	21.2%	19.7%	20.9%	19.5%	28.5%	25.2%
19.4%	32.9%	27.0%	33.5%	28.4%	32.4%	27.7%	49.4%	38.5%

69	70	71	72	73	74	75	76	77
Houston	Houston	Atlanta	Atlanta	Phoenix	Phoenix	Houston	Houston	Atlanta
2	4	2	4	2	4	2	4	2
Demand Recirc	Demand Recirc	Demand Recirc	Demand Recirc	Home Run	Home Run	Home Run	Home Run	Home Run
Short run-outs	Short run-outs	Short run-outs	Short run-outs					
Ins	Ins	Ins	Ins	None	None	None	None	None
Compact	Compact	Compact	Compact	Compact	Compact	Compact	Compact	Compact
2,530	3,553	3,066	4,394	1,899	2,914	2,222	3,272	2,739
16,105	25,209	16,930	27,124	16,657	27,007	17,500	27,407	18,501
18,662	29,354	19,080	30,607	20,220	32,731	20,251	31,810	20,818
2,173	3,196	2,652	3,980	1,599	2,614	1,865	2,916	2,324
353.0	353.7	410.8	411.2	296.5	296.3	353.5	353.2	410.6
103.0	156.3	144.2	240.6	94.9	169.8	117.3	191.8	178.4
1,804	2,663	1,945	3,161	2,407	3,833	2,626	4,094	2,889
631.4	768.3	713.8	869.6	208.3	321.9	235.0	355.5	263.7
202.1	211.5	234.6	245.2					
734.3	924.6	858.0	1,110.2	303.2	491.7	352.3	547.3	442.2
1,442	2,275	1,797	2,873	1,299	2,126	1,516	2,372	1,886
57.0%	64.0%	58.6%	65.4%	68.4%	73.0%	68.2%	72.5%	68.9%
25.0%	21.6%	23.3%	19.8%	11.0%	11.0%	10.6%	10.9%	9.6%
4.1%	4.4%	4.7%	5.5%	5.0%	5.8%	5.3%	5.9%	6.5%
14.0%	10.0%	13.4%	9.4%	15.6%	10.2%	15.9%	10.8%	15.0%
11.2%	10.6%	11.5%	11.7%	14.4%	14.2%	15.0%	14.9%	15.6%
12.6%	11.8%	13.0%	13.2%	16.9%	16.5%	17.7%	17.6%	18.5%
29.0%	26.0%	28.0%	25.3%	16.0%	16.9%	15.9%	16.7%	16.1%
50.9%	40.6%	47.7%	38.6%	23.3%	23.1%	23.2%	23.1%	23.4%

78	79	80	81	82	83	84	85	86
Atlanta	Phoenix	Phoenix	Houston	Houston	Atlanta	Atlanta	Phoenix	Phoenix
4	2	4	2	4	2	4	2	4
Home Run	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run
None	Ins	Ins	Ins	Ins	Ins	Ins	None	None
Compact	Compact	Compact	Compact	Compact	Compact	Compact	Typical (Waste)	Typical (Waste)
4,125	1,876	2,869	2,197	3,224	2,709	4,064	2,006	3,069
29,817	16,417	26,546	17,269	26,947	18,256	29,327	17,740	28,575
33,500	20,086	32,446	20,121	31,513	20,680	33,177	21,128	34,041
3,712	1,576	2,570	1,840	2,868	2,294	3,651	1,706	2,769
409.4	296.6	296.4	353.5	353.3	410.6	409.5	296.5	296.2
325.0	91.1	158.7	113.4	181.8	172.0	307.3	113.1	202.3
4,975	2,246	3,474	2,468	3,743	2,716	4,582	3,602	5,535
399.0	182.7	274.3	206.2	303.8	230.6	338.5	334.5	497.0
723.9	273.8	433.0	319.6	485.6	402.6	645.8	447.5	699.3
2,991	1,306	2,140	1,524	2,386	1,895	3,009	1,262	2,073
72.5%	69.6%	74.6%	69.4%	74.0%	70.0%	74.0%	62.9%	67.6%
9.7%	9.7%	9.6%	9.4%	9.4%	8.5%	8.3%	16.7%	16.2%
7.9%	4.9%	5.5%	5.2%	5.6%	6.3%	7.6%	5.6%	6.6%
9.9%	15.8%	10.3%	16.1%	11.0%	15.2%	10.1%	14.8%	9.7%
16.7%	13.7%	13.1%	14.3%	13.9%	14.9%	15.6%	20.3%	19.4%
20.0%	15.9%	15.1%	16.7%	16.1%	17.5%	18.5%	25.5%	24.0%
17.6%	14.6%	15.1%	14.5%	15.1%	14.9%	15.9%	22.3%	22.8%
24.2%	21.0%	20.2%	21.0%	20.4%	21.2%	21.5%	35.5%	33.7%

