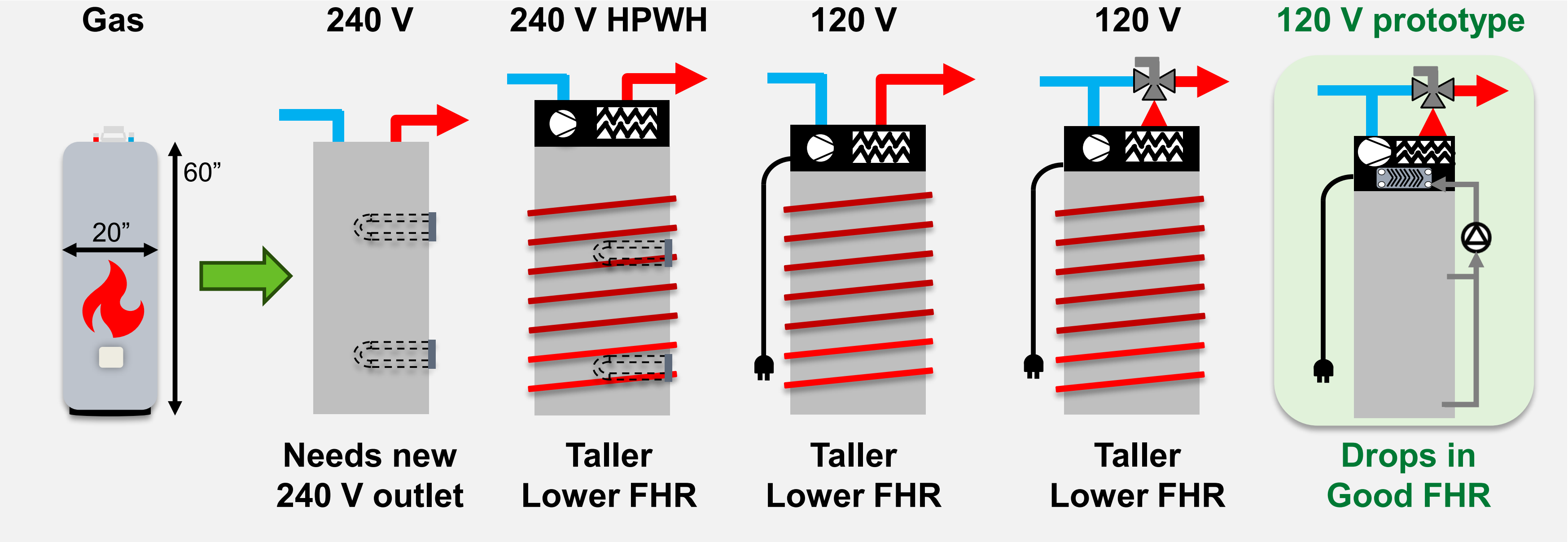
2024 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review:

120 V Heat Pump Water Heater

Replacement Solution for
30–40 gal Gas Water Heaters

120 V Heat Pump Water Heater Replacement Solution for 30–40 gallon Gas Water Heaters



Oak Ridge National Laboratory
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03.02.02.36

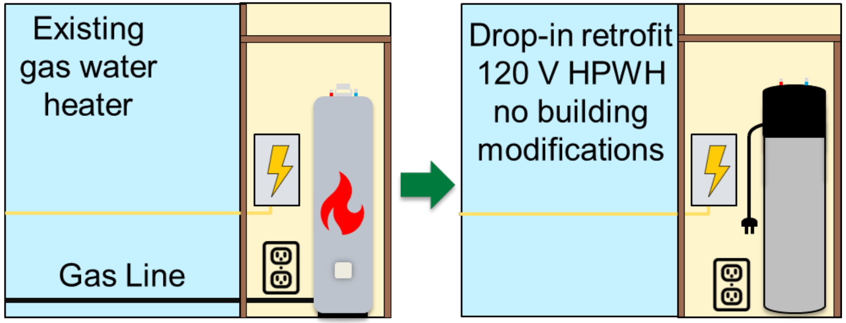
Project Summary

Objective

- Develop and evaluate in the laboratory a 120 V-powered electric heat pump water heater (HPWH) as direct replacement for 30-40 gallon tall and slim gas water heaters (<20 inch diameter)
- Maximize FHR within the form factor constraint

Outcome

- Development of a prototype 120 V HPWH diameter 20” and height of 60” with minimum FHR = 65 gal. and ENERGY STAR-qualified UEF ≥ 2.20



ORNL TEAM

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STATS

Performance Period: FY24-FY26

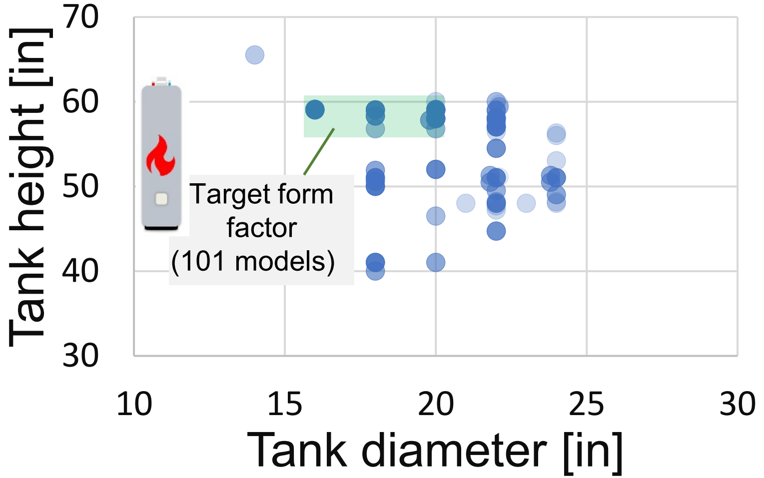
DOE Budget: $450k/yr (FY23-25)

