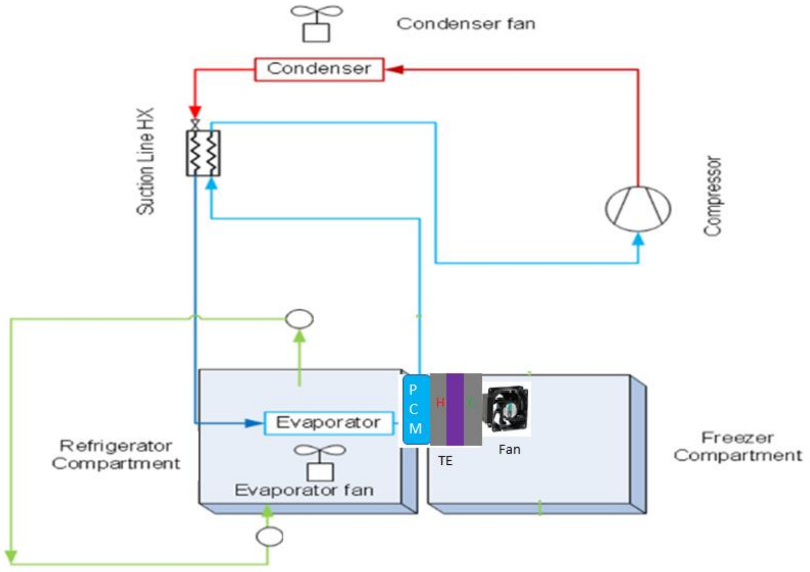
Dual-Evaporator, Variable-Capacity Refrigerator, Coupled with Thermo-electric Freezer

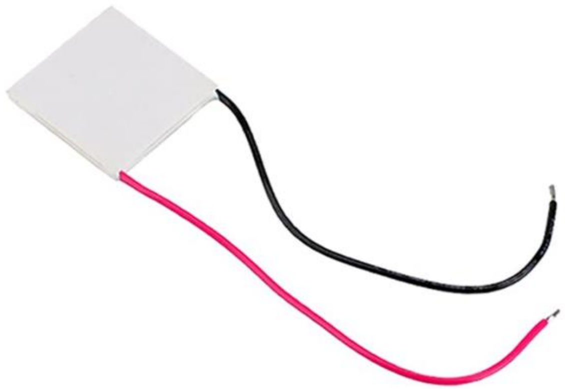


Oak Ridge National Laboratory
PI & Speaker: Bo Shen
865-574-5745, shenb@ornl.gov
WBS #3.2.6.47

Project Summary

Objective and outcome

- Develop an innovative refrigerator with a thermoelectric cooler cascaded with a vapor compression system
- Optimize energy usage with a coordinated control strategy and new defrosting mechanism
- Verify performance, achieve >15% electricity savings, >30% utility cost reduction, and conduct a field demonstration.
- Solar powered refrigerator driven by thermoelectric modules and thermal energy storage



Thermo-electric module having a max cooling capacity of 150 Watts, Dimensions: 40mm x 40mm x 3.2mm

Team and Partners

ORNL:
Bo Shen
Hanlong Wan
EPRI:
Sreenidhi Krishnamoorthy
Don Shirey

Stats

Performance Period: 10/2022 – 09/2025

DOE budget: $900K; $300K per year.

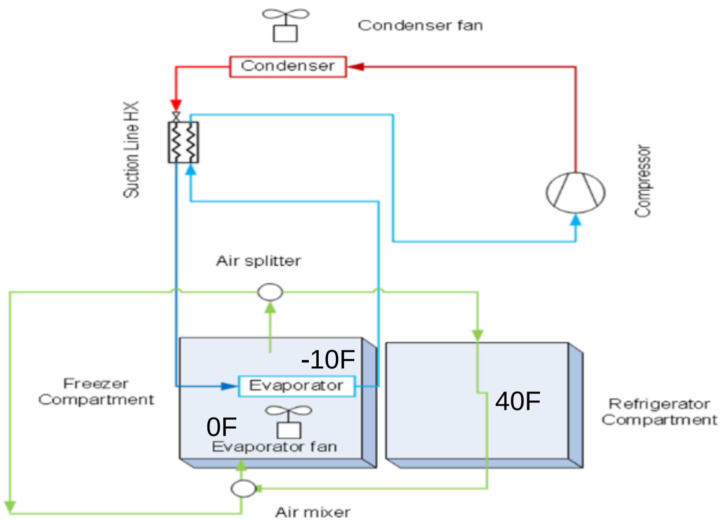
Milestone 1: Market and technology assessment (12/22)

Milestone 2: TE heat pump verification (09/23)

Milestone 3: Shakedown test (06/24)

Problems

- Refrigerators in the US consume 121 billion kWh of electricity annually;
- Fresh food compartment temperature@40˚F, freezer compartment temperature@0˚F. However, the single evaporator temperature is -10˚F. The project aims to address energy inefficiency in mainstream single-evaporator refrigerators
- Refrigerator can't provide grid-responsive energy storage to use low-cost electricity.
- Most refrigerators use electric resistance for defrosting.



