2024 PROJECT PEER REVIEW

U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review:

Flexible Heat Pump Water Heater with Embedded Energy Storage

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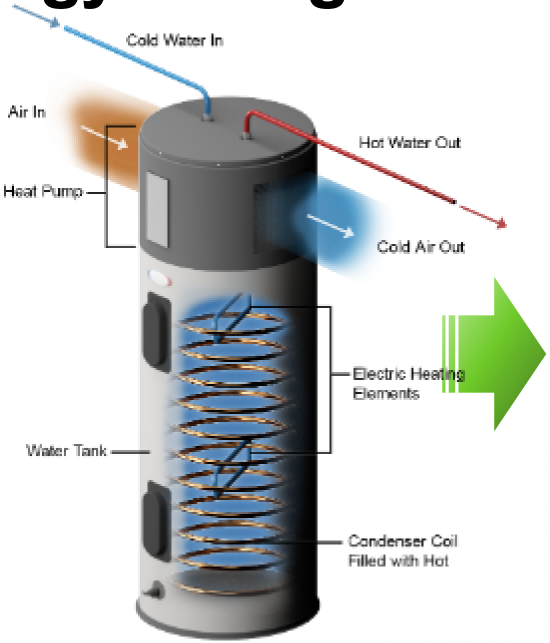

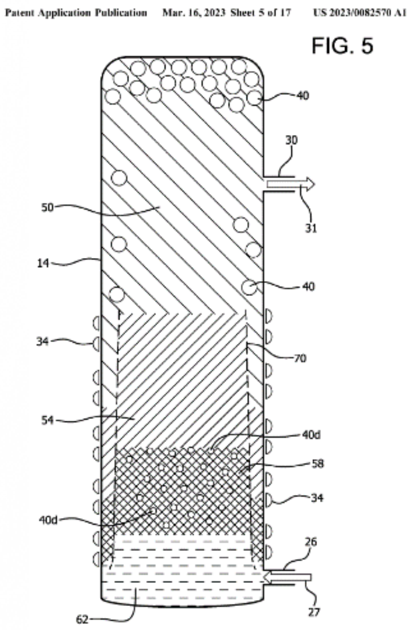

Oak Ridge National Laboratory
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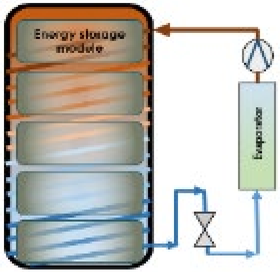
WBS 03.02.02.36, FY 21 AOP Water Heating R&D

Project Summary

OBJECTIVE, OUTCOME, & IMPACT

- This project is focused on the development and performance optimization of a next-gen heat pump water heater (HPWH) with an embedded thermal energy storage (TES) solution
- Demonstration of cost-effective technology to enhance the performance through selection and deployment of an energy storage medium



TEAM & PARTNERS

Oak Ridge National Laboratory
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A.O. Smith (CRADA)
Steven Memory, Jiamin Yin, Timothy Rooney

STATS

Performance Period: FY21-FY24

DOE Budget: $1.05M, Cost Share: $250K

Milestone 1: Alpha prototype enables at least 20% higher capacity (2021)

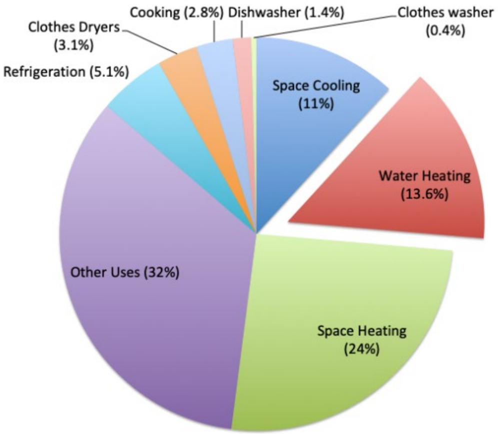
Milestone 2: Demonstration of beta prototype with an efficiency improvement (2022)

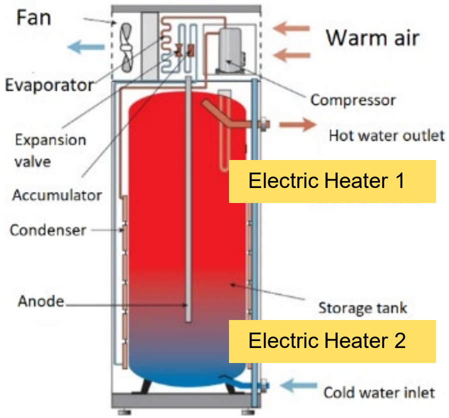
Milestone 3: Demonstration of epsilon prototype with both capacity and efficiency improvements (2023)