87	88	89	90	91	92	93	94	95
Houston	Houston	Atlanta	Atlanta	Phoenix	Phoenix	Houston	Houston	Atlanta
2	4	2	4	2	4	2	4	2
Home Run	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run	Home Run
None	None	None	None	Ins	Ins	Ins	Ins	Ins
Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)
2,351	3,457	2,892	4,352	1,984	3,025	2,328	3,408	2,865
18,705	29,121	19,734	31,639	17,504	28,092	18,486	28,651	19,515
21,316	33,311	21,927	35,130	21,004	33,741	21,205	33,002	21,815
1,994	3,100	2,478	3,939	1,684	2,725	1,971	3,051	2,451
353.3	353.1	410.4	409.1	296.5	296.3	353.4	353.1	410.4
141.6	236.3	217.1	396.8	114.4	200.0	143.1	235.0	217.4
3,961	5,974	4,268	6,976	3,424	5,107	3,789	5,557	4,094
382.5	554.4	428.4	622.7	301.6	434.2	346.0	486.0	387.2
524.1	790.7	645.5	1,019.5	416.1	634.2	489.1	721.0	604.6
1,473	2,313	1,836	2,923	1,272	2,094	1,485	2,334	1,850
62.7%	66.9%	63.5%	67.2%	64.1%	69.2%	63.8%	68.5%	64.6%
16.3%	16.0%	14.8%	14.3%	15.2%	14.4%	14.9%	14.3%	13.5%
6.0%	6.8%	7.5%	9.1%	5.8%	6.6%	6.1%	6.9%	7.6%
15.0%	10.2%	14.2%	9.4%	14.9%	9.8%	15.2%	10.4%	14.3%
21.2%	20.5%	21.6%	22.0%	19.6%	18.2%	20.5%	19.4%	21.0%
26.9%	25.8%	27.6%	28.3%	24.3%	22.2%	25.8%	24.1%	26.5%
22.3%	22.9%	22.3%	23.4%	21.0%	21.0%	21.0%	21.2%	21.1%
35.6%	34.2%	35.2%	34.9%	32.7%	30.3%	32.9%	30.9%	32.7%

96	97	98	99	100	101	102	103	104
Atlanta	Phoenix	Phoenix	Houston	Houston	Atlanta	Atlanta	Phoenix	Phoenix
4	2	4	2	4	2	4	2	4
Home Run	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
Ins	None	None	None	None	None	None	Ins	Ins
Typical (Waste)	Compact	Compact	Compact	Compact	Compact	Compact	Compact	Compact
4,293	1,871	2,870	2,192	3,226	2,708	4,065	1,850	2,827
31,152	16,362	26,560	17,229	26,978	18,252	29,343	16,140	26,095
34,811	19,996	32,385	20,036	31,473	20,628	33,118	19,861	32,072
3,880	1,571	2,570	1,835	2,869	2,294	3,652	1,550	2,527
409.2	296.6	296.3	353.5	353.2	410.6	409.5	296.6	296.4
392.0	86.0	152.4	106.6	173.1	163.4	295.4	83.1	145.0
6,546	2,146	3,410	2,374	3,705	2,658	4,520	1,986	3,050
544.1	183.8	283.9	209.0	316.4	238.5	352.7	160.9	238.7
936.1	269.8	436.2	315.6	489.5	401.9	648.1	244.0	383.7
2,948	1,305	2,138	1,523	2,383	1,895	3,007	1,310	2,147
68.7%	69.7%	74.5%	69.5%	73.9%	70.0%	74.0%	70.8%	75.9%
12.7%	9.8%	9.9%	9.5%	9.8%	8.8%	8.7%	8.7%	8.4%
9.1%	4.6%	5.3%	4.9%	5.4%	6.0%	7.3%	4.5%	5.1%
9.5%	15.8%	10.3%	16.1%	10.9%	15.2%	10.1%	16.0%	10.5%
21.0%	13.1%	12.8%	13.8%	13.7%	14.6%	15.4%	12.3%	11.7%
26.6%	15.1%	14.7%	16.0%	15.9%	17.0%	18.2%	14.0%	13.2%
21.8%	14.4%	15.2%	14.4%	15.2%	14.8%	15.9%	13.2%	13.6%
31.8%	20.7%	20.4%	20.7%	20.5%	21.2%	21.6%	18.6%	17.9%

