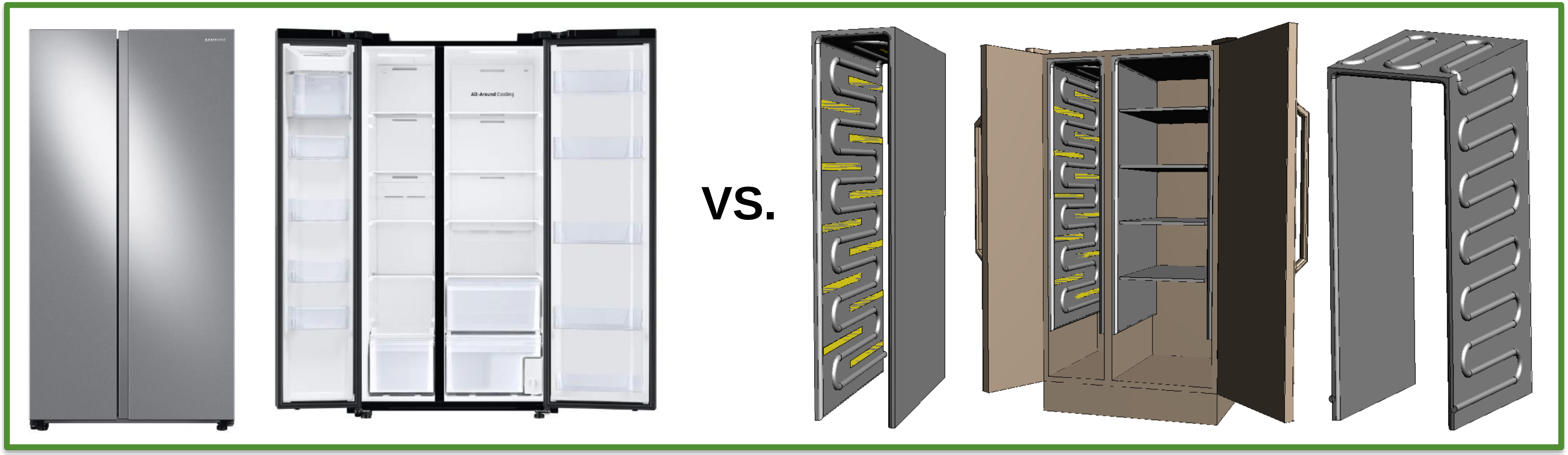
# High-Efficiency Refrigerator with Cold Energy Storage Enabling Demand Flexibility

(This is a new project launched in FY 2023)




Performing Organizations: Oak Ridge National Laboratory, Heat Transfer Technologies LLC,
and Southern University and A&M College

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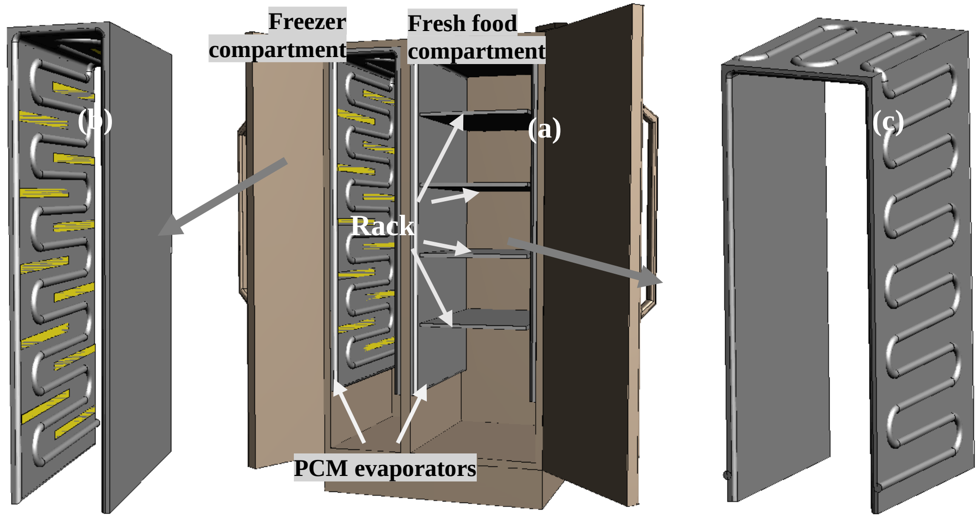
WBS # 3.2.6.48 ORNL, BTO Emerging Technologies FY22 Lab Call # DE-LC-000L095

# Project Summary

## Objective and Outcome

The objective is to develop a novel household refrigerator that uses advanced evaporators with phase change material (PCM)-based, long-duration cold energy storage and a low–global warming potential alternative refrigerant to achieve flexible load demand management and transformational efficiency improvement in excess of 20%. This objective will enable a 30% reduction in $CO_2$ emissions and a nearly 100% load shift from daytime to nighttime operation.




## Team and Partners

Oak Ridge National Laboratory

Southern University and A&M College
(A historically black US land-grant university)

Heat Transfer Technologies LLC (Industrial partner)

SubZero Group, Inc. (Industrial partner)

## Stats

Performance Period: 09/01/2022–09/30/2025

DOE budget: $1050,000, Cost Share: $30,000

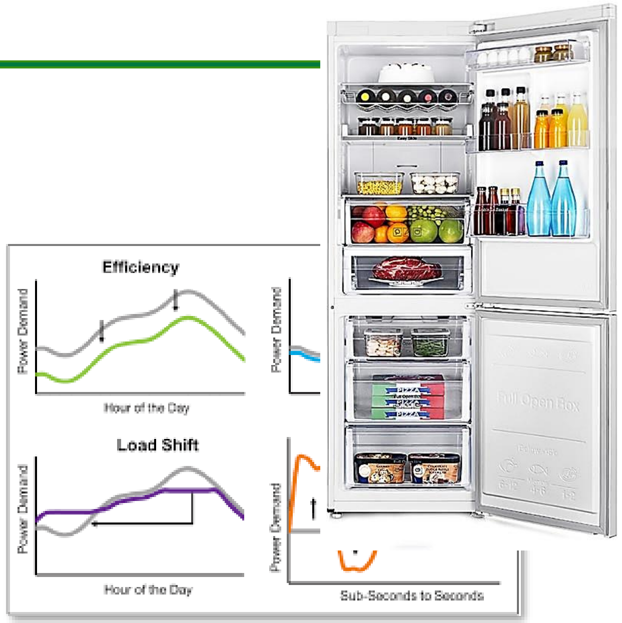
Key Milestone 1: 3D CFD simulations of the refrigerator with advanced PCM evaporators (06/30/2023)

