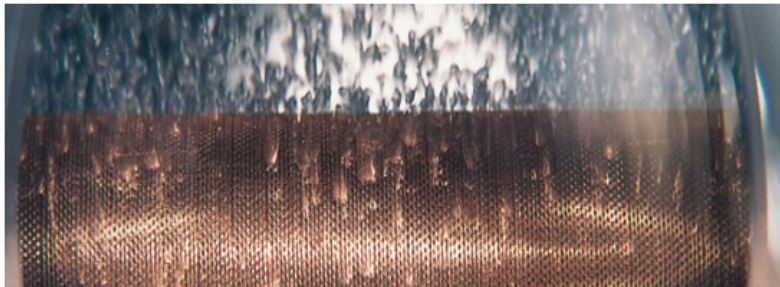
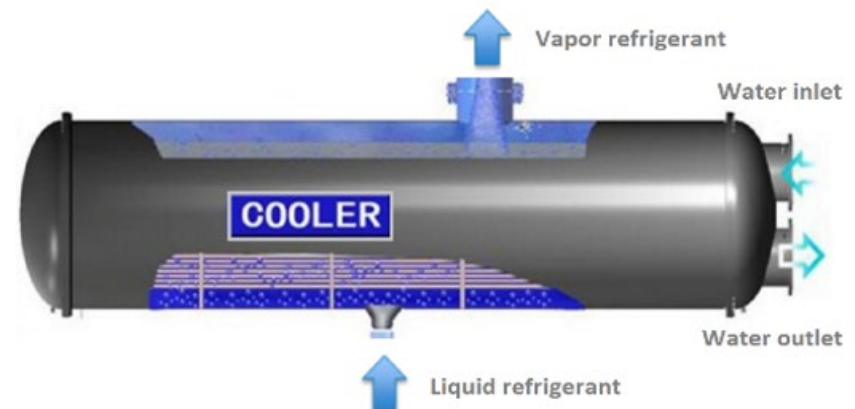


# Novel Compact Flooded Evaporators for Commercial Refrigeration



Oak Ridge National Laboratory  
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# Project Summary

## Timeline:

Start date: October 2019

Planned end date: October 2022

## Key Milestones

1. Pool boiling of refrigerants on surfaces, single tube performance, October 2019
2. Performance of an enhanced tube bundle, enhanced flooded evaporator, October 2020

## Budget:

	DOE funds	Cost share
FY20	200K	50K
FY21	150K	50K
FY22	250K	150K

**Total system charge reduction is an important factor (safety and cost aspects), the proposed design will assist with easy substitution of emerging refrigerants (A2L and A3) with acceptable GWP!!**

## Key Partners:



## Project Outcome:

- The project has the potential to revolutionize the commercial refrigeration and cooling industry
- The highly compact design not only will improve overall system performance by reducing power consumption (pumping power) but also will lead to a substantial reduction in total refrigerant charge requirements
- Since a total system charge reduction is an important factor (safety and cost aspects), the proposed design will assist with easy substitution of emerging refrigerants

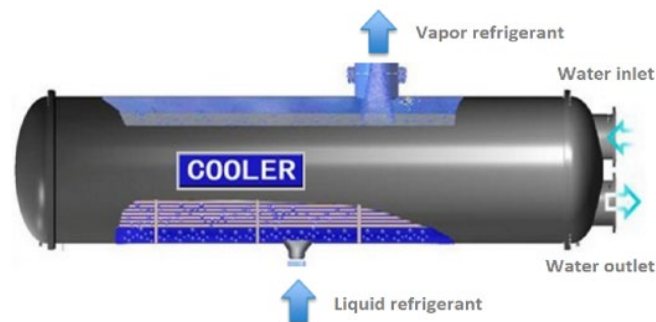
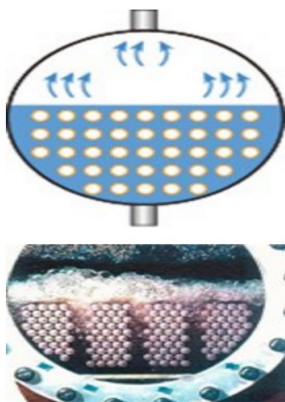
# Project Team

- **Oak Ridge National Laboratory**
  - Kashif Nawaz (R&D staff)
  - Brian Fricke (R&D staff)
  - Mingkan Zhang (R&D staff)
  - ChengMin Yang (Postdoctoral associate)
  - Saad Jajja (Postdoctoral associate)
  - Tim Laclair (R&D staff)
- **Isotherm Inc.**
  - Zahid Ayub (Director R&D)
- **Johnson Controls Inc.**
  - Jay Kohler (R&D Director)
- **Carrier Corporation**
  - Satyam Badapudi (Product development manager)
- **Emerson Technologies**
  - Robert Comparin (VP Research)
- **University of Illinois, Oregon State University**
  - Nenad Miljkovic, Tabeel Jacob, James Carpenter