105	106	107	108	109	110	111	112	113
Houston	Houston	Atlanta	Atlanta	Phoenix	Phoenix	Houston	Houston	Atlanta
2	4	2	4	2	4	2	4	2
Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
Ins	Ins	Ins	Ins	None	None	None	None	None
Compact	Compact	Compact	Compact	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)
2,168	3,179	2,678	4,004	1,966	3,003	2,307	3,380	2,846
16,994	26,517	18,011	28,853	17,312	27,873	18,307	28,409	19,367
19,888	31,157	20,465	32,758	20,768	33,452	20,963	32,684	21,612
1,811	2,822	2,264	3,591	1,666	2,703	1,950	3,023	2,432
353.5	353.3	410.6	409.5	296.5	296.3	353.3	353.1	410.4
103.3	165.8	157.1	280.4	112.3	196.0	140.4	226.0	213.3
2,208	3,340	2,470	4,112	3,120	4,738	3,506	5,174	3,845
183.1	266.8	208.7	295.5	278.5	407.0	322.1	457.5	364.3
286.4	432.6	365.8	575.8	390.8	603.0	462.5	683.4	577.6
1,528	2,393	1,901	3,019	1,279	2,104	1,491	2,343	1,858
70.5%	75.3%	71.0%	75.4%	65.0%	70.1%	64.6%	69.3%	65.3%
8.4%	8.4%	7.8%	7.4%	14.2%	13.6%	14.0%	13.5%	12.8%
4.8%	5.2%	5.9%	7.0%	5.7%	6.5%	6.1%	6.7%	7.5%
16.3%	11.1%	15.3%	10.2%	15.1%	9.9%	15.3%	10.4%	14.4%
13.0%	12.6%	13.7%	14.3%	18.0%	17.0%	19.2%	18.2%	19.9%
14.9%	14.4%	15.9%	16.6%	22.0%	20.5%	23.7%	22.3%	24.8%
13.2%	13.6%	13.7%	14.4%	19.9%	20.1%	20.0%	20.2%	20.3%
18.7%	18.1%	19.2%	19.1%	30.6%	28.7%	31.0%	29.2%	31.1%

114	115	116	117	118	119	120
Atlanta	Phoenix	Phoenix	Houston	Houston	Atlanta	Atlanta
4	2	4	2	4	2	4
Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
None	Ins	Ins	Ins	Ins	Ins	Ins
Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)	Typical (Waste)
4,260	1,945	2,959	2,285	3,334	2,821	4,204
30,902	17,091	27,410	18,093	27,959	19,154	30,439
34,471	20,628	33,121	20,831	32,358	21,482	34,142
3,847	1,645	2,660	1,928	2,977	2,407	3,792
409.2	296.5	296.3	353.4	353.2	410.5	409.3
376.8	111.9	192.5	140.6	223.8	212.6	371.2
6,143	2,941	4,328	3,336	4,771	3,673	5,733
514.5	252.7	356.0	293.4	401.4	331.5	450.2
891.3	364.7	548.5	434.0	625.2	544.1	821.4
2,959	1,284	2,115	1,498	2,356	1,866	2,974
69.5%	66.0%	71.5%	65.5%	70.7%	66.2%	70.7%
12.1%	13.0%	12.0%	12.8%	12.0%	11.8%	10.7%
8.8%	5.8%	6.5%	6.2%	6.7%	7.5%	8.8%
9.6%	15.2%	10.0%	15.5%	10.6%	14.6%	9.7%
19.9%	17.2%	15.8%	18.4%	17.1%	19.2%	18.8%
24.8%	20.8%	18.7%	22.6%	20.6%	23.7%	23.2%
20.9%	18.7%	18.5%	19.0%	18.8%	19.3%	19.5%
30.1%	28.4%	25.9%	29.0%	26.5%	29.2%	27.6%