Key Milestone 2: Optimize, fabricate, and assemble advanced PCM evaporators (09/30/2024)

Key Milestone 3: Comprehensive tests on the new refrigerator with PCM cold energy storage (06/30/2025)

# Problem

- **Flexible building loads benefit consumers, electric grid, and community**
- **The domestic refrigerator is one of the most common electrical appliances in US homes and buildings.**
  - 12.44 million refrigerator shipments in the United States in 2019
  - More than 120 million refrigerators across the United States
  - Nearly 7% of home electricity consumption
    - 836 TBtu of energy consumption
    - 36.1 million tons of $CO_2$ annually (Scout's Baseline Energy Calculator)

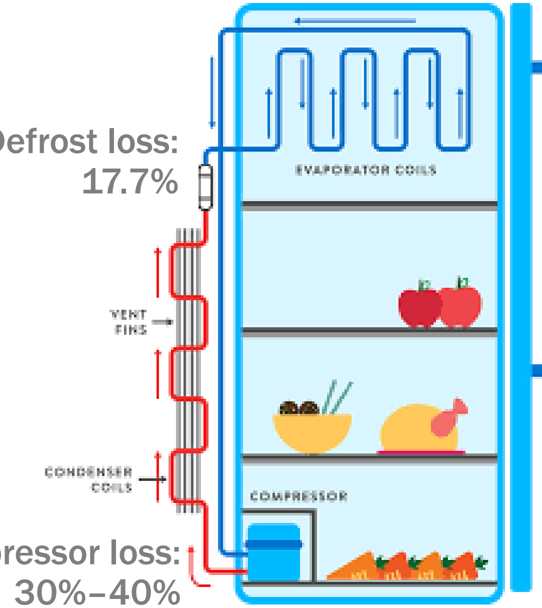



- **A representative US household refrigerator consumes 1.5–2.0 kWh electricity per day**
  - Representative approaches for saving energy:
    (1) Use of high-efficiency compressors; (2) Improving the thermal insulation of refrigerator compartments; (3) Heat transfer enhancement for the evaporator and condenser

**Representative technologies cannot easily achieve further efficiency enhancement and demand flexibility simultaneously.**

Defrost loss: 17.7%

On/off cycling loss: ~14.3%–24.7%




Door open loss: 7%–13%

Compressor loss: 30%–40%

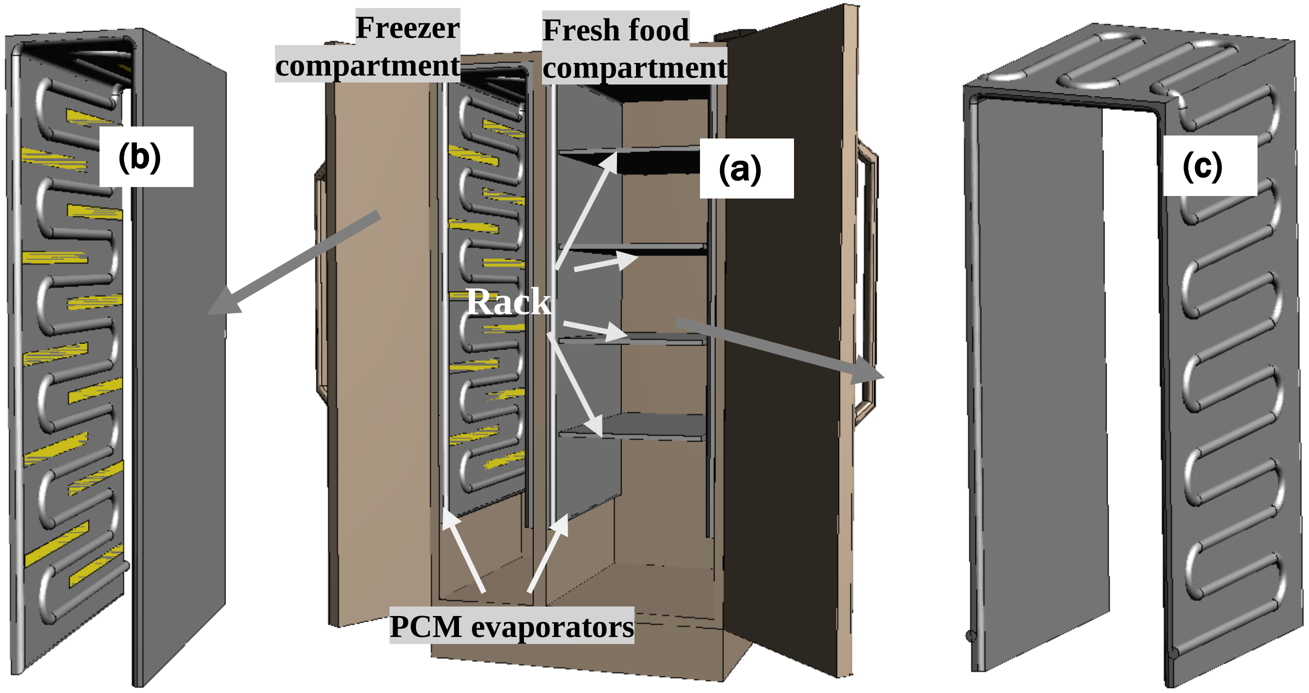
# Alignment and Impact

- Directly contributes to 4 EERE/BTO visions for net-zero emission of the US building stock by 2050:
  - Increasing building energy efficiency by saving up to 167 TBtu of primary energy consumption
  - Accelerating building electrification by reducing 7.2 million tons of $CO_2$ emissions in buildings
  - Transforming the grid edge at buildings by increasing building demand flexibility with shifting 0.7%–1.0% of the US daytime electricity demand to nighttime operations
  - Improve the resilience and economic sustainability of communities by minimizing risk of energy disruptions and natural disasters
- Indirectly contributes to other EERE/BTO visions:
  - Grid security and resilience, clean energy job opportunities, supporting small business
- Directly supports EERE/BTO’s DEI/EJ goals:
  - Nurtures an inclusive culture that fosters DOE/ORNL’s diversity, equity, and inclusion (DEI) vision
  - Prioritizes equity, affordability, and resilience by ensuring that decarbonization investments flow to disadvantaged communities (environmental justice [EJ])
  - Provides unique opportunities for underrepresented students from Southern University and A&M College to engage in R&D, creative activities, and public service