# Challenge

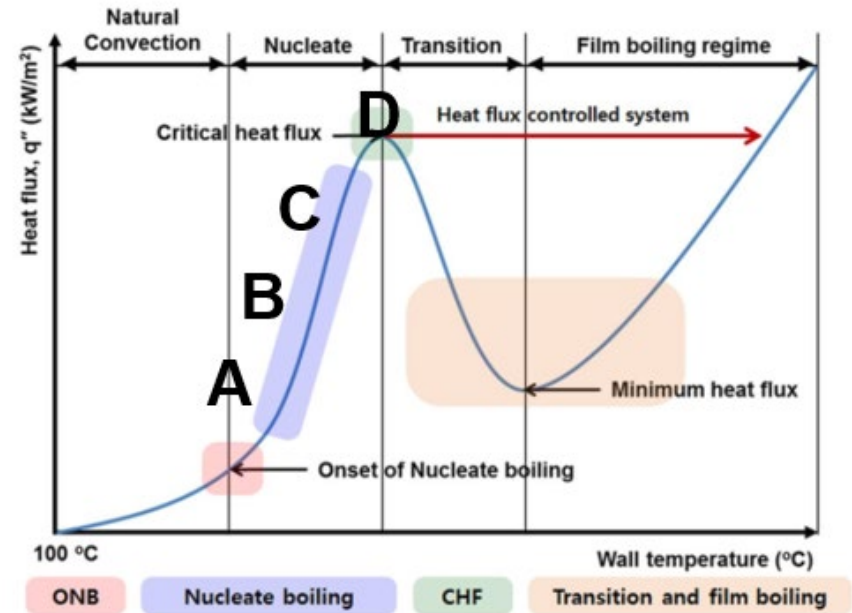
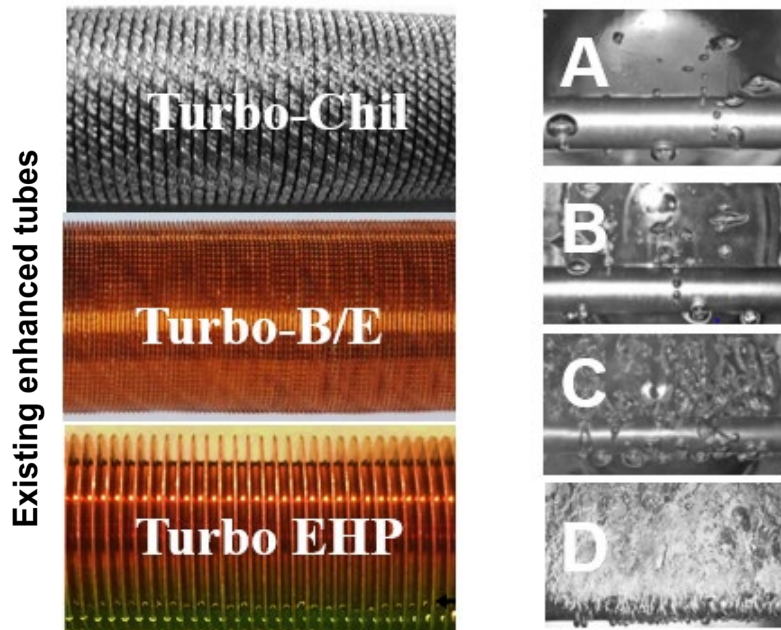
- Development of energy-efficient equipment is critical to enhancing national energy security. A major energy user is commercial processes such as refrigeration/process cooling ( $\sim 2.67$  Quads/year)
- A flooded evaporator configuration is more common compared with direct expansion configuration because of improved system efficiency
- The large flooded evaporator in such systems is a major disadvantage that not only results in excessive refrigerant charge but also increases the pumping work.



Operation of a flooded evaporator for water cooling  
60-70% of charge inventory,  $\sim 800$ -1200 lbs for 60 tons

# Challenge

- The evaporator size depends on the rate of heat transfer from the fluid flowing through the tubes to the refrigerant; the heat transfer rate, in turn, is a function of the heat transfer surface area and nucleation site density
- Most existing tubes used in flooded evaporators have special surface enhancements. However, these enhancements are not cost effective and provide limited advantages



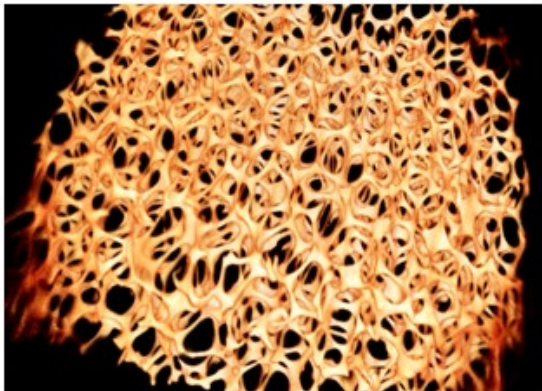
$$q_s'' = \mu_l h_{fg} \left[ \frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left( \frac{c_{p,l} \Delta T_e}{C_{s,f} h_{fg} Pr_l^n} \right)^3$$

Rohsenow, ASME Transactions, 74, 969, 1952.

