Analysis of Frost Formation and Novel Defrost Techniques for Commercial Refrigeration Applications (CRADA Hillphoenix/Dover Food Retail)

Oak Ridge National Laboratory
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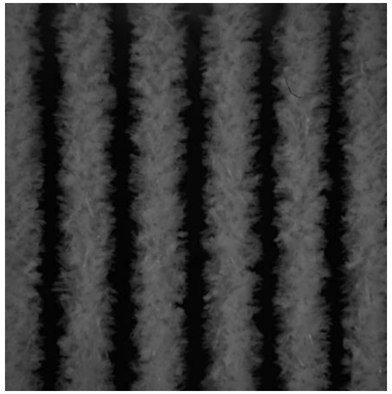
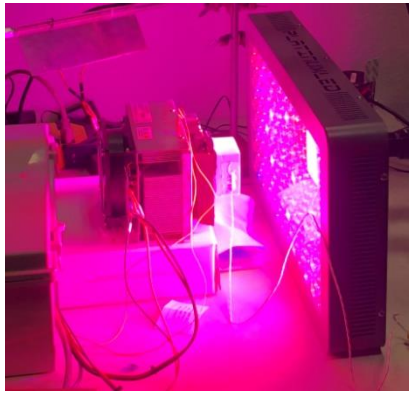
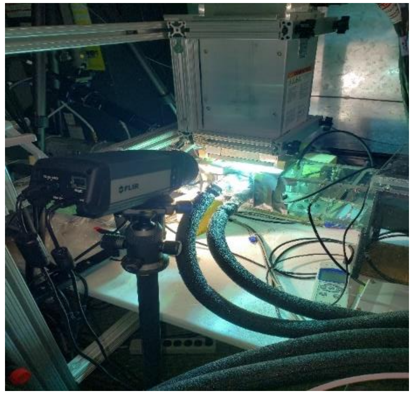
WBS # 3.2.2.38



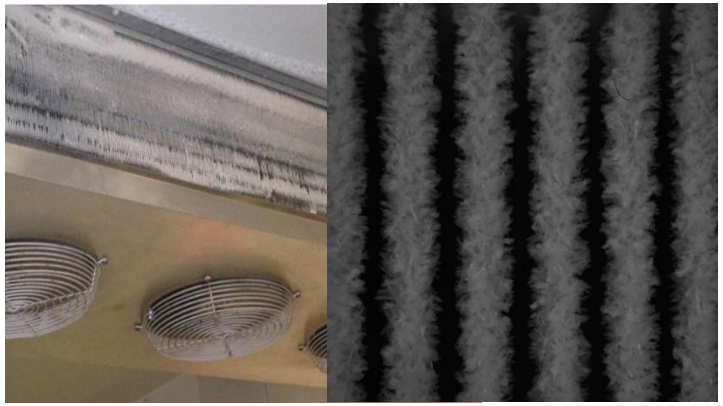




Project Summary

Objective and outcome

Development of an understanding of frost formation on heat exchanger surfaces and establishment of framework to (i) delay frost formation and (ii) defrost using passive and active technique including radiations and vibrations. The team will demonstrate scalable and cost-effective techniques for defrost.



Team and Partners

Oak Ridge National Lab

Kashif Nawaz, Brian Fricke, Ahmed Elatar, Tony Gehl, Pengtao Wang

Johnson Controls Inc.

Roy Crawford

Hillphoenix

Scott Martin

Status

Performance Period: Oct 2021 –Dec 2024

DOE budget: $200K/year, Cost Share: $75K/year

Milestone 1: Evaluation of frost formation on surfaces

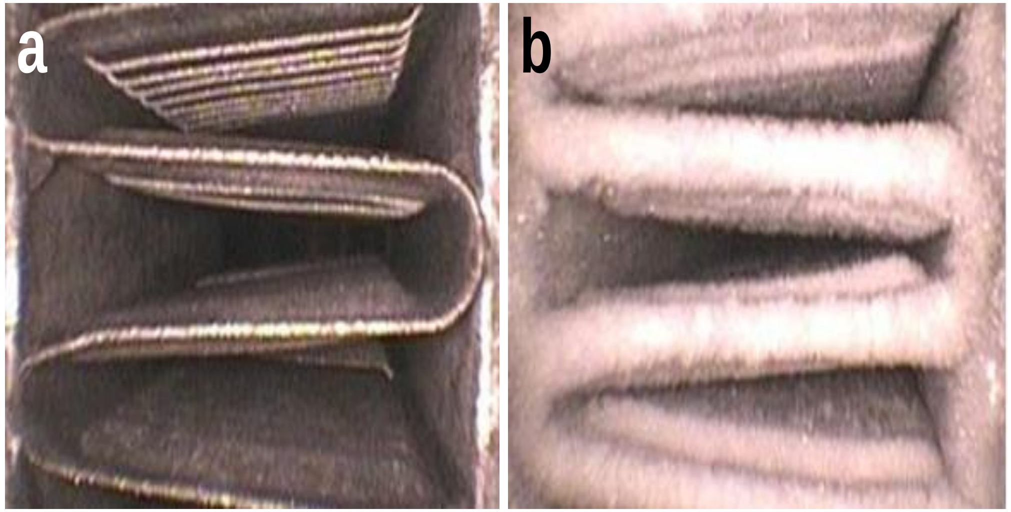
Milestone 2: Analysis of active defrost (Radiation)

Milestone 3: Analysis of active defrost (Vibration)

Milestone 4: Filed study of passive/active defrosting.

Problem

- Frost formation presents a challenge for refrigerators/freezers and cold climate heat pumps in commercial and residential applications.
- Frost buildup increases pressure drop (fan power) and decreases heat transfer, due to the reduced airflow area and thermal conductivity when compared to the base heat exchanger material.
- The efficiency degradation, due to frost growth and the energy required to defrost, can account for 15-25% of commercial refrigerators' annual electric energy consumption.
- The development of effective frost mitigation and defrost technology can lead to more than 200TBtu/year of U.S. primary energy savings, and carbon reduction of 12 MMT CO_2/year.