# Approach: General

- **Novel long-duration load demand management: 1 on/off cycle and 100% of peak load shed/shift/modulate**
  - More than 20% efficiency improvement
  - 30% reduction in greenhouse gases
  - 100% reduction in peak electricity use

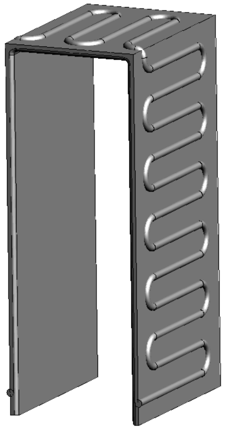
| 9 p.m. to 9 a.m. (nighttime) | 9 a.m. to 9 p.m. (daytime) |
|---|---|
| • Compressor on<br>• Keep the freezer and fresh compartments at appropriate temperature<br>• Store cooling energy in PCMs | • Compressor off<br>• PCM provides cooling energy to manage the temperature of the two compartments |




The high-efficiency refrigerator has advanced PCM evaporators with long-duration cold energy storage. (a) A representative household refrigerator with the proposed PCM evaporators; configuration of PCM evaporators placed in the (b) freezer compartment and (c) fresh food compartment.

# Approach: Integrate Advanced Materials, Low-GWP Refrigerant, Heat Exchangers, and Controls in the Novel Refrigerator with Cold Energy Storage

Advanced evaporators with PCM cold energy storage

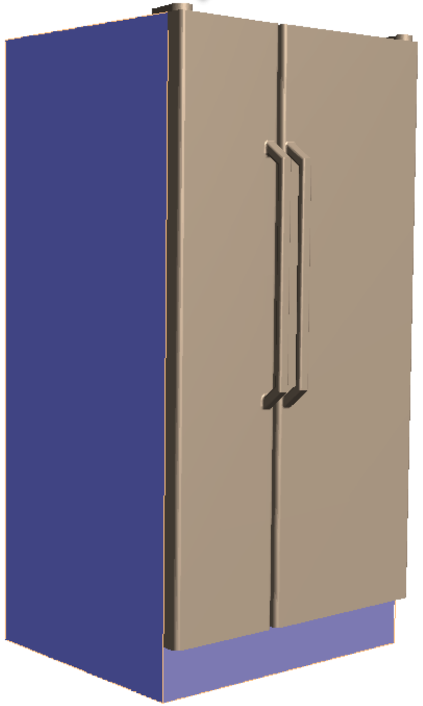


Advanced PCM materials



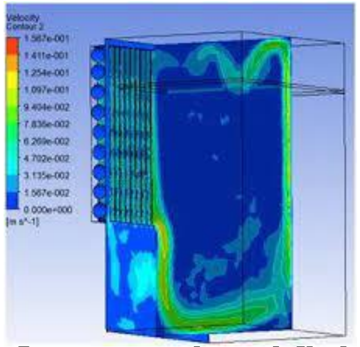
Low–global warming potential (GWP) refrigerant

Open-cell metal foam



Testing chamber lab

Refrigeration/defrosting control

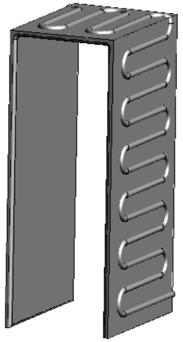


Computational fluid dynamics (CFD) simulation

# Approach: Innovation

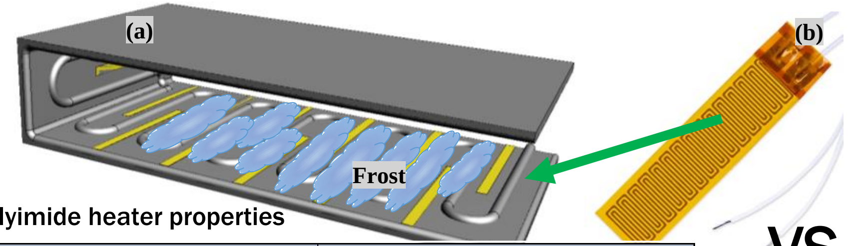
- **Advanced evaporators with PCM cold energy storage**
  - Two PCM evaporators: one in the freezer compartment and one in the fresh food compartment
  - Optimal PCMs used in each PCM evaporator

| | Heat storage capacity | Peak melting point | Liquid thermal conductivity | Liquid density |
|---|---|---|---|---|
| PCM A for freezer compartment | 240 J/g | −20°C | 0.55 W/mK | 1.06 g/mL |
| PCM B for fresh food compartment | 187 J/g | 4°C | 0.15 W/mK | 0.88 g/mL |



The PCMs are produced from renewable agricultural sources and have consistent, repeatable performance over thousands of thermal cycles.

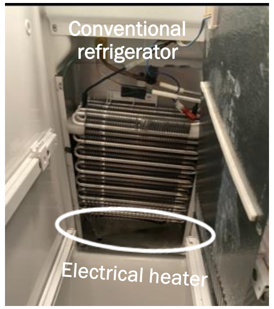
- **Direct-contact defrosting approach**
  - Polyimide heater array heats the surface of the PCM evaporator, achieving precise heat distribution for defrost
  - Temperature controller cycles the heater within a narrow temperature range (4°C–5°C), enabling energy savings



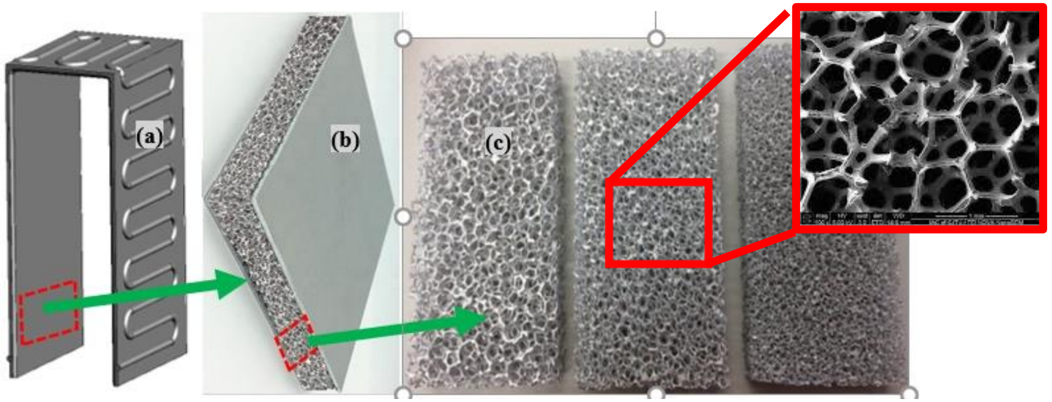

Polyimide heater properties

| Standard thickness | Maximum watt density |
|---|---|
| 0.18mm | 7.8 W/cm$^2$ |

VS.




