2024 PROJECT PEER REVIEW

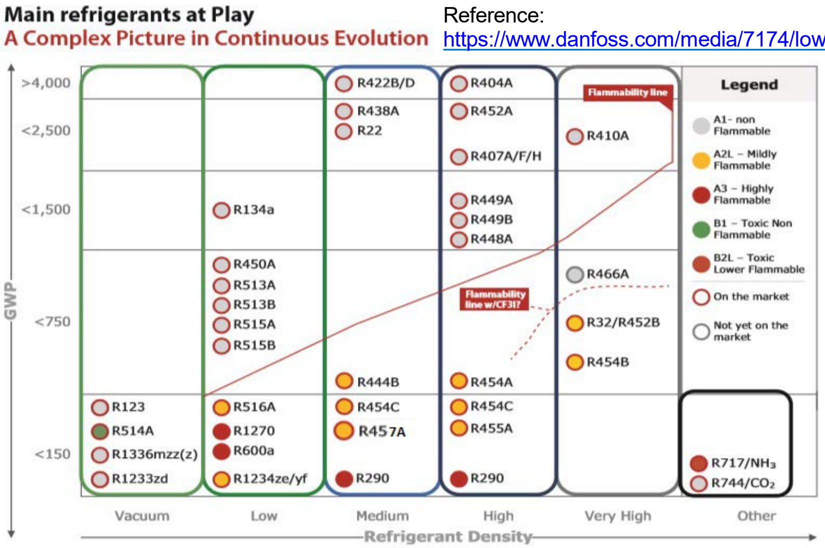
U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review:

Next-Generation Low-Cost Direct-Expansion Heat Pumps Using Refrigerant Mixtures with GWP <150

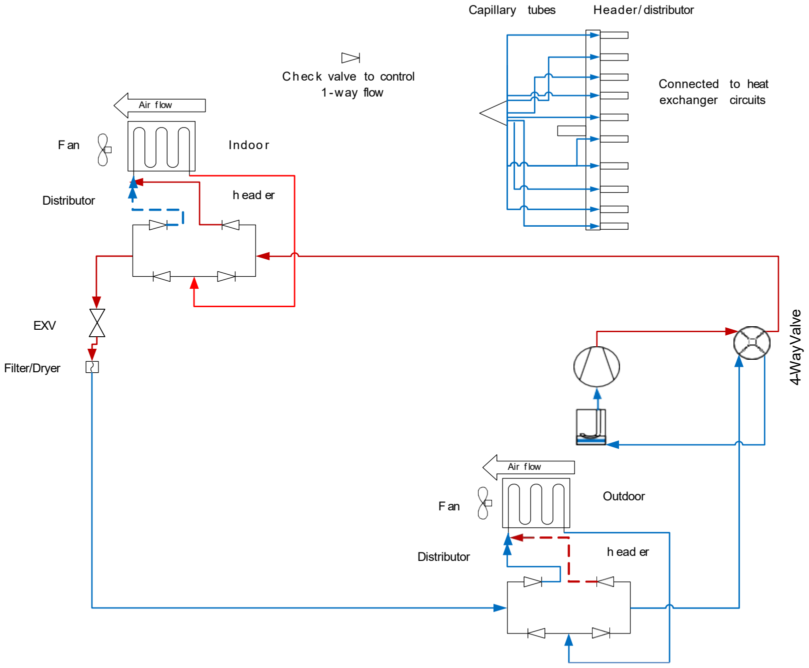
Next Generation Low-Cost Direct-Expansion Heat Pumps Using Refrigerant Mixtures with GWP <150

Reference:
https://www.danfoss.com/media/7174/low-gwp-whitepaper.pdf



GWP versus Density (pressure) of the main refrigerant groups

Check-valve assembly to facilitate counter -flow heat exchangers in both cooling and heating modes (arrows in heating mode)



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Presenter: Zhenning Li, Associate R&D Staff
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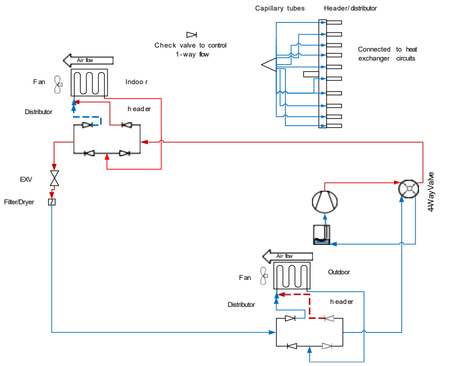
WBS # 03.02.02.26

Project Summary

OBJECTIVE, OUTCOME, AND IMPACT

- Develop low-cost, direct-expansion heat pump using long-term refrigerants with GWP <150 and suitable for mainstream building and equipment structures
- Optimize cooling and heating performance
- Achieve seasonal cooling performance of season energy efficiency ratio (SEER) >16.0
- Achieve seasonal heating performance of heating seasonal performance factor (HSPF) >9.0



5-mm tube cross-counterflow outdoor coil

TEAM AND PARTNERS

ORNL Team: Bo Shen, Zhenning Li

Partner:

Copeland Helix Innovation Center

Super Radiator Coils

Arkema

COPELAND

SUPER RADIATOR COILS

ARKEMA

STATS

Performance Period: 10/2020–09/2025

DOE budget: $600k (FY24)

FY21–FY23: Develop cost-optimized, GWP <150 residential heat pumps

FY21: Develop optimized component technologies and novel system configuration to maintain counterflow in both modes

FY22–FY23: Laboratory evaluation of GWP <150 heat pump prototype and verification of high-end performances

FY24–FY25: Develop low-cost, direct-expansion heat pump using ultra-low-GWP refrigerants (GWP <10)—focus on propane hydronic and CO_2 mixture systems