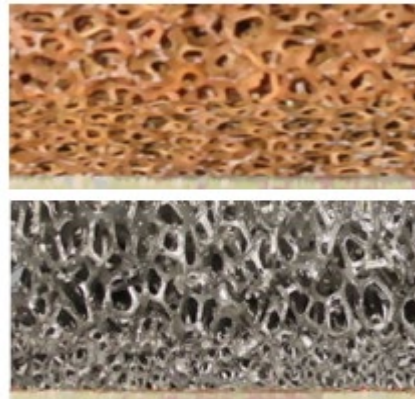


# Solution Approach

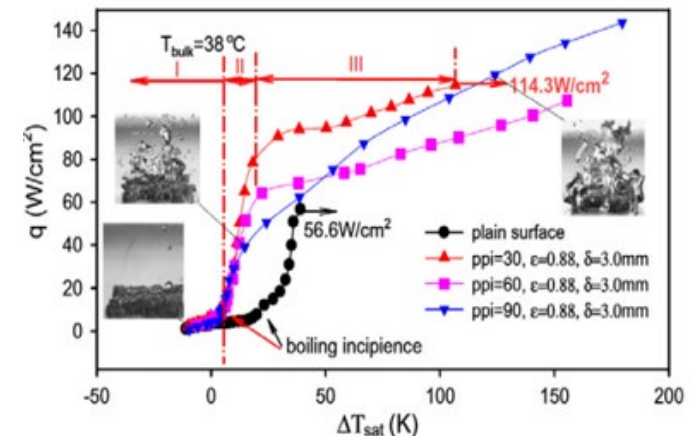
- Metal foam has shown promising results for thermal applications
- The greater surface area ( $\sim 2,500 \text{ m}^2/\text{m}^3$ ) and tortuous structure provide higher nucleation site density
- The variable porosity achieved through an appropriate compression process is another obvious advantage
- Metal foam can provide a  $\sim 35\text{--}45\%$  enhancement in heat transfer coefficient, higher surface-area-to-volume ratio, and higher heat transfer coefficient lead to 40% higher heat transfer rate



Complex structure of a metal foam (x-ray TC image).



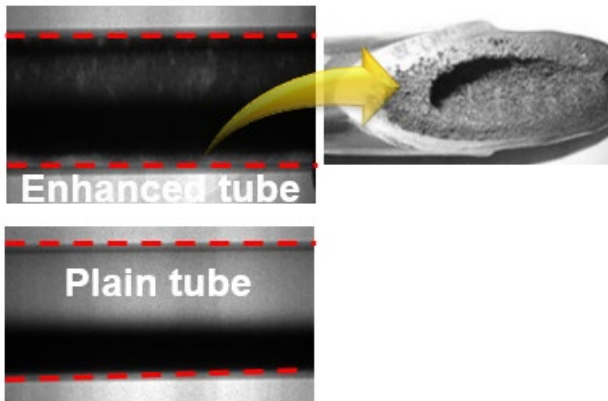
Metal foam with variable pore size.



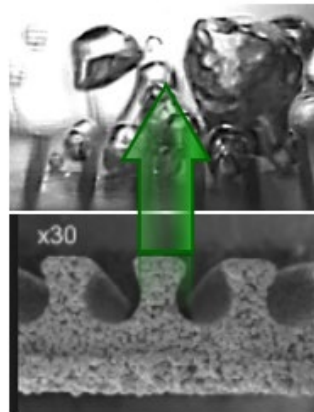
The metal foam's enhanced surface can accommodate higher heat flux.

# Solution Approach

- Deployment of metal foam-enhanced tubes can lead to  $\geq 40\%$  reduction in the size of the flooded evaporator due to the improved heat transfer rate
- The volume occupied by foam material can further reduce the refrigerant charge by 30–40%. The design allows easy substitution of A2L and A3 refrigerants
- The wicking effect accommodates a larger heat flux to keep liquid always in contact with the boiling surface → ***No dry-out***



Neutron radiograph of flow boiling for enhanced and plane tube.



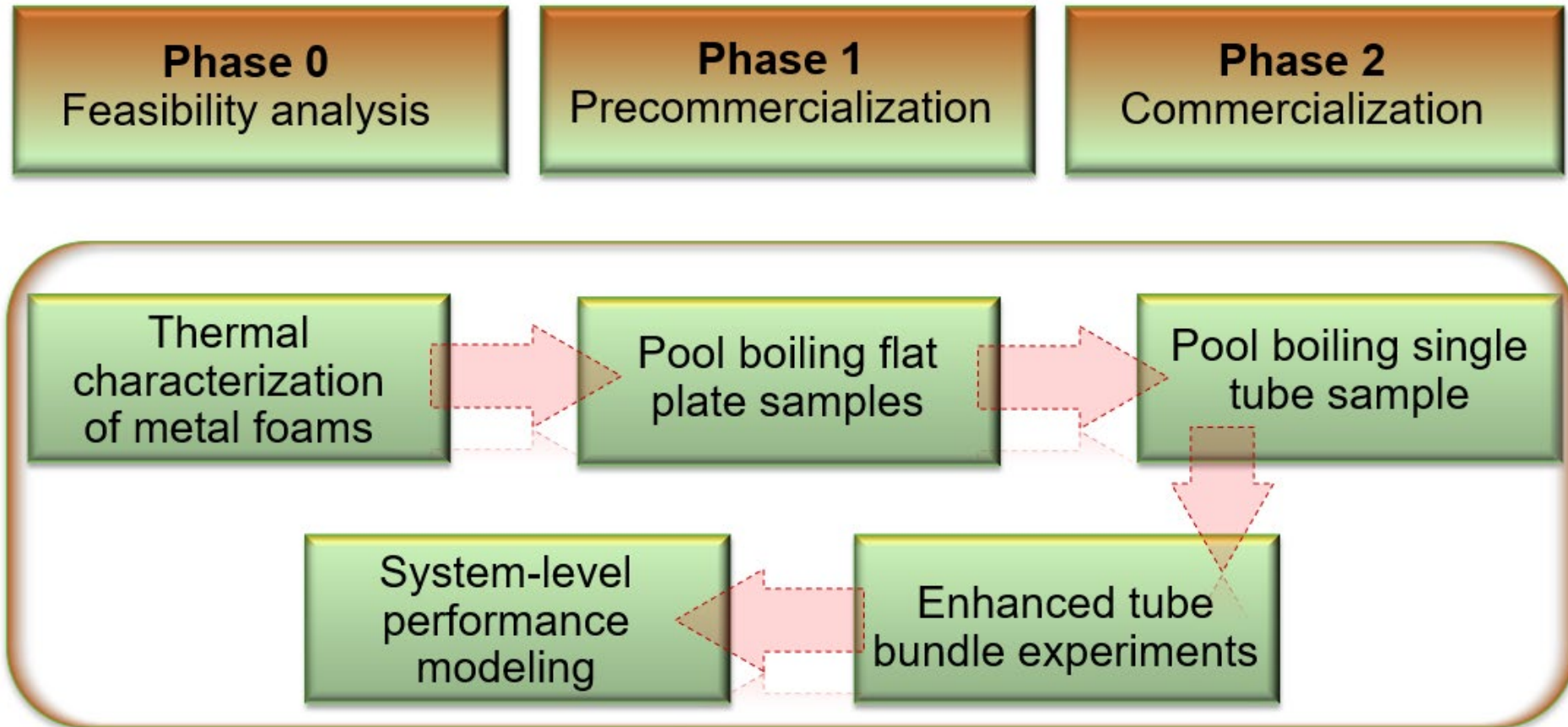
Wicking structures assist in avoiding dry-out.