- **PCM heat conduction enhancement using open-cell metal foam**
  - Improve bulk thermal conductivity by 10–30 times
  - Reduce the PCM freezing or melting time by 50%–60%




| Bulk thermal conductivity | Coefficient of thermal expansion | Specific surface area |
|---|---|---|
| 5.8 W/mK | 23.6 × 10$^{-6}$ m/mK | 45 m$^2$/m$^3$ |

- **Low-GWP alternative refrigerant**
  - Low-GWP alternative refrigerant (e.g., HFO-1234ze, HFO-1234yf)

| Refrigerant | GWP | GWP reduction | ASHRAE safety class | Flammability limits at 20°C | Flammability limits at 100°C | LCCP $CO_{2}e$ emissions reduction |
|---|---|---|---|---|---|---|
| R134a | 1,430 | - | A1 | Nonflammable | Nonflammable | Baseline |
| HFO-1234ze | 6 | >99% | AL2 | Nonflammable | 7.0–12.0 vol % | 8.1% [14] |
| HFO-1234yf | 4 | >99% | AL2 | Nonflammable | 6.2–12.3 vol % | 5.5% [14] |

# Approach: Commercialization and Stakeholder Engagement

- The project is at early stages with successful testing setup, preliminary simulations, and model development completed
- Cross-cutting team engagement to address barriers and maximize technical innovation
  - Multifunctional Equipment Integration Group, ORNL
  - Building Envelope Material Research Group, ORNL
  - Grid-Interactive Control Group, ORNL
  - Southern University and A&M College
- Working with industrial partners and ORNL OTT to achieve market success
  - Heat Transfer Technologies LLC
  - SubZero Group, Inc.
  - Rheem Manufacturing
  - Invention Disclosure ID#: 202205159, 2022
- Related ORNL refrigerator R&D activities
  - Next-generation Domestic Refrigerator with Unprecedented Performance Using Isobutane as Refrigerant (3.2.6.46 ORNL)
  - Dual-evaporator, Variable-capacity Refrigerator Coupled with Thermo-electric Freezer (3.2.6.47 ORNL)

# Project Progress: Choosing and Purchasing Baseline Refrigerators

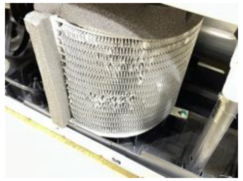
- **Three representative full-size refrigerators (All ENERGY STAR–Rated)**
  - 1 Samsung refrigerator (23 ft$^3$): 625 kWh/year
  - 2 Whirlpool refrigerators (25 ft$^3$): 574 kWh/year

**Samsung**


- Refrigerator capacity: 14.6 ft$^3$
- Freezer capacity: 8 ft$^3$
- Wi-Fi enabled: Control and monitor remotely
- In-door ice maker