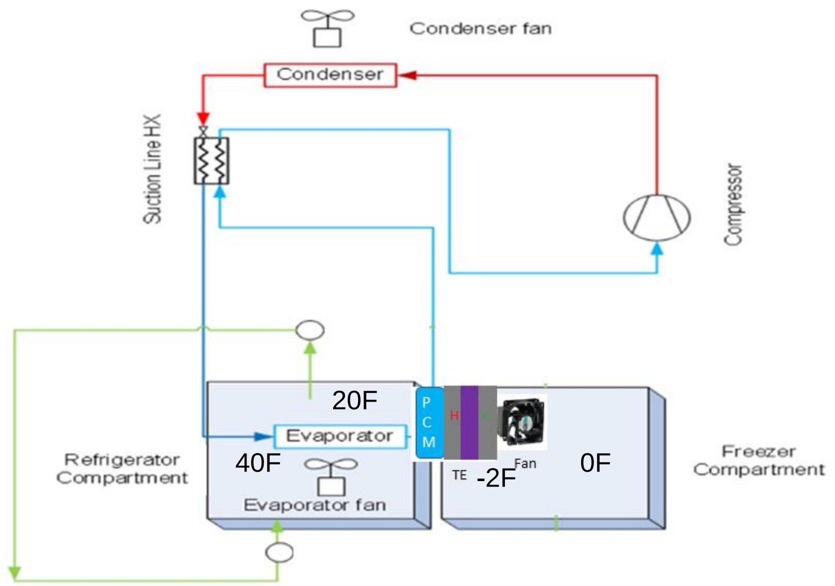
→Develop an innovative refrigerator with a thermoelectric cycle integrated with a vapor compression system

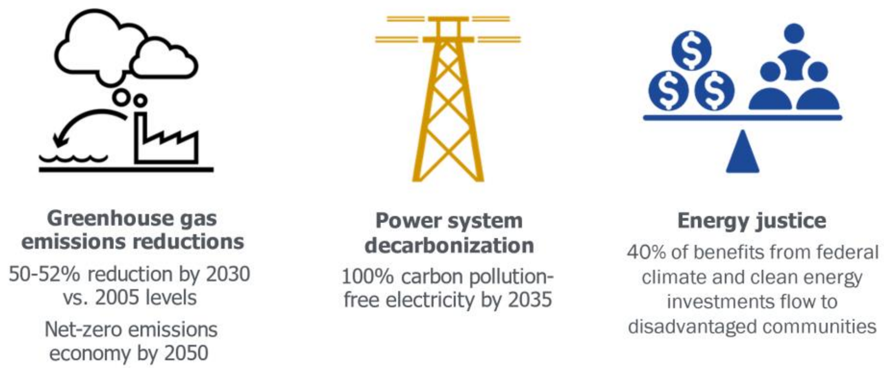
→Aim to improve defrosting operation via reversing TE heat pump cycle

→Independent temperature controls in the two compartments for better food preservation quality.

Alignment and Impact

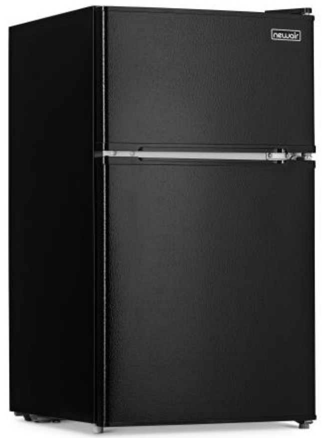
- Power system decarbonization: Success defined by achieving project objectives, including an innovative refrigerator with cascading a thermoelectric cycle and vapor compression system, new defrosting mechanism, and grid-interactive control; PCM/ice storage enables grid-responsive energy storage.
- Energy justice: Targets include energy savings >15%, utility cost reduction >30%, and verifying energy performance through AHAM tests; Estimated impact includes energy savings of up to 18.1 billion kWh in the US and reduced emissions from reduced electricity demand.
- Greenhouse gas emissions reductions: solid state cooling doesn't use refrigerant.
- Energy justice: Separate chambers' control and flexible DC voltage input address energy justice concerns and improve food preservation quality.





Approach – Market and Technology Survey

	Brand	Capacity in original units	Capacity [cu. Ft.]	Price [$/Piece]	Cost per cu. Ft. [$/cu. Ft.]
TE	AstroAI Mini Fridge	4 Liter/6 Can	0.14	49.99	357.07
	AstroAI Mini Fridge	15 Can/10 Liter	0.35	99.99	285.69
	Koolatron	20 Bottle	0.54	199.99	370.35
	ICECO JP50	50 Liter	1.77	559.00	315.82
	Koolatron	34 Liter	1.20	149.99	124.99
	AstroAI	6 Liter	0.21	69.99	333.29
	Ivation	8 Bottle	0.21	179.99	857.10
	Ivation	12 Bottle	0.36	269.99	830.74
VCC	Frigidaire	N.A.	3.20	168.32	52.60
	Frigidaire	N.A.	4.60	268.00	58.26
	BANGSON	N.A.	3.20	149.99	46.87
	Midea	N.A.	3.10	239.99	77.42
	RCA	N.A.	3.20	254.99	79.68
	COMFEE	N.A.	3.30	191.00	57.88
	Galanz	N.A.	10.00	599.99	60.00
	kalifon	N.A.	49.00	2789.00	56.92
	HCK	N.A.	5.12	1049.99	205.08
	Frigidaire	N.A.	17.4	1199.00	68.91