A metal foam enhanced tube bundle.

Intellectual property, 2021 “High efficiency compact boilers/evaporators and condensers”

# Solution Approach



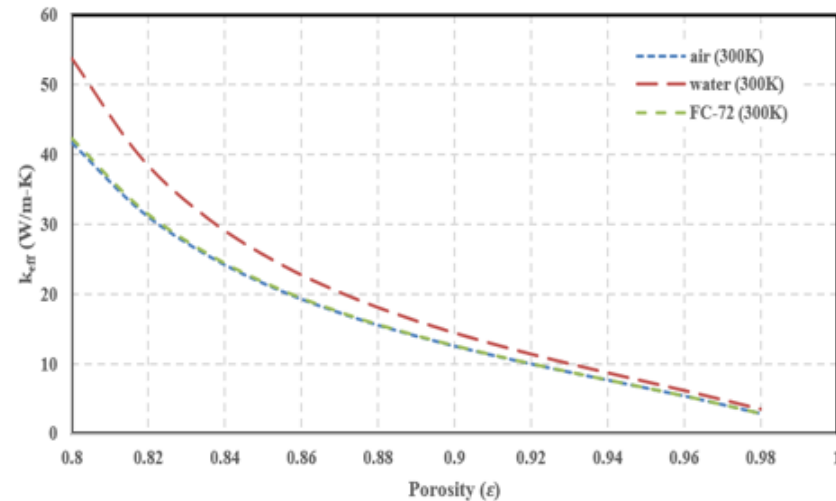
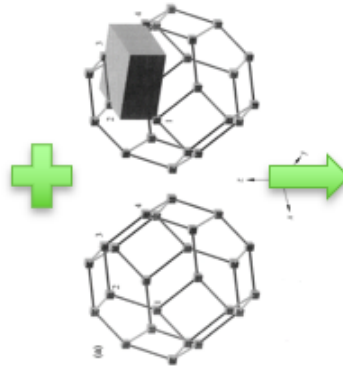
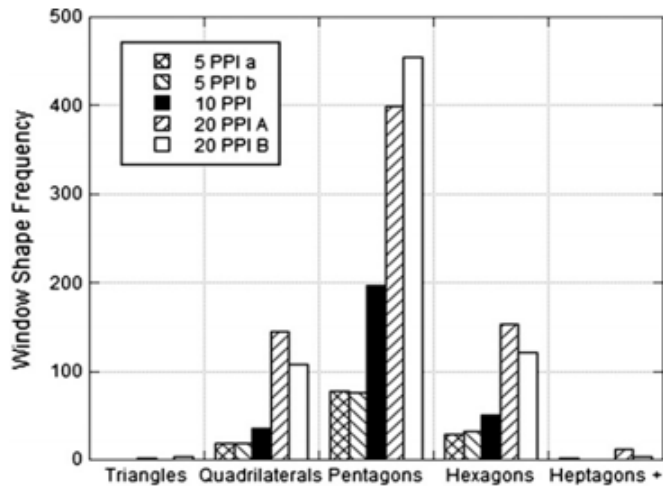
Design, demonstrate, and analyze the performance of a, ultracompact flooded evaporator that can lead to an increased efficiency by at least 20%, with a 35% reduction in total system refrigerant charge.



# Project Impact

- **An improved refrigeration/commercial cooling technology**
  - Unprecedented thermal-hydraulic performance (30% improvement)
  - Reduced footprints (~40% smaller equipment size)
  - Reduced manufacturing cost (20%-30%)
  - Reduced CO<sub>2</sub> footprints (20%-30%)
- **Enables development for deployment of A2L and A3 refrigerants**
  - Reduction in refrigerant charge (at least 30%)
  - Reduced cost of working fluid (at least 30%)
  - Reduced required maintenance due to improved superheat
- **Implications for additional processes**
  - Power generation, waste heat recovery, electronics cooling
- **At least 800 TBtu of energy savings in commercial refrigeration sector**
  - Aligned with BTO goal to develop energy-efficient technology to effect 45% energy saving by 2030 compared with 2010 technologies with significant reduction in GHG emissions.