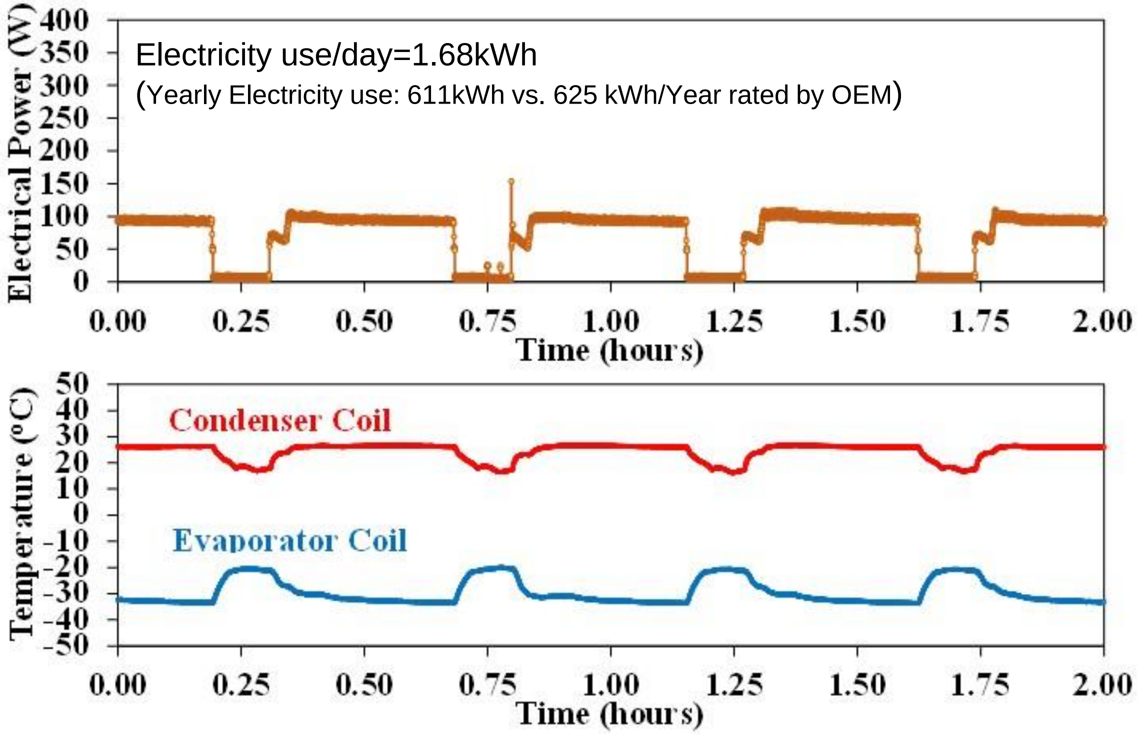
**Whirlpool**

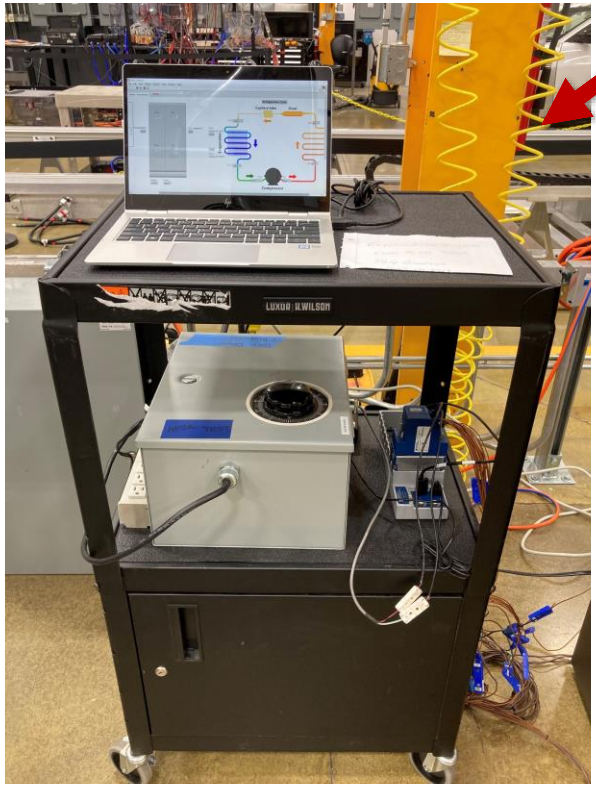

- Refrigerator capacity: 15.5 ft$^3$
- Freezer capacity: 9.6 ft$^3$
- Not Wi-Fi enabled
- No in-door ice maker



# Project Progress: Preliminary Baseline Setup and Testing

- **Baseline Samsung refrigerator testing at ORNL PICARD Lab**
  - PICARD: Platform for Integrated Controls of Appliances R&D
  - Data acquisition using a Campbell Scientific CR1000 data logger
    - Measurements: Power consumption, temperatures at ambient, fresh food compartment, frozen food compartment; Evaporator, condenser, compressor, and more

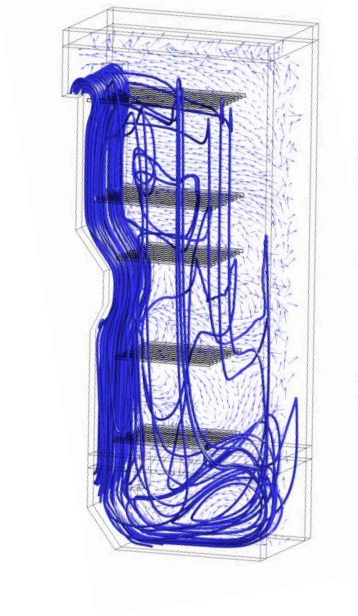


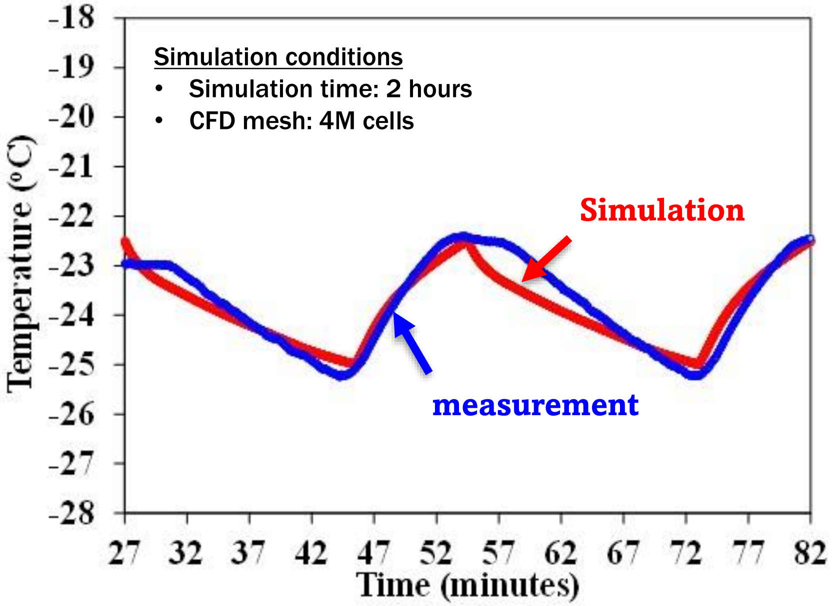



# Project Progress: High-fidelity CFD Modeling

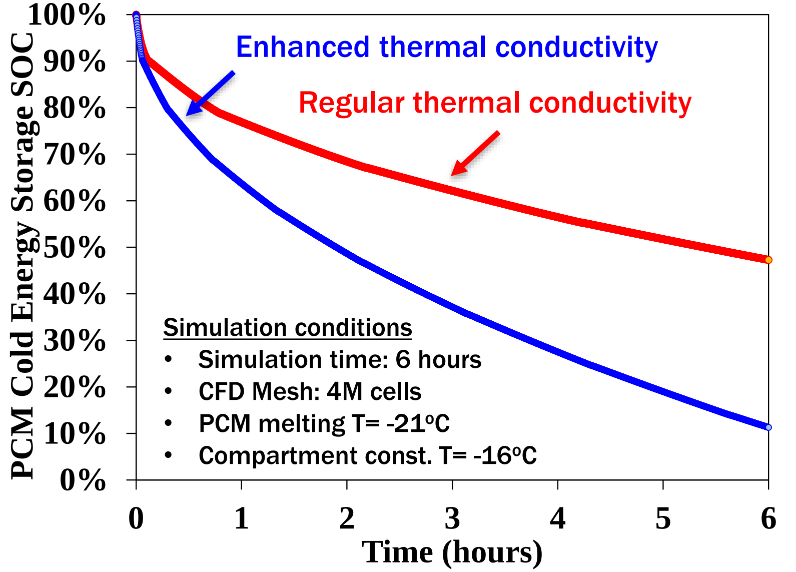
- **High-fidelity modeling on baseline refrigerator compartment**
  - CAD model with comprehensive compartment geometry measured using 3D scanning
  - Detailed CFD model using Ansys/Fluent & CAD model
- Conclusions:
  - Comprehensive air flow movement is explored
  - The simulations reasonably match the measurement