Problem

- Requirements to reduce environmental impacts of heat pump systems: refrigerants with GWPs >750 will be banned after 2023; long-term, industry will pursue refrigerants with GWP < 150
- Most low-GWP mixtures are flammable; new heat pump designs must reduce refrigerant charge and avoid explosion risk
- Low-GWP mixtures have high temperature glide; switching from cooling to heating mode makes counterflow HX as parallel-flow, inducing performance degradation
- New heat exchanger designs and new flow control devices (i.e., valves) are needed to guarantee desirable heat pump performance under cooling and heating modes
- New low-GWP heat pumps must accommodate current manufacturing and installation processes and fit into current house structures
- New design method for heat pump with low-GWP refrigerants is needed to make products cost effective and easily accepted by end users

Alignment and Impact

Increase building energy efficiency and reduce GHG emissions

Greenhouse gas emissions reductions

- Deliver component technologies (heat exchangers, flow controls, and compressors) and system configuration to support transition to refrigerant with high glide and GWP <150 and to reduce direct GHG emissions
- Demonstrate high-end efficiency levels in cooling and heating modes for high-glide refrigerants and reduce indirect GHG emissions
- SEER >16.0 (SEER2 >15.3) and HSPF >9.0 (HSPF2 >7.5)

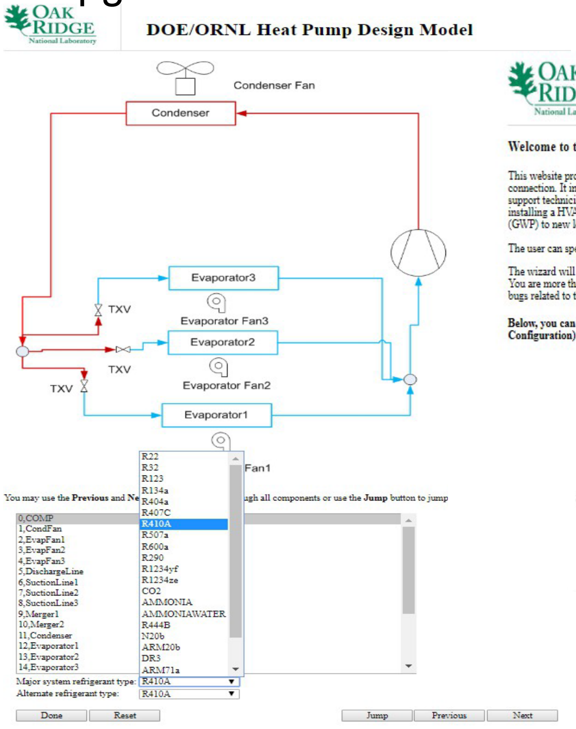
Prioritize equity, affordability, and resilience

Energy justice

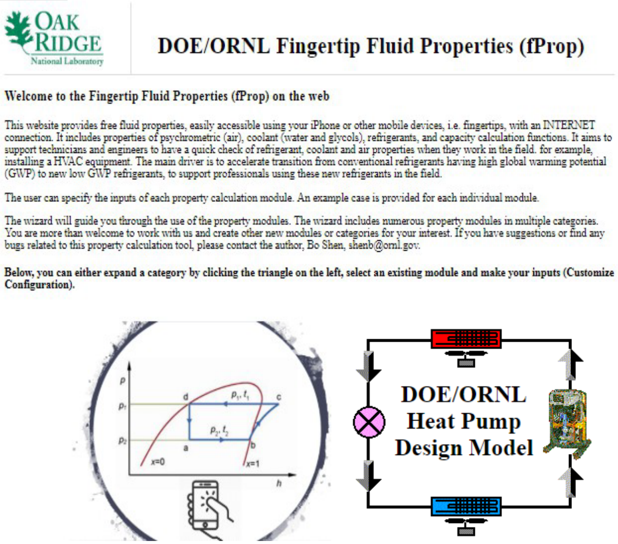
- Optimize cost structure for residential users to improve affordability
- Establish production and installation path to apply low-GWP, high-glide refrigerants

Approach Public-domain heat pump /coil design and optimization tool capable of HFC, HFO, natural refrigerants, and more

DOE/ORNL Heat Pump Design Model (HPDM) upgraded to simulate low-GWP mixtures



https://hpdmflex.ornl.gov/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DOE/ORNL Fingertip Fluid Properties (fProp)

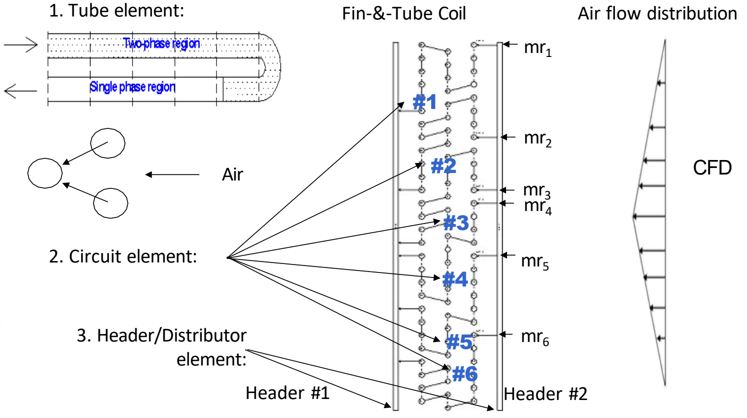
Welcome to the Fingertip Fluid Properties (fProp) on the web

This website provides free fluid properties, easily accessible using your iPhone or other mobile devices, i.e. fingertips, with an INTERNET connection. It includes properties of psychrometric (air), coolant (water and glycols), refrigerants, and capacity calculation functions. It aims to support technicians and engineers to have a quick check of refrigerant, coolant and air properties when they work in the field. for example, installing a HVAC equipment. The main driver is to accelerate transition from conventional refrigerants having high global warming potential (GWP) to new low GWP refrigerants, to support professionals using these new refrigerants in the field.

The user can specify the inputs of each property calculation module. An example case is provided for each individual module.

The wizard will guide you through the use of the property modules. The wizard includes numerous property modules in multiple categories. You are more than welcome to work with us and create other new modules or categories for your interest. If you have suggestions or find any bugs related to this property calculation tool, please contact the author, Bo Shen, shenb@ornl.gov.