Microchannel sample under frosting conditions. Images (a) and (b) represent times of 0 and 8 minutes, respectively, after starting the test. T_{surface} = -8°C and T_{air} = 1.7/0.6°C $T_{\mathrm{db}}/T_{\mathrm{wb}}$.

Frost/ice buildup in the outdoor coils of cold climate heat pumps in Alaska.

Approach

Frost growth

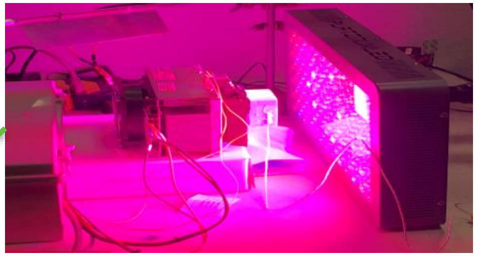
Air conditions (frost growth rate, defrost energy)

Surface morphology (frost density, adhesion to surface, condensate drainage)

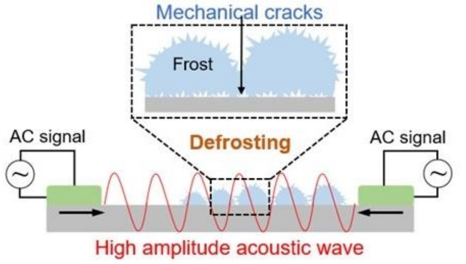
Fin geometry (frost growth rate, drainage behavior)

TRL 2→ TRL 5

Novel defrost process



Radiation, UV light



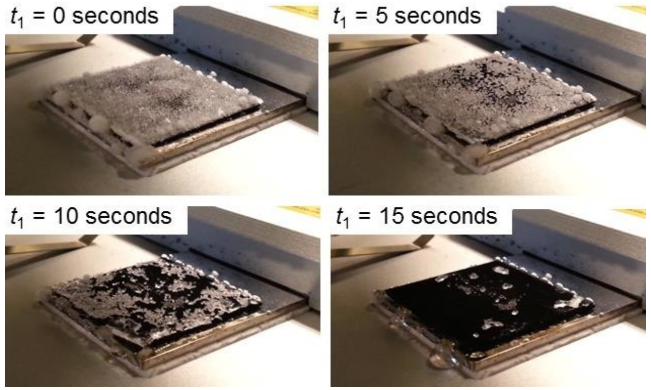
Vibration, ultrasonic

*Evaluate the potential of **radiation-based** and **vibration-based** defrost processes for deployment in commercial refrigeration and cold climate heat pumps.*

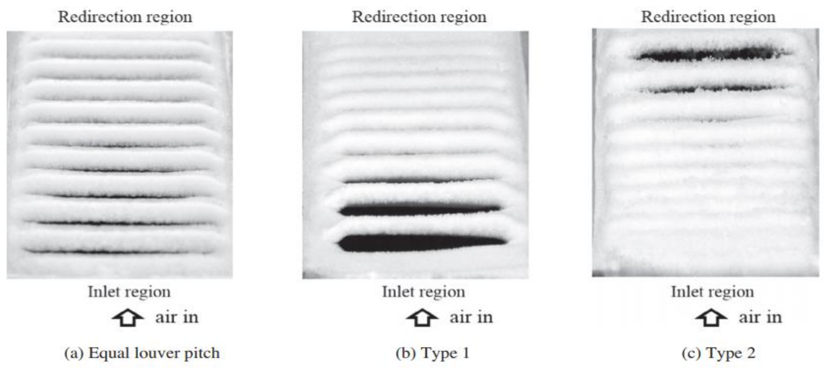
- Radiation-based and vibration-based defrost can provide novel approaches with significantly lower energy requirements; the process can be accomplished continuously or intermittently.
- To evaluate the impact, it is important to
  I. Characterize the frost growth on various surfaces (density, thermal conductivity, thickness, etc.)
  II. Analyze various radiation and/or vibration sources for appropriateness for the proposed applications (interaction with air, bare surface, and surface with frost)

Progress- Overview of Existing Technology

Frost Mitigation Techniques	
Upstream air treatment	1-Reducing inlet air humidity 2-Preheating inlet air 3-Increasing inlet airflow rate
Heat exchanger modifications	1-Adjusting fin and tube geometry 2-Fin type selection 3-Coating treatment on fin surface
System modifications	1-Vapor-injection technique 2-Two-stage technique 3-Adding outside heating source 4-Adjusting refrigerant distribution



Oil-infused SLIPS can assist the condensate removal after defrost



Variable louver angle/pitch fins can mitigate the adverse effect of frost growth better than those with uniform geometry

Progress- Overview of Existing Technology

Method	System complexity	System stability	Frost mitigation	Scalability	Capital cost	Operational cost
Preheating the air stream	High	High	High	Moderate	High	High
Increasing air flow rate	High	High	Moderate	Moderate	High	High
Adjusting fin geometry	Low	High	Moderate	High	Moderate	Low
Fin type selection	Low	High	Low	High	Moderate	Low
Surface morphology for fin surface	Moderate	High	Moderate	Moderate	Moderate	Low
Vapor injection technique	High	Low	Moderate	Low	High	Moderate
Two stage technique	High	Low	Moderate	Low	High	Moderate
Adding outside heat source	Moderate	Moderate	Moderate	Moderate	Moderate	High
Adjusting refrigerant distribution	Low	High	Moderate	Moderate	High	Low

Most of the existing frost mitigation methods have limited implications due to scalability, durability, and cost issues.