Milestone 4: Demonstration of load shifting (2024)

Problem

- Space constraints exist in some applications.
- HPWHs are unable to meet the demand through the base operation (heat pump), requiring ancillary heat through electric heaters (hybrid configuration)
- Potential solutions through the deployment of a suitable thermal energy storage medium are required for cost-effective load shifting





Alignment and Impact

Increasing the capacity by at least 20%, reducing carbon by 60%, reducing cost by 30%: aligned with BTO's goal of reducing U.S. building emissions 60% by 2035 and 90% by 2050.

Increase resilience & transform the grid edge

Enabling development of grid-interactive efficient buildings

- Improved capacity (higher first-hour rating [FHR]): >20% higher capacity with the same footprints
- At minimum, 4 hours of load-shifting capability for medium and higher usage patterns

Accelerate on-site emissions reductions

A highly flexible water-heating technology

- Reduced carbon emissions (~60% compared with electric resistive and 10% compared with hybrid HPWHs)

Increase affordability

Low cost to broaden HPWH utilization

- At least 30% cost savings compared with the state of the art
- Reduced required maintenance due to compact design
- Embedded energy storage solution (no engagement of additional vendors)

Extendable

Implications for additional processes

- Residential air cooling/heating, refrigeration, process water heating

Approach – Project Execution

Phase 1 Market assessment	**Phase 2** Preliminary evaluation	**Phase 3** System optimization & Demonstration

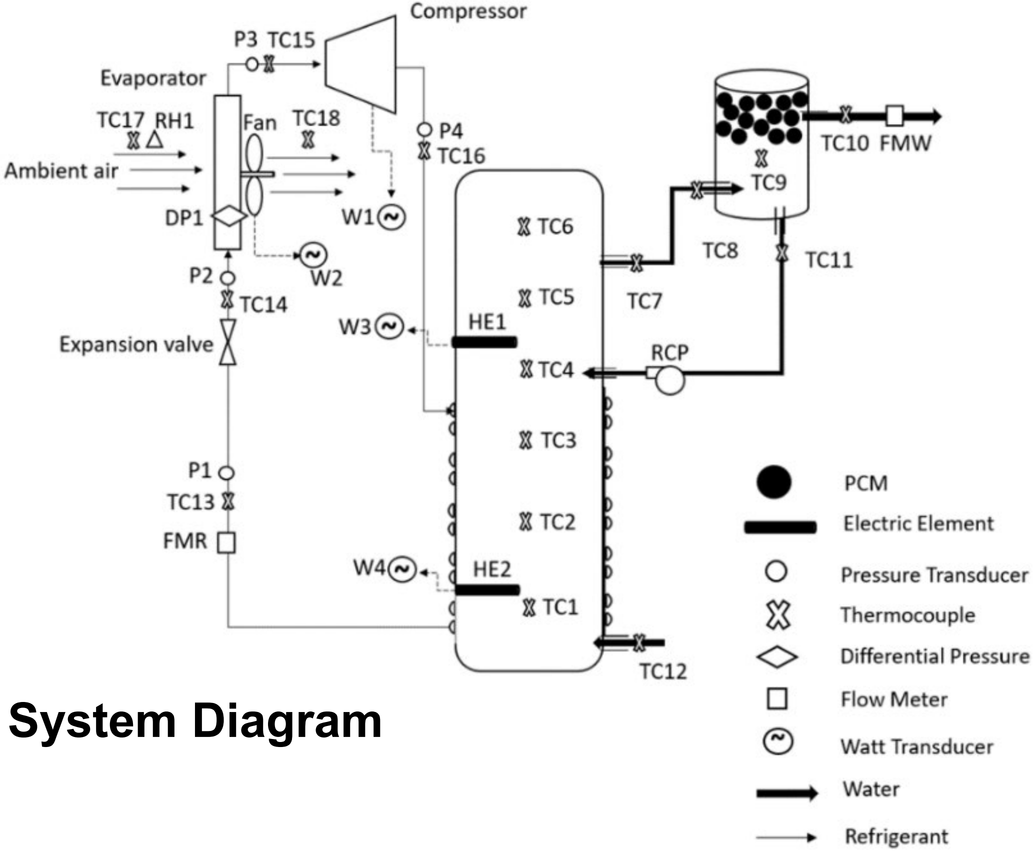
Phase 2- Preliminary evaluation

Platform selection → Selection of storage materials → Deployment strategies

Phase 3- System optimization and demonstration

Prototype- developments and testing → Process control and optimization → Prototype- field evaluation