✓ Milestone 3: Baseline characterize a commercial WH (FY24)
✓ Milestone 4: Prototype Fabrication and shakedown (FY24)
✓ Milestone 5: Gen 1: FHR > 50gal; UEF > 2.2 (FY24)
✓ Milestone 6: Gen 2: design and parts (FY24)
☐ Milestone 7: Gen 2: Fabrication and shakedown (FY25)
☐ Milestone 8: Gen 2: FHR > 65gal; UEF > 2.2 (FY25)

Problem how to decarbonize existing gas water heaters

- 60 million[1] US homes have gas-fired water heaters
  - 93% of California water heaters are gas
- Many do not have electrical connections for conventional 240 V electric water heaters
- A common **form factor** is the "tall and slim" (~60 in. tall, and 20 in. diameter) gas-fired water heater, which lacks direct drop options on the market
- These have large burners to achieve **high water delivery capacity from a small tank** – much higher than a HPWH with the same tank

Natural gas ENERGY STAR-certified water heaters [2] (~360 models)



[1] U.S. Energy Information Administration, Office of Energy Demand and Integrated Statistics, Form EIA-457A of the 2020 Residential Energy Consumption Survey

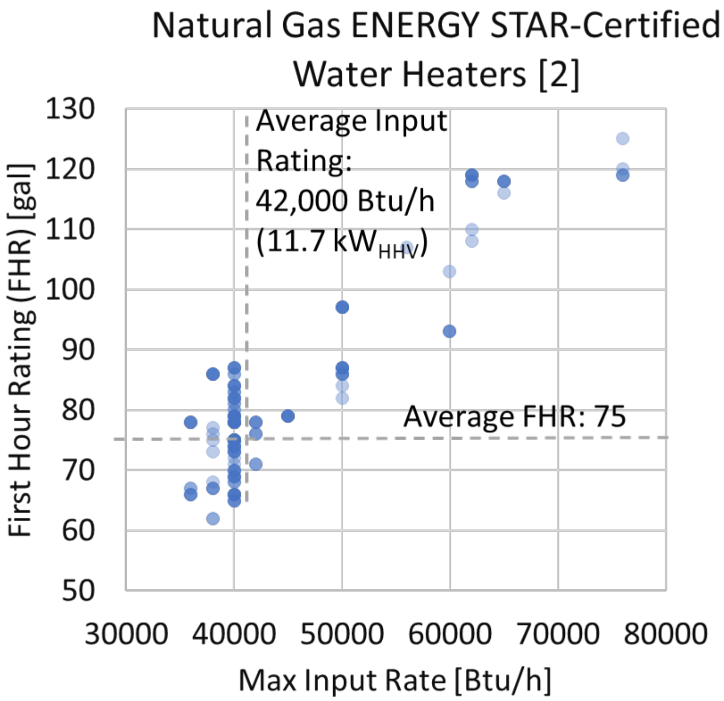
[2] Data from ENERGY STAR qualified product list https://www.energystar.gov/productfinder/product/certified-water-heaters/results

Problem: deliver the same with 88% less power

Challenges of replacing a gas unit:

- Small electrical power replaces large gas power
- Consumer expects the same hot water delivery capacity (65-85 gal FHR) with 88% less power
- Installations are often in tight quarters (e.g., closet), so replacement unit's external dimensions must fit

Water heater type	Power source	Source power available	
Tall and slim gas-fired	Gas burner	40 $kBtu_{thermal}/h$	**11.7 $kW_{thermal}$**
120 V HPWH dedicated circuit	120 V × 12 A (80% of 15 A breaker)	4.9 $kBtu_{elec}/h$	**1.44 kW_{elec}**



[2] Data from ENERGY STAR qualified product list https://www.energystar.gov/productfinder/product/certified-water-heaters/results

Alignment and impact

Affordability and Equity

- Develop an electric option to replace gas with similar FHR are cost
  - Currently available electric options on the market to replace gas with similar FHR are cost prohibitive: either require costly 240 V electrical upgrades, or don't fit the space
- The "tall and slim" gas water heaters are extremely common, including in low- and moderate-income households; typically installed in a tight space

Increase building energy efficiency

- Project demonstrates a 120 V HPWH with ENERGY STAR efficiency, with delivery capacity and size equivalent to the "tall and slim" gas form factor

Accelerate onsite emissions reductions

- Enable electrification of residential water heating, by developing an affordable replacement option for gas units

Transform the grid edge at buildings

- Electrical infrastructure costs are reduced by using lower power draw, and by using existing 120 V outlet (avoiding electrical upgrades for 240 V)

