Gravity-Independent Heat Exchangers and Oil-Free Compressors for Modular Refrigeration System

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Presented By
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Thermal & Fluids Analysis Workshop
TFAWS 2026
August 31 – September 4, 2026
NASA Marshall Space Flight Center
Huntsville, AL

Acknowledgements

This work was conducted under an SBIR Phase I Award, Contract No. 80NSSC25C0288. The project team would like to thank the NASA team overseeing this work including Jon-Michael Tucker and Bruce Conger. The project team would also like to thank project partners Jeff Didion and Dr. Eckhard Groll.

Overview

- Background: SBIR solicitation, vapor compression in space
- Preliminary design work and decision making
- Experimental testing and findings
- Detailed design work
- Synthesis and conclusions

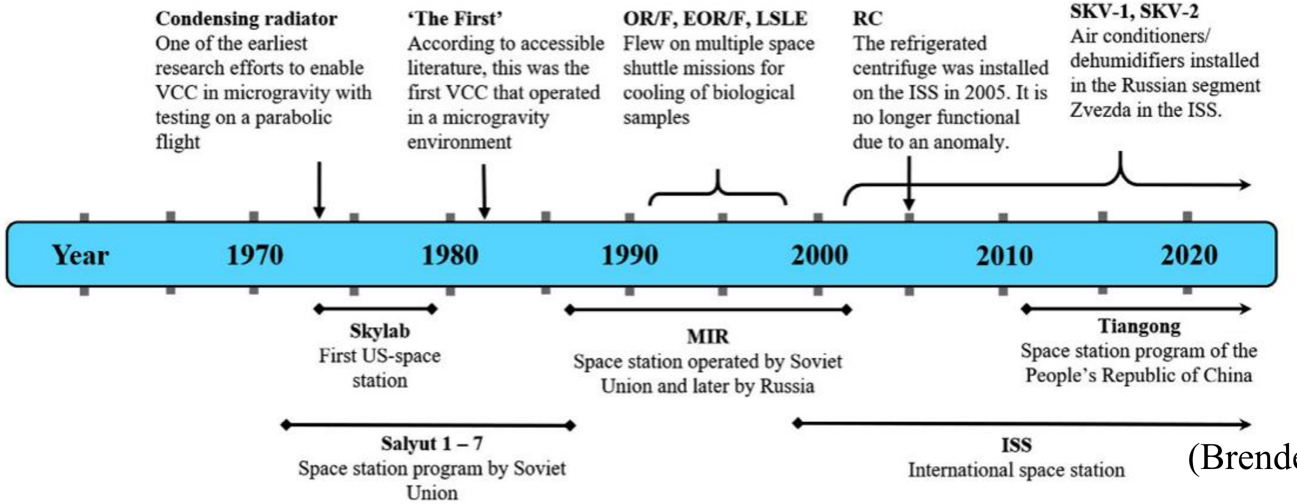
Background and Context

SBIR Solicitation and Project Objectives

- **Food refrigeration systems** with one of two temperature levels: A cold air temperature of **+5C / -25C**, rejecting heat to a pumped liquid spacecraft cooling loop or directly to a space radiator in the range of **+10C to +50C / +5C to +25C**.
- Coefficient of performance (COP) should exceed **45% of Carnot COP**.
- Ground tested with good evidence shown that the technology will be able to operate for at least **5 years** in gravity environments ranging from **0 (interplanetary space) to 1 (Earth normal)**.
- The technology should be scalable from heat loads of **200 to 1,000 Watts** of cooling.
- **Vapor compression**, Stirling cycle or other solid-state cycle

Background: Vapor Compression in Space

- VCC systems have a limited spaceflight history, but not unprecedented



(Brendel, 2021)

Device	Temperature Range	Refrigerant	Compressor Type
Mission participation 1982: STS-4	−13.8 °C to 18.8 °C / Condenser 36.4 °C to 40.7 °C	R12	Oil-free diaphragm compressor
OR/F (Orbiter Refrigerator/ Freezer)	−20°C to 4°C	CFC refrigerant	Oil-free diaphragm compressor
EOR/F (Enhanced Orbiter Refrigerator/Freezer)	−22°C to 10°C	CFC and HCFC refrigerants	Oil-free diaphragm compressor
LSLE (Life Sciences Laboratory Equipment Refrigerator/ Freezer)	−22°C to 10°C	CFC refrigerant	Oil-free diaphragm compressor
VCD-FE (Vapor compression distillation flight experiment)			Oil free rotary lobe compressor
SKV-1/SKV-2		R218	Micro-compressor with cylinder-piston group, contains lubricant but separated
RC (Refrigerated Centrifuge)	4°C to 20°C	R404A	Oil-less hermetic reciprocating compressor