121	122	123	124	**Parametric Options for Run ID**
Atlanta	Atlanta	Atlanta	Atlanta	Climate
2	4	2	4	Occupants
Trunk & Branch	Trunk & Branch	Demand Recirc	Demand Recirc	Distribution Type
		Long run-outs	Long run-outs	Recirculation Type
None	None	None	None	Insulation
Compact	Compact	Compact	Compact	Plumbing Practice
				Annual Results
2,688	4,039	2,976	4,360	Water Heater Energy Use (kWh)
18,115	29,177	17,232	27,679	Hot Water Draw (gal)
20,399	32,788	19,302	31,012	Total Water Use (gal)
2,274	3,626	2,561	3,945	Energy Delivered (kWh)
410.6	409.4	410.9	411.3	Tank Losses (kWh)
168.6	315.8	166.4	282.2	Use Point Wasted Energy (kWh)
2,555	4,518	2,429	4,029	Wasted Hot Water (gal)
244.9	360.8	625.9	839.5	Pipe Loss, All (kWh)
		176.1	212.3	Recirc Losses (kWh)
413.5	676.5	792.3	1,121.7	Total Distribution Losses (kWh)
1,864	2,953	1,772	2,827	Total Useful Energy (kWh)
69.3%	73.1%	59.6%	64.8%	Useful Energy (% of water heater energy use)
9.1%	8.9%	21.0%	19.3%	Pipe Losses (% of water heater energy use)
6.3%	7.8%	5.6%	6.5%	Wasted Energy (% of water heater energy use)
15.3%	10.1%	13.8%	9.4%	Water Heater Losses (% of water heater energy use)
14.1%	15.5%	14.1%	14.6%	Water Waste (% of total hot water)
16.4%	18.3%	16.4%	17.0%	Wasted Water (% of useful water delivered)
15.4%	16.8%	26.6%	25.7%	Distribution Losses (% of water heater energy use)
22.2%	22.9%	44.7%	39.7%	Distribution Losses (% of useful energy delivered)

Appendix B. Plumbing Layouts

Table 5. List of Plumbing Layout Variations

Distribution Types	Water Heater Location Options	Line Sizes	Insulation
Trunk and Branch	Remote location: 15-ft run Central located: 4.5-ft run	Trunk and main feed, ¾ in. Use-points, ½ in.	No insulation: all lines uninsulated Insulated: all lines insulated
Home Run	Waste: 15-ft run of 1 in. to manifold Compact: 4.5-ft run of ¾ in. to manifold	Waste: all lines ½ in. Compact: sinks and dishwasher ⅜ in., all others ½ in.	Waste: insulate to manifold Compact: insulate everything
Hybrid	Waste: 15-ft run of 1-in. to manifold Compact: 4.5-in. run of ¾-in. to manifold	Waste: all lines ½ in. Compact: sinks and dishwasher ⅜ in., all others ½ in.	Waste: insulate to manifold Compact: insulate everything
Recirculation	Centrally located, 4.5-ft run of 1 in. to start of loop	Recirc line: 1 in. supply, ¾ in. return Use-points: ½ in. Long Runouts: recirc loop is far from use-points Short Runouts: recirc loop is within 15 ft from all use points	All lines insulated