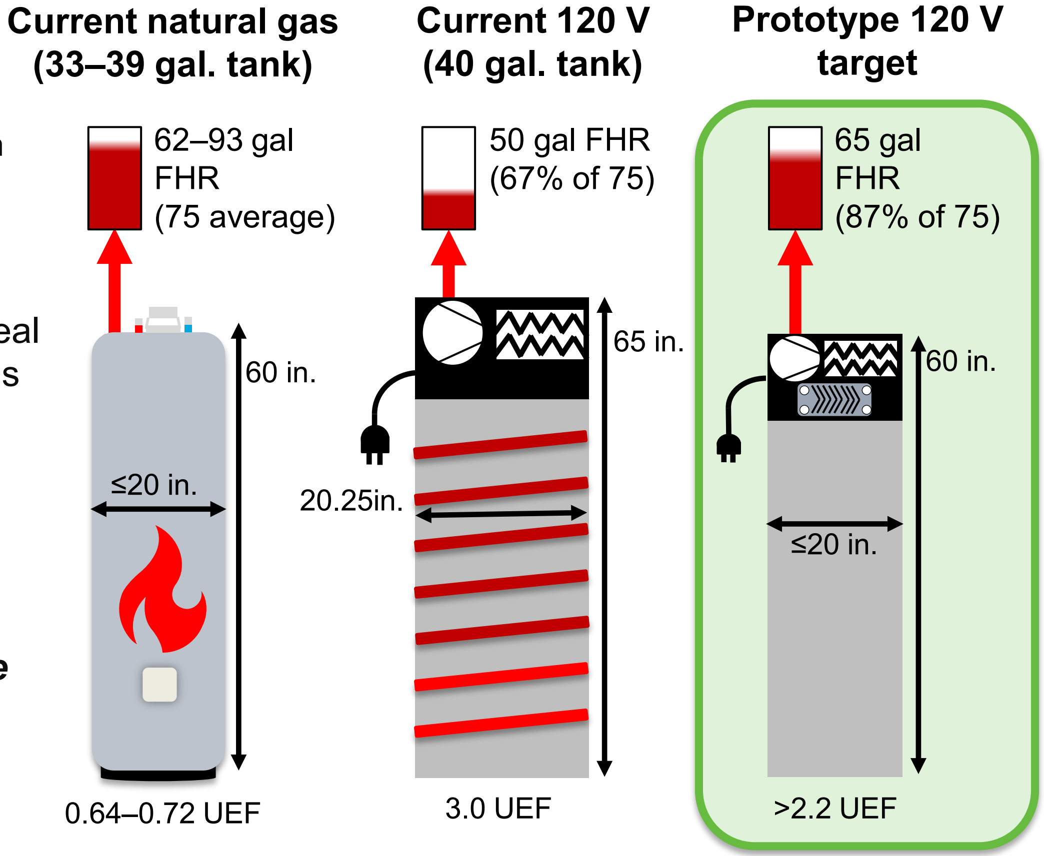
Approach: maximize FHR using 120 V

Focus on consumer acceptance

- Critical parameters for a direct drop-in:
  - Physical dimension of current gas-fired tall and slim unit
  - FHR water delivery capacity

- Commercially available 120V HPWHs are not ideal for direct drop-in replacement for tall and slim gas units
  - Too tall (65 in. vs. 60 in.)
  - Too low FHR (50 gal vs. 75 gal average)

This project targets achieving market adoption by meeting space constraints while maintaining hot water delivery capacity that meets consumer expectations



Approach – reduce installed cost of electrifying

		Baseline 240 V elec. resistance	Baseline 240 V HPWH hybrid	Commercialized 120 V dedicated circuit (<12 A)	Commercialized 120 V shared circuit (<7.5 A)	**ORNL 120 V prototype**
Product price (list price)		$0.5k	$1k–$2k	$1.9k–$3.1k[7]		Yet to be estimated
Installation cost	Electrical panel upgrade[3]	$0–$3k	$0–$3k	$0	$0	**$0**
	Carpentry modifications to space to fit larger product[4]	$0–$3k	$0–$3k	$0–$3k	$0–$3k	**$0**
	Service line to house[5]	$0–$2.5k	$0–$2.5k	$0	$0	**$0**
	Water heater general installation costs[6]	$0–$1.4k	$0–$1.4k	$0–$1.4k	$0–$1.4k	$0–$1.4k
Total installed cost		**$0.5k–$10.4k**	**$1.7k–$11.9k**	**$1.9k–$7.5k**	**$1.9k–$7.5k**	***Lowest in most cases***

[3] https://www.thisoldhouse.com/electrical/reviews/cost-to-upgrade-electrical-panel