Below, you can either expand a category by clicking the triangle on the left, select an existing module and make your inputs (Customize Configuration).



2-D air side distribution; Independent circuit refrigerant entering conditions; Arbitrary circuitry, provides more accurate real-world heat exchanger performance predictions

HPDM discretized coil modeling reveals temperature glide and variation of local properties, enable optimized coil circuitry with arbitrary refrigerant mixtures

Approach (cont'd)

- Designed a system configuration to maintain HX cross-counterflow configurations in cooling or heating mode

$$\text{Maximize: } EER$$

$$\text{Subject to:}$$

Operation constraints

$$\Delta T_{\text{superheat, evaporator outlet}} = 10 - \frac{\Delta T_{glide}}{2} \ [R]$$

$$2\ [R] \le \Delta T_{\text{subcooling, condenser outlet}} \le 15\ [R]$$

$$Q_{evaporator} = 10.55 \text{ kW}$$

Dimension constraints

$$|SHR_{evaporator} - SHR_{baseline,evaporator}| \le 1\%$$

$$1 \le N_{circuits,evaporator} \le Ntubes\ per\ bank\ of\ evaporator$$

$$1 \le N_{circuits,condenser} \le Ntubes\ per\ bank\ of\ condenser$$

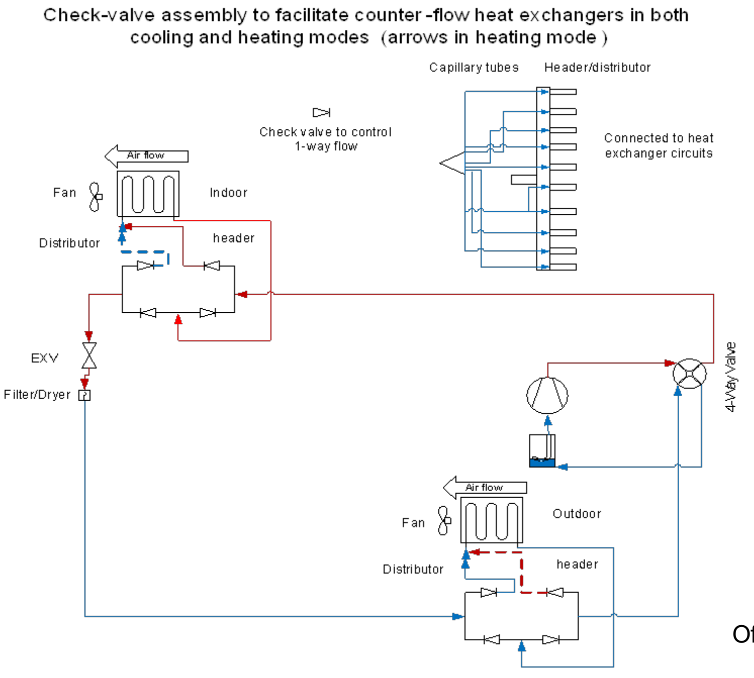
$$\text{Height}_{evaporator} = \text{Height}_{baseline}$$

$$\text{Length}_{evaporator} = \text{Length}_{baseline}$$

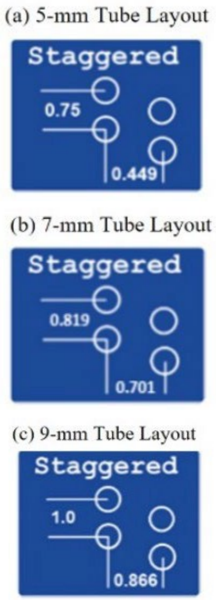
$$\text{Height}_{condenser} = \text{Height}_{baseline}$$

$$\text{Length}_{condenser} = \text{Length}_{baseline}$$

$$Tube\ diameter \text{ varies among } 5\ mm, 7\ mm, 9\ mm$$



New system configuration maintaining counterflow HXs in dual modes



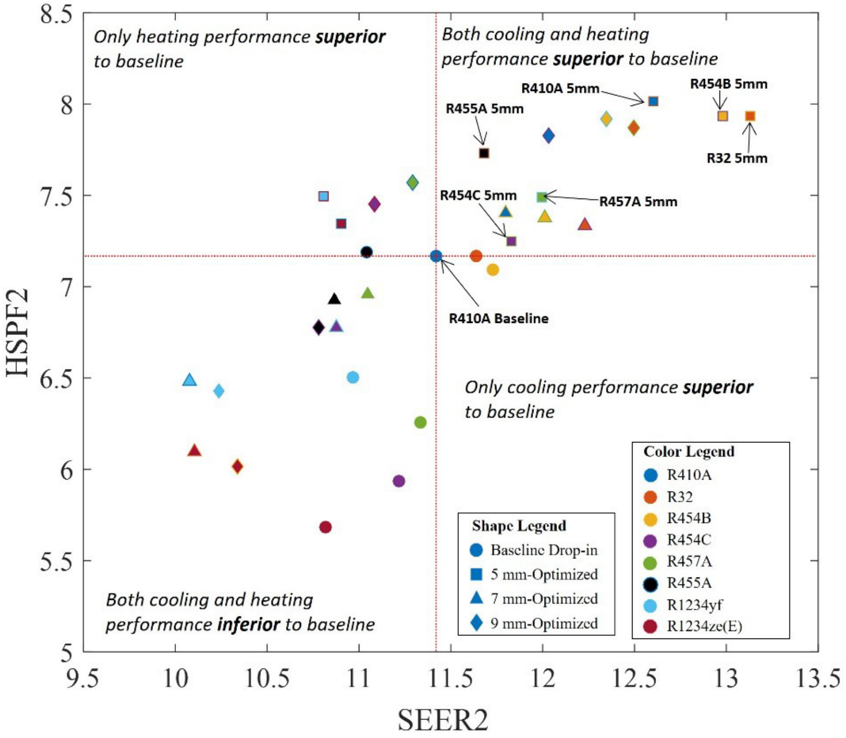
Off-the-shelf tube layout

Progress Model-Based Design Optimization

Fluid	GWP	Safety Class	T_{Glide} in Condenser [K]	T_{Glide} in Evaporator [K]	Critical T [C]
R-444B	295	A2L	7.6	8.9	92.11
R-454A	238	A2L	5.4	6.2	78.94
R-454C	146	A2L	6.0	6.0	82.4
R-457A	139	A2L	6.1	6.9	90.15
ARM20B	251	A2L	5.3	6.0	88.74