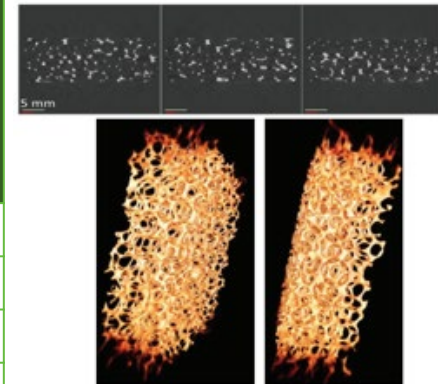
# Progress—Characterization of Metal Foams



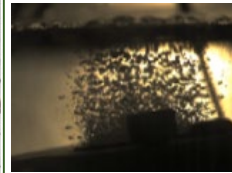
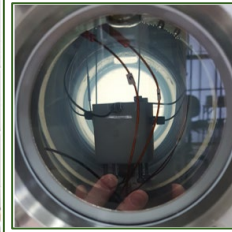
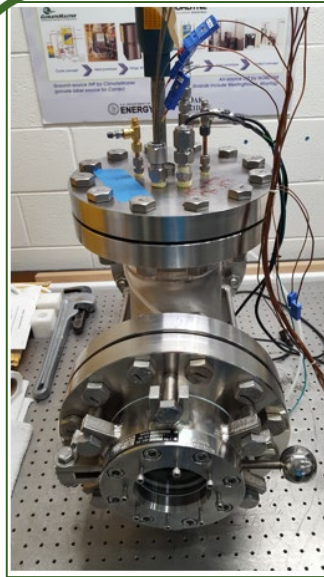
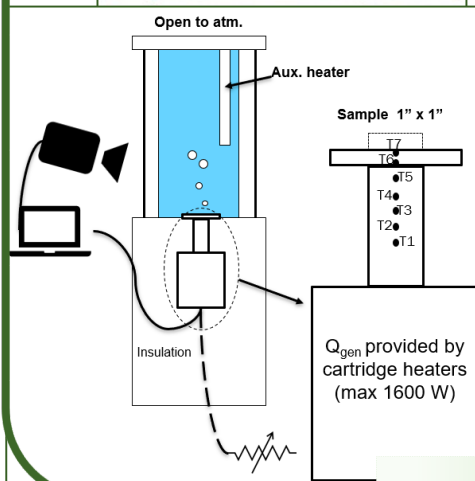
**Development of thermal conductivity model.**

**Geometric properties of metal foam (x-ray CT analysis).**

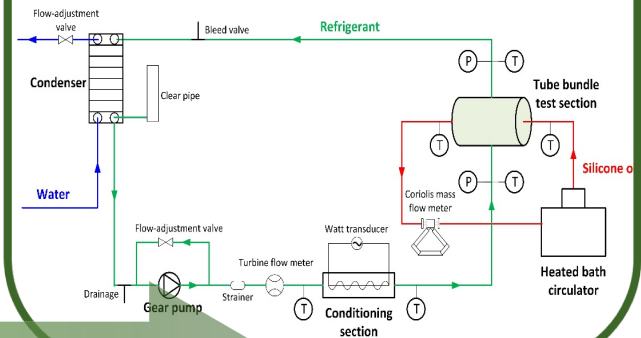
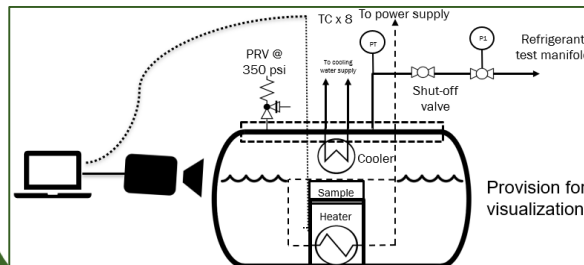
Foam type	Measured minimum flow area to front area ratio ( $A_{min}/A_{fr}$ )	Pore diameter, $D_p$ (mm)	Ligament diameter, $D_f$ (mm)
5 PPI	0.988	4.02	0.50
10 PPI	0.977	3.28	0.45
20 PPI	0.971	2.58	0.35
40 PPI	0.957	1.80	0.20