[4] https://www.homeadvisor.com/cost/additions-and-remodels/mudroom/

[5] https://homeguide.com/costs/cost-to-run-power

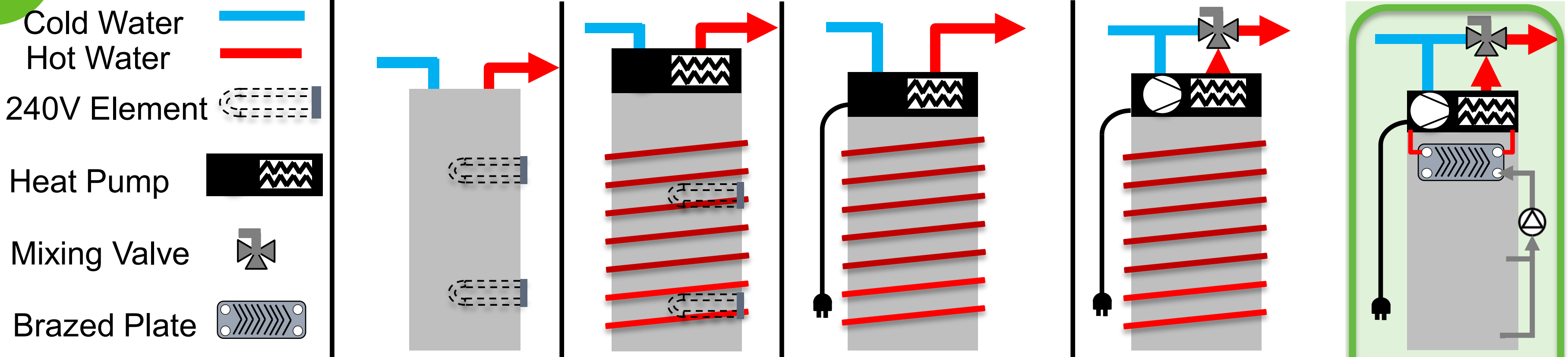
[6] DOE BTP Res Htg Prod Final Rule Analytical Tool

[7] depending on options https://www.canarymedia.com/articles/heat-pumps/finally-a-heat-pump-water-heater-that-plugs-into-a-standard-outlet

Project approach for market impact

- Catalyze market innovation by experimentally demonstrating the **maximum technically achievable delivery capacity** from a 120 V power source.
- ORNL is implementing:
  - combination of techniques used in commercially available products
  - additional novel techniques developed by ORNL
- Project plan: after prototype laboratory evaluation, seek a CRADA partner to optimize the system for manufacturability and cost, for the widest market impact.
- In parallel, ORNL is fabricating a second generation prototype to demonstrate the maximum technically achievable.

Approach: Max-Tech FHR

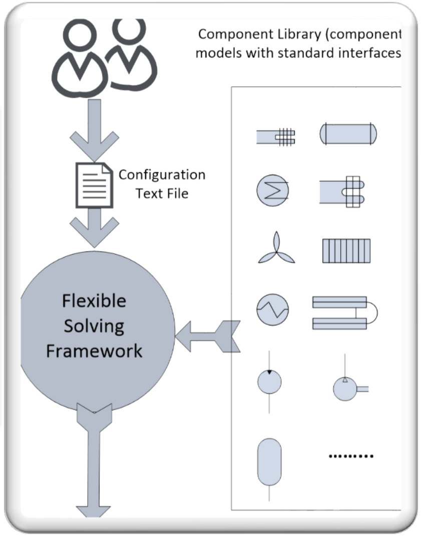


		Baseline 240 V ER	Baseline 240 V HPWH Hybrid	Commercialized 120 V Dedicated Circuit (<12 A)	Commercialized 120 V Shared Circuit (<7.5 A)	ORNL 120 V Prototype
what	Electrical drop-in?	needs 30 A/240 V	needs 30 A/240 V	✓	✓	✓
what	Physical drop-in?	✓	no, taller	no, taller	no, taller	✓
what	Delivery capacity	✓ comparable	✓ comparable	low	low	✓ comparable
how	Heat pump size		normal	larger	normal	larger
how	Mixing valve				✓	✓
how	Brazed-plate HX					✓
how	Ports switching					✓
how	Packaging optimizations					✓

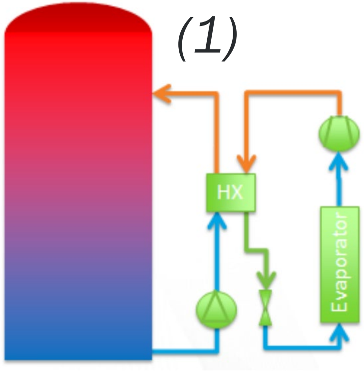
Design approach using DOE/ORNL HPDM

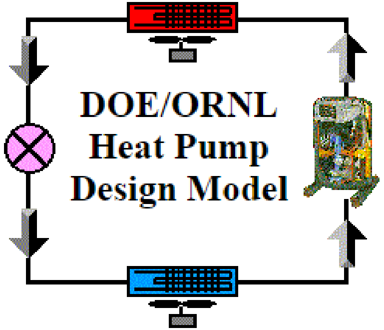
Component-Based

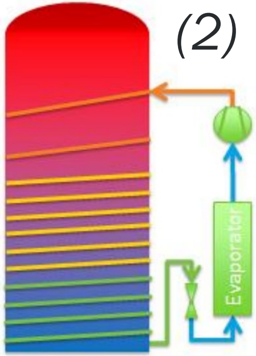
Component models have standard interfaces to the solving framework, and generic connections to each other.