Keys:

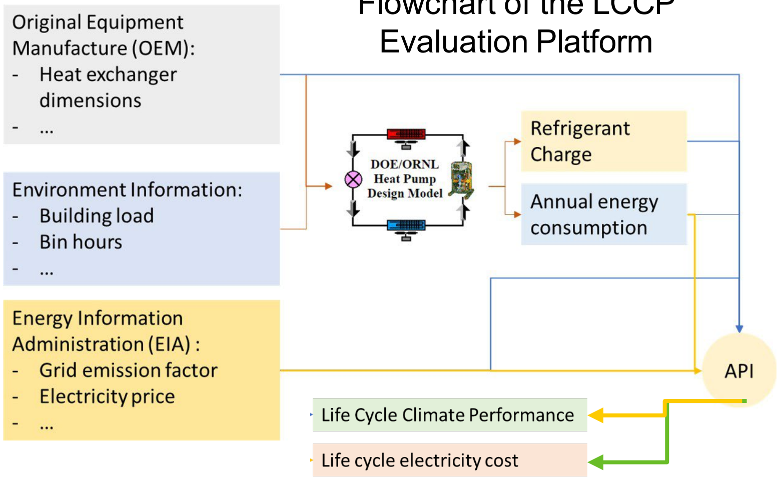
- Optimize multirow coils, 5 mm tubes
- Flow control devices maintain optimum heat exchanger configurations in heating/cooling modes
- Develop multistage compressors for low-GWP refrigerants
- Selected R-457A provided by Arkema for prototyping

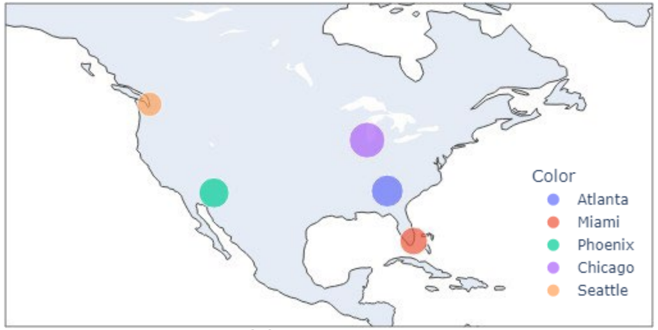


Heat exchanger optimization shows multi-row 5 mm tube coil in cross-counterflow offers preferable performance

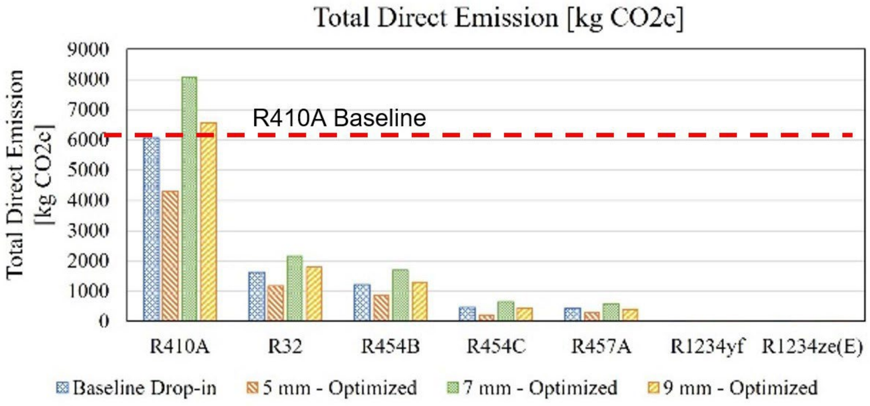
Progress Life Cycle Climate Performance Analysis

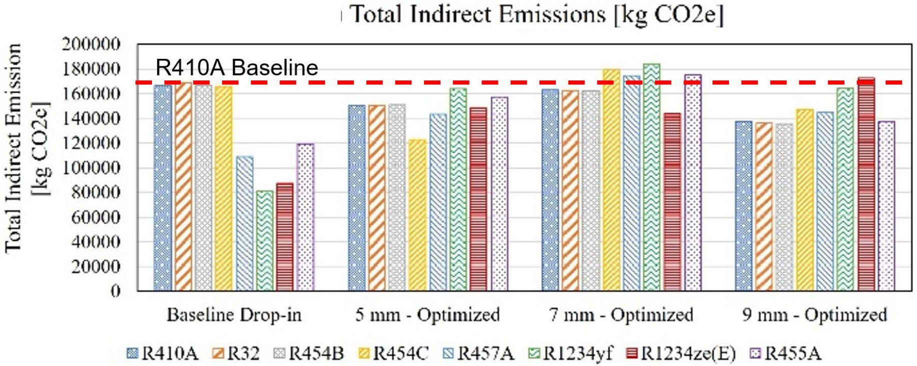
Flowchart of the LCCP Evaluation Platform