# Project Progress

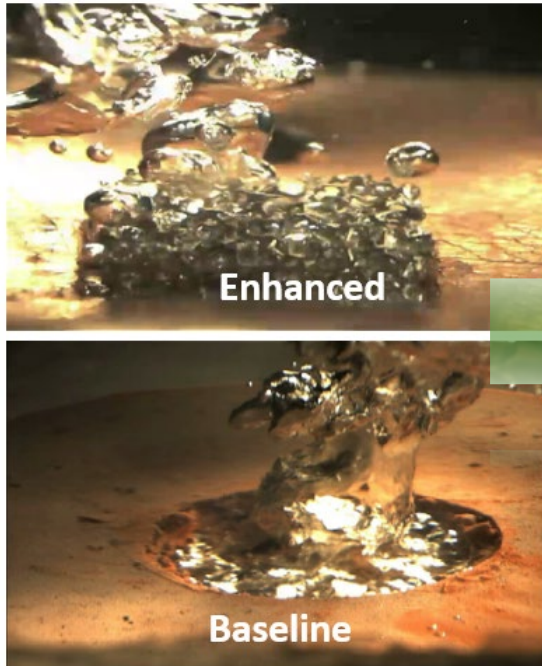


R134a boiling

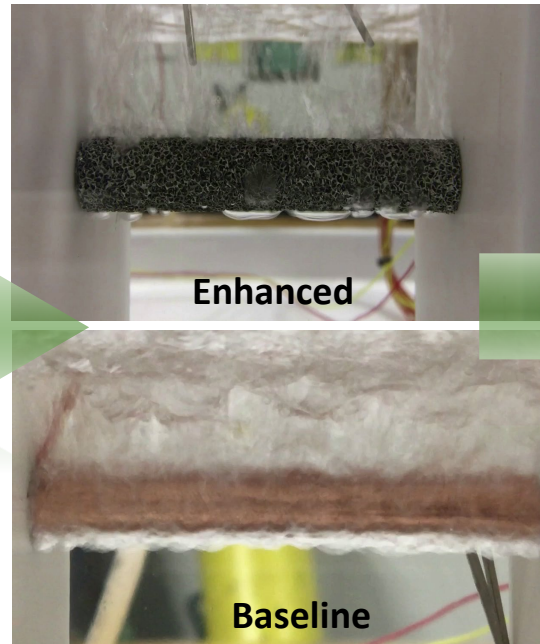


# Project Progress

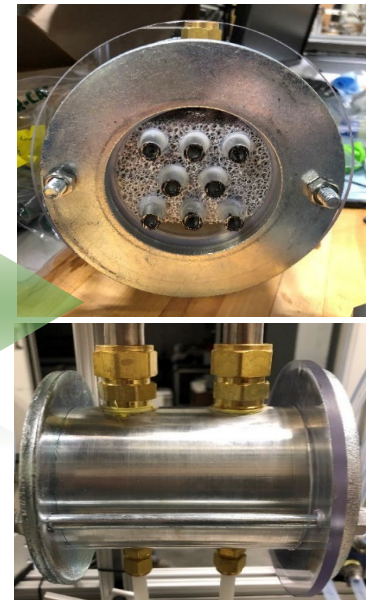
Flat surface (unit cell)



Individual tube (unit cell)



Tube bundle



**40% reduction in refrigerant has been demonstrated!!**

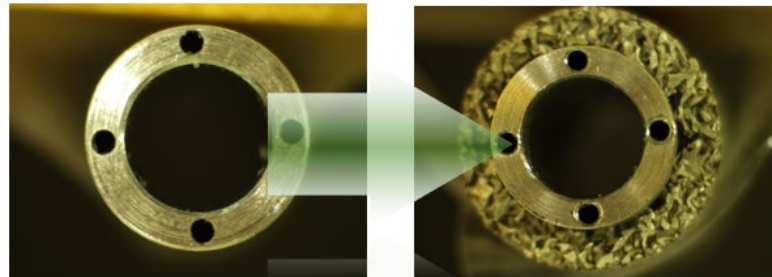
TRL 2-3  
Fundamental technology

TRL 4-5  
Applied technology

Intellectual property, 2021 "High efficiency compact boilers/evaporators and condensers"



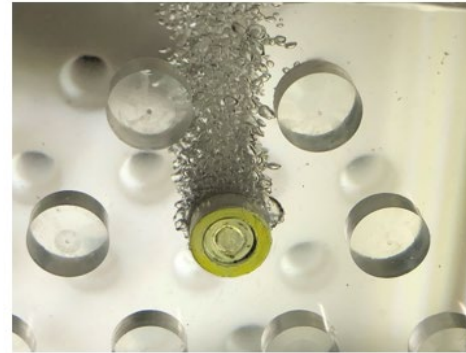
# Project Progress



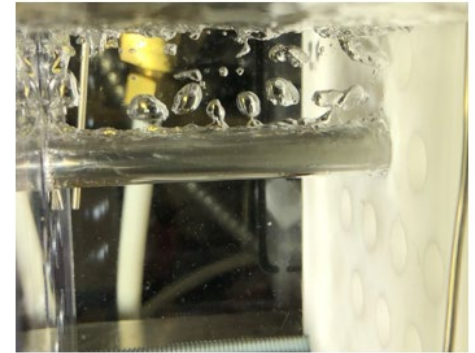
Plain tube

Enhanced tube

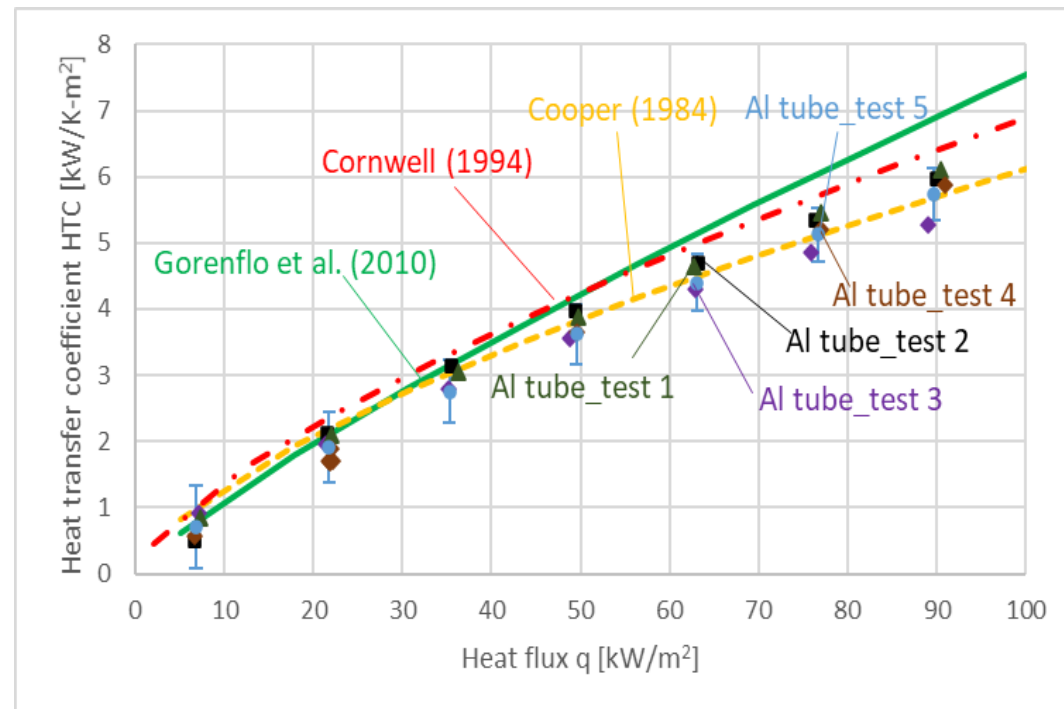
- A careful experimentation has assisted to establish the boiling process on individual tubes.
- First of its kind “enhanced tube” experiments are in-progress.