Automatically connect components into required system configuration by user input file.







Detailed HPWH system design tool

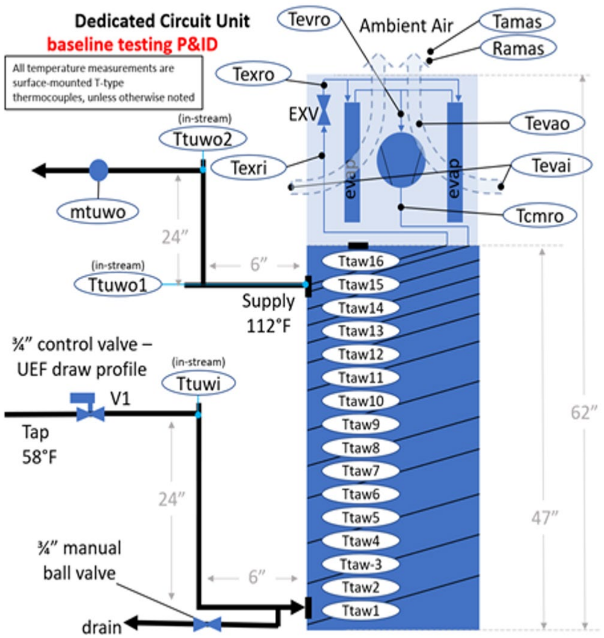
- *UEF & FHR Simulation*
- *External HX (1) and wrapped condenser (2) modeling*

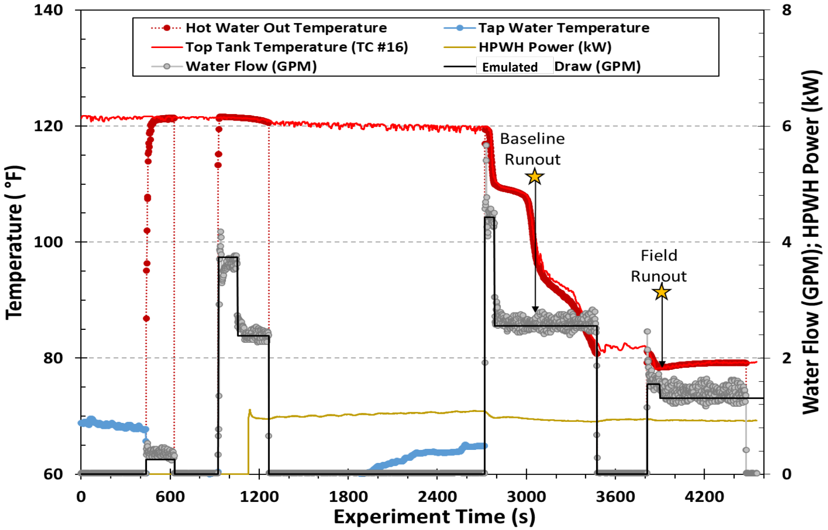
https://hpdmflex.ornl.gov/hpdm/wizard/welcome.php

Progress: Emulation of field runout event

40 gal, 120 V dedicated circuit

Baseline HPWH system

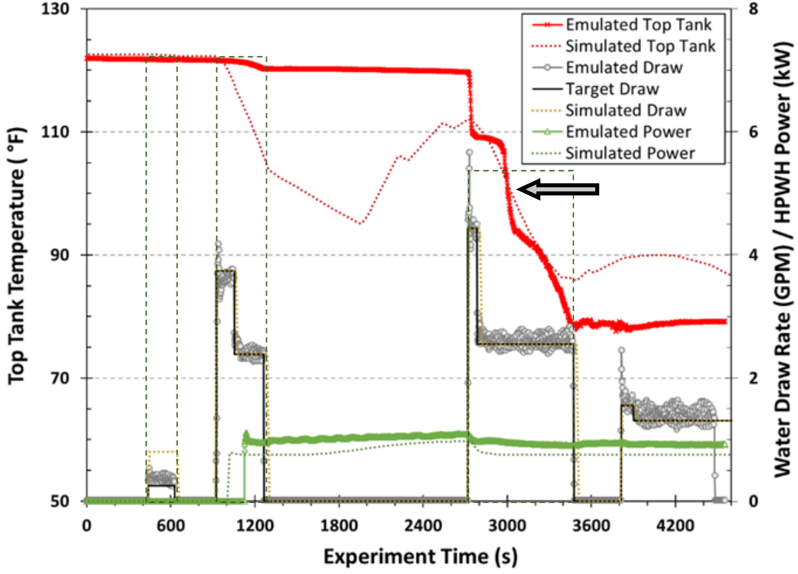




- ORNL analyzed Advanced Water Heater Initiative field data from New Buildings Institute*
- Hot water runout search criteria:
  - < 100°F for >30 s, AND
  - 0.5 gal during 1 min window
- Hot water runout occurs during Draw #3 at around 3,200 s

*New Buildings Institute, July 2023: Amruta Khanolkar, Mischa Egolf, Noah Gabriel. "*Plug-In Heat Pump Water Heater Field Study Findings & Market Commercialization Recommendations.*" Prepared for Pacific Gas and Electric, Southern California Edison, Sacramento Municipal Utility District, TECH Clean California Program, and Department of Energy. Link