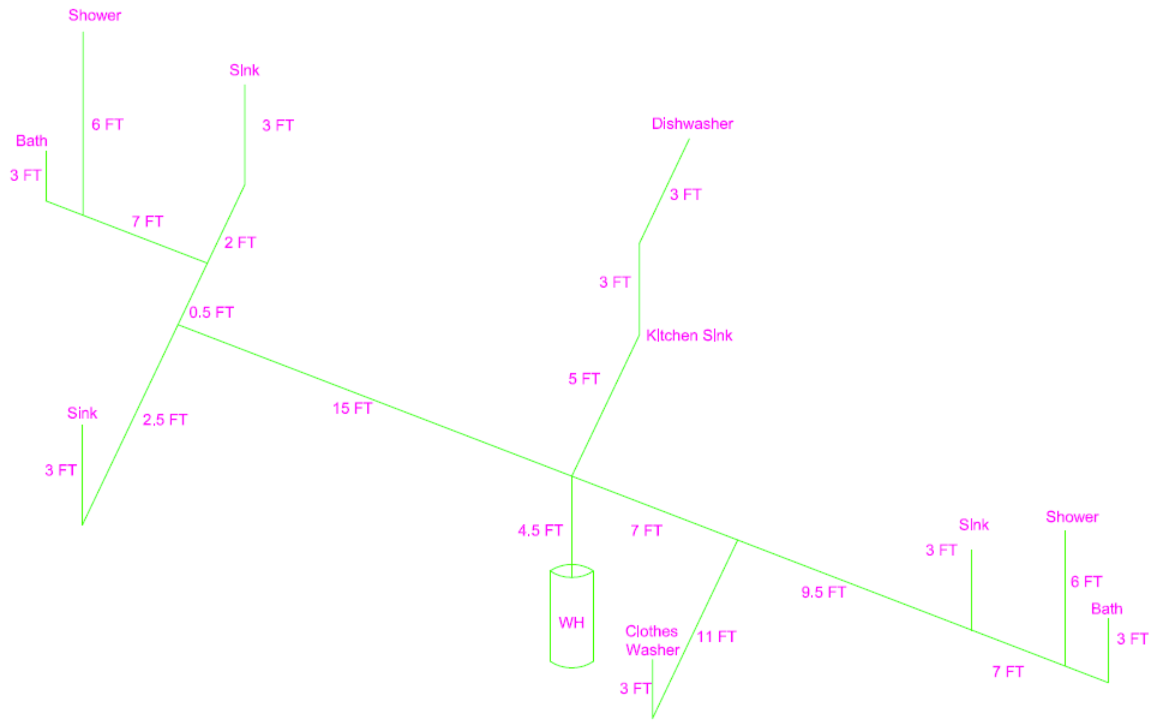

Figure 12. Trunk and branch distribution layout, basement

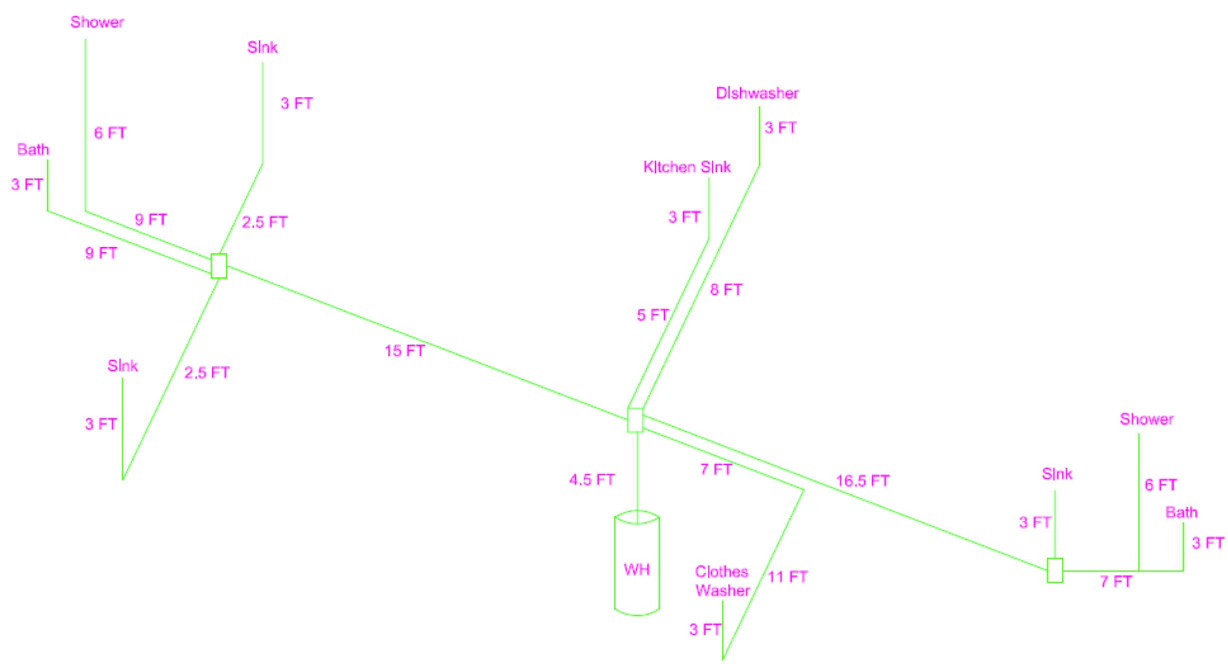

Figure 13. Hybrid distribution layout, basement