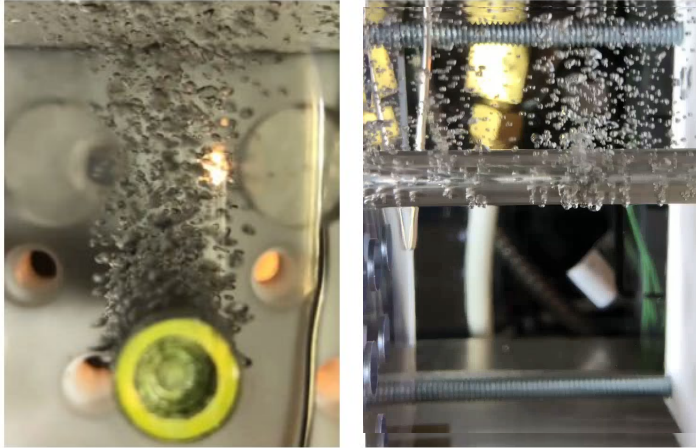
End view (sub-critical boiling)



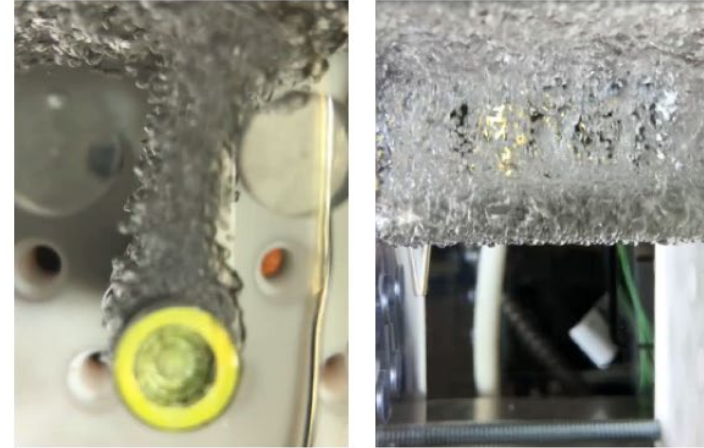
Side view (critical boiling)



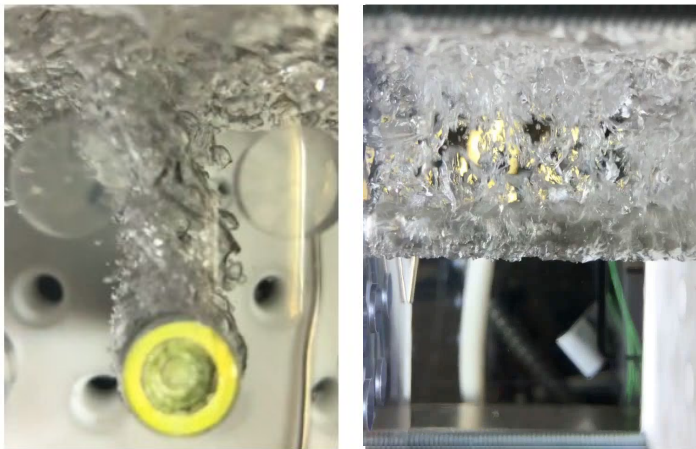
# Project Progress



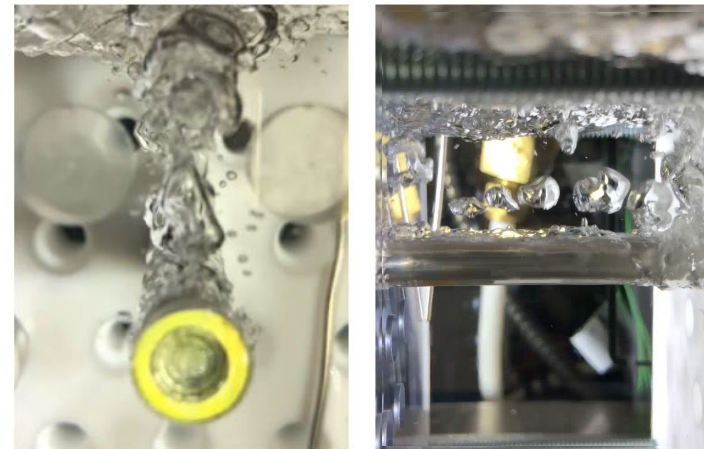
5% heating power



15% heating power



45% heating power



65% heat power (CHF)

# Stakeholder Engagement

- **Development of the technology**
  - Tube bundle arrangement
  - Major challenges (oil management, maintenance)
  - Techno-economic analysis
  - Prototype development and testing (Isotherm & Emerson)
- **Meetings with experts at technical platform**
  - ASHRAE (TC 8.4)
  - ASME (IMECE, SHTC)
  - Purdue, Gordon Research Conference
- **Presentations/Conference papers**
  - GRC on enhanced heat transfer 2019
  - ASHRAE (Speaker at 2019 Annual Conference)
  - ASME (Speaker at SHTC 2019)
  - Purdue Conference 2021