Approach—Experimental Platform

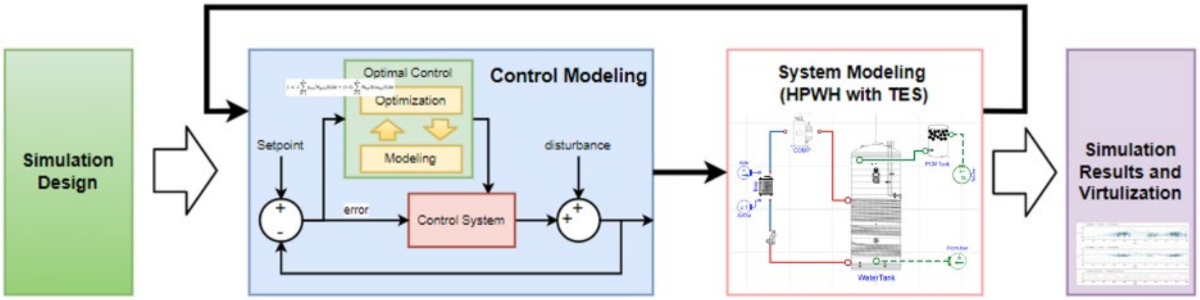


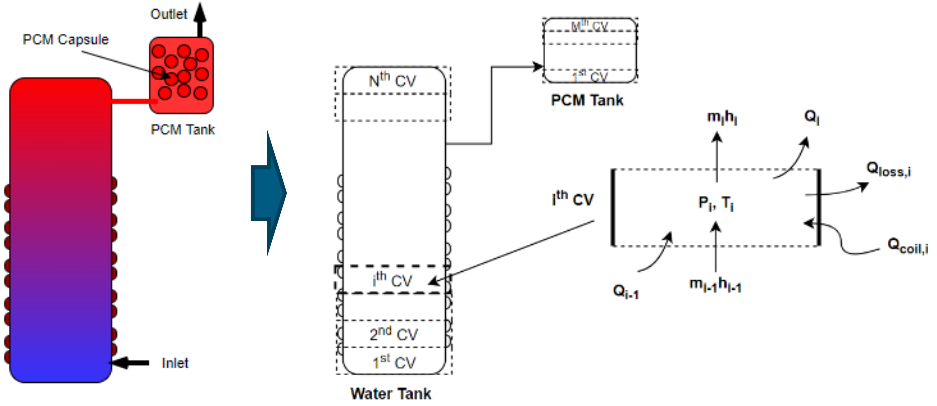
System Diagram

Approach—Modeling Platform

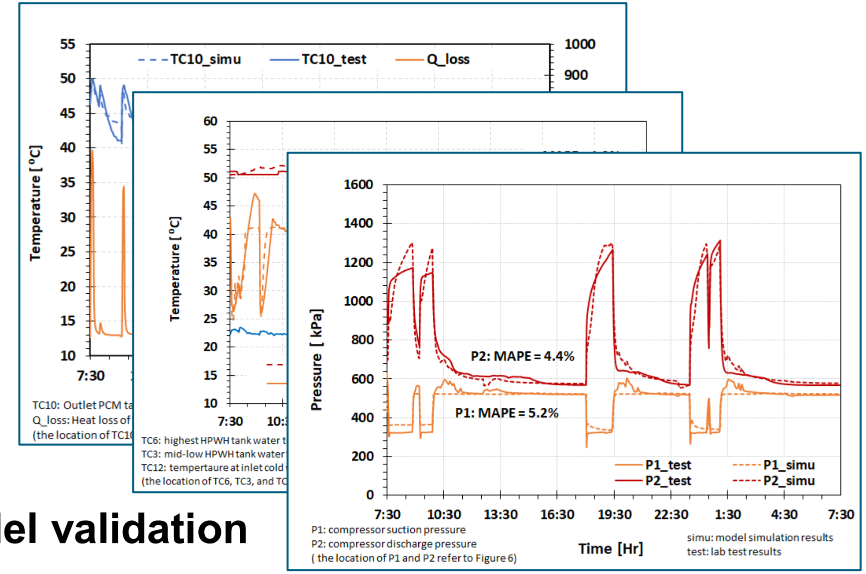
Model-Based Development

- Model-in-the-loop framework
- Physical-based dynamic models
- Calibration and validation with experimental data





