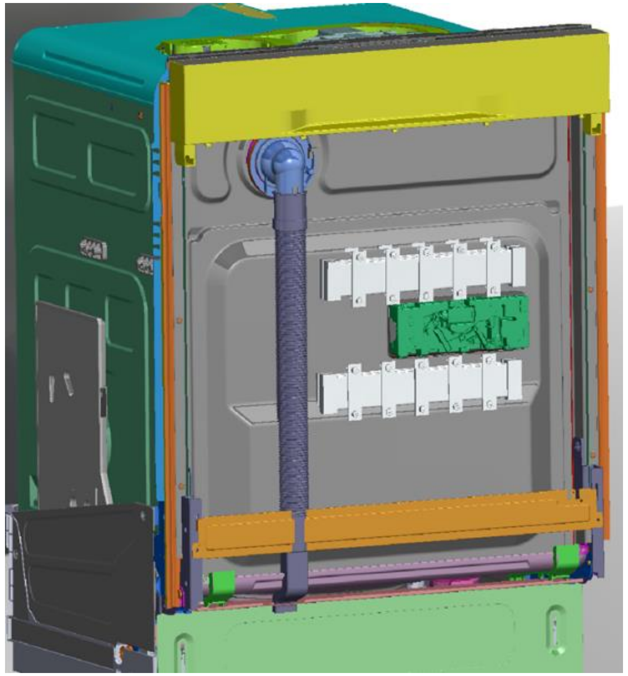
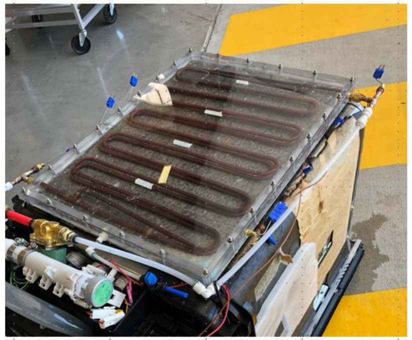
Thermoelectric Heat Pump Dishwasher with Heat Recovery





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BTO WBS 3.2.2.47

Project Summary

Objective and outcome

- Develop pre-commercial thermoelectric (TE) heat pump dishwasher with heat recovery.
- Reduce energy consumption by 20% compared to conventional ENERGY STAR-rated resistance heater-based dishwasher.
- Improve drying performance by 60% compared to conventional ENERGY STAR-rated resistance heater-based dishwasher.

Team and Partners

Samsung Electronics America, Inc. (SEA), CRADA partner

Stats

Performance Period: 7/28/2022 – 7/28/2024

DOE budget: $172K, Cost Share: In-kind contribution from CRADA partner – exact total is confidential information

Milestone 1: Model-based design

Milestone 2: Shakedown operation

Milestone 3: Evaluation of prototype dishwasher system

Milestone 4: Fabrication of final prototype complete

Milestone 5: Performance evaluation of final prototype

Problem

- The residential sector represents around 20% of global energy consumption and 18% of US energy consumption, with residential appliances consuming 27% of overall residential energy.
- Dishwashers account for 3.2% of the residential primary energy use in the US.
- The US dishwasher market has annual sales of 8.7 million units, with the potential for a significant impact on the energy consumption of households.

Objectives:

- The project aims to reduce the energy consumption of residential dishwashers in the US market.
- The novel dishwasher offers consumers faster and more effective drying, reduced or eliminated steam discharge, and best-in-class energy consumption.

Benefits and impacts:

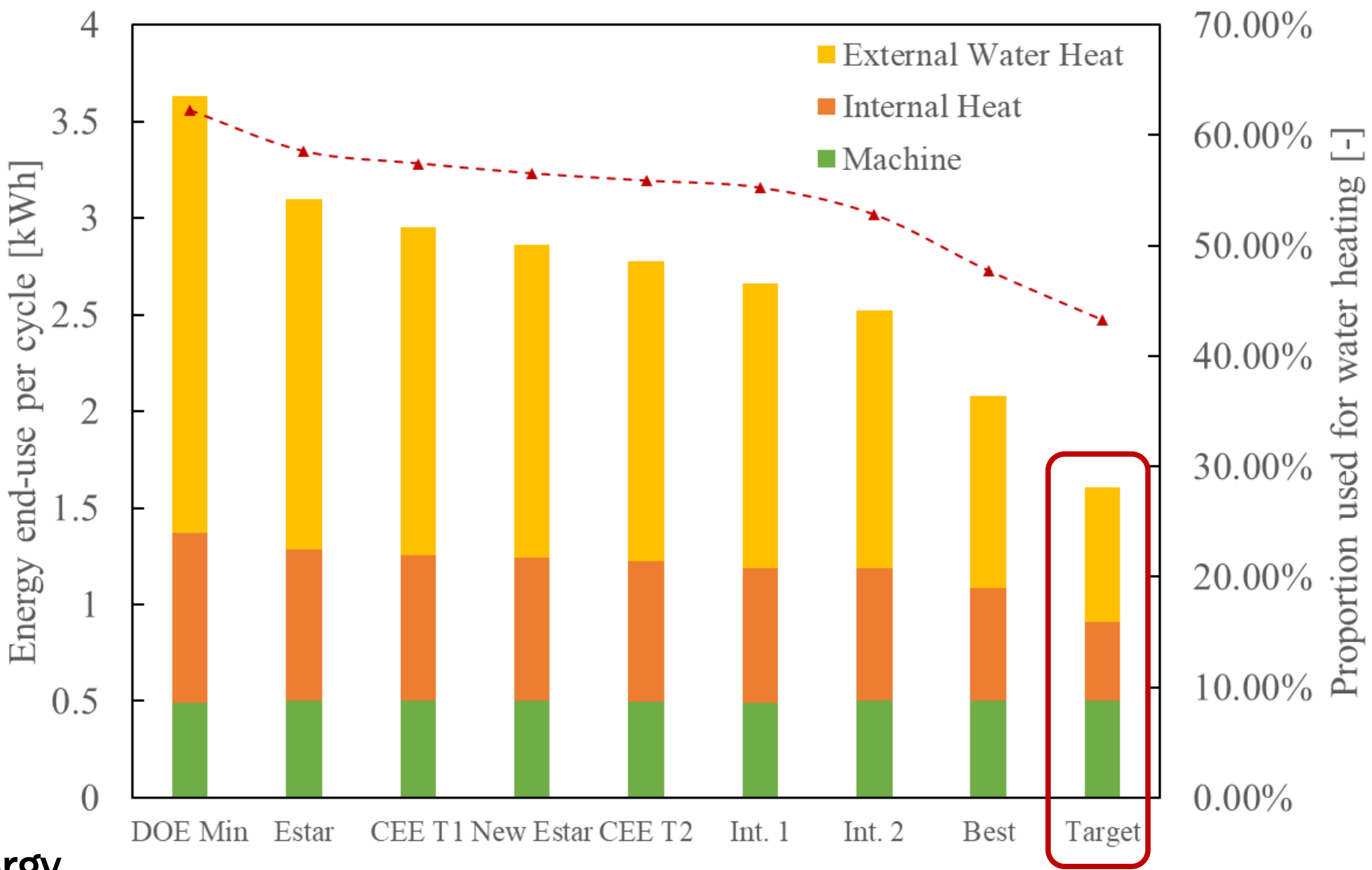
- **A reduction of 27% in energy consumption compared to conventional resistance heater-based dishwashers**
- **A 60% improvement in dish dryness after a faster drying phase**
- **Reduced steam venting during the drying phase**