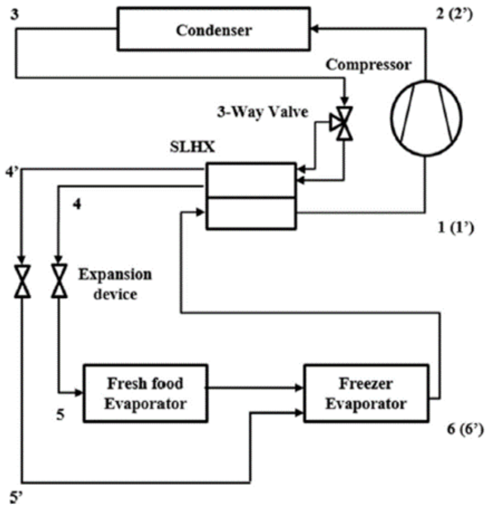
VCC Refrigerator

TE Refrigerator

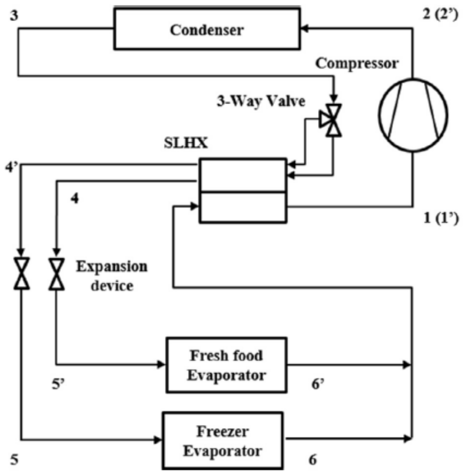
- TE refrigerator has a low initial price but with low capacity;
- TE refrigerator is much more expensive than VCC refrigerator per unit cu. Ft.
- The cost per cu. Ft. of one TE module is only **0.24 $** (Amazon purchased TE modules).

Progress – Technology Survey

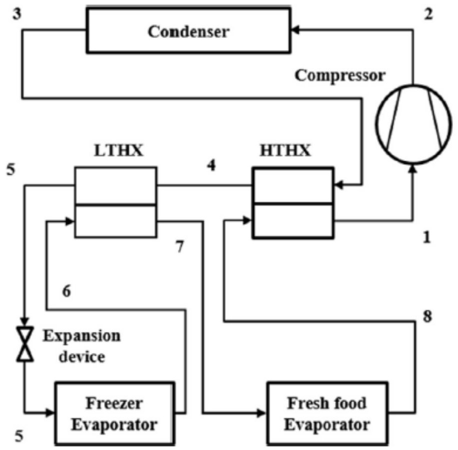
Working Mechanisms of Different Cycles



Bypass Circuit Cycle

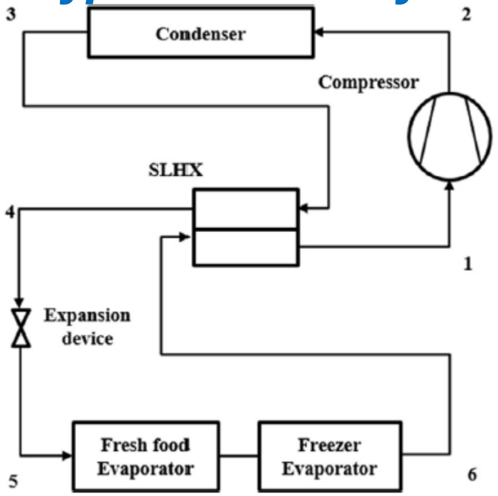


Parallel Circuit Cycle

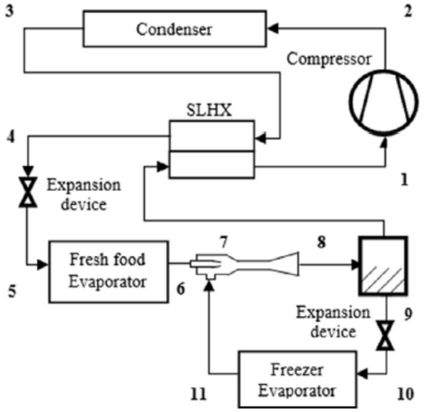


Lorenz-Meutzer Cycle

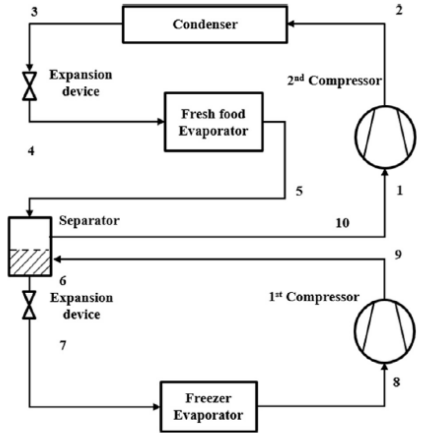
- Efficiency improvements focus on differentiating evaporating temperatures for freezer and fresh food compartments.