Progress- Overview of Existing Technology

Defrost techniques	
Defrost by cycle interruption	1-Compressor shutdown 2-Electric heating 3-Hot gas bypass 4-Reverse cycle
External source based defrost	1-Hot water spraying defrost 2-Air jet defrost

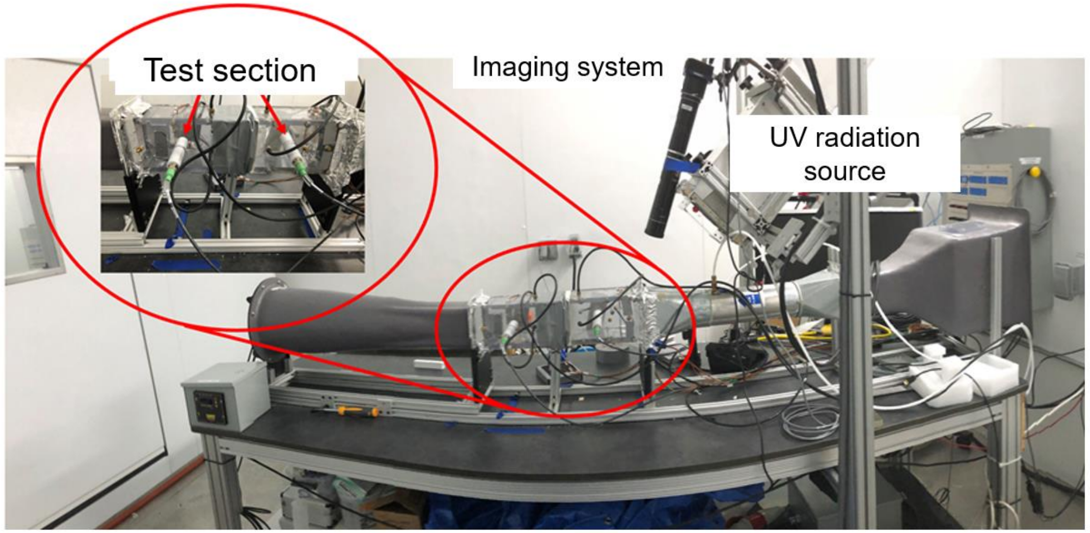
Method	Compressor	Thermal source	System complexity	System stability	Defrost effect	Scalability	Efficiency degradation
Compressor shutdown	OFF	Ambient air	Low	High	Low	High	Moderate
Electric heater	OFF	Electric power	High	High	High	Moderate	High
Hot gas bypass	ON	Electric power	Moderate	Moderate	Moderate	Low	Moderate
Reverse cycle	ON	Electric power	High	Low	High	Low	High

Cycle interruption defrost is the most deployed strategy to remove frost from the heat exchanger surface.

Progress- Experimental System

Experimental System

An open loop wind tunnel placed in a controlled environmental chamber for forced air convection

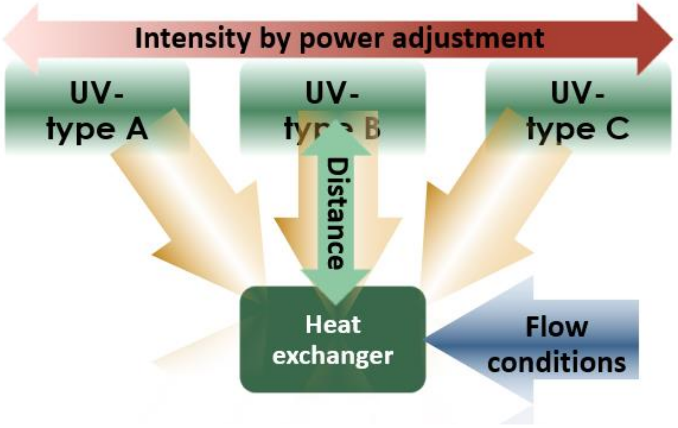


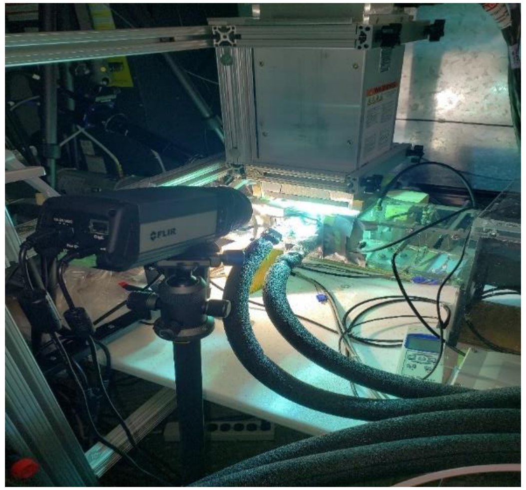
Experiments classification

- Frost growth process
- Natural/forced convection defrost process
- Radiation and/or vibration-assisted defrosting process w/o natural/forced convection