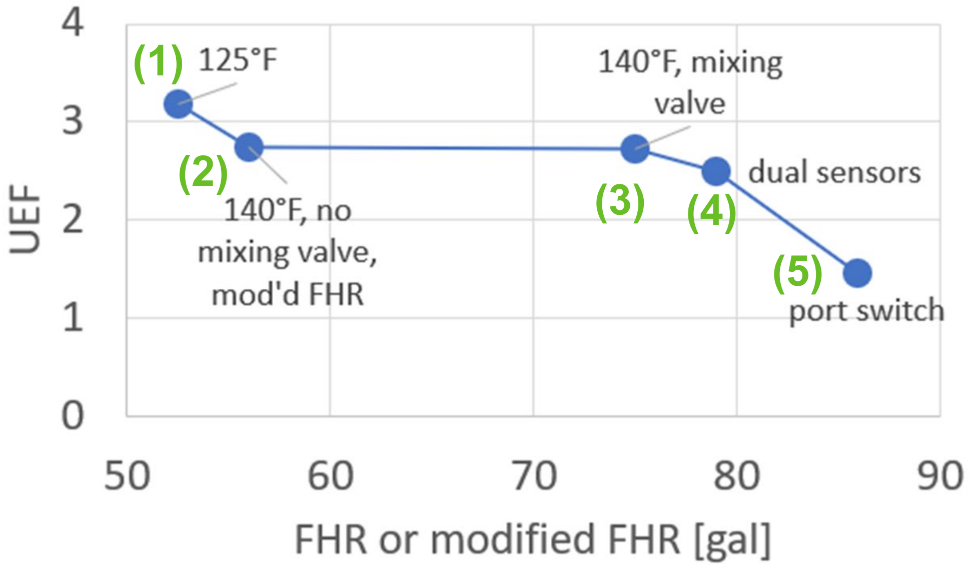
Model validation using runout scenario results



- Model-predicted condenser temperature fluctuation is larger than that of experimental wrapped-tank condenser configuration
- Simulation and experiment reach same run-out moment when supply water temperature dropped below 100°F at around 3,000 s
- Both results show identical HPWH power consumption

Simulation can provide reasonable representation of FHR and UEF values of the baseline 120 V HPWH system

5 Simulated Cases to Maximize FHR/UEF



Case (1): **Baseline**

Case (2): **High initial tank temperature**

Case (3): **Mixing valve addition**

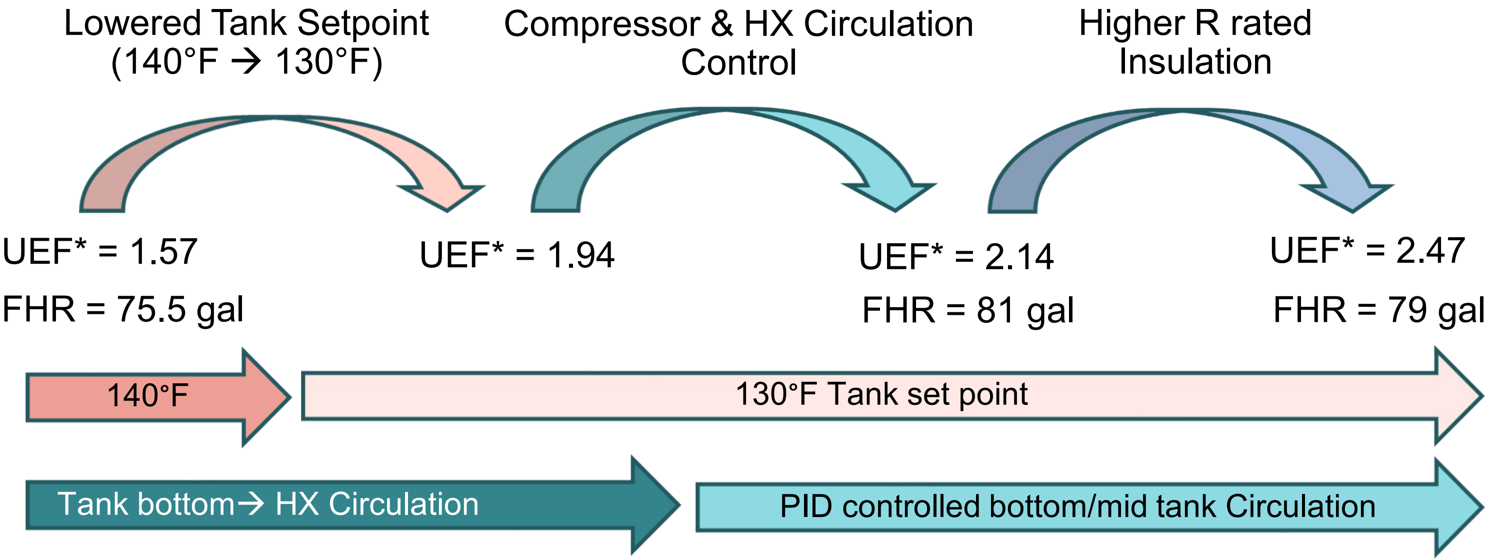
Case (4): **Enhanced control with dual sensors**