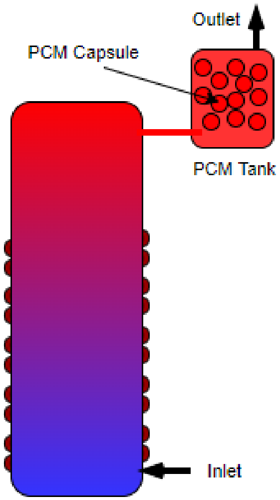
Dynamic modeling



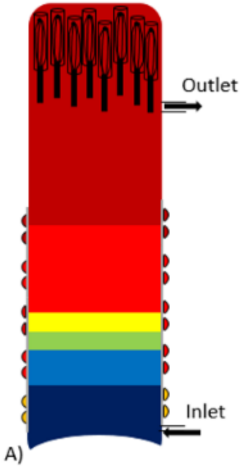
Model validation

Approach – Prototype Development Strategy

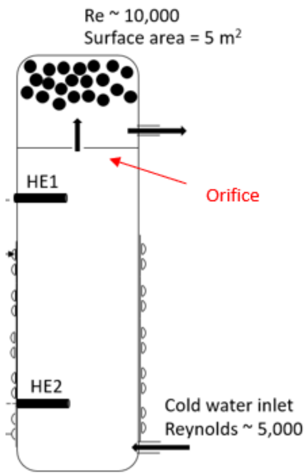
- Experimental validation of phase change material (PCM) heat transfer
- Prototyping to reduce the number of components while keeping heat-transfer performance high