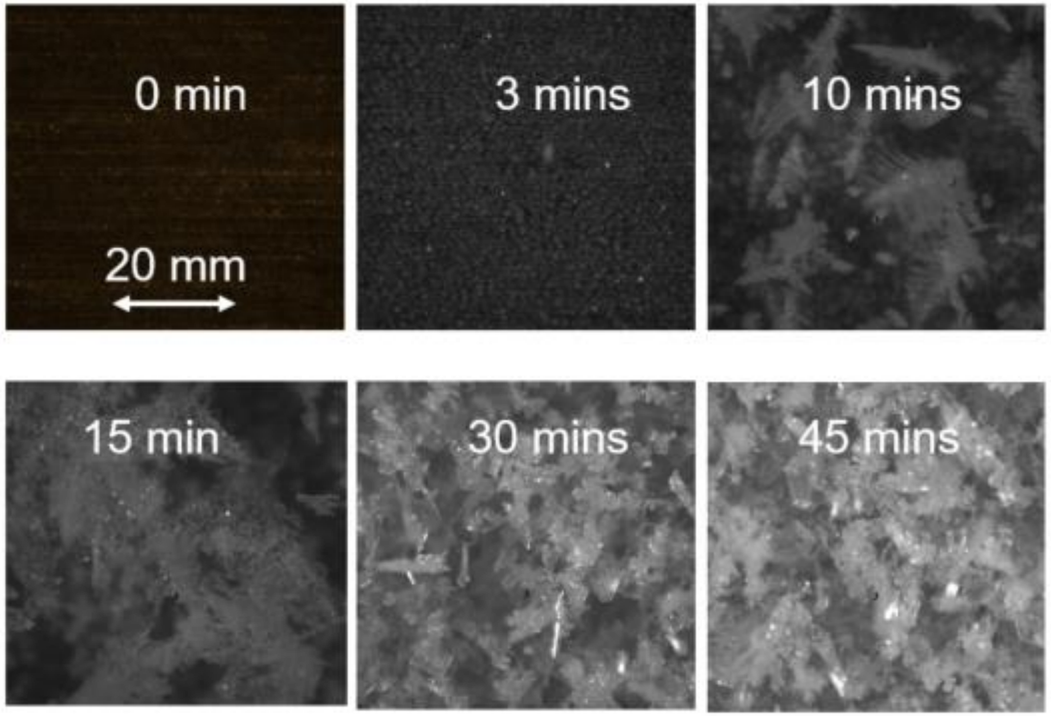
Parameters of interest

- Frost density, thermophysical properties (conductivity, specific heat, latent heat)
- Radiation properties (absorptivity, emissivity)
- Vibration properties (amplitude, frequency)
- Energy and time required for defrost process

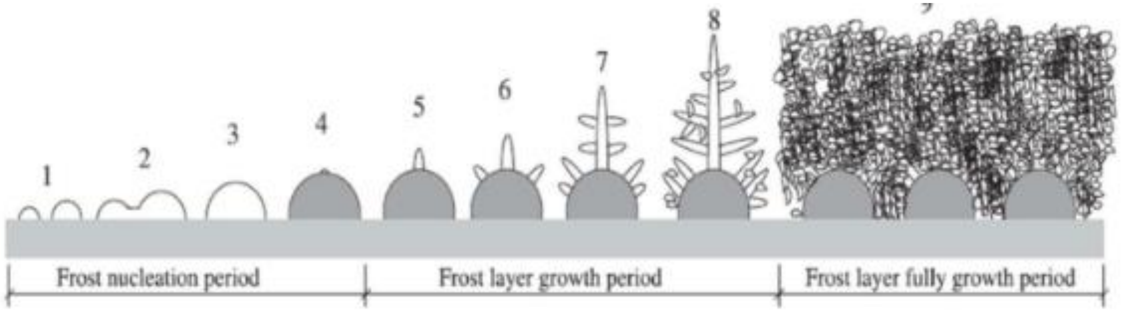


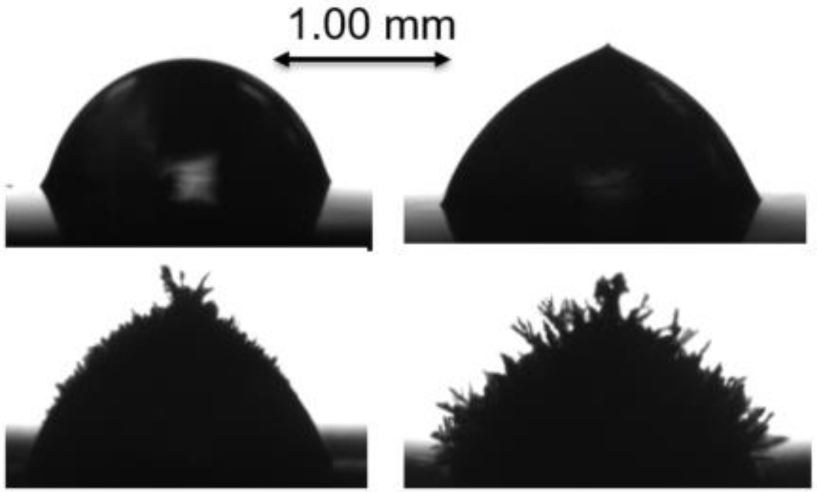


Progress- Analysis of Frost Growth Process

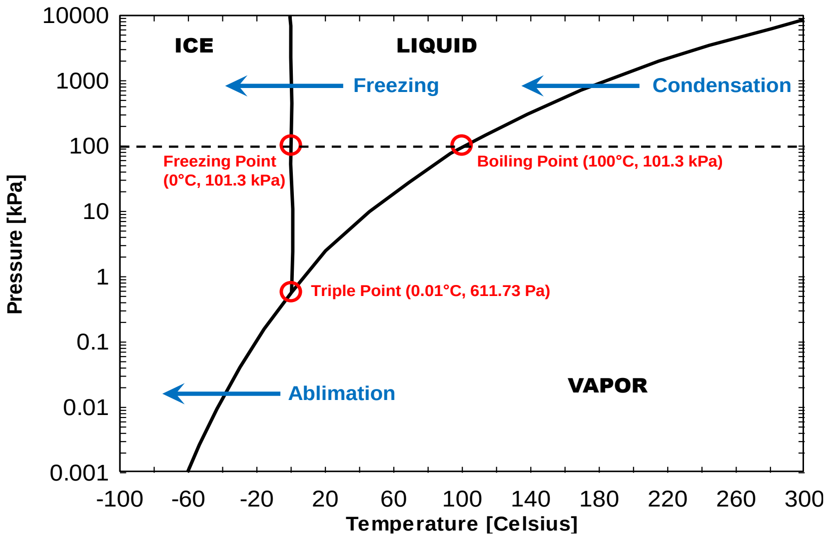


Natural convection: DB 40 ºF (4.4 ℃), WB 37 ºF (2.8 ℃),
Baseplate temperature: 12 ºF (-11.1 ℃)