Residential dishwashers in the US market
1,200 $/piece (240 kWh/year)

Pi-type (π) commercialized TE module 4 $/piece (60 W)

Alignment and Impact

Success is defined by:
The project aims to reduce energy consumption for water heating using an innovative thermoelectric (TE) heat pump system with thermal storage and reduce Samsung's best model energy consumption by 30%.



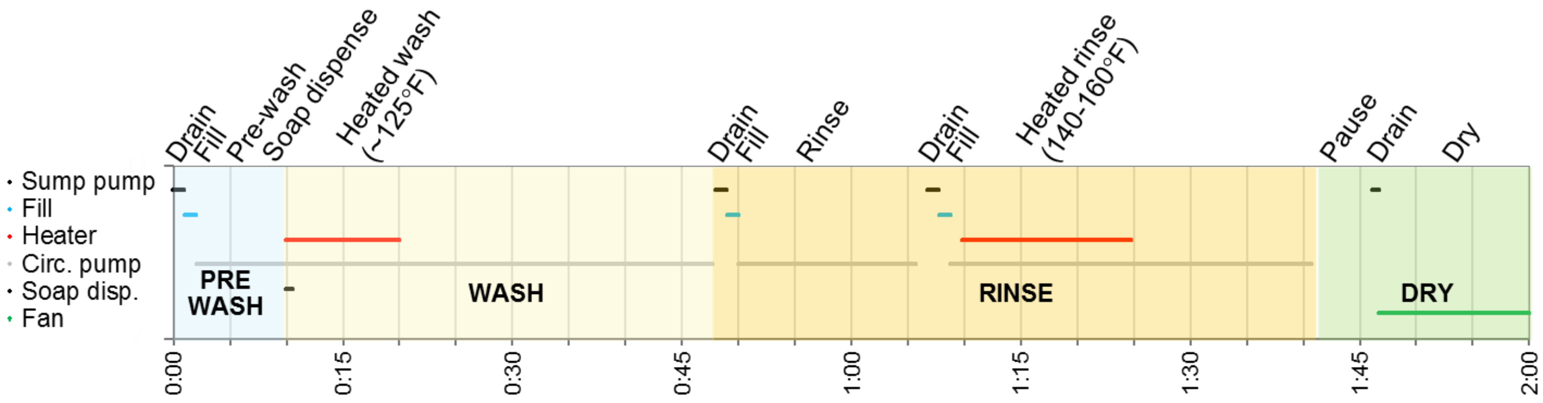
Dishwasher impacts on energy use showing that the largest savings stem from reduced hot water use

(Parker, Danny, Philip Fairey, and Robert Hendron. "Updated miscellaneous electricity loads and appliance energy usage profiles for use in home energy ratings, the building America benchmark procedures and related calculations." Florida Solar Energy Center, FSECCR-1837-10 (2010).)

Outcomes:

- **Technology performance: Reducing energy consumption aligns with EERE/BTO's goal to decrease US building energy intensity by 30% by 2030.**
- **Market adoption: The project could increase the use of energy-efficient dishwasher technologies.**
- **DEI/EJ goals: The project could lower energy bills and reduce indoor latent loads for all communities.**

Approach – Typical Dishwasher



- **Gantt chart of a typical operating sequence**

Gluesenkamp, Kyle, Mini Malhotra, Anthony Gehl (2015). *High-Efficienc* *Dishwasher Performance: Cleanliness, Water Use, and Energy Use*. ORNL report ORNL/TM-2015/267. Unpublished.