LCCP evaluation results



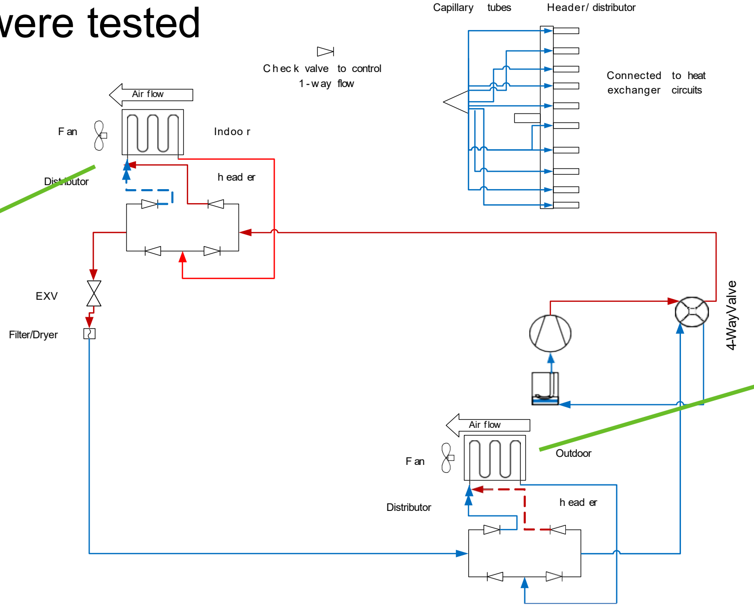


Optimized systems using GWP < 150 refrigerants reduce total lifetime CO_2 emission by 13%–33%, depending on choice of refrigerant and climate zone

Progress Laboratory Evaluation of Low-GWP Heat Pump

- Designed system configuration to maintain HX counterflow configurations in dual mode
- Fabricated 5 mm tube coils and assembled with the chasses, fans, and electric boxes of a 4.5 ton HP
- A bi-direction EXV with a suction line accumulator was used to control the superheat and optimize charge
- For indoor coil options were tested

Outdoor 5 mm tube coil installed on 4.5 ton chassis



Tested Indoor coil:
Option 1: microchannel heat exchange
Option 2: tube-fin heat exchanger

Progress AHRI 210/240 Two-Stage Heat Pump Test Matrix

Heating mode (70°F indoor return air)

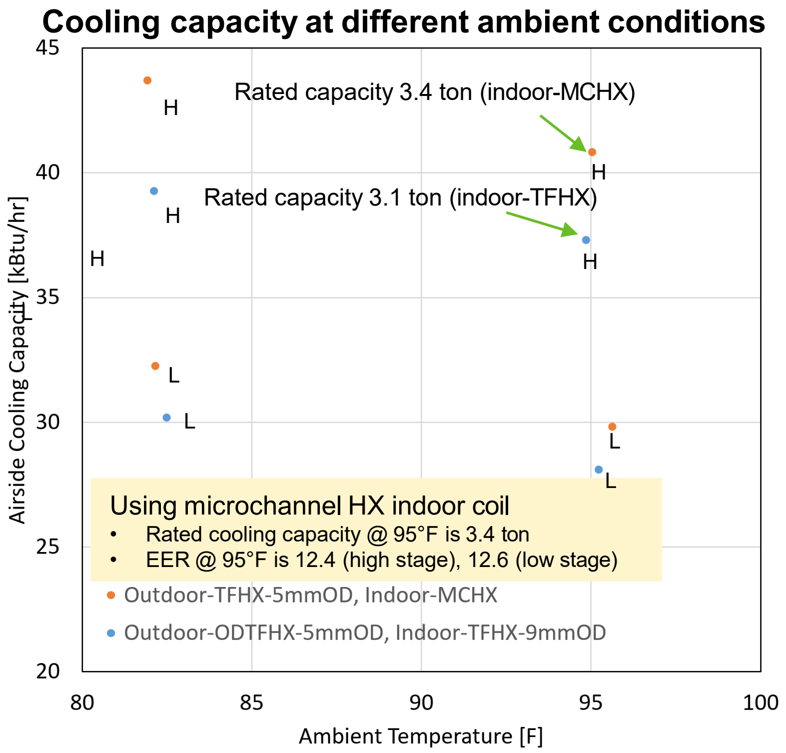
- 62°F, compressor L, indoor blower H
- 47°F, compressor H and L, indoor blower H
- 35°F, compressor L+ blower H or L; compressor H blower H
- 17°F, compressor L + blower L; compressor H + blower L or H
- 5°F, compressor H + blower L

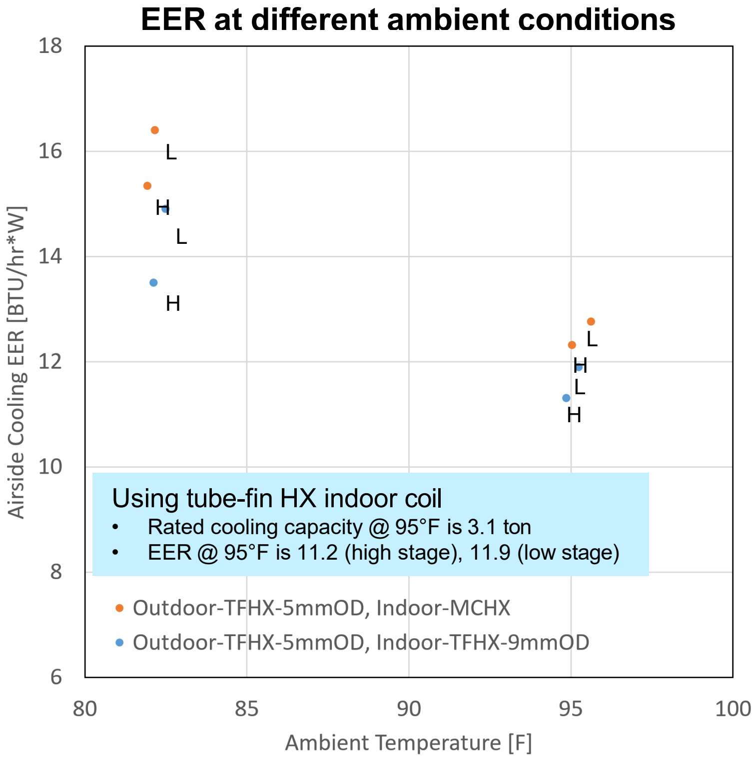
Cooling mode (80°F DB/67°F WB indoor return air)

- 95°F ambient, compressor L + indoor blower L; compressor H + indoor blower H
- 82°F ambient, compressor L + indoor blower L; compressor H + indoor blower H

L: compressor low stage operation
H: compressor high stage operation
DB: Dry-bulb temperature
WB: Wet-bulb temperature