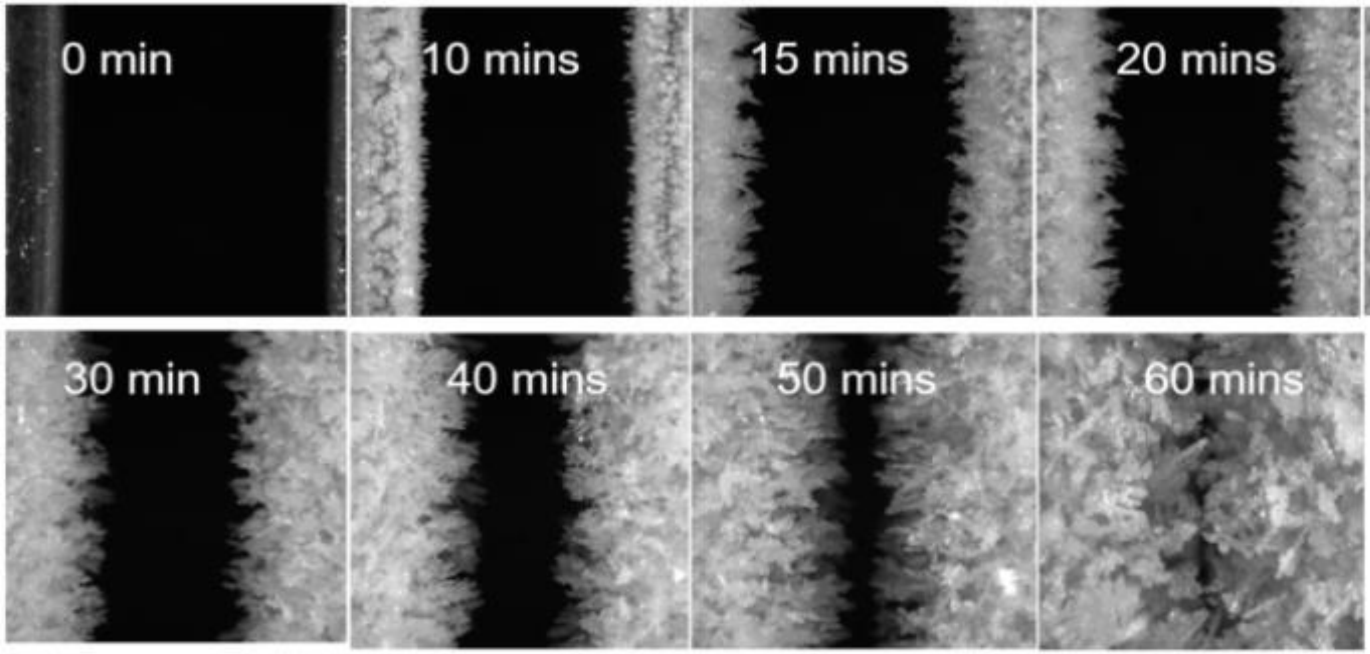


Frost growth process on a cold plate



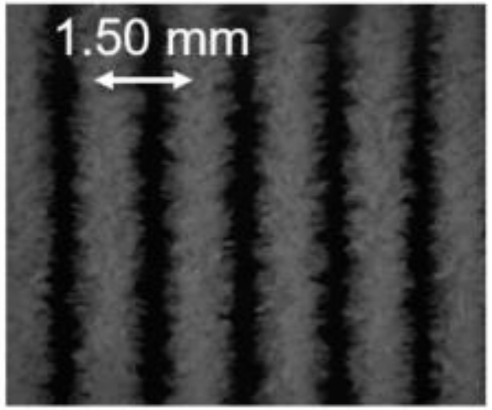
Phase change processes

Progress- Analysis of Frost Growth Process

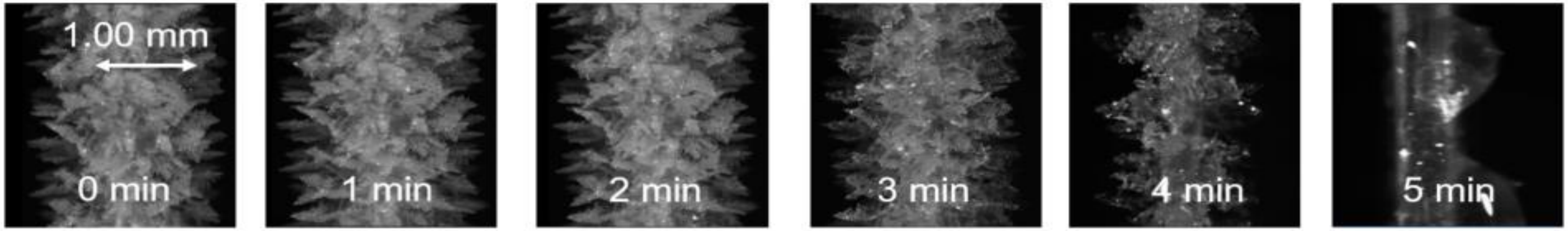


Frost growth on extended surfaces

Natural convection: DB 40 ºF (4.4 ℃), WB 37 ºF (2.8 ℃),
Baseplate temperature: 12 ºF (-11.1 ℃)