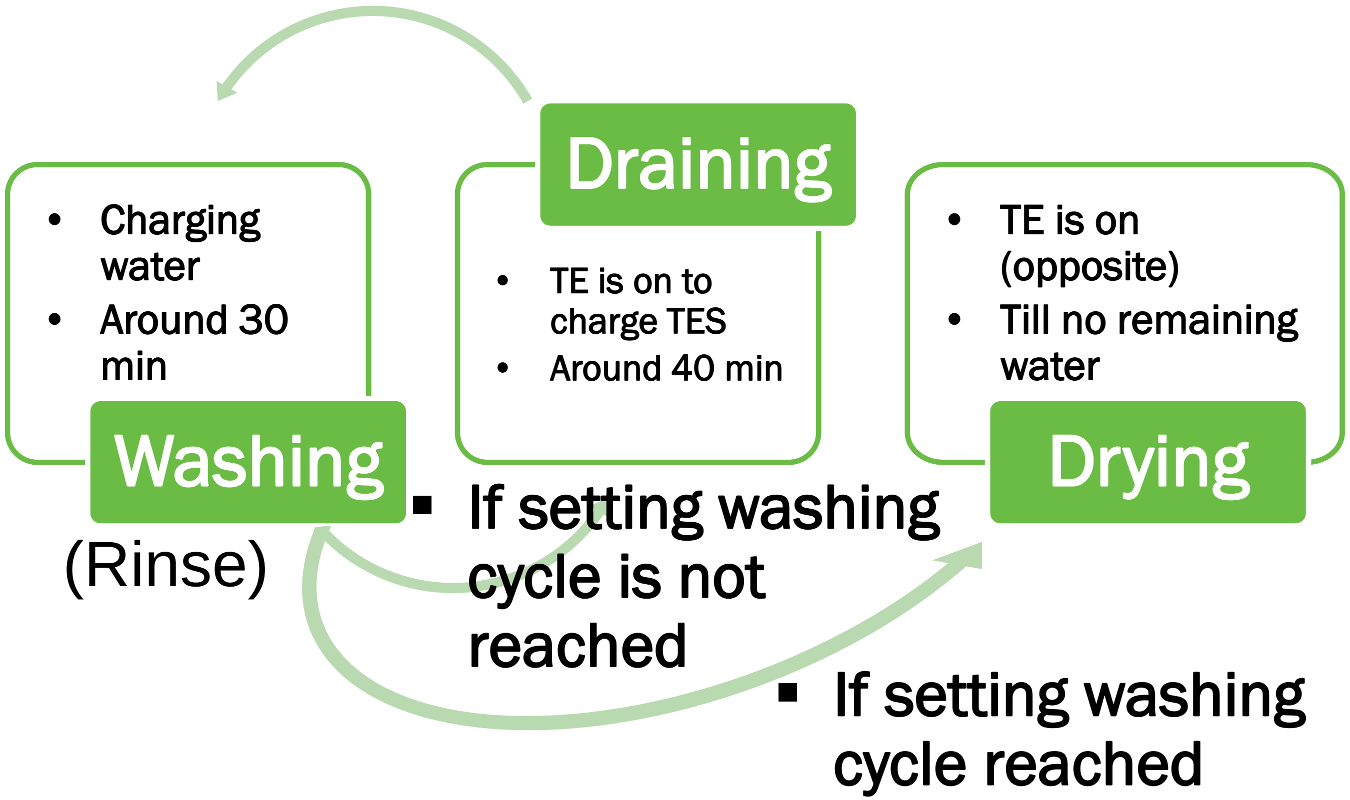
Metrics of BTO and end user interest

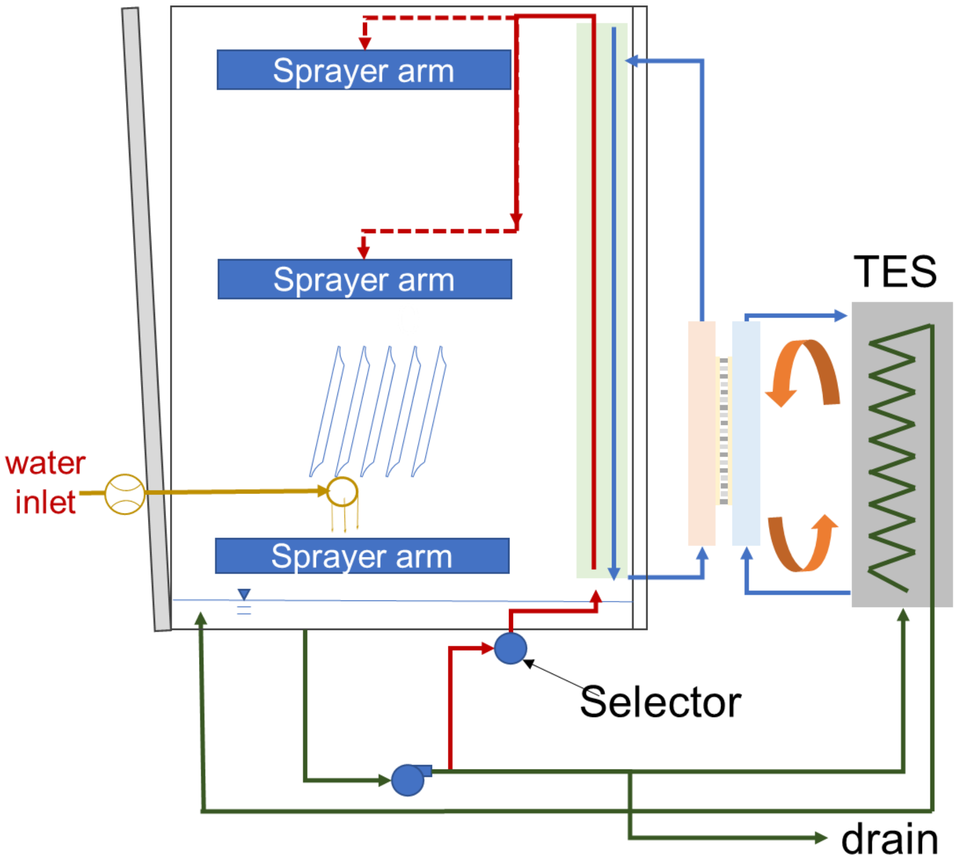
4 common drying methods on the market today

This project

	Drying speed	Dryness of plastic items	Energy consumption during drying phase	Impact on energy of whole cycle	Steam discharge
Passive method	Slow	Poor	0	Baseline	Okay
Heated dry method	Faster	Moderate?	High (800 W)	Bad	Okay
Door prop method	Faster	Poor	0	Neutral – maybe some efficiency gain	Bad
Fan method	Moderate	Poor	Low (10 W)	Neutral	Bad
TEDW goal	Fastest	Good? (TBD)	Moderate (200 W)	Improve efficiency via lower-T final rinse	Best (lowest)

Approach – Concept Working Principle





Kumar, N., Gluesenkamp, K.R., Rendall, J., Patel, V., Gehl, T., Abu-Heiba, A., Turnaoglu, T., Wu, G. and Vaidhyanathan, R., 2021. Novel Dishwasher with Thermal Storage and Thermoelectric Heat Recovery.

- During the washing and rinsing phases, drain water waste heat is recovered and stored.
- TE modules pump heat from storage to heat to the washing and rinsing phases, reducing energy consumption.
- TE modules with reversed polarity cool the tub to enhance drying performance.

Approach – Background

- A TE dishwasher was developed during a Department of Energy Technology Commercialization Funding project in 2018-2020, based on an ORNL patent. In this prior work, a down selection of designs was accomplished, and promising performance results were obtained.