Alpha



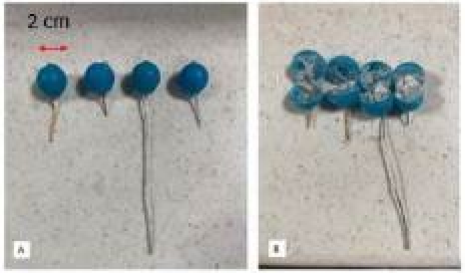
Beta

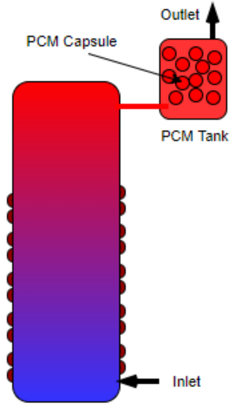


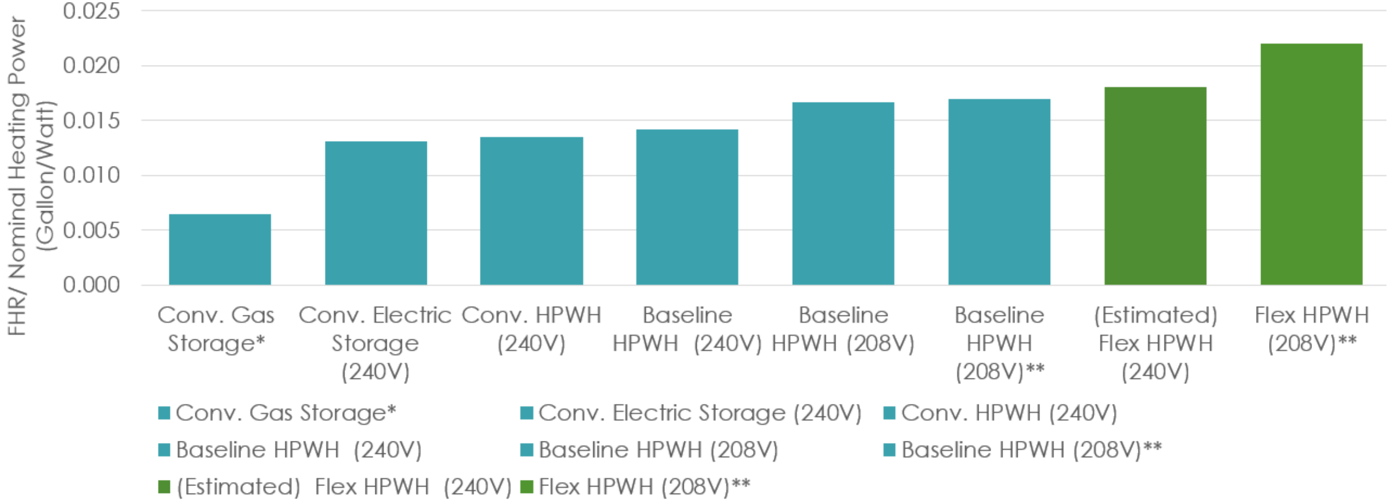
Epsilon

Progress: Experimental Prototype Alpha

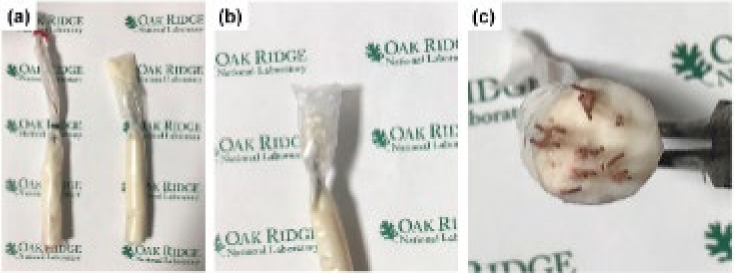
- Two-tank system
- Higher FHR by 30%
- Best FHR/nominal heating power
- Large surface area on spheres
- Significant heat losses





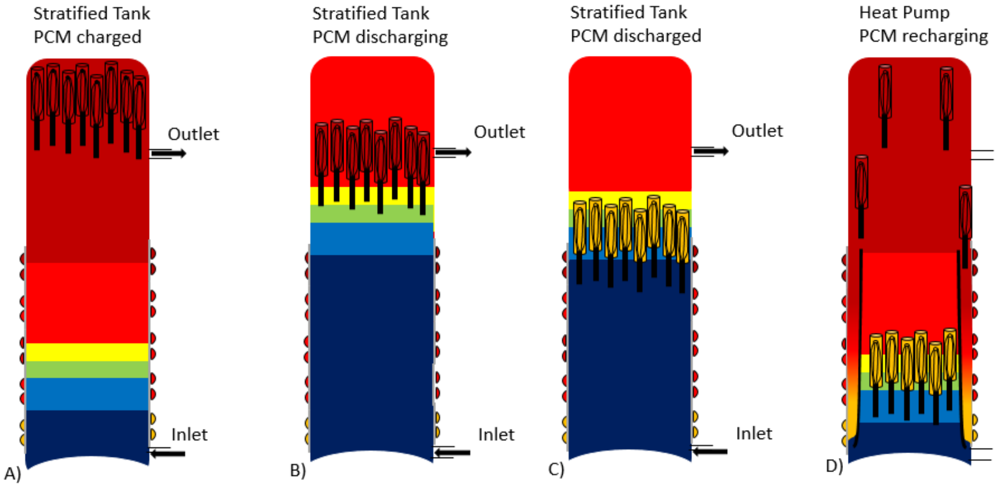


Progress: Experimental Prototype Beta



Modification

- Single Tank
- Few capsules
- Distributed internal fins
- Density control

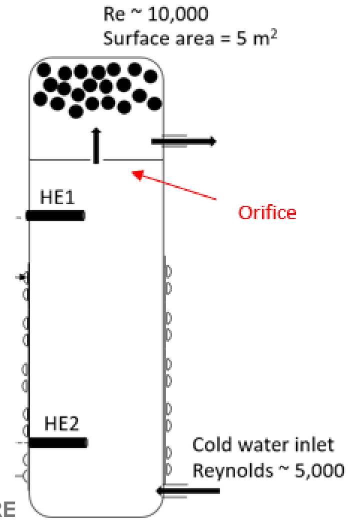


Results

- Lower heat losses
- Less improvement to FHR

Progress: Experimental Prototype Epsilon

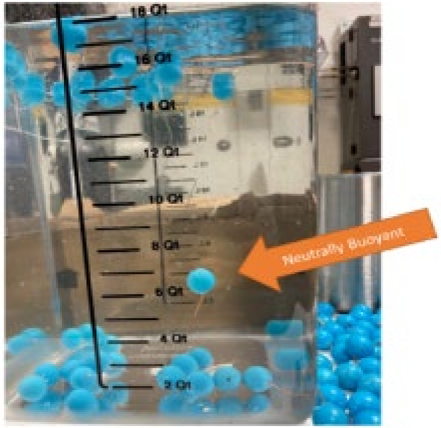
- One tank system and spherical capsule to have a large surface area.
- Orifice design to maintain a high Reynolds number.
- 3D-printed flexible design allows for density tuning of the capsules.