# Remaining Project Work

Name	Description
Establishment of thermal conductivity of metal foams	Develop a model to determine the thermal conductivity of metal foams (various PPI)
Establish the geometry of metal foams	X-ray imaging to evaluate the key geometrical characteristics of metal foams
Water boiling on enhanced surfaces	Conduct detailed analysis of water boiling performance on metal foams and enhanced surfaces
Pool boiling of refrigerants	Conduct detailed analysis of pool boiling performance of various refrigerants
Development and performance evaluation of single enhanced tubes	Based on the preliminary evaluation, design and fabricate an enhanced tube that can be used for single tube performance evaluation; conduct experiments and develop the performance model
Development of enhanced tube bundle	Design and fabricate an enhanced tube bundle that can be used as a prototype to demonstrate the technology
Performance evaluation of tube bundle	Conduct detailed parametric analysis of tube bundle using various refrigerants and develop the performance models
Field study	With the assistance of DOE and Isotherm, initiate and complete a field study deploying the proposed technology at an appropriate site
Commercialization plan	Develop reports and advertisements to facilitate the commercialization of the proposed technology. Identify and mitigate the market risks



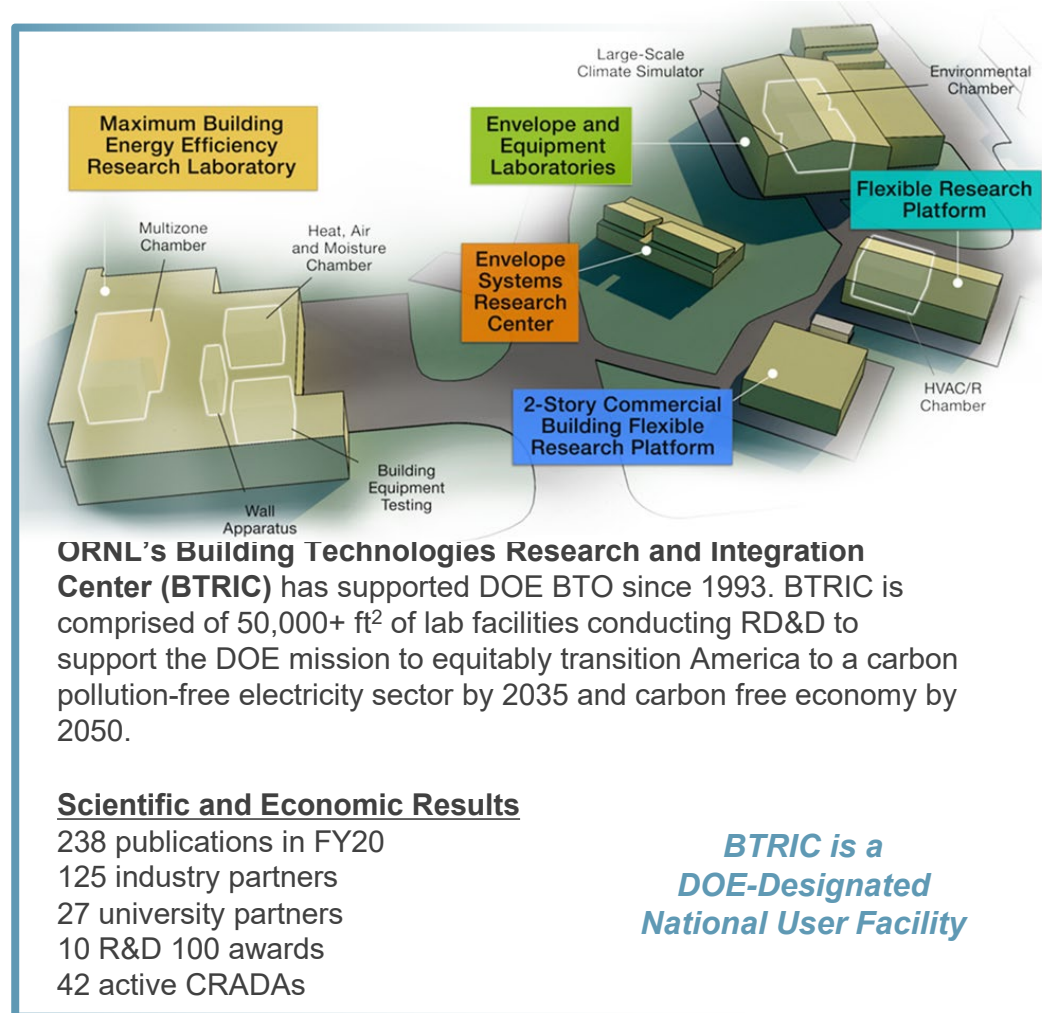
# Thank you

Oak Ridge National Laboratory

Kashif Nawaz

(Group Leader- Multifunctional Equipment Integration)

865-241-0792, nawazk@ornl.gov



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# REFERENCE SLIDES

# Project Budget

**Project Budget: \$750K**

**Variances: None.**

**Cost to Date: \$450K**

**Additional Funding: None.**

## Budget History

FY 2020 (past)		FY 2021 (current)		FY 2022 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
\$300K	\$100K	\$150K	\$50K	\$300K	\$50K

# Project Plan and Schedule

Project Schedule												
Project Start: 2020		Completed Work										
Projected End: 2023		Active Task (in progress work)										
		◆	Milestone/Deliverable (Originally Planned)									
		◆	Milestone/Deliverable (Actual)									
	FY2020				FY2021				FY2022			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Establishment of thermal conductivity of metal foams		◆										
Establish the geometry of metal foams			◆	◆								
Water boiling on enhanced surfaces				◆								
Pool boiling of refrigerants					◆							
Development and performance evaluation of single enhanced tubes						◆	◆					
Development of enhanced tube bundle												
Performance evaluation of tube bundle								◆				
Field study									◆			