Progress Cooling Performance

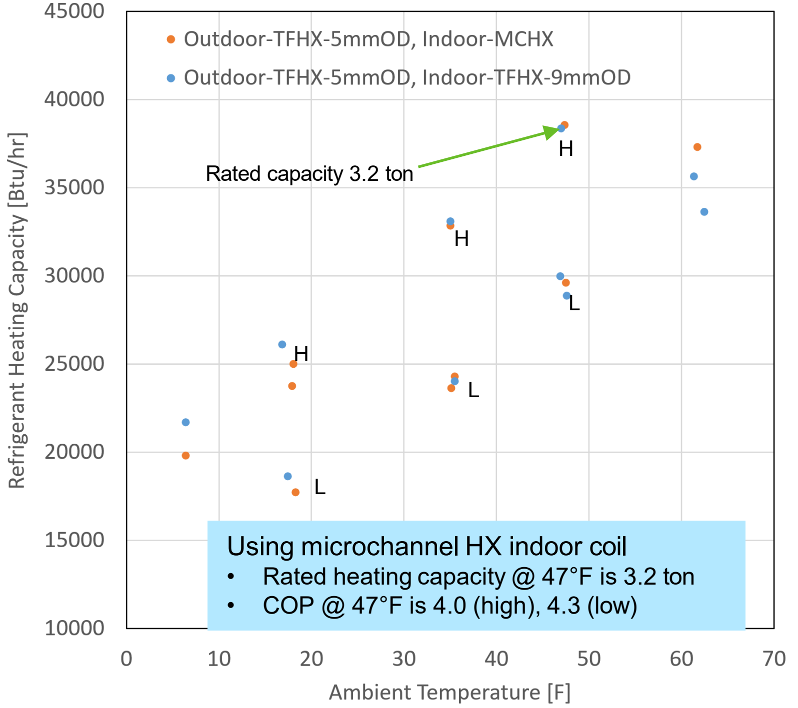




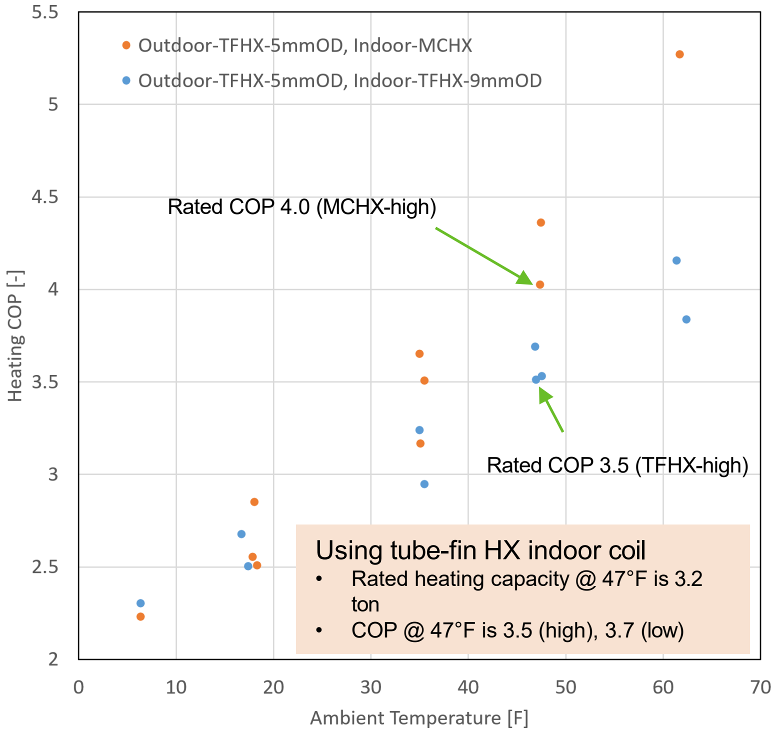
SEER target is achieved with an acceptable tolerance: i.e., 15.7 (MCHX), 14.3 (TFHX) vs. 16.0 (goal)