Generation	Heat pump method	Additional components	TE volts [V]	Key lessons	Heating COP	Energy savings [%]	Drying energy [Wh]	RMC [%]
Gen. 1a FY. 2018	8 TE DWC	NA.	NA.	CPU circuit board failed	NA.	NA.		
Gen. 2 FY. 2019 Q1	8 TE DWC	IWJ, Tank	24	• Pump underpowered • 2 TEs failed • Single load measurement	1.07	5	44	5.8
Gen. 3a FY. 2020 Q3	10 TE MCHX	Tank, IHX, 2 pumps	40	• RH consistently 100% in top of tub • Single recovery for 7 minutes • In-situ drying measurement	1.14	12.1	112	Bottom: 2.9% Top: 2.1 %
Gen.3b FY 2020 Q4	10 TE MCHX	Tank, IHX, IAJ, 3 pumps	35	• RH decreases in both top and bottom • Top air calculation during drying • Double recovery for 3 minutes each • In-situ drying measurement	1.17	14.9	120	Bottom: 2.9% Top: 1.8 %
Gen.4 FY 23-24	TBD # TE MCHX	Conformal polymer tank, pump	TBD	• TBD	TBD	30% expected	<100 Wh expected	TBD. Lower than gen 3b expected

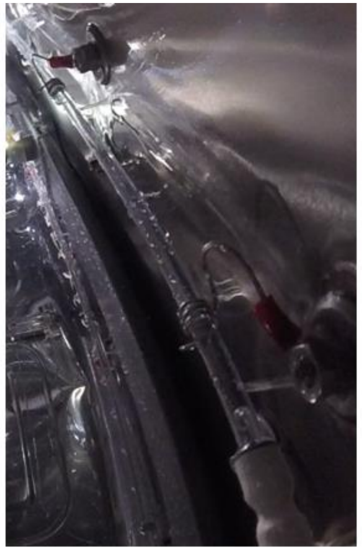
Approach – Past Work

- **Prototype Evolution – Key Design Features**

Generation 1-2:
8 TE modules mounted directly to tub wall

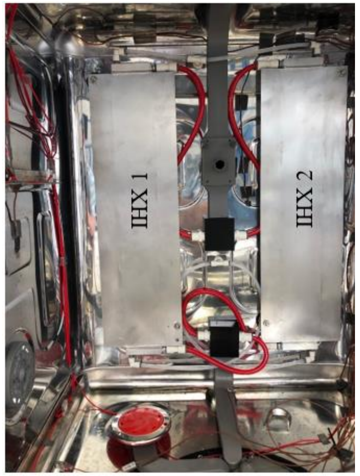


Generation 1
- Low heat transfer

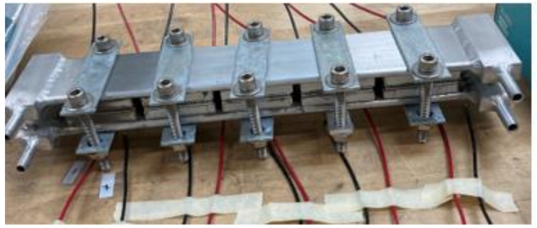



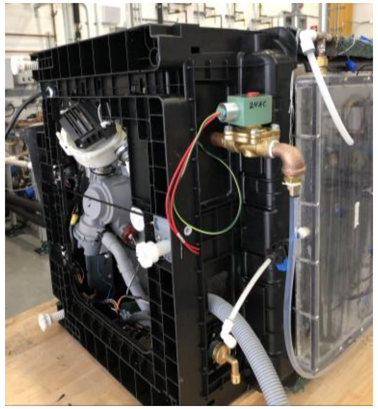
Generation 2
- Impinging water jets inside the tub
- Heat conducts from storage to tub

Generation 3:
10 TE modules with internal/external exchangers



TE HP Assembly





- Improved heat transfer in the internal heat exchanger and detached thermal storage
- Compactness important to SEA

Progress – Model Development

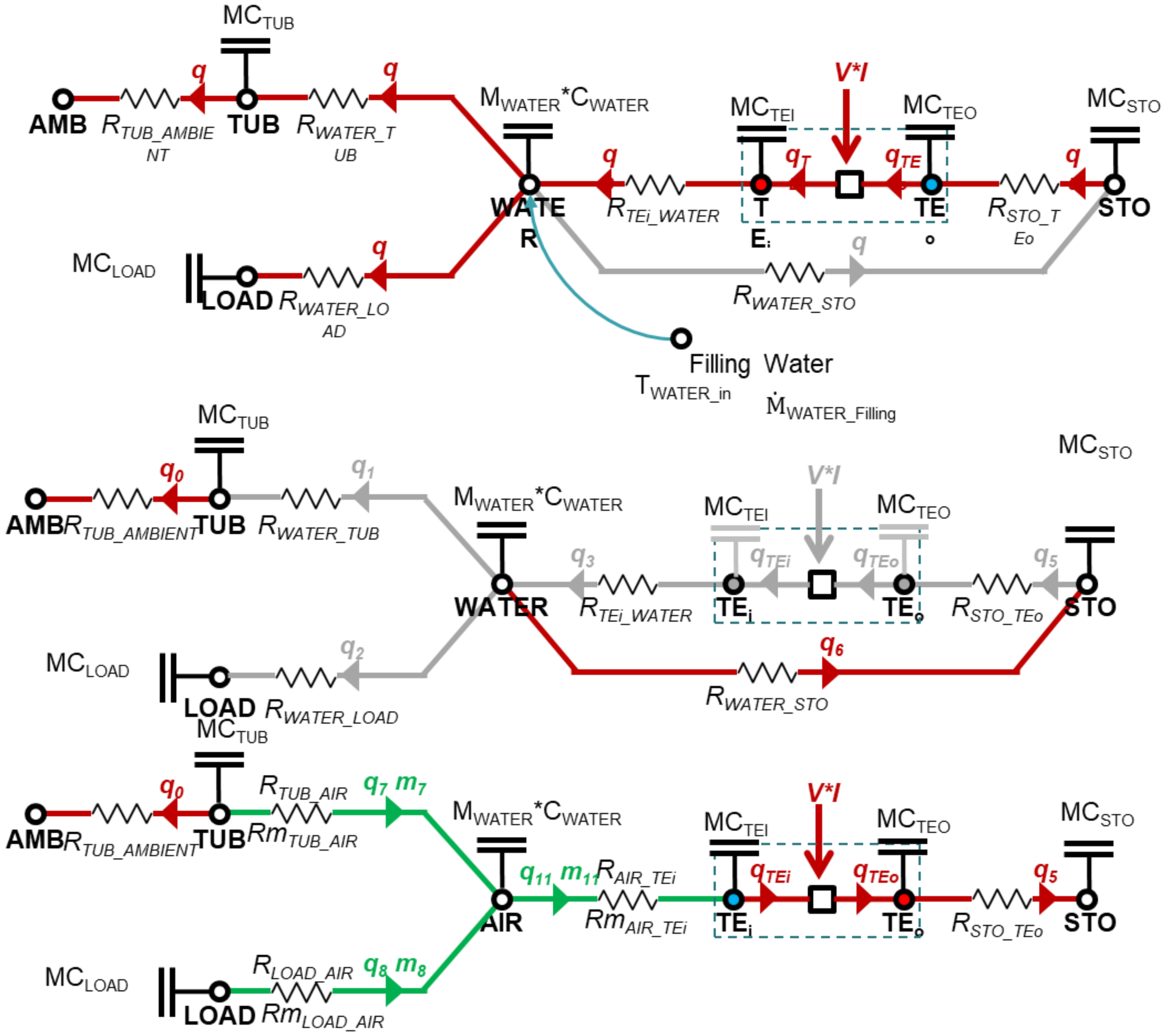
- **Developed a Thermal Resistance Network**

- The model solves a heat transfer resistance-capacitance network at each quasi-steady state timestep;
- TEHP model[1] is a detailed model using heat transfer correlations and Goldsmid's TE governing equations;
- The model was utilized to help make decisions about hardware design;
- The model was validated using experimental data

Washing

Draining

Drying



[1]Wan, Hanlong, et al. "A Thermodynamic Model of Integrated Liquid-to-Liquid Thermoelectric Heat Pump Systems." International Journal of Refrigeration (2023).