Case (5): **Circulation location adjustment**

Prototype results and evolution: UEF

Goals: FHR > 65 gal; ENERGY STAR–rated UEF > 2.2

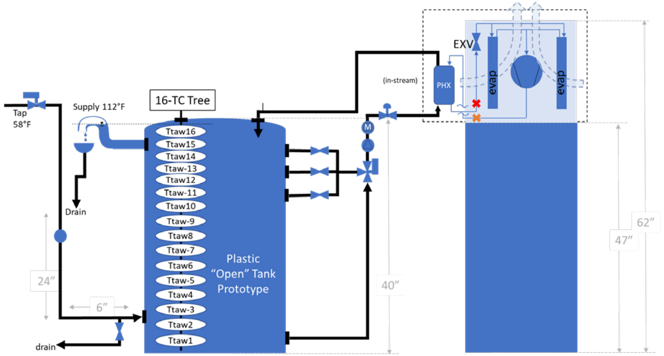
Setpoint	**Compressor control**			**PID set pt**	**Tank circulation switch from bottom to mid**			**UEF***
	TC	**High °F**	**Low °F**	**Thxwo**	**TC**	**High °F**	**Low °F**	
140°F	Tavg	139	134	wide open	---	---	---	**1.57***
130°F	Tavg	128	124	wide open	---	---	---	**1.94***
130°F	# 6	130	115	115°F	# 12	130	125	**2.14***
130°F	# 6	130	115	**115°F**	# 12	130	125	**2.47***



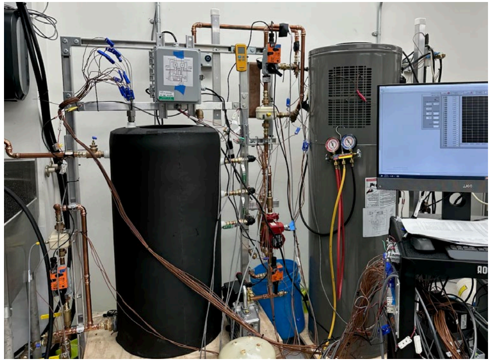
UEF *= power from oversized pump not included in calculation*

Prototype FHR results and project plan

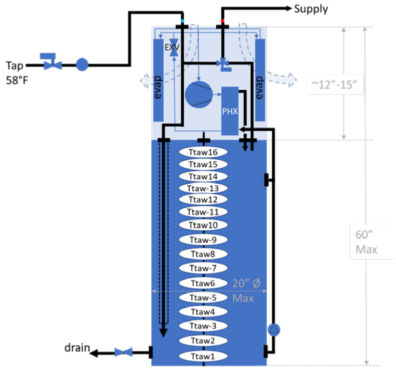
Gen 1: Plan



Gen 1: Breadboard Prototype



Gen 2: Plan



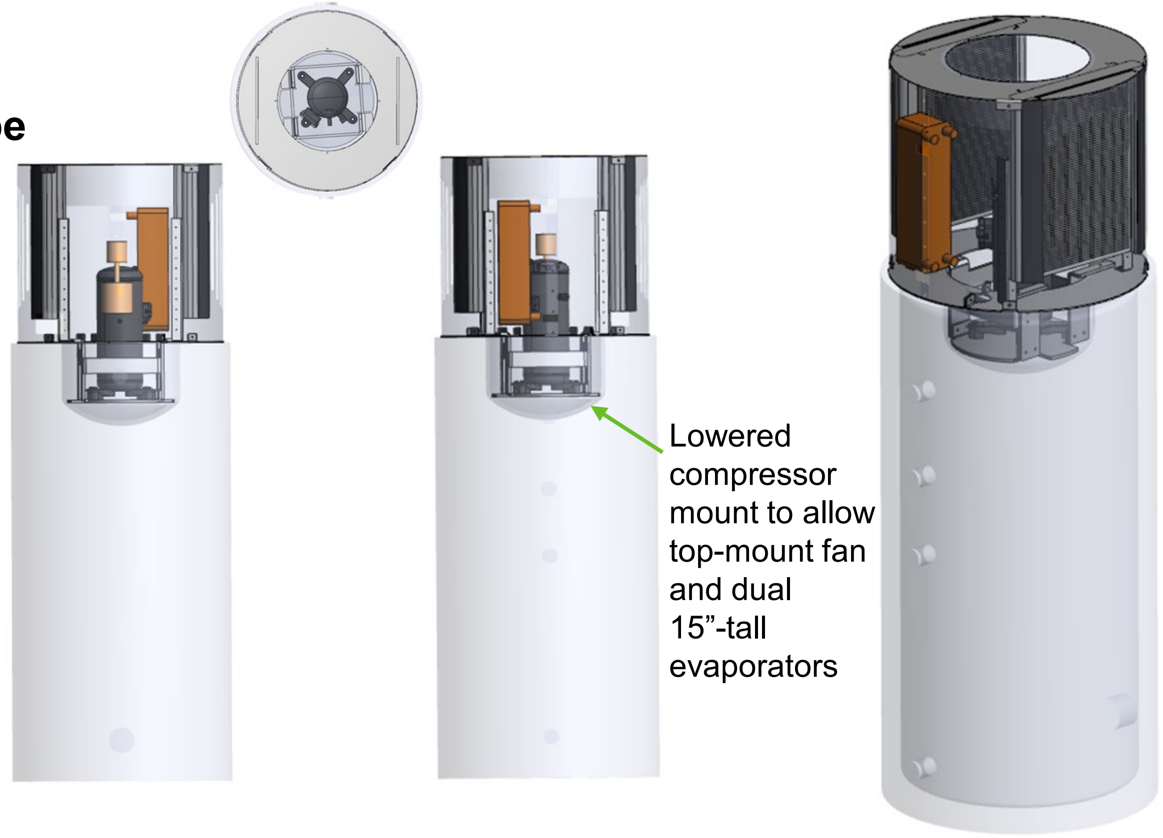
Intermediate targets:	Best achieved to date:	Final targets:
UEF > 2.2	UEF* = 2.47	UEF > 2.2
FHR ≥ 50 gals	FHR = 80 gals	FHR ≥ 65 gals
≤60" H and ≤ 20" OD	Tank: ≤ 40"H & ≤ 20" OD	≤60" H and ≤ 20" OD