Extended surfaces

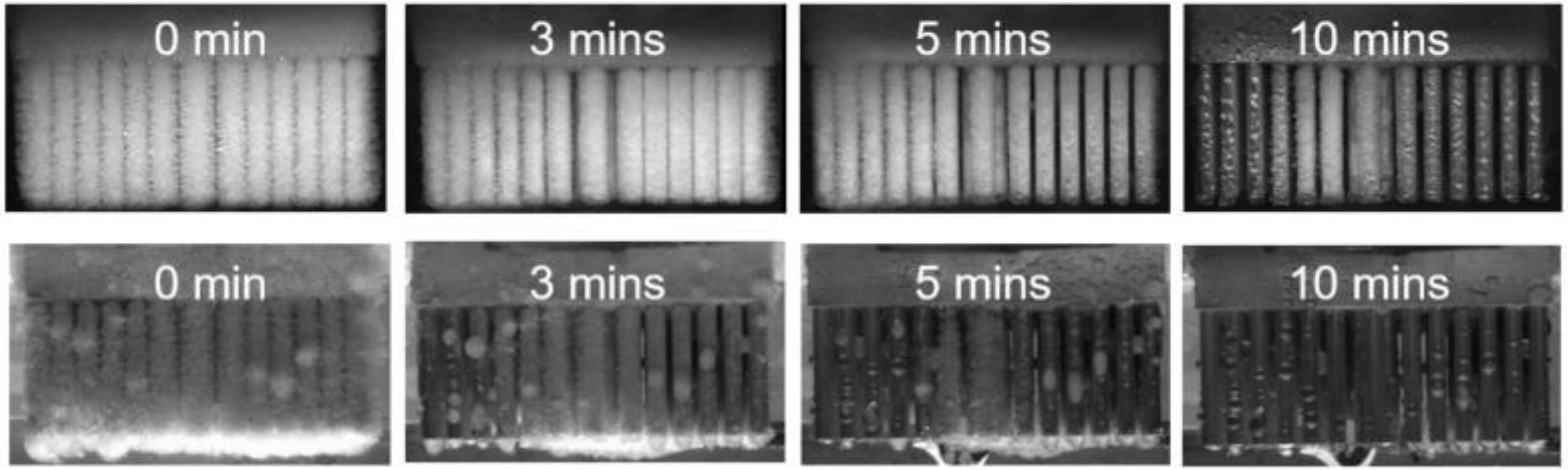


Defrost on extended surfaces

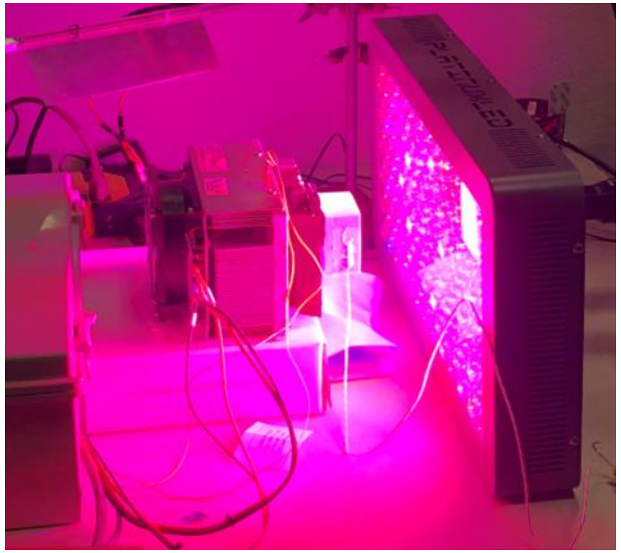
Progress- Analysis of Radiation Defrost

Forced convection without UV

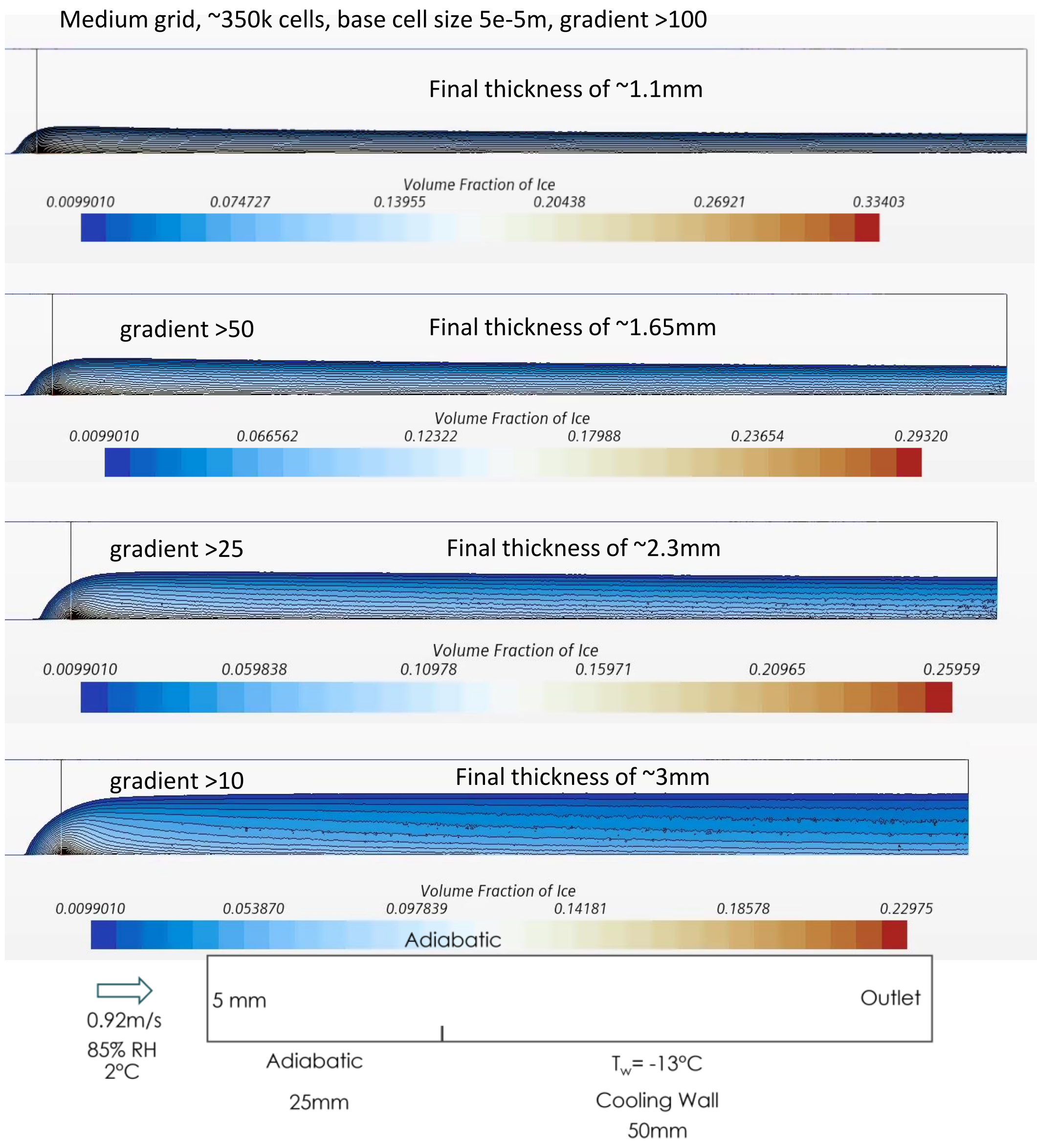
Forced convection with UV (200 W/m^2)