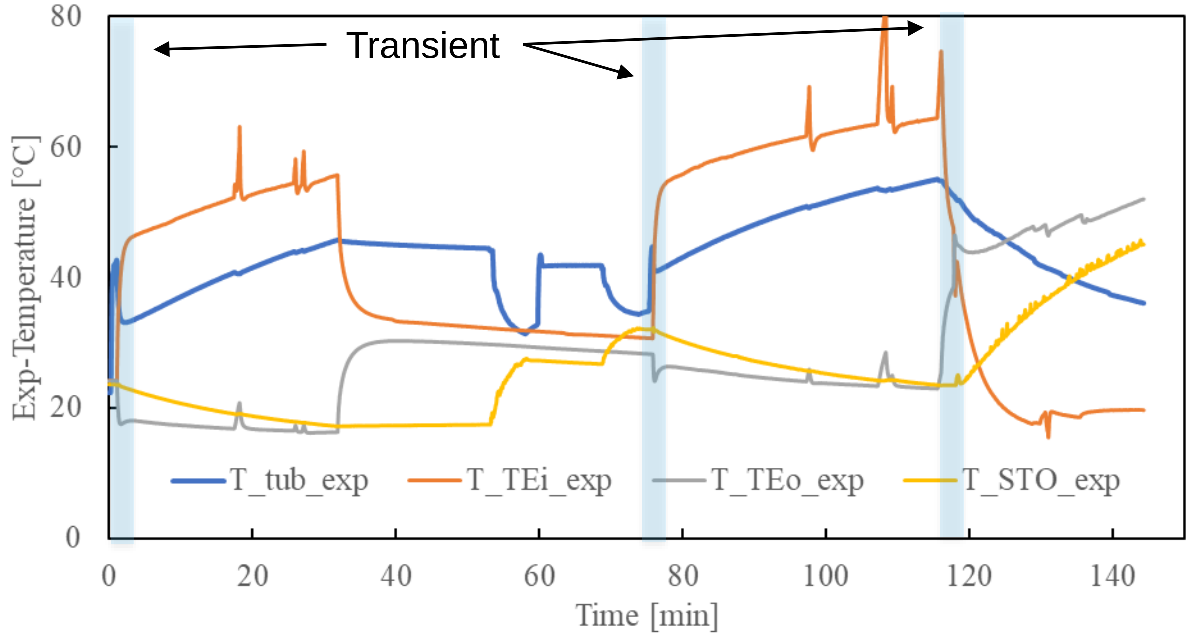
Progress – Model Validation

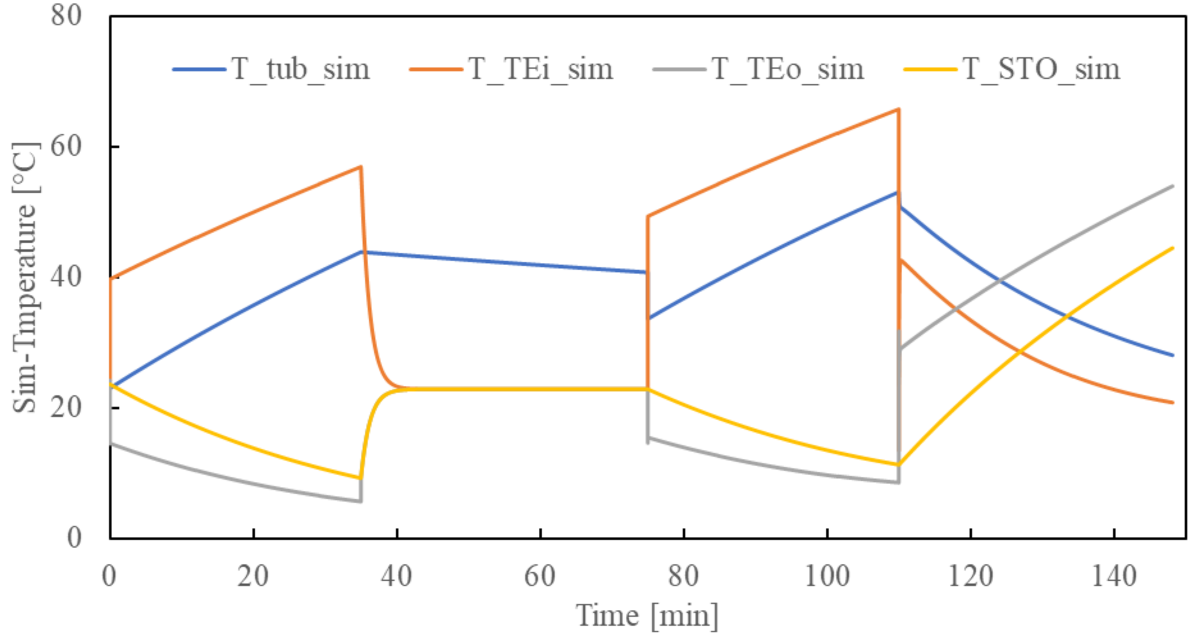
- Can predict significant temperature points (max tub temperature, STO average temperature, storage temperature after drying, etc.) within 5% error;
- Measured drying time: 2520 seconds; simulated drying time: 2289 seconds

[°C]	Max tub temperature	STO average temperature	Storage temperature after drying
Modeling	53.4	22.9	44.5
Experimental	53.9	22.0[1]	45.0

1: Average temperature from 1910 s to 4540 s.