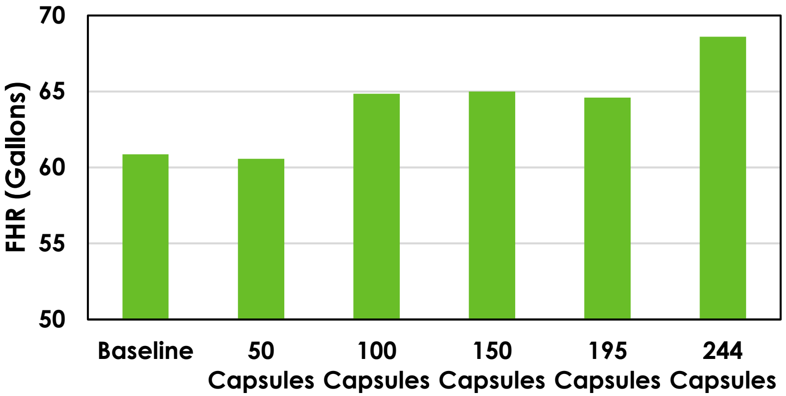


	Nominal Storage (gal)	FHR Rating	UEF (Uniform Energy Factor) Rating	Reynolds Number	Surface Area (m²)
Baseline HPWH	50	61	3.9		
Prototype Alpha HPWH	56	79.0	2.78	10,000	5
Prototype Beta HPWH	50	69.0	3.86	250	3.2
Prototype Epsilon HPWH	50	75	3.5	10,000	5

Progress: Experimental Prototype Epsilon

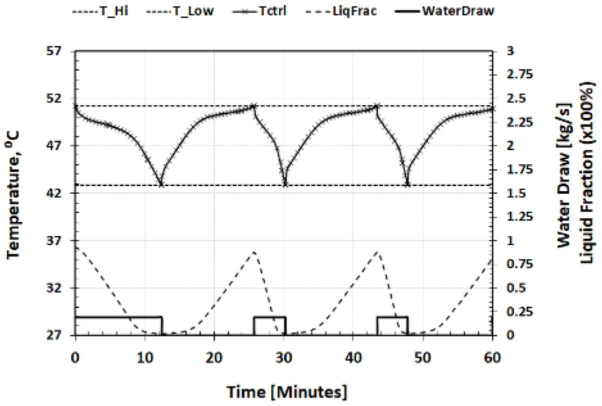
- Buoyancy optimization: the behavior of the 3D-printed flexible capsule material with 1.5 mm wall thickness yielded the desired results.
- FHR testing with different number of PCM capsules



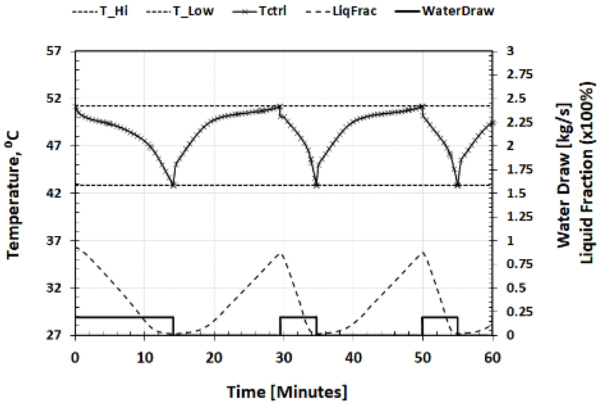


Progress: Optimization

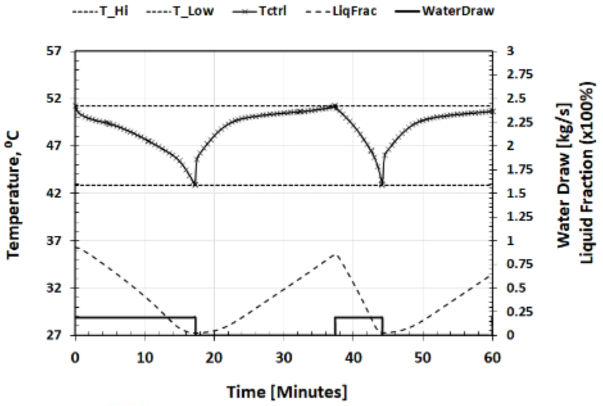
FHR = 66 gal (4.5 lb PCM)