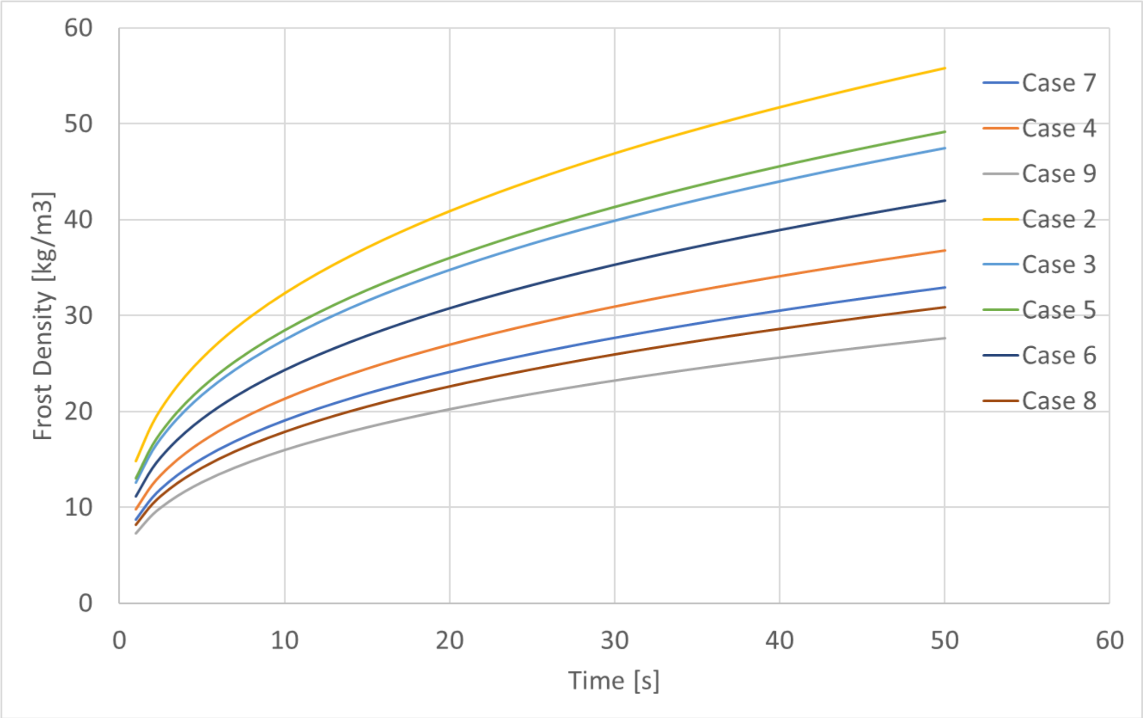


Indoor conditions: 42°F/4.4℃ (BD), 37 °F/2.8℃ (WB)
Baseplate temperature: 12 °F/-11.1℃
Face velocity: 1.0 m/s
Operation time (frost growth): 1.5 hrs
Defrost time: 10 minutes (Forced convection only)
Defrost time: 6 minutes (Forced convection and UV radiations)
Radiation flux: 200 W/m^2



Progress- Numerical Analysis of Frost Growth





Predicted frost density under different operating conditions

Work in Progress and Future Tasks

Work in progress

1- Assess various types of radiation for their potential in defrosting.

2- Comprehensive study of the characteristics of radiation (wavelength, view factors, intensity, etc.) on the characteristics of frost (density, thermal conductivity, thickness, etc.) w/wo natural/forced convection.

Future tasks

1- Preliminary assessment of vibration-based defrost.

2- Development of performance models for defrosting process based on the previous experimental results.

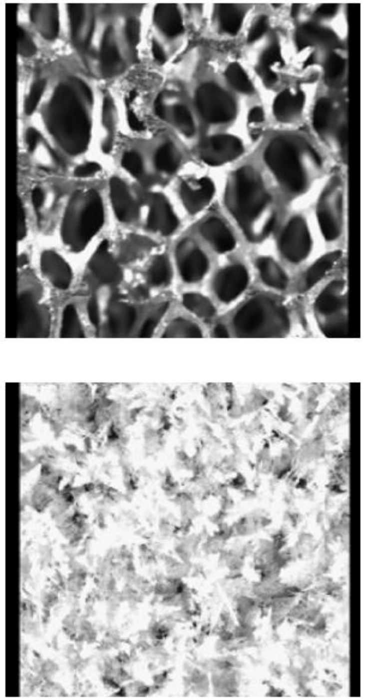
3- Construction and installation of a radiation-based and/or vibration-based defrost system for field performance evaluation.

4- Conducting a detailed 12-month field study to understand the performance of the developed technology under real operating conditions of commercial refrigerators.

5- Development of a commercialization plan based on lab-scale and field-level assessments.