- ❑ T_tub: Dishwasher tub temperature
- ❑ T_TEi: TE module hot side (wash) lumped temperature
- ❑ T_TEo: TE module cold side (wash) lumped temperature
- ❑ T_STO: Water tank bottom temperature (exp)/Water tank lumped temperature (sim)





Progress – System Design

System design

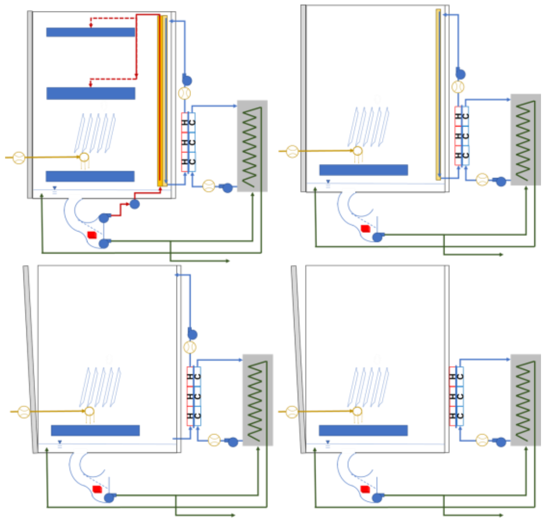
Work with Samsung representatives to come up with variables and targets:

Variables:

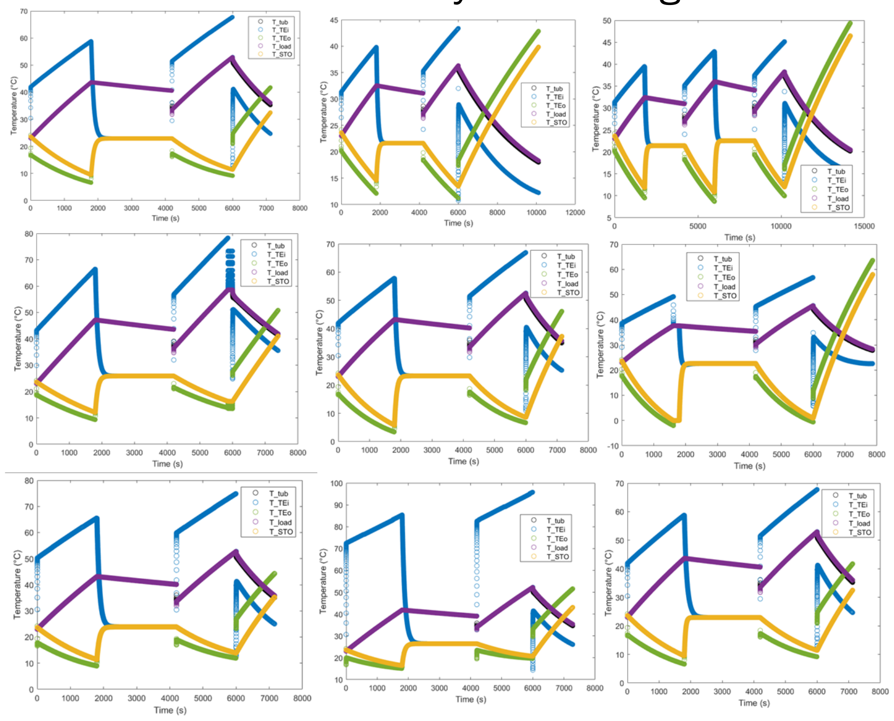
- Number of TE modules
- Storage volume
- Insulation thickness (R_tub_ambient)
- Recirc pump speed (R_TEi_water)
- ✓ Module contact or not
- ❑ Door open/close

Targets:

- ❑ Dry time reduction
- ❑ Energy reduction
- ❑ Tub max temp increase



System configs



Simulation results

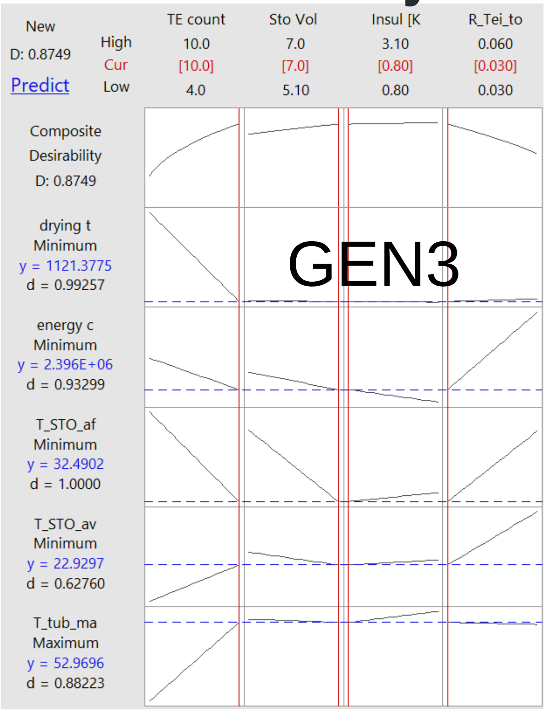
Part of the parametric study table

TE count	Sto Vol [kg]	Insul [K/W]	T_tub_max [C]	T_STO_average [C]	T_STO_after_dry [C]	energy consumption [J]	drying time [s]
4	5.1	0.8	36.0	21.3	48.6	2.74E+06	4.48E+03
10	5.1	1.6	54.0	23.4	38.2	2.43E+06	1.14E+03
4	7	1.6	37.0	21.6	39.4	2.44E+06	3.97E+03
10	7	0.8	52.9	22.9	32.4	2.40E+06	1.12E+03

Progress – System Optimization

Minitab

Software Interface – Parametric Study



Comparison between Gen3(Base) vs New:

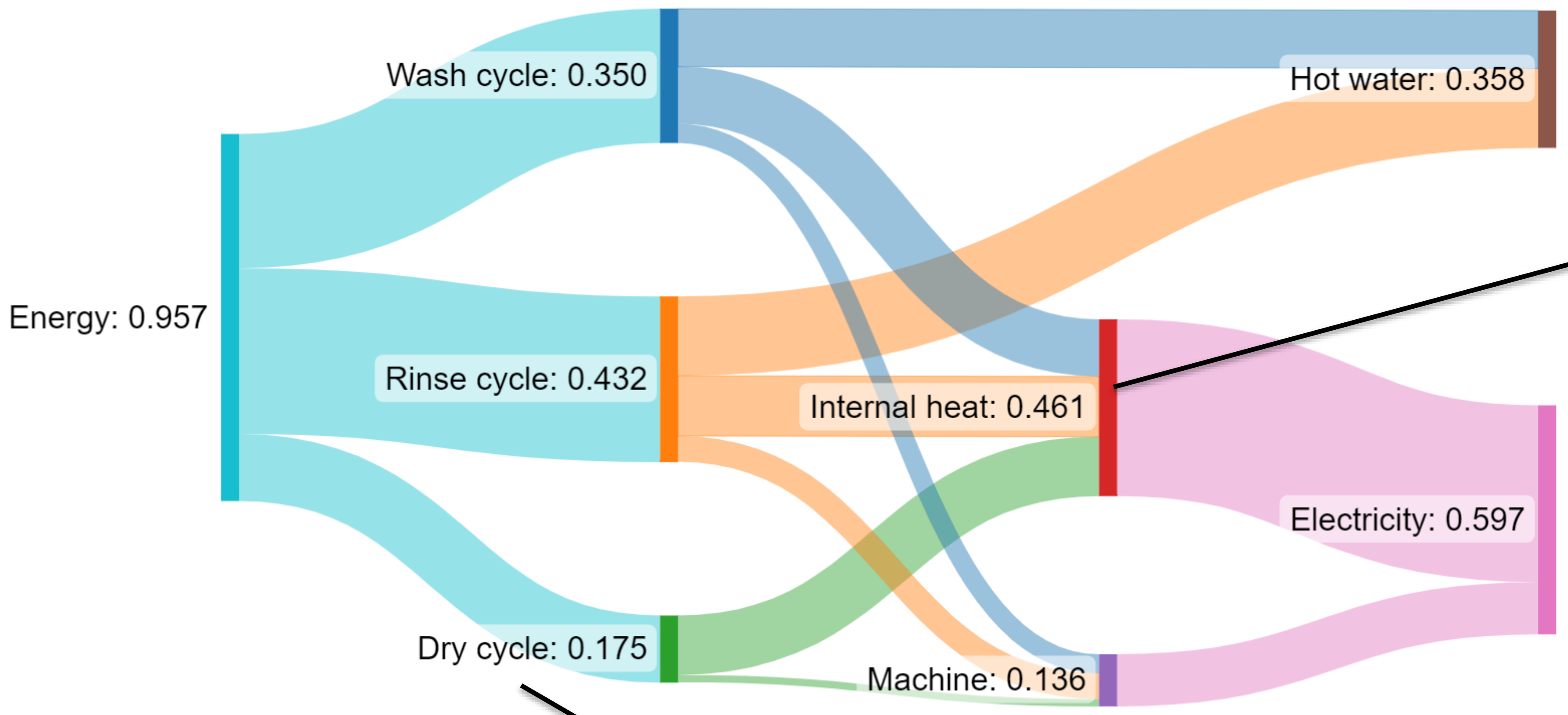
- Number of TE modules: 10
- Storage volume: 7 kg
- Insulation thickness: 3.1 K/W (R_tub_ambient)
- Recirc pump speed: 0.03 K/W (R_TEi_water)

❑ Dry time reduction ~2%
❑ Energy reduction ~1%
❑ Tub max temp increase ~4%

Conf	TE count	Sto Vol [kg]	Insul [K/W]	R_Tei_to_water [K/W]	t_dry [s]	E cons [J]	Tsto after [C]	Tsto avg [C]	Ttub max[C]	t_dry %	E con %	Tsto after %	Tsto avg %	Ttub max %
Rec	10.0	7.0	3.1	0.03	1096.2	2.37E+06	33.2	23.1	55.2	-2.2%	-1.0%	2.2%	0.8%	4.3%
Gen3	10.0	7.0	8.0	0.03	1121.4	2.40E+06	32.5	22.9	53.0	base				

Progress – Summary

Gen 3 prototype test results [kWh/cycle]



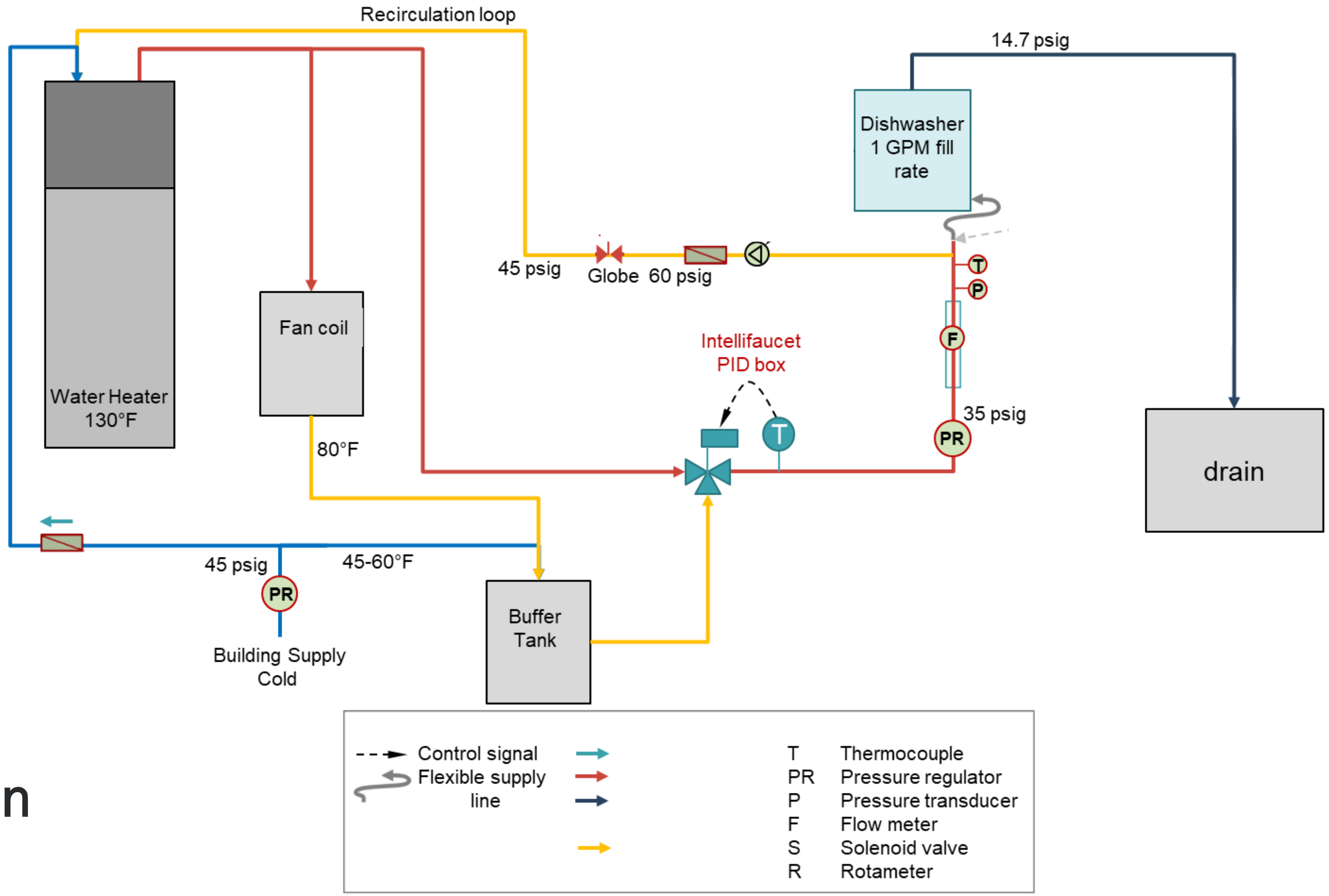
- Traditional system has energy consumption during dry cycle almost zero