Serial Circuit Cycle

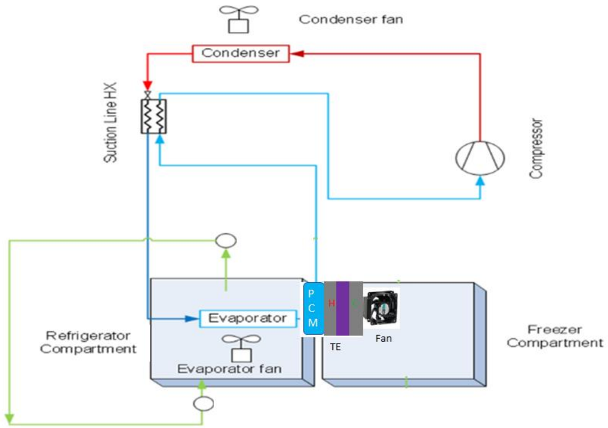


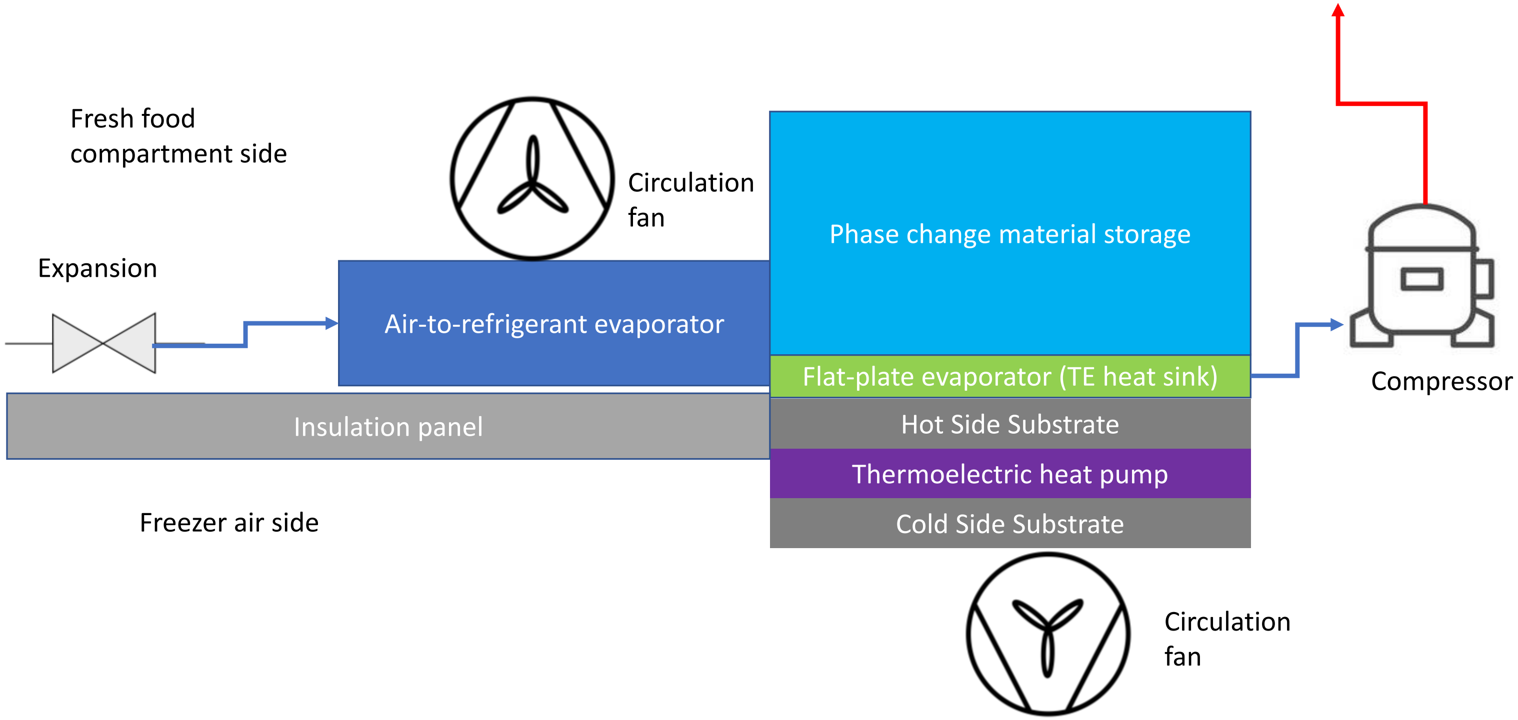
Ejector cycle



Approach – Dual Evaporator. TE cascaded with vapor compression system

- Engage with industry partners and stakeholders to promote technology adoption and transform the market.
- Demonstrate and validate expected benefits through energy factor tests and field demonstration of the prototype in a real-world setting.
- Conduct extensive modeling and simulation to optimize technology performance.