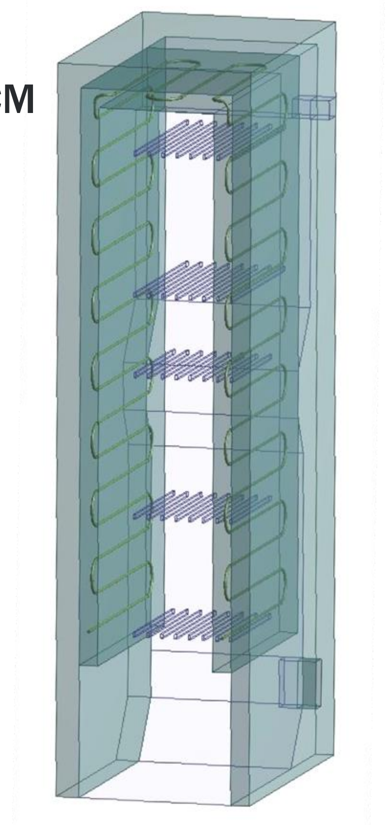
Air temperature in Samsung refrigerator frozen compartment





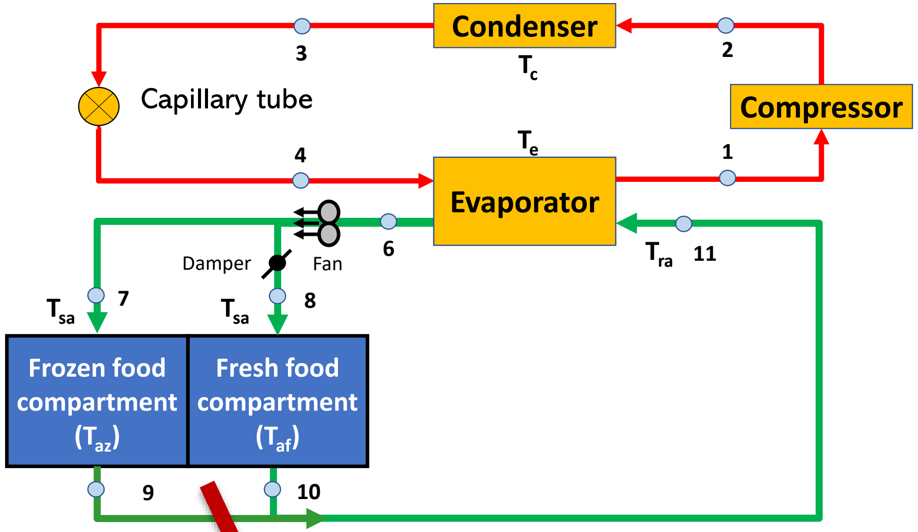

- **CFD modeling on PCM cold energy storage**
  - Adopted fluid solidification and melting model
  - Integrated the baseline compartment with PCM cold energy storage panel implanted with a coil
- Preliminary PCM simulation conclusions:
  - PCM model enables stable converge
  - Higher thermal conductivity reduce PCM freezing & melting time by >50%



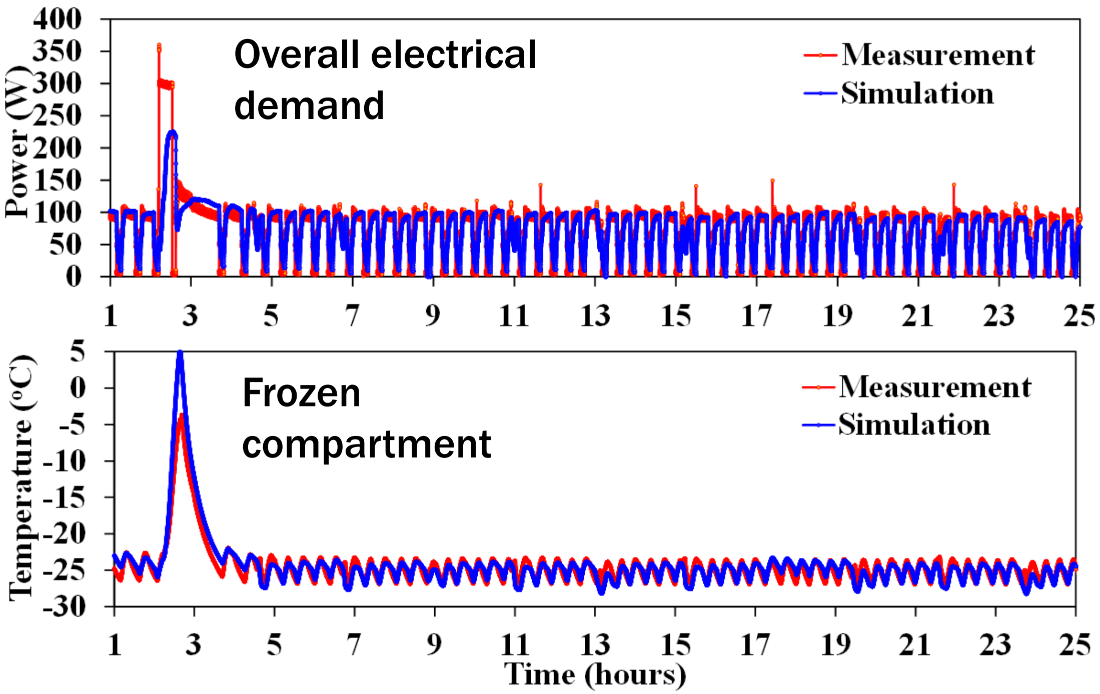



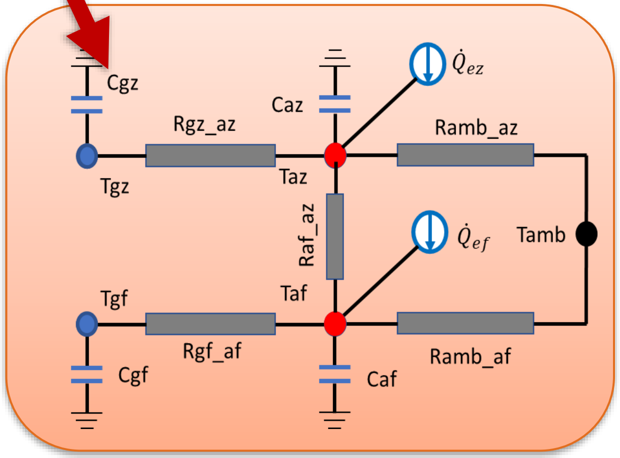
# Project Progress: Preliminary Refrigerator Dynamic Modeling