UEF* *= power from oversized pump not included in calculation*

Future Work

This second-generation prototype design to be fabricated and evaluated in FY25

- Fit existing heat pump on Gen 1 tank
- Maintain 20” diameter and 60” height



FY25: secure industry partnership to develop a market-viable product

Thank you

Oak Ridge National Laboratory

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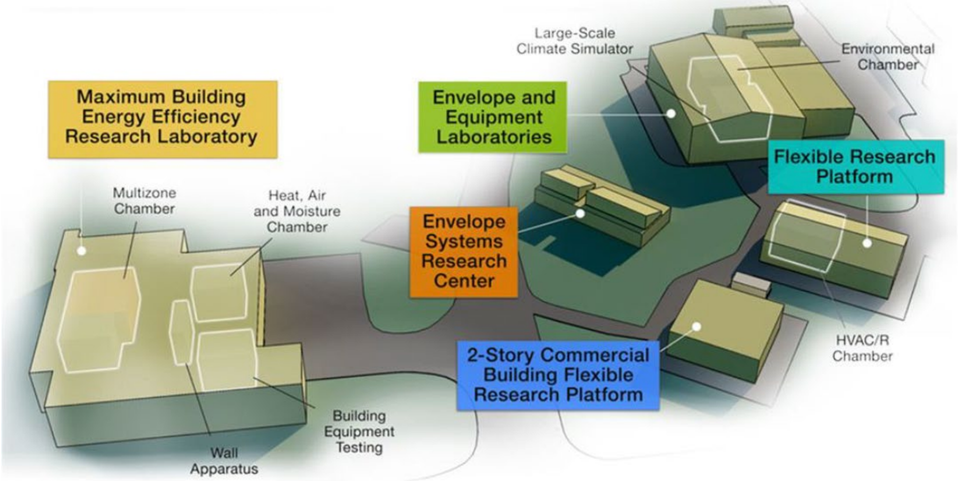

The **Building Technologies Research and Integration Center** (**BTRIC**) at ORNL has supported DOE BTO since 1993. BTRIC is comprised of more than 60,000 square feet of lab facilities conducting RD&D to develop affordable, efficient, and resilient buildings while reducing their greenhouse gas emissions 65% by 2035 and 90% by 2050.

Scientific and Economic Results
139 publications in FY24
140+ industry partners
60+ university partners
16 R&D 100 awards
64 active CRADAs

BTRIC is a DOE-Designated National User Facility

Reference Slides

Project Execution

	FY2023				FY2024				FY2025			
Planned budget												
Spent budget												
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Milestone 1: Identify key consumer issues of 120V HPWHs												
Milestone 2: Gen 1 Prototype design and procurement												
Milestone 3: Baseline Characterization of commercial WH												
Milestone 4: Gen 1 Prototype fabrication and shakedown												
Milestone 5: Gen 1 Evaluation: ≥ 50 gal FHR & > 2.2 UEF								*go/no-go*				
Milestone 6: Gen 2 Prototype design and parts ordered												
Current/Future Work												
Milestone 6: Gen 2 Prototype fabrication and shakedown												
Milestone 7: Gen 2 Evaluation: ≥ 65 gal FHR & > 2.2 UEF												
Milestone 8: Dissemination												

- **Go/no-go decision**: Exceeded targets with max FHR of 81 gallons with a UEF of 2.44
- GNG Milestone 5 slipped by 5 weeks
  - FHR target was met on time, but UEF was low at 2.14 (i.e. not > 2.2)
  - Further optimization of controls and higher R-value insulation met UEF target without dropping FHR

Team

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Distinguished R&D Staff

- Project leadership
- Conceptualization and design

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Senior R&D Staff

- Prototype design
- System modeling

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Senior R&D Staff

- Experimental design and evaluation
- Project management

Ed Vineyard

Senior Advisor

- Prototype design

Brian Kolar

Technical Professional

- Experimental fabrication and evaluation

James Manley

Technical Professional

- Prototype controls and evaluation

nbi new buildings institute — field data sets used in hot water runout event