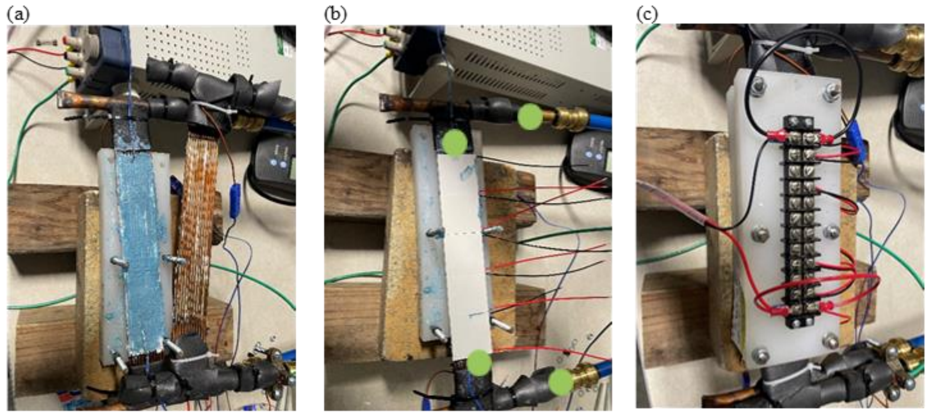




- A thermoelectric cooler cools the freezer compartment, cascaded with a vapor compression cycle that discharges its heat to the VC system's evaporator. A PCM storage layer balances the capacities between the TE freezer and VC evaporator.
- Assembly of Serial evaporators, upstream fin-and-tube evaporator to cool Fresh food compartment, and downstream flat plate evaporator to remove condenser heat of the TE heat pump