- **Preliminary lumped parameter dynamic model using resistance and capacitance (RC)**
  - The model addresses the compressor, condenser, evaporator, capillary tube, and fresh food and frozen compartments
  - Code: Python and dynamic model solver




## Example of the predicted results by dynamic model




**Simulation conditions**
- Refrigerator: Samsung
- Simulation: 60 hours
- Defrosting: Two events

**Conclusions**
- Preliminary dynamic model enables cyclic and simple defrosting operation
- The simulated results reasonably match the measurement

# Milestone Achievement and Future Work

- **FY 2023 project milestones**

| Milestone Name | Description | End Date | Status |
|---|---|---|---|
| ZG_Invention disclosure | An invention disclosure for the proposed refrigerator and component technologies | 12/31/2022 | Completed |
| ZG_CFD modeling | Preliminary 3D CFD model and user-defined function codes for advanced PCM evaporators enabling cold energy storage | 03/31/2023 | Completed |
| ZG_Parametric study | Simulate results of the performance of PCM evaporators on air flow and cold energy storage/release | 06/30/2023 | On Track |
| ZG_Transient modeling | Develop a transient refrigerator model for system and control strategy optimization | 09/30/2023 | On Track |

- **FY 2023 rest plan**
  - Improve 3D CFD model and user-defined function codes for advanced PCM evaporators
  - Refine and update the dynamic model accounting for frozen and fresh compartments
  - Refine baseline tests and study effect of remote Wi-Fi control on the baseline performance
  - Purchase appropriate PCM, metal forms, and other materials

# Thank you

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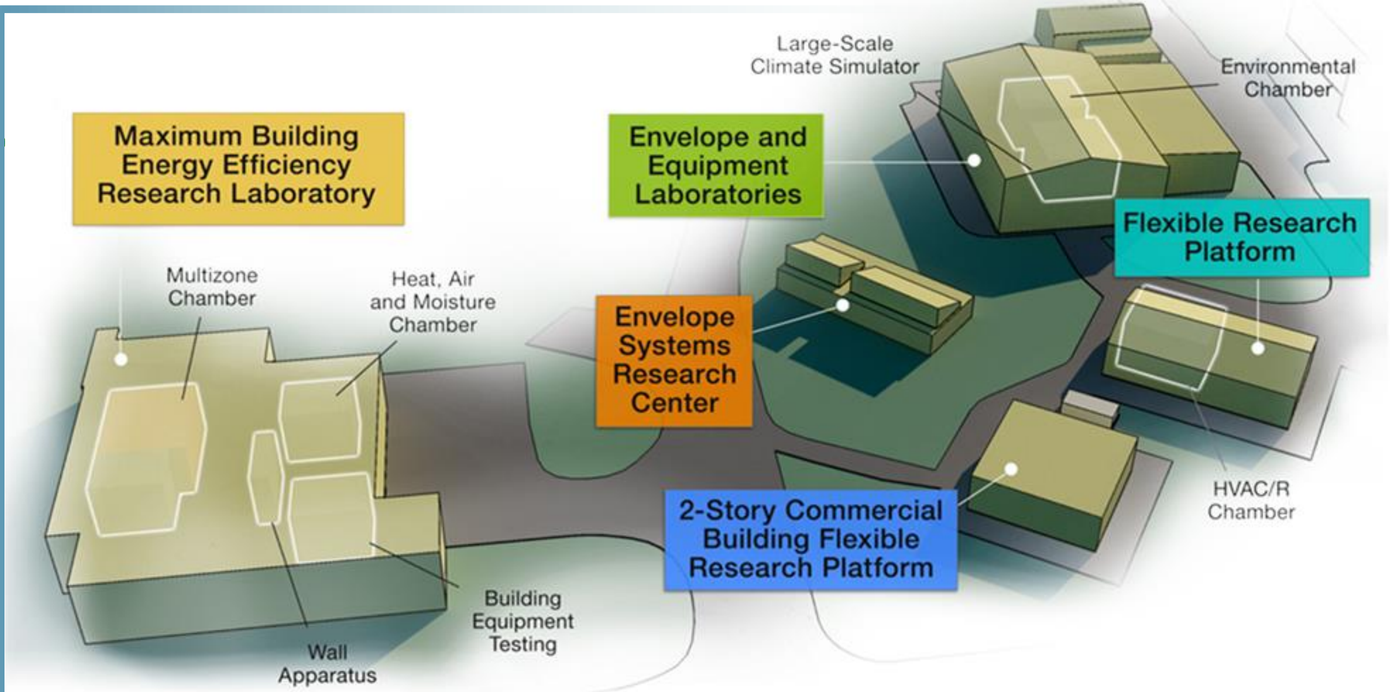



**ORNL's Building Technologies Research and Integration Center (BTRIC)** has supported DOE BTO since 1993. BTRIC comprises 60,000+ $ft^2$ of lab facilities conducting R&D to support the DOE mission to equitably transition the United States to a carbon pollution–free electricity sector by 2035 and carbon-free economy by 2050.

**Scientific and Economic Results**

236 publications in FY 2022
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

| | FY2023 | | | | FY2024 | | | | FY2025 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Planned budget | $350K | | | | $350K | | | | $350K | | | |
| Spent budget | $150K | | | | - | | | | - | | | |
| | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| **Past Work** | | | | | | | | | | | | |
| An invention disclosure for the proposed refrigerator technology | | | | | | | | | | | | |
| 3D CFD model for new refrigerator with PCM cold energy storage | | | | | | | | | | | | |
| **Current/Future Works** | | | | | | | | | | | | |
| Simulated results of new refrigerator with PCM cold energy storage | | | | | | | | | | | | |
| A transient model for new refrigerator control optimization | | | | | | | | | | | | |
| Tests of a 2022 commercially available refrigerator | | | | | | | | | | | | |
| Refinement of transient refrigerator & PCM cold energy storage models | | | | | | | | | | | | |
| Successful simulation design of the new refrigerator enabling 20% efficiency improvement | | | | | | | | | | | | |
| Optimize PCM cold energy storage systems using the developed models | | | | | | | | | | | | |
| Fabricate and assemble PCM cold energy storage systems | | | | | | | | | | | | |
| Integration of the PCM cold energy storage systems into the refrigerator | | | | | | | | | | | | |
| Develop direct-contact defrosting control technology | | | | | | | | | | | | |
| Test the new refrigerator with PCM cold energy storage | | | | | | | | | | | | |
| Final report and other closeout documents | | | | | | | | | | | | |