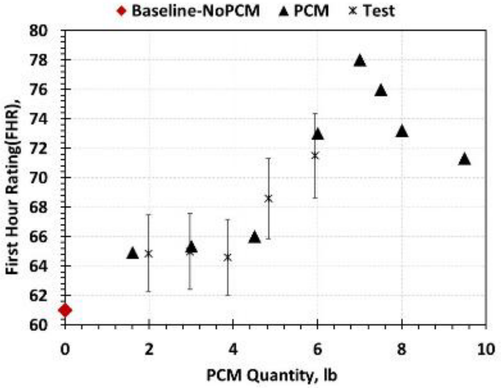
FHR = 73 gal (6 lb PCM)



FHR = 71 gal (9.5 lb PCM)

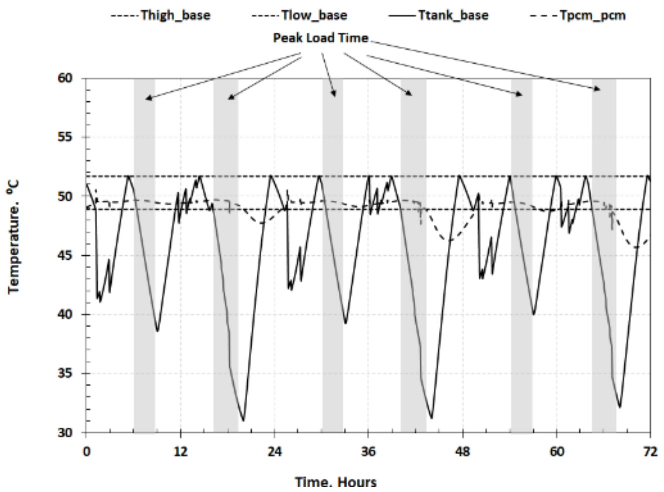


- Increasing PCM lengthens both HPWH discharge and charge/recovery time, reduces the number of times for the water draw in the first hour
- Increasing PCM does not always improve FHR: there is an optimal amount of PCM (7 lb) that maximizes the FHR (78 gal)

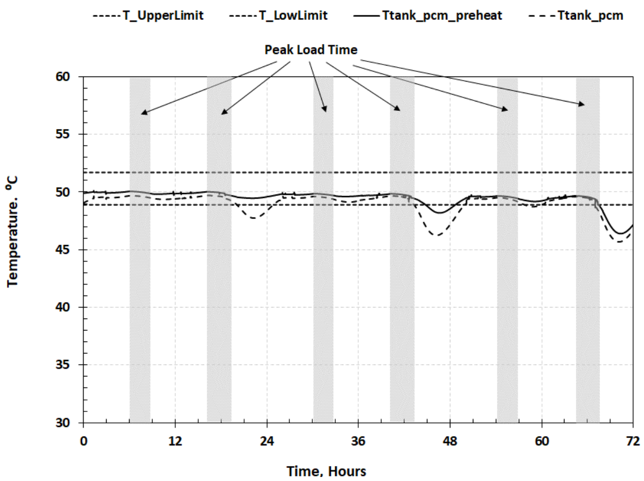


Progress: Demand Response Operation

A 3 h morning curtailment (6:00–9:00) and a 4 h evening curtailment (17:00–21:00)



Basic demand response operation



Advanced demand response operation

- More consistent hot water supply temperature, thereby reducing temperature fluctuations.
- More sophisticated operation strategies will be needed to maximize the demand response benefit of the embedded PCM-TES HPWH.

Future Work

Experimental Study

- Field pilot/demonstration: FHR, efference, and load shifting
- Precommercial prototype
- Commercialization: cost, reliability…
- Work with manufacturers for mass production of the capsules.

Design, Modeling and Control

- Better design to enhance heat transfer among refrigerant, water and PCMs.
- Control optimization: manage the discharge/charge cycle according to the water draw schedule and peak load demand.