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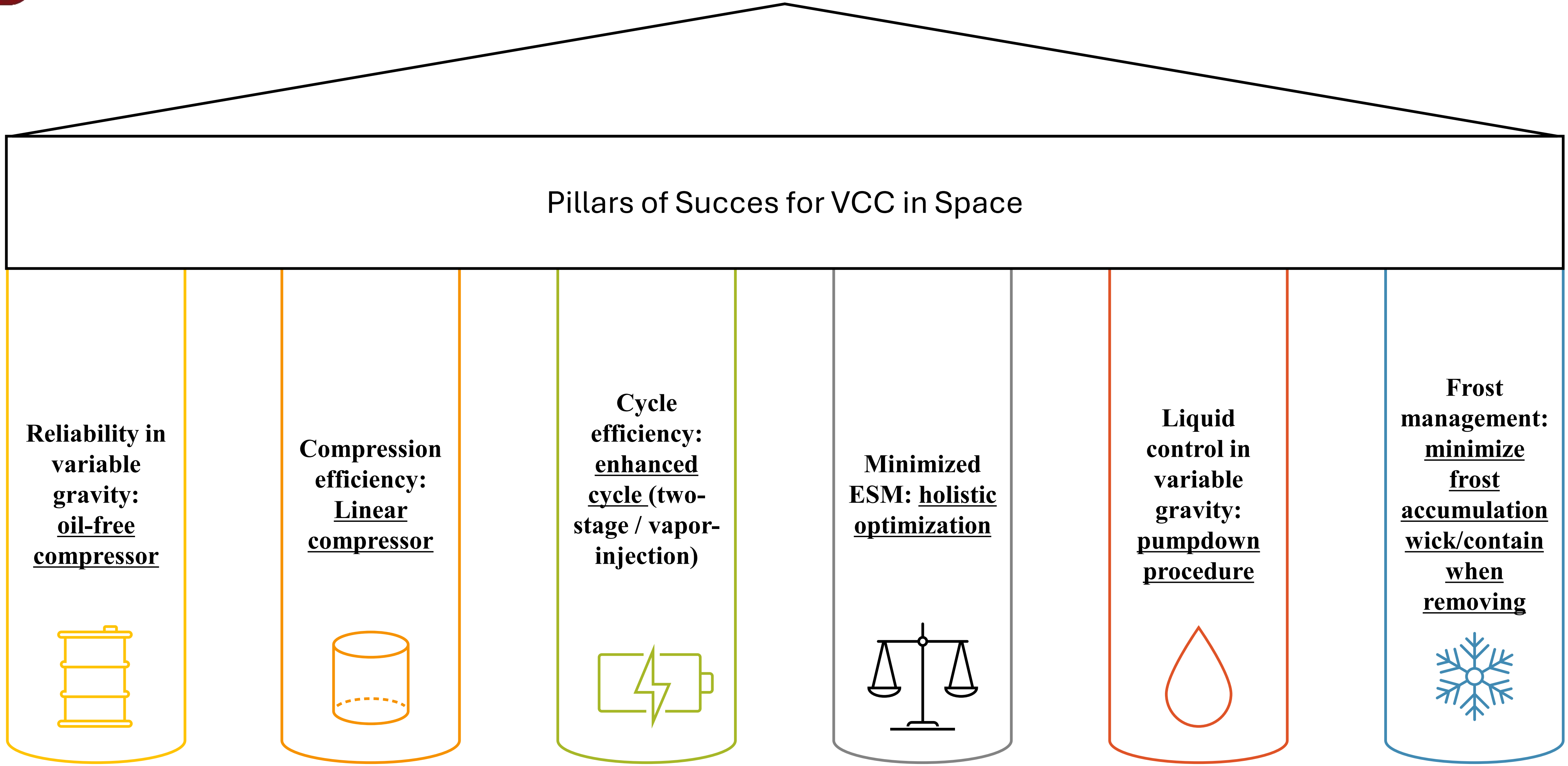