- Baseline heat energy consumption is 1.11 kWh
- System optimization was expected to decrease internal heat consumption to 0.45 kWh
- Now Gen3 achieved 15% energy saving;
- Gen4 prototype 1 is expected to achieve 0.94 kWh and prototype 2 is expected to achieve 0.82 kWh target.

Progress – Laboratory Test Facility Established

New system set up in the laboratory

Piping and instrumentation diagram



- "Door open/close" will be validated;
- Prototype 2 will be made based on prototype 1.

Conclusions and Future Work

Conclusions:

- A design model has been developed that can predict the system performance within a 5% error
- Hardware choices have been made to maximize system performance
- Experimental setup has been done for the next stage laboratory test.

Future works:

- Experimentally determine TE performance characteristics
- Determine a method to quantify drying performance quantitatively
- Determine whether the door opens or closes during the drying phase
- Evaluate prototype 1 based on the parametric optimization
- Improve design based on prototype 1 test data
- Manufacture and evaluate the final prototype

Thank you

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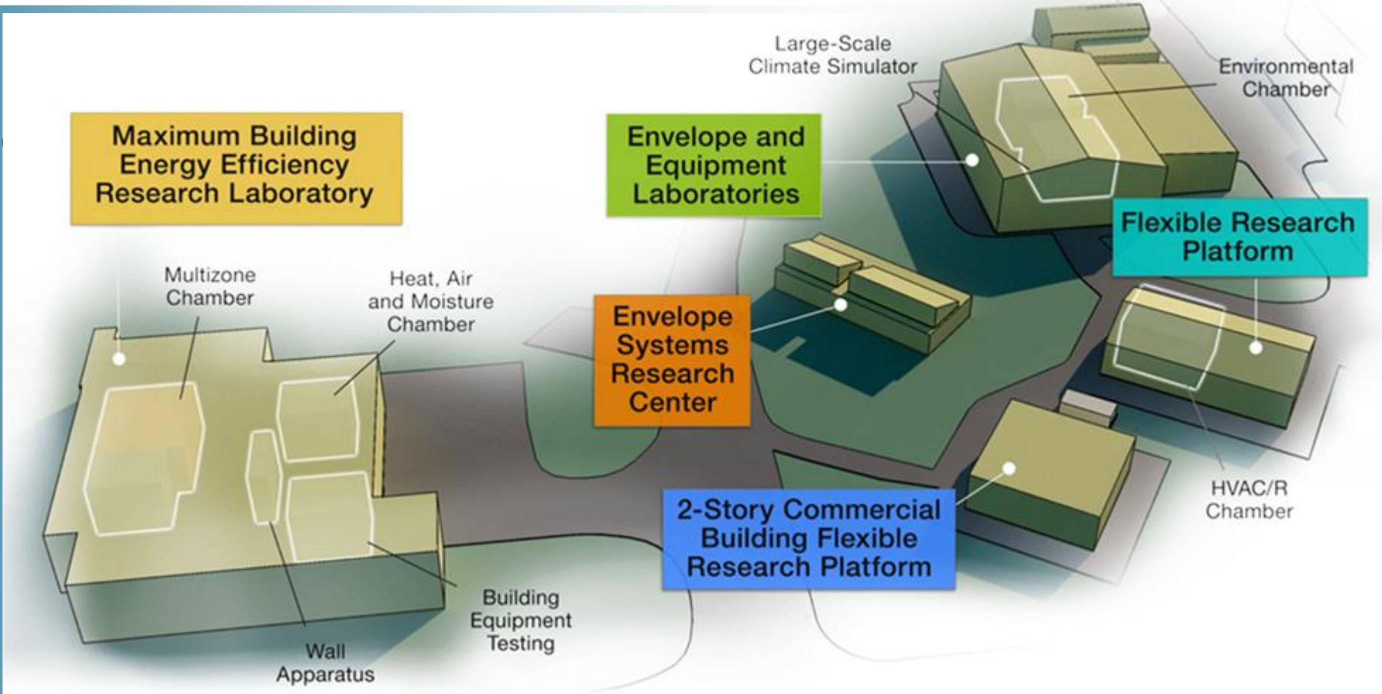

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Scientific and Economic Results
236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Execution

	FY2022				FY2023				FY2024			
Planned budget	350k											
Spent budget	78k											
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone: Model-based design												
Q2 Milestone: Shakedown operation												
Current/Future Work												
Q3 Milestone: Evaluation of prototype dishwasher system												
Q4 Milestone: Fabrication of final prototype complete												
Q5 Milestone: Performance evaluation of final prototype												
Q6 Milestone: CRADA Final Report												

Team

ORNL

- Kyle Gluesenkamp (PI)
- Zhiming Gao (Test facility design)
- Hanlong Wan (TE and system modeling)
- Joe Rendall (Test facility and prototype design)
- Saad Jajja (Prototype design and development)
- Mini Malhotra (Experimental data analysis)
- Brian Kolar (Prototype evaluation)

Samsung Electronics America

- Raveendran Vaidhyanathan (SEA ATO lead)
- Guolian Wu (Consultant, Steering Committee)
- Ken Jang (Project engineering lead, prototype design)
- Alexander Minkin (Engineer, prototype evaluation)

Team roles:

- ORNL will have primary responsibility for fabrication of prototypes and their evaluation. SEA will fabricate some prototype components to be provided to ORNL for integration into the system prototype.
- Prototype designs will be developed through close collaboration between the SEA and ORNL teams. The SEA team will provide dishwasher hardware and components, product knowledge, consumer insights, product design, and product performance evaluation.
- The SEA team will have primary responsibility for cost and manufacturability analysis, and commercialization determination. Financial support from SEA will include materials, appliances and components, and in-kind engineering support.