Progress Heating Performance

Heating capacity at different ambient conditions



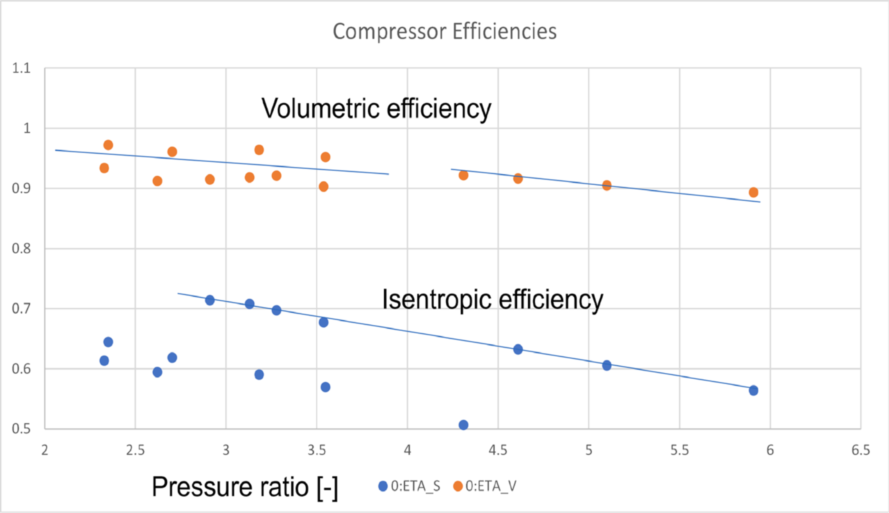
COP at different ambient conditions



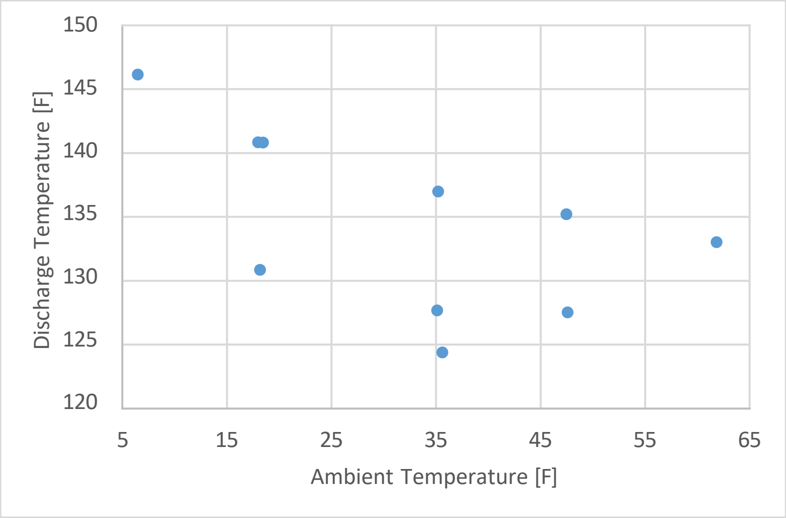
HSPF target is exceeded: 10.1 (MCHX), 9.16 (TFHX) vs. 9.0 (goal)

Progress Compressor Efficiency and Discharge Temperature

- Performance of a Copeland two-stage R-457A compressor achieves project goals
- 50% increase in displacement volume compared with R-410A compressor
- Smaller motor torque than R-410A compressor owing to R-457A's lower working pressures
- Isentropic efficiency comparable to R-410A compressor



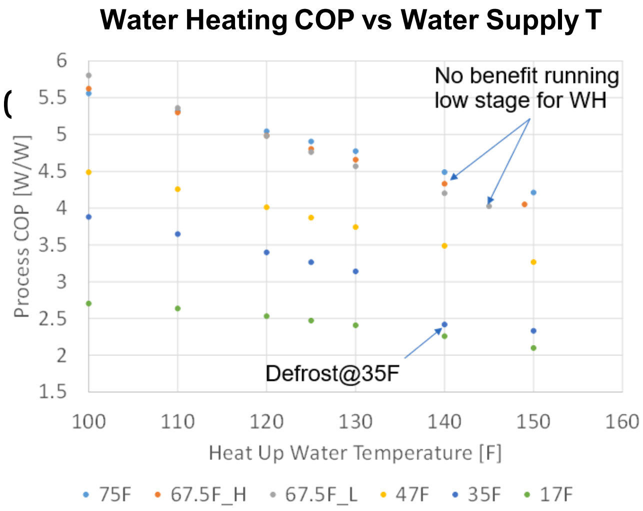
Validated compressor efficiency in entire application range

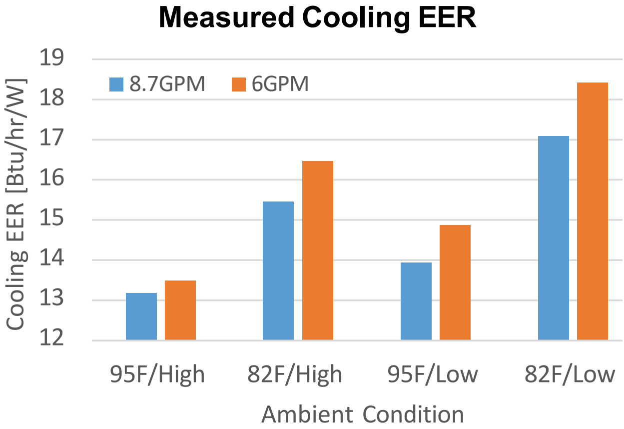


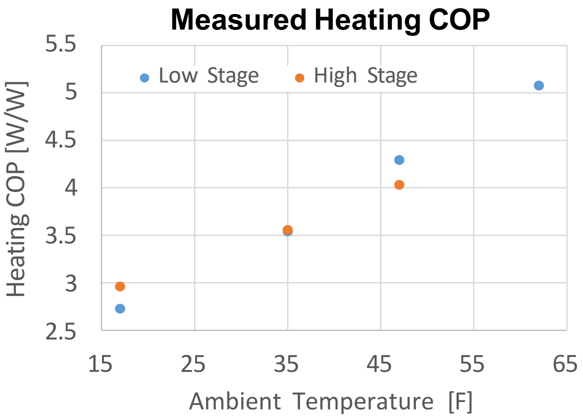
Compressor discharge temperature at different ambient conditions

Progress Propane Hydronic Heat Pump

- @ 95˚F cooling capacity > 38 k BTU/hr (3-ton), EER > 13. (
- @ 47 °F heating capacity > 40K Btu/hr, COP > 4
- SEER> 16.0, HSPF> 9.9
- Annual water heating COP > 4.0.
- Heat hot water up to 150˚F with good efficiency
- Propane charge < 2.5 lbm



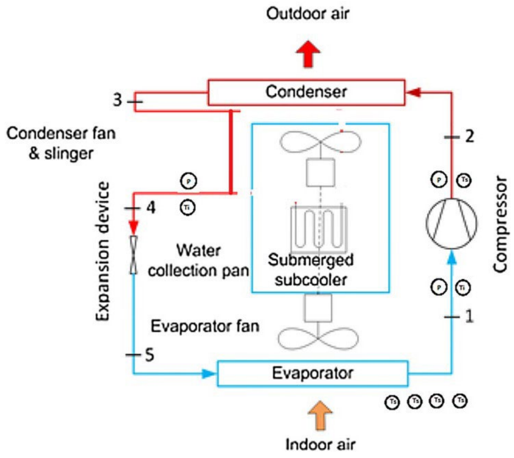




Outcome: Enable propane application in residential HVAC & WH.