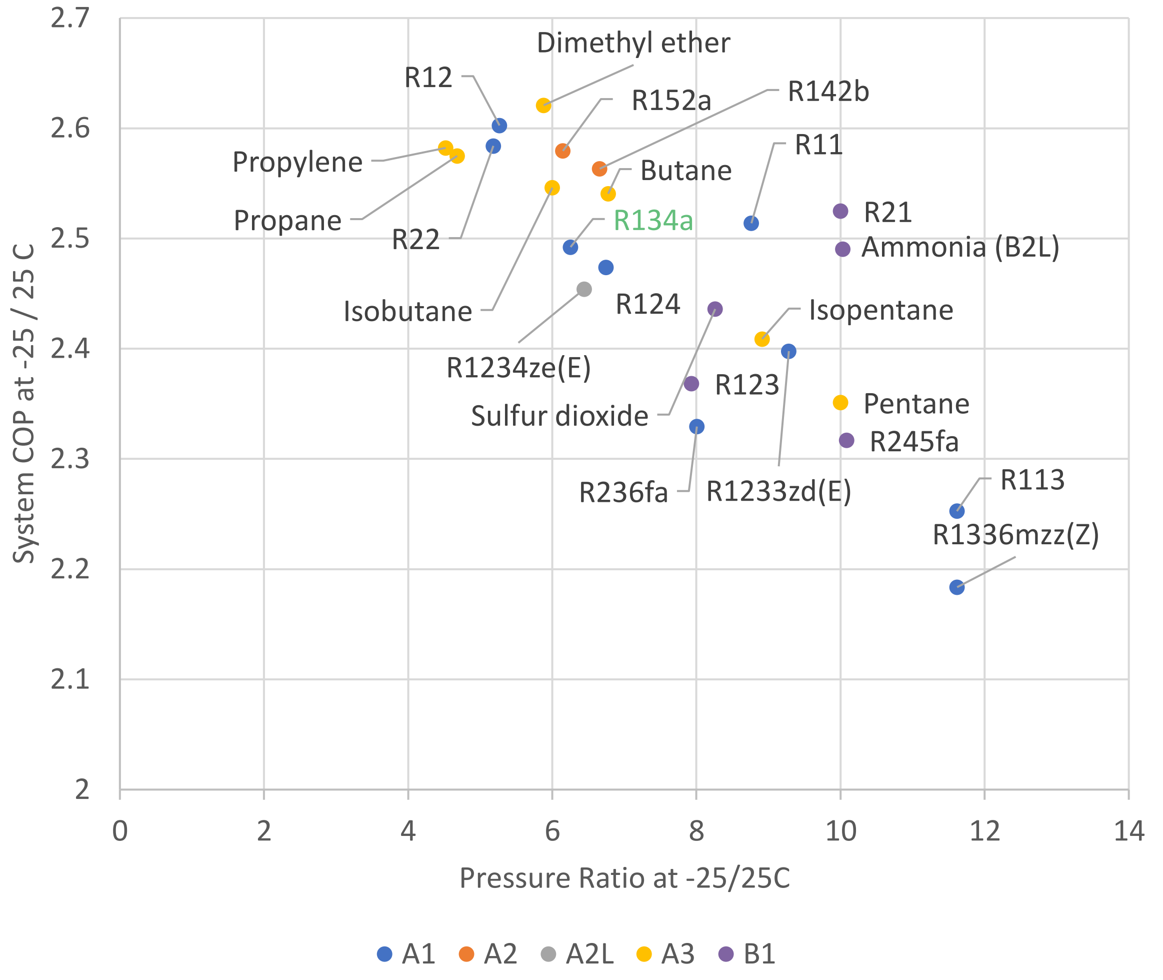
Project Approach