- Go/no-go decision points:
- Explanation for slipped milestones and slips in schedule

# Team

- **Oak Ridge National Laboratory**

  **Zhiming Gao, Kashif Nawaz, Philip Boudreaux, Anthony Gehl, Yanfei Li, and Mingkan Zhang**

  **Multifunctional Equipment Integration Group**

  - 40+ years of experience in building equipment research
  - Comprehensive testing facility for HVAC and refrigeration
  - CFD lab and PCM fabrication lab
  - Excellent fabrication services complex
  - Successful project experience—2 R&D 100 Awards (2021–2022)

- **Southern University and A&M College**

  **Patrick Mensah and Stephen Akwaboa**

- **Heat Transfer Technologies (industrial partner)**

  **Yoram Shabtay**

- PCM HX design
- Refrigerator optimization
- Tests

Zhiming Gao

- Metal form
- Heat transfer enhancement

Kashif Nawaz

- DAQ
- Refrigerator tests

Philip Boudreaux

- DAQ
- Instruments
- Control hardware

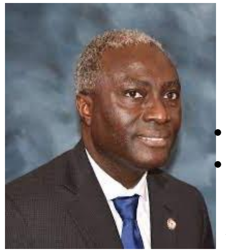
Tony Gehl

- Dynamic modeling
- Control strategy design

Yanfei Li

- CFD simulation
- CAD design

Mingkan Zhang



- Modeling
- Mentoring underserved students

Patrick Mensah

- Modeling
- Mentoring underserved students

Stephen Akwaboa

- HX fabrication

Yoram Shabtay

# Approach: Project Risks and Mitigation

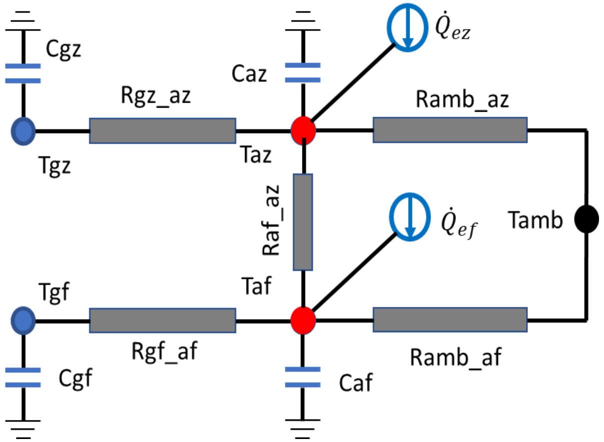
| Challenges/Risks | | Mitigation Strategies |
|---|---|---|
| **No. 1** | Inexperience in PCM evaporator component design | The project's measured data can refine CFD modeling of the PCM evaporator and transient refrigerator modeling of the entire system and the updated models can substantially reduce the uncertainties of the component design. |
| **No. 2** | Full-sized, U-shaped PCM evaporators with sufficient structural strength may be difficult and expensive to fabricate in the regular manufacturing technology | ORNL's Manufacturing Demonstration Facility will help the project produce 3D printed component efficiently at low cost. This strategy will provide affordable and convenient access to facilitate rapid PCM evaporator fabrication and refrigerator retrofitting. |
| **No. 3** | Direct-contact defrosting control strategy optimization may be extremely challenging and have uncertainties | The developed transient refrigerator model will be used to optimize the defrosting control strategy. CFD models will also be used to numerically evaluate the surface temperature distribution under various defrosting conditions to reduce defrosting control uncertainties. |

**The team's exceptional knowledge and experience on refrigeration, PCM and metal foam materials, heat transfer enhancement, CFD, and HVAC energy management will manage the risks successfully with the appropriate mitigation strategies.**

# Acronym Definitions and Nomenclature

| | |
|---|---|
| $C_{af}$ | Heat capacity of air in the fresh compartment |
| $C_{az}$ | Heat capacity of air in the frozen compartment |
| $C_{gf}$ | Heat capacity of fresh food |
| $C_{gz}$ | Heat capacity of frozen food |
| $\dot{Q}_{ef}$ | The cooling rate from the evaporator to the fresh compartment |
| $\dot{Q}_{ez}$ | The cooling rate from the evaporator to the frozen compartment |
| $R_{amb\_az}$ | Heat resistance between the frozen compartment air and ambient |
| $R_{amb\_af}$ | Heat resistance between the fresh compartment air and ambient |
| $R_{af\_az}$ | Air heat resistance between the fresh and frozen compartments |
| $R_{gz\_az}$ | Heat resistance between frozen food and air in the frozen compartment |
| $R_{gf\_af}$ | Heat resistance between fresh food and air in the fresh compartment |
| $T_{amb}$ | Ambient temperature |
| $T_{af}$ | Fresh compartment air temperature |
| $T_{az}$ | Frozen compartment air temperature |
| $T_{gf}$ | Fresh food (goods) temperature |
| $T_{gz}$ | Frozen food (goods) temperature |
| $T_{ra}$ | Returned air temperature |
| $T_{sa}$ | Supply air temperature |

| | |
|---|---|
| PCM | Phase Change Material |
| BTO | Building Technologies Office |
| CAD | Computer-Aided Design |
| CFD | Computational fluid dynamics |
| DEI | Diversity, Equity, and Inclusion |
| EERE | Energy Efficiency and Renewable Energy |
| EJ | Environmental Justice |
| GWP | Global warming potential |
| ORNL | Oak Ridge National Laboratory |
| OTT | Office of Technology Transitions |
| SOC | State of Charge |



# EERE/BTO Goals

## The nation's ambitious climate mitigation goals

**Greenhouse gas emissions reductions**

50-52% reduction by 2030 vs. 2005 levels

Net-zero emissions economy by 2050

**Power system decarbonization**

100% carbon pollution-free electricity by 2035

**Energy justice**

40% of benefits from federal climate and clean energy investments flow to disadvantaged communities

## EERE/BTO's vision for a net-zero US building sector by 2050