Progress Propane High Efficiency Window Air Conditioner

- **Key Metrics**
  - Propane charge < 260 g, inline with regulation recommended by EPA.
  - Rated cooling capacity > 10,000 Btu/hr.
  - Rated EER >12.0 (Energy Star).
  - Operated up to 131°F/55 °C ambient temperature, capable of high ambient applications
- **Achievements**
  - Developed rotary compressor optimized for propane
  - Conducted model-based design optimization
  - Achieved optimal performance metrics within the charge constraint (safety)



Laboratory instrumentations

Laboratory Tested Propane Window AC

Accomplishments and Future Work

- For low-GWP refrigerant (GWP<100), achieved high-end efficiency level using R-457A
  - Exceed the HSPF goal, i.e., 10.0 versus 9.5
  - Reach the SEER goal within allowed tolerance, i.e., 15.7 vs 16.0
- For ultra low-GWP refrigerant (GWP<10), a hydronic propane residential heat pump was developed
  - cooling mode: SEER > 16.0; @ 35°C capacity > 3 tons, EER > 13.0
  - Heating mode: HSPF >10.0; @ 47F, capacity > 3 tons, COP > 4.0
  - Heat water 50-gallon from 14.4°C to 65.6°C in with a COP of 4.05 at 19.7°C ambient, and a COP of 2.1 at -8.3°C
- Starting from the current structure and working with the industry partners, we will develop low cost, direct expansion heat pump using ultra low-GWP refrigerants (propane hydronic and CO_2 mixture)

Outcome:

1 Li, Zhenning, Samuel Yana Motta, Bo Shen, and Brian Fricke. "Optimization of Residential Air Source Heat Pump using Low–Global Warming Potential Refrigerants." Heat Pumping Technologies Magazine 42, no. 1 (2022).

2 Li, Zhenning, Samuel Yana Motta, Bo Shen, and Hanlong Wan. "Optimization of Residential Air Source Heat Pumps using Refrigerants with GWP <150 for Improved Performance and Reduced Emission."14th IEA Heat Pump Conference, Chicago (2023)

3 Bo Shen, Zhenning Li, Hanlong Wan, Samuel Yana Motta, Kyle Gluesenkamp. "Direct Expansion Heat Pump Using High Glide Low GWP Refrigerant", 26th International Congress of Refrigeration, Paris (2023)

4 Bo Shen, Zhenning Li, Hanlong Wan, Kyle Gluesenkamp, Brian Fricke. "A Propane Hydronic Heat Pump with Energy Storage", 26th International Congress of Refrigeration, Paris (2023)

5 Hanlong Wan, Zhenning Li, Bo Shen, "A Hybrid Method To Evaluate The Life Cycle Climate Performance", 26th International Congress of Refrigeration, Paris (2023)

Thank you

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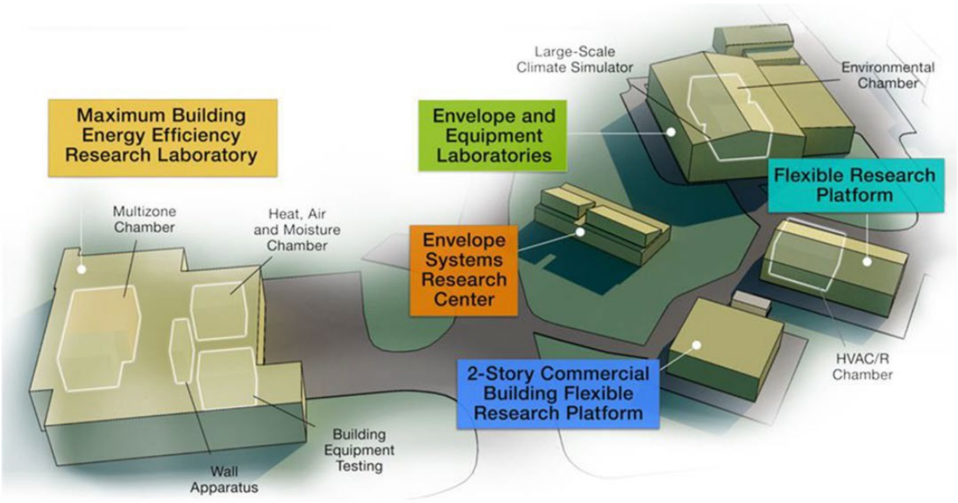

The **Building Technologies Research and Integration Center** (**BTRIC**) at ORNL has supported DOE BTO since 1993. BTRIC is comprised of more than 60,000 square feet of lab facilities conducting RD&D to develop affordable, efficient, and resilient buildings while reducing their greenhouse gas emissions 65% by 2035 and 90% by 2050.

Scientific and Economic Results
139 publications in FY24
140+ industry partners
60+ university partners
16 R&D 100 awards
64 active CRADAs

BTRIC is a DOE-Designated National User Facility

Project Execution

	FY2022				FY2023				FY2024			
Planned budget	$400k				$400k				$600k			
Spent budget	$350k				$380k				$410K			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
FY22 Q1 Milestone: Perform LCCP analysis, select candidate refrigerants												
FY22 Q2 Milestone: Model-based design of system and component to achieve the performance goals												
FY22 Q3 Milestone: Development of a 2-stage scroll compressor for selected refrigerant and smart four-way valve												
FY22 Q4 Milestone: Construct prototype system												
FY23 Q1 Milestone: Verify component technologies												
FY23 Q2 Milestone: Verify the >90% efficiency performance goals via lab testing												
FY23 Q3 Milestone: Prototype improvement and verification (achieve 16.0 SEER/9.5 HSPF)												
FY23 Q4 Milestone: Cost assessment												
Current/Future Work												
FY24 Q2 Design optimization of ultra-low-GWP refrigerants heat pump with focus on propane												
FY24 Q4 Construct low-cost, direct-expansion ultra-low-GWP refrigerants ptototype												

Team

OAK RIDGE National Laboratory

COPELAND

SUPER RADIATOR COILS

ARKEMA

Dr. Bo Shen
PI

System design and Team coordination

Dr. Zhenning Li

Heat pump optimization, Laboratory investigation, and Life cycle climate analysis

Drew Welch
Senior Lead HVAC Systems Engineer

Led development of multistage compressor, valves, and accessories for <150 GWP refrigerant(s)

Dr. Jian Yu
Vice President of R&D at Super Radiator Coils

Fabrication of 5 mm multirow coils

Kris Crosby
Lead HVAC/R Technical Service Engineer

Low-GWP refrigerants