Preliminary Design Process and Decision Making

Refrigerant Selection

- Refrigerant should be: non-flammable, non-toxic, thermodynamically efficient, high heat capacity (low quantity required), operate at reasonable pressures at target temps
- Screening simulations using REFPROP:
- **R134a** selected for good performance, available components, precedent for use (refrigerated centrifuge, past Purdue work)

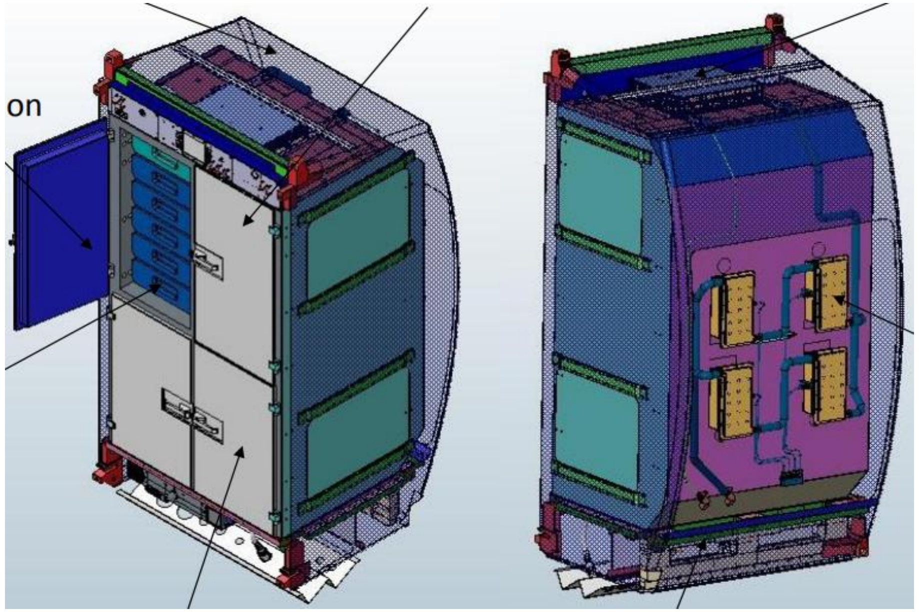


Rough Cabinet and System Sizing

- Nutrition requirements and form factor for Mars mission not finalized/public
- Reference – RFR: 0.615m^3 stowage volume (ISPR: 2m^3 outer volume)

- BVAD: 1.83 kg/CM-d of food x 6 crew x 3 years = 12,023 kg
  - Packed density 480 kg/m^3
  - 25-50% refrigerated/frozen
  - 6.25-12.5m^3

- **Target: 6 modules with order of 1m^3 storage volume**
- ISPR dimensions for reference
- Modules can be added/subtracted (redundancy)

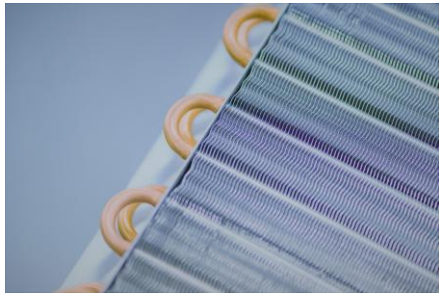


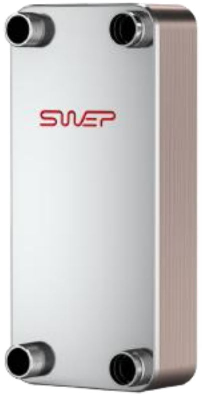
RFR (image from Shepherd, 2014)

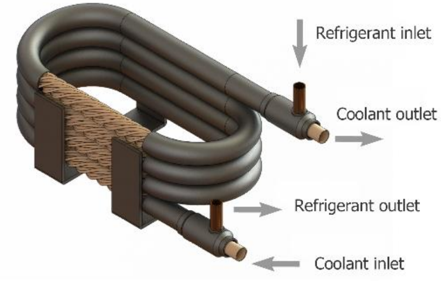
Heat Exchangers

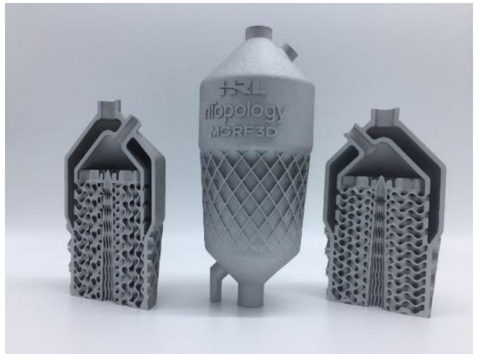
Key considerations:

- Minimize: approach temperatures (maximize heat transfer), flow resistance (fan/pump power), volume, and mass
- Avoid flow maldistribution in variable gravity: single circuits and high Re
- Evaporator: consider tube-fin, microchannel, bare microtube
- Condenser: coaxial tube-in-tube more orientation independent than brazed plate HX (from Brendel, 2021)