Progress – TE performance characterization

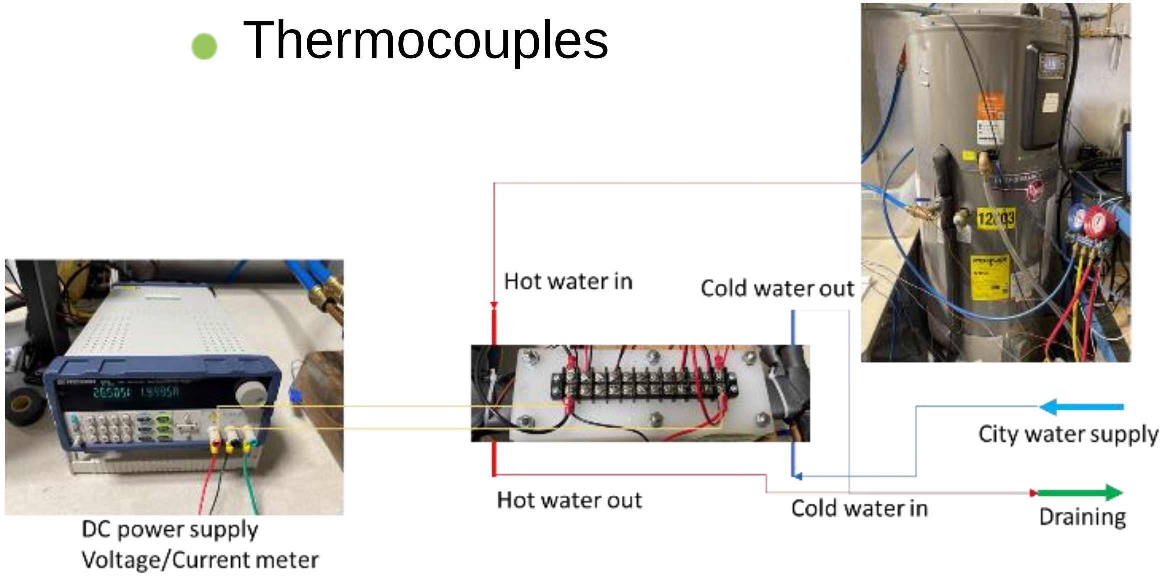
- TE heat pump fabrication



TEHP a) tube layer b) TE module layer c) outlook

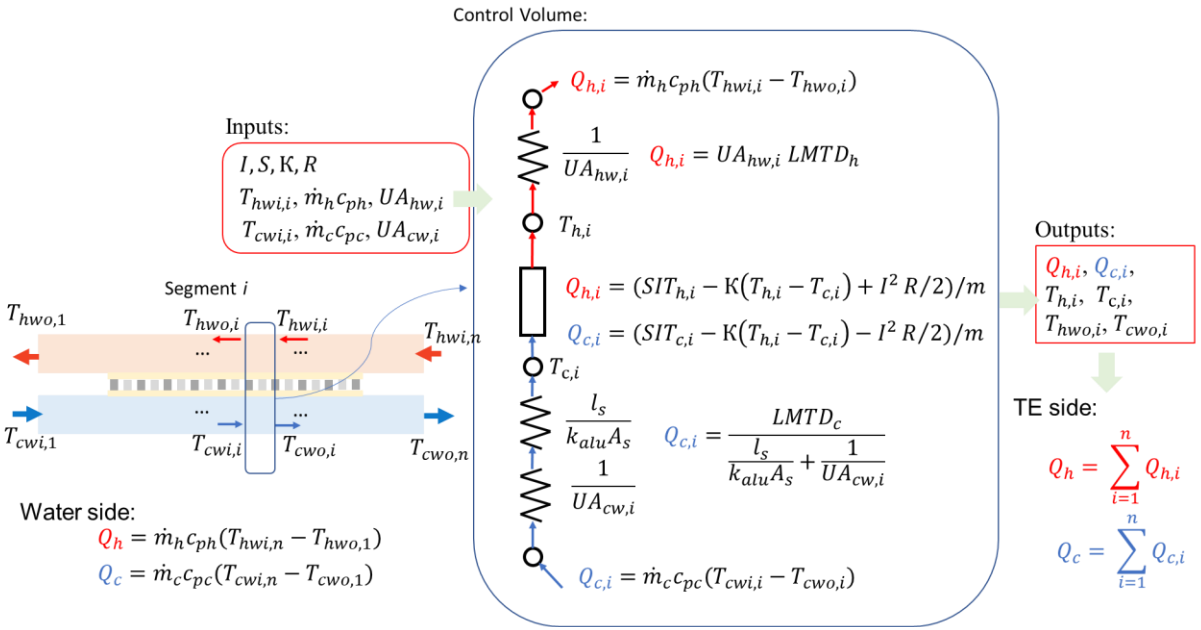
● Thermocouples

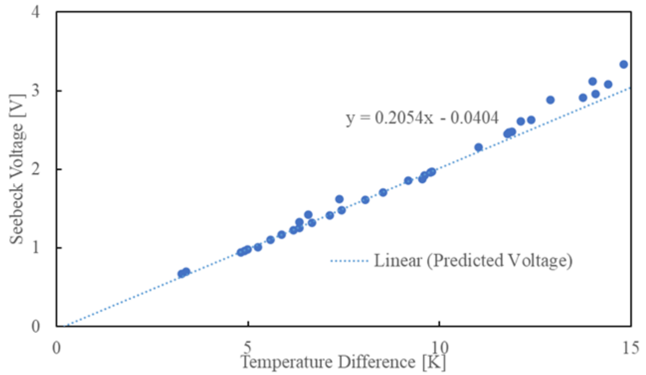
- A water heater was used to supply hot water. The cold side inlet water is the city water.
- Thermocouples to measure inlet/outlet water and tube surface temperatures.



Progress – Model Development of TE Heat Exchanger

TEHP model structure





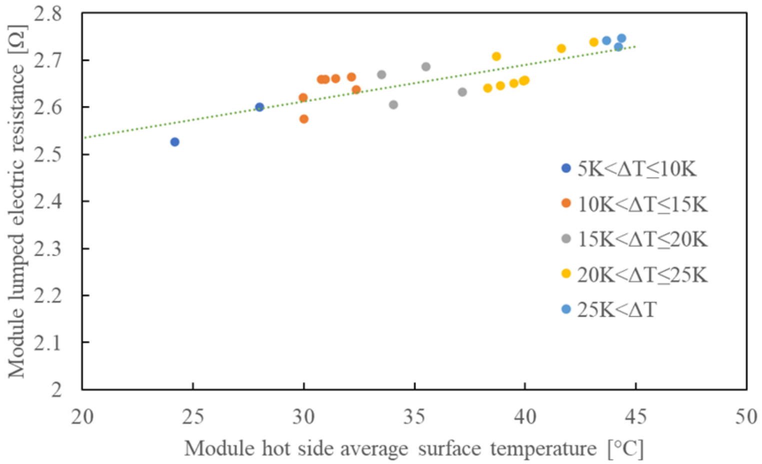
Seebeck Coefficient (S)

TEHP model validation

Measured: 37.36℃ Measured: 39.03℃

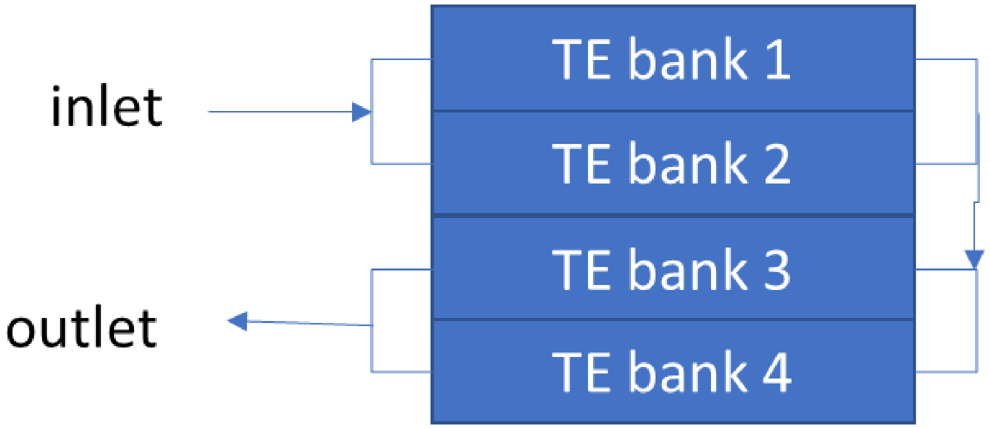
37.36	37.69	38.03	38.37	38.7
21.50	21.59	21.67	21.76	21.84

Measured: 21.34℃ Predicted water temperature in tubes [℃] Measured: 21.84℃



Electric Resistance (R)

Progress: TEHP Assemble



TEHP assembling

- TEHP has been assembled with 28 TEC12706 modules;
- Modules were placed on 4 banks;
- The bank was made with 10 capillary tubes (covered with thermal paste) to improve heat transfer.