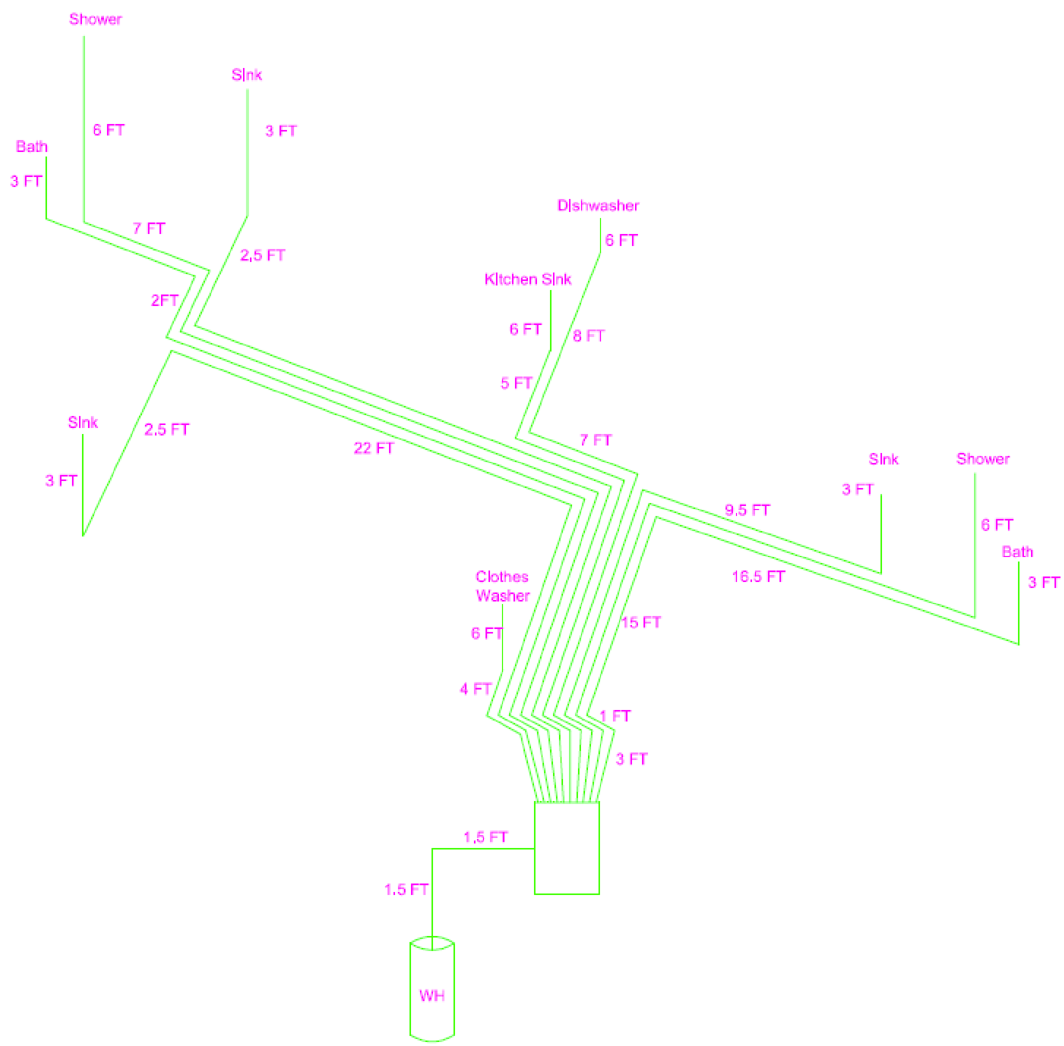

Figure 14. Home run distribution layout, basement

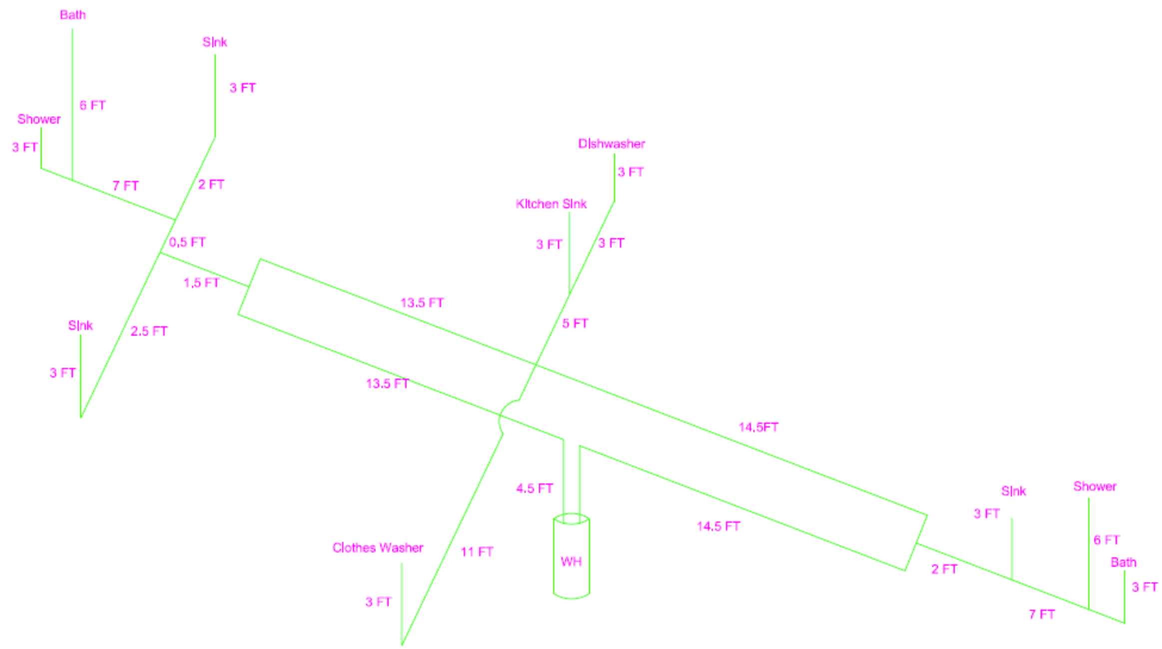

Figure 15. Short run-out recirculation distribution layout, basement