Publication and Intellectual Property

- **Conference proceedings or presentations**
  - Sun, J., Nawaz, K., Rendall, J., Brechtl, J., and Elatar, A., 2022, “Model-based co-simulation of heat pump water heater with embedded phase change materials thermal energy storage,” *Herrick Conferences*.
  - Rendall, J., Asher, W., Brechtl, J., Li, K., Yang C., Sun, J., and Nawaz K., 2022, “Experimental results of density-controlled phase change material capsules for increased first hour rating for heat pump water heaters,” *Herrick Conferences*.
- **Journal publications**
  - Sun, J., Nawaz, K., Rendall, J., Elatar, A., Kowalski, S., and Li, Y., 2024, “Unlocking the potential of using embedded phase change materials as thermal energy storage in a heat pump water heater,” *Applied Energy*, under review.
  - Sun, J., Nawaz, K., Rendall, J., Elatar, A., and Brechtl, J., 2023, “Heat pump water heater enhanced with phase change materials thermal energy storage: modeling study” *ICHMT,* 146, 106917.
  - Rendall, J., Elatar, A., Nawaz, K., and Sun, J., 2023, “Medium-temperature phase change material integration in domestic heat pump water heaters for improved thermal energy storage,” *Renewable and Sustainable Energy Reviews*, 185, 113856.
  - Rendall, J., Brechtl, J., Nawaz K., Elatar, A., Sun, J., An, K., Liu, X., and Asher, W., 2023, “Experimental results of density-controlled phase change material capsules for increased first hour rating for heat pump water heaters,” *ICHMT*, 145, 106806.
- **Patent applications or invention disclosure**
  - Rendall, J., Nawaz, K., Asher, W., Elatar, A., Sun, J., Brechtl, J., Liu, X., An, K., Zhang, M., 2023, “Density controlled phase-changing materials (PCM) spheres for increased heating power and optimal delivery temperature in hot water tanks,” *patent application US 20230082570A1*.
  - Sun, J., Nawaz, K., Rendall, J., Wang, P., Gao, L., Kowalski, S., Elatar, A., Brechtl, J., Murugan, M., Krishnan, E., Li, Y., Enhance the heat transfer of heat pump water heater with embedded phase change material thermal energy storage, *invention disclosure, 2024*

Thank you

Oak Ridge National Laboratory

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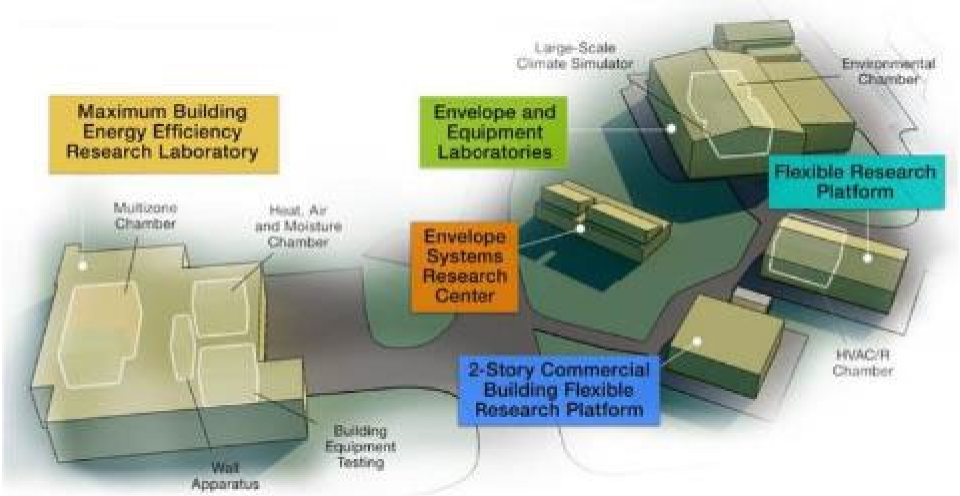
WBS 03.02.02.36,
FY 21 AOP Water Heating R&D



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

	FY2021				FY2022				FY2023				FY2024			
Planned budget	300K				300K				300K				150K			
Spent budget	300K				300K				300K				150K			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work																
Q1 Milestone: Literature Review																
Q2 Milestone: Downselection of TES Materials																
Q3 Milestone: Alpha Prototype Construction																
Q4 Milestone: FHR Testing Showing 20% Savings (G/NG)																
Q2 Milestone: CFD Analaysis of Alpha Design																
Q3 Milestone: Beta Prototype Construction																
Q4 Milestone: FHR Testing Showing 5% Increase (G/NG)																
Q2 Milestone: Market Analysis																
Q3 Milestone: CFD Capsule Optimization																
Q4 Milestone: Epsilon Prototype Testing																
Current/Future Work																
Q2 Milestone: Optimization																
Q3 Milestone: Epsilon Testing: Capsule wall and buoyance																
Q4 Milestone: Control Analsyis																

Team

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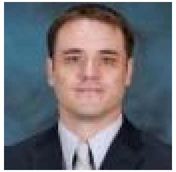
Jamieson Brechtl


Muneesh Murugan


Easwaran Krishnan

AO Smith
Innovation has a name.


Steve Memory


Jiamin Yin


Tim Rooney