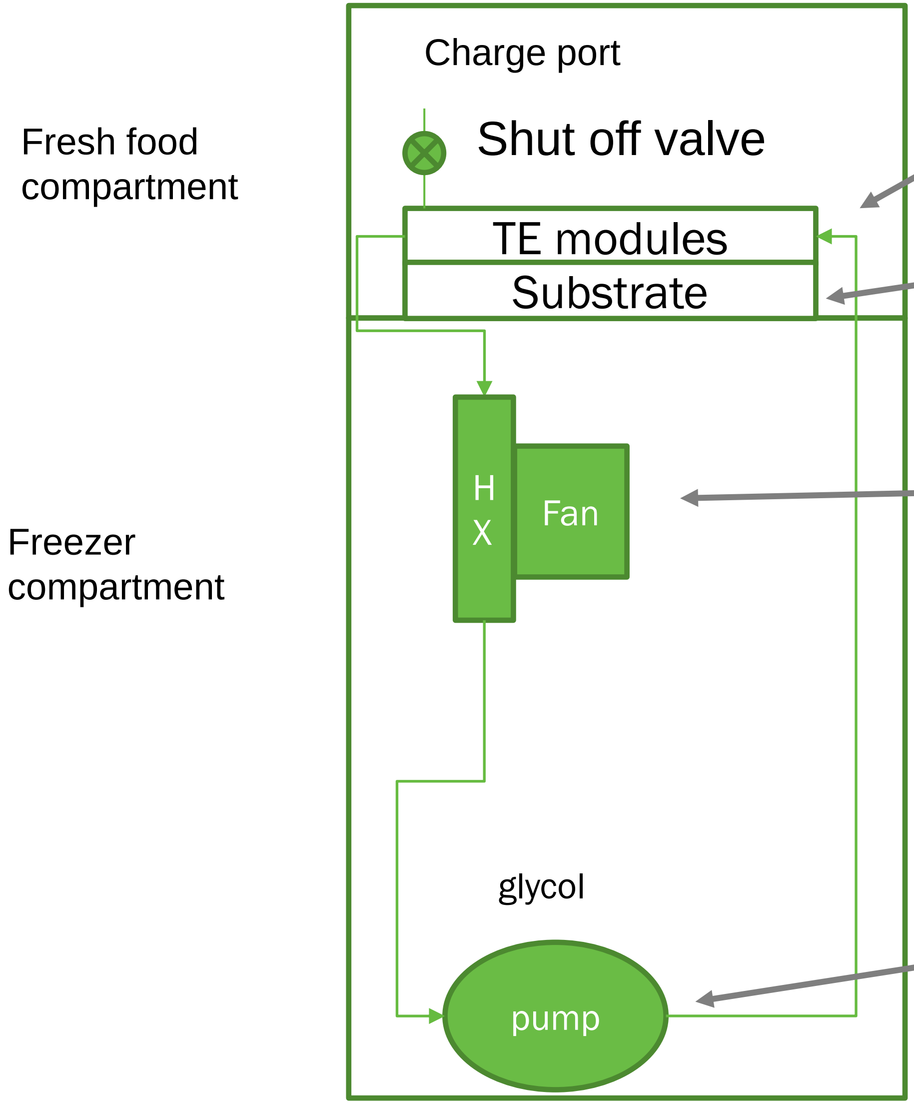
Items	Geometry parameters
Capillary tubes	2.54 mm in ID, and 4.00 mm in OD