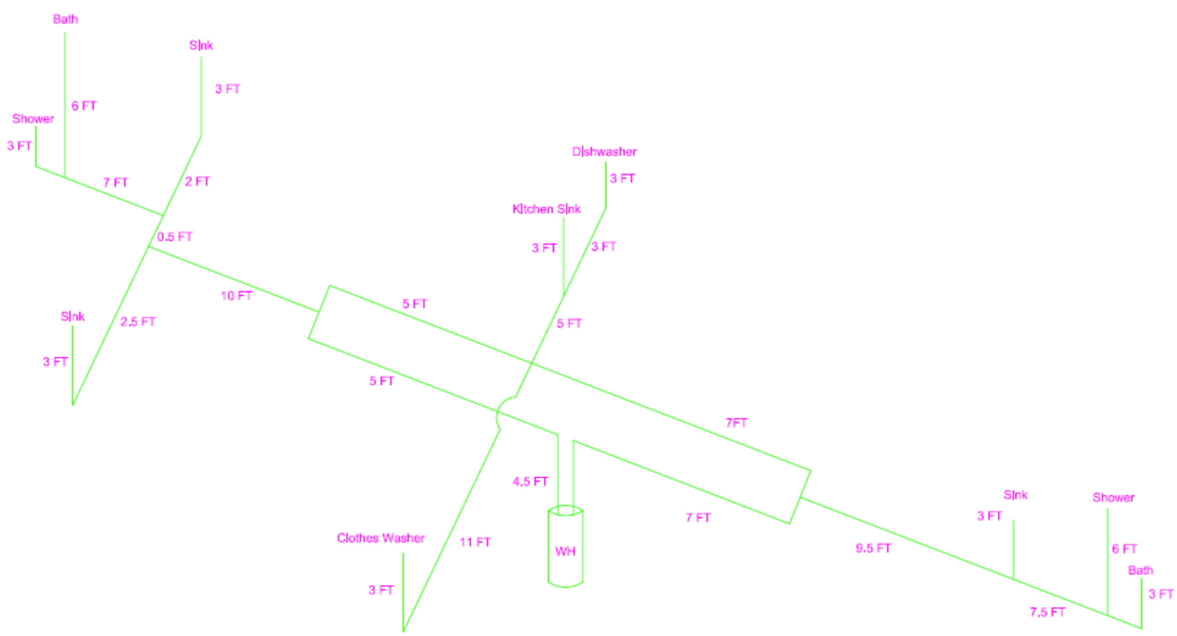

Figure 16. Long run-out recirculation distribution layout, basement

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