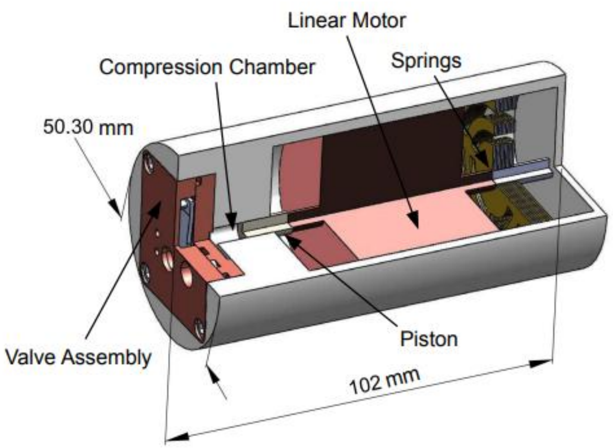




Linear Compressor

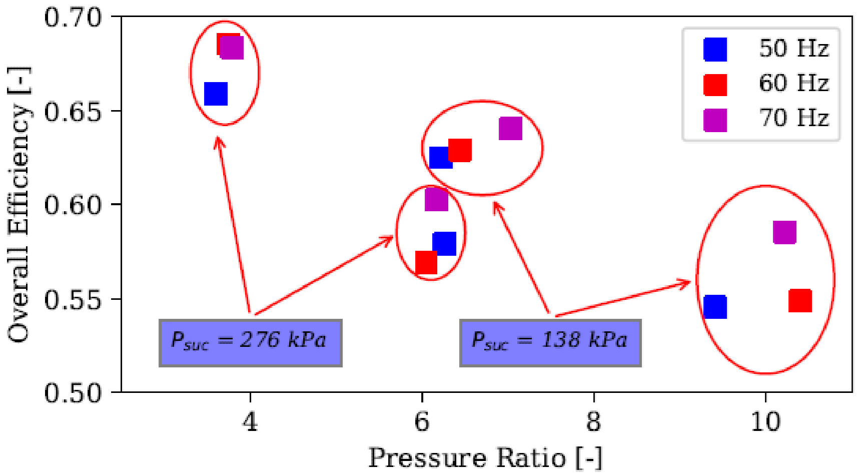
High efficiencies are possible and commercial products available

- Bradshaw, 2012: theoretical designs with volumetric and isentropic efficiencies as high as 0.96 and 0.86, respectively
- Zhang, 2020: measurements of commercially-available linear compressor showed overall efficiencies approaching 70%



(Bradshaw, 2012)

Embraco Wisemotion



(Zhang, 2020)

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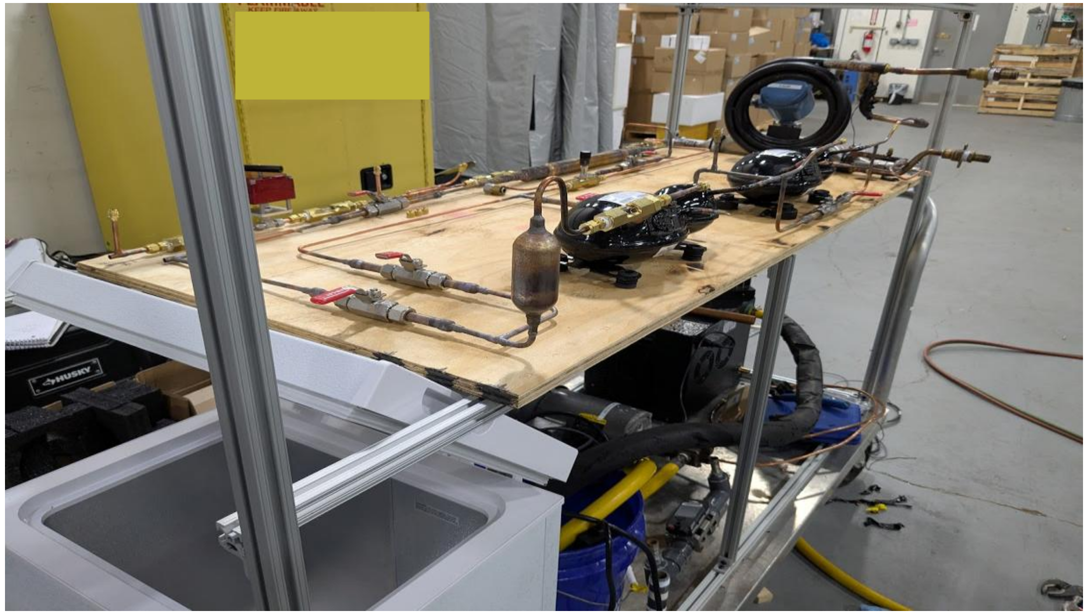
Experimental Work