TEHP – 1 bank

TEHP – 28 modules

TEHP – hot side melts ice

Progress: Prototype Assemble



5 W DC fan

12VDC pump


TEHP


Substrate

Glycol


HX and Fan

Outlook

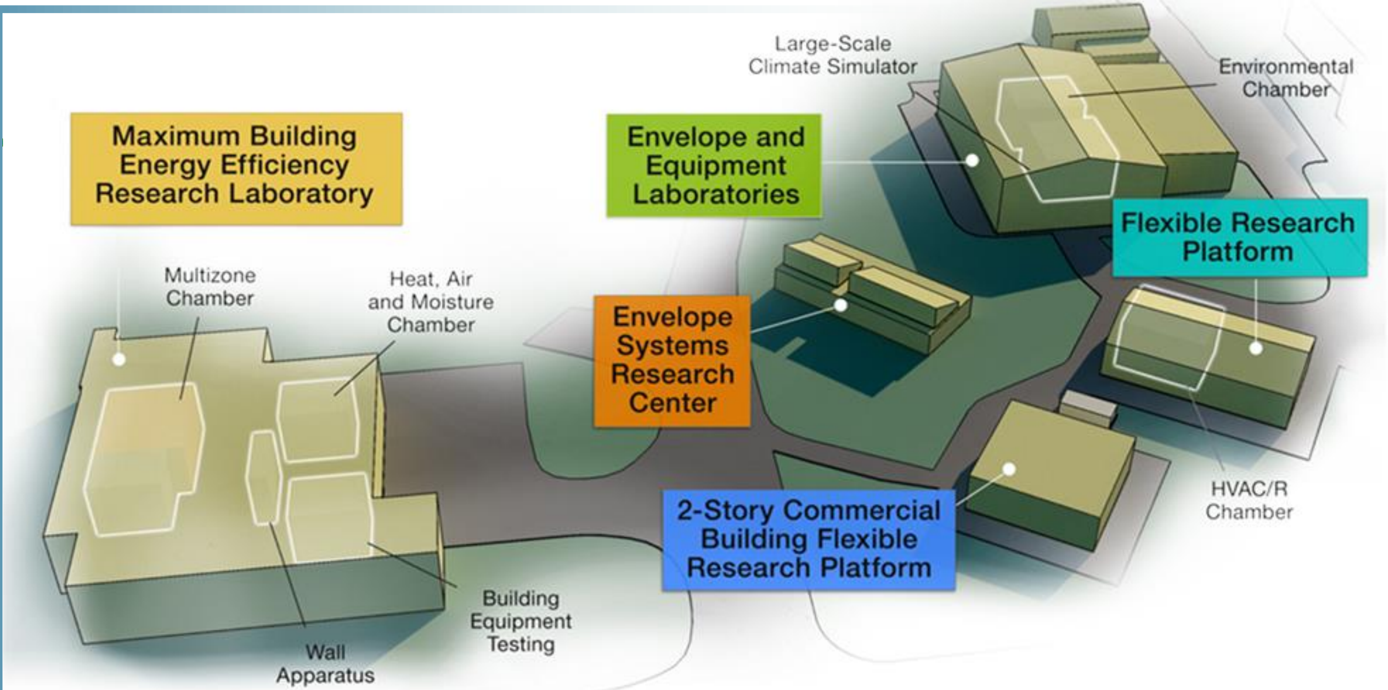
Progress and Future Work

Conclusions

- Market Assessment
  - TE refrigerator has a low initial cost but much higher cost per unit capacity compared with VCC refrigerator
  - TE module has low cost, so the TE refrigerator has great potential to decrease the cost
- Experiments setup for Thermoelectric Heat Pump
  - TEHP sample has been successfully assembled
  - A math model was developed to predict the system's performance
  - Property parameters (R and S) are validated

Future works

- TE Heat Pump Prototype Evaluation and Improvement
- Refrigerator system integration and config optimization
- Field performance demonstration



Thank you

Oak Ridge National Laboratory
Bo Shen
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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

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REFERENCE SLIDES

Project Execution

	Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
1	Market and technology survey												
2	Acquire and evaluate a baseline residential refrigerator												
3	Develop a TE heat pump module												
4	Develop a phase change storage module												
5	System integration and evaluation												
6	Unit level control development												
7	Standard Energy Factor Test												
8	Development of TE cascaded refrigerator modelling and design tool												
9	Development of Grid-responsive supervisory control												
10	Start a field demonstration												
11	Final Report												
	Milestone												
1	Baseline refrigerator evaluation												
2	TE heat pump verification: We will develop a TE heat pump to reach a >2.5 cooling COP corresponding to a temperature lift around 20 R, and the surface temperature at the cold side around 0˚F				Go/No-Go								
3	Shakedown test of an integrated system												
4	Breadboard unit performance verification: The prototype refrigerator tested in our appliance chamber following the AHAM refrigerator standard to verify the performance goals i.e., reaching a 24-hour energy factor, 15% higher than the baseline refrigerator								Go/No-Go				
5	Initialize field demonstration												
6	Final report												

- Go/no-go decision points
  - TE heat pump verification: We will develop a TE heat pump to reach a >2.5 cooling COP corresponding to a temperature lift around 20 R, and the surface temperature at the cold side around 0˚F;
  - The prototype refrigerator tested in our appliance chamber following the AHAM refrigerator standard to verify the performance goals i.e., 15% higher efficiency than the baseline refrigerator

Team

ORNL:

•**Dr. Bo Shen** is a senior R&D stuff, the author of the DOE/ORNL Heat Pump Design Model, he graduated from Purdue University, and worked at Trane Commercial Systems before joining ORNL. He has 20+ years' experience in vapor compression system development and modelling. He collaborated with the Whirlpool team to develop dual-evaporator refrigerator using a linear compressor in a prior collaboration. He leads the prototype design, fabrication and laboratory tests, as well as development of unit level and supervisory controls.

•**Dr. Hanlong Wan** is a postdoctoral research associate in ORNL. He conducted the TEHP prototype field tests and TEHP modeling.

Team

EPRI:

•**Sreenidhi Krishnamoorthy,** Engineer/Scientist III (Principal Investigator). Dr. Krishnamoorthy has 10 years of technical and project management experience in building space heating and cooling system research including laboratory and field testing of heat pump systems, market potential analytics of electrification of residential and commercial HVAC systems, component and system level modeling, and thermoelectric heat pump prototype design. He leads the market and technology assessment in the project.

•**Don Shirey**, Sr. Project Manager. Mr. Shirey has over 30 years of experience with research and development of cooling, heating, dehumidification, and ventilation technologies for both residential and commercial buildings across multiple climate regions. He was a member of the EnergyPlus development team for over 10 years, primarily adding models for conventional and emerging HVAC technologies. He has extensive experience in field testing of heat pumps. He leads the field demonstration in the project.