Project Progress

Tasks	Details
Market assessment for existing frost mitigation/defrost technologies	A critical review of the state-of-the-art frost mitigation/defrost technologies will be completed,
Development of framework to characterize frost growth on various surface	The frost growth process on various heat exchanger surfaces can be a function of various parameters including ambient air temperature and relative humidity, surface temperature, fin density orientation, etc.
Preliminary assessment of radiation-based defrost	Under this task, a comprehensive study will be conducted to relate the characteristics of radiation (wavelength, view factor, intensity, etc.)
Preliminary assessment of vibration-based defrost	This task will be dedicated to a detailed analysis of a defrost process where surfaces are subjected to vibrations to accelerate defrost and/or detachment of the frost layer from the surface.
Equipment construction and installation for field study	At the conclusion of Task 5, through appropriate model developed based on an assessment of the proposed technology and using the experimental results, a defrost system will be developed and installed in a commercial refrigerator display case.
Field study, risk mitigation	Two to three different product lines will be selected for such analysis.
Development of commercialization plan	The project team, led by the participant, will review the overall development of the proposed technologies under proposed workplan



Frost growth and defrost analysis on metal foam

A frostless operation with continuous exposure of UV radiation has been demonstrated!!

Stakeholder Engagement

- Development of the technology
  - Selection and characterization of desiccants
  - Coating process on substrates materials
  - Process controls
  - Independent latent load management
- Meetings with experts at the technical platform
  - ASHRAE (TC 8.5, TC 1.1)
  - Purdue
- More than seven **journal articles** published
- One non-provisional patent application
- More than twelve conference papers and presentations!!
- New IEA Annex and workshop “Comfort and Climate Box solutions for warm and humid climates”
- OEM engagement

Thank you

Oak Ridge National Laboratory

Kashif Nawaz, Section Head of Building Technologies Research; Group Leader of Multifunctional Equipment

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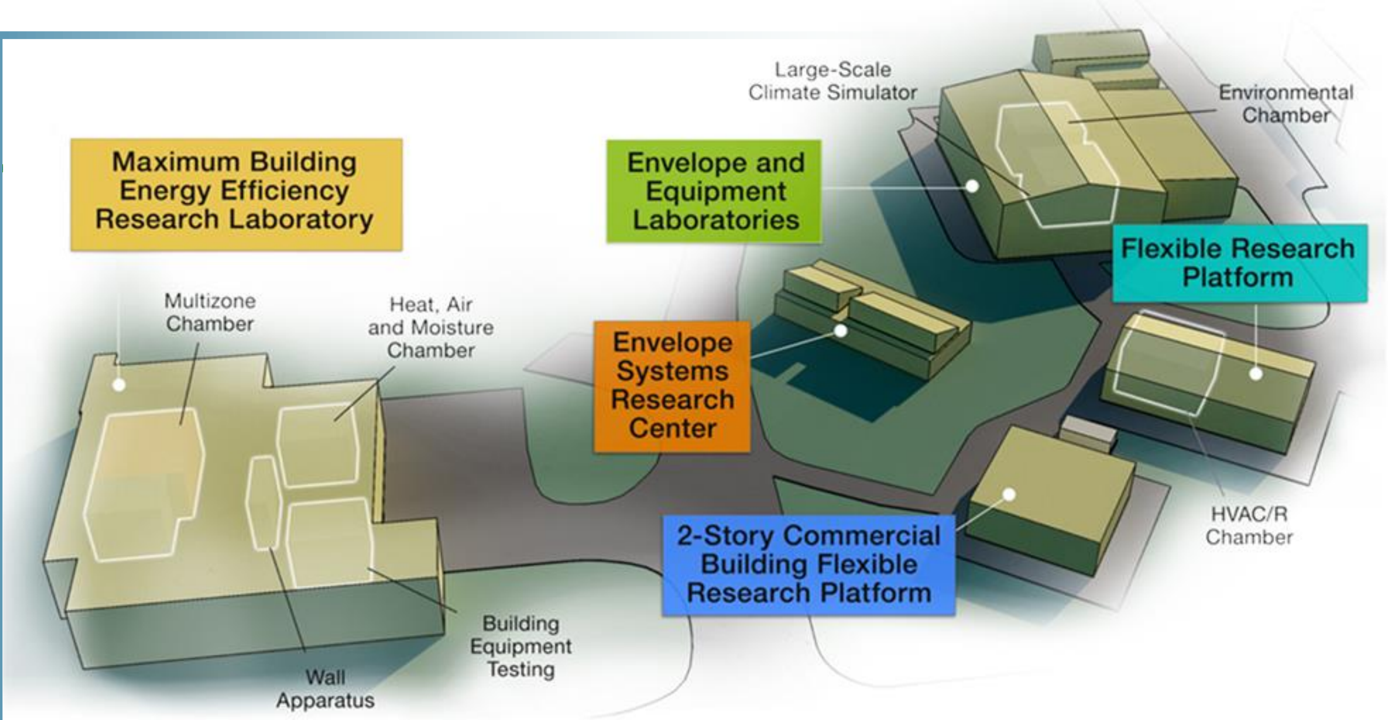

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Scientific and Economic Results

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

		2022				2023				2024			
Planned Budget		275k				275k				275k			
Spent Budget		275k				210k				-			
Tasks	Task Description	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1	Market assessment for existing frost mitigation/defrost technologies												
Task 2	Development of framework to characterize frost growth												
Task 3	Preliminary assessment of radiation-based defrost												
Task 4	Preliminary assessment of vibration-based defrost												
Task 5	Development of performance models for defrost process												
Task 6	Equipment construction and installation for field study												
Task 7	Field study and risk mitigation												
Task 8	Development of commercialization plan												
Task 9	Completion of CRADA final report												

Milestones

1. Evaluation of frost formation on surfaces. (Due date: Q4)
2. Analysis of active defrost using radiation. (Due date: Q7)
3. Analysis of active defrost using vibration. (Due date: Q10)
4. Filed study and demonstration of passive/active defrosting. (Due date: Q11)

Team

National Laboratory

Industrial Partners

Academic Partners

Contribution to EERE/BTO goals

Novel defrost technologies

- ≤30% degradation in the capacity of the HX
- ≥30% reduction in energy required for defrosting

Big impacts on the US building sector

- Energy Saving, 200TBtu/year
- GHG emissions reductions, 12 million MT CO_2/year

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 U.S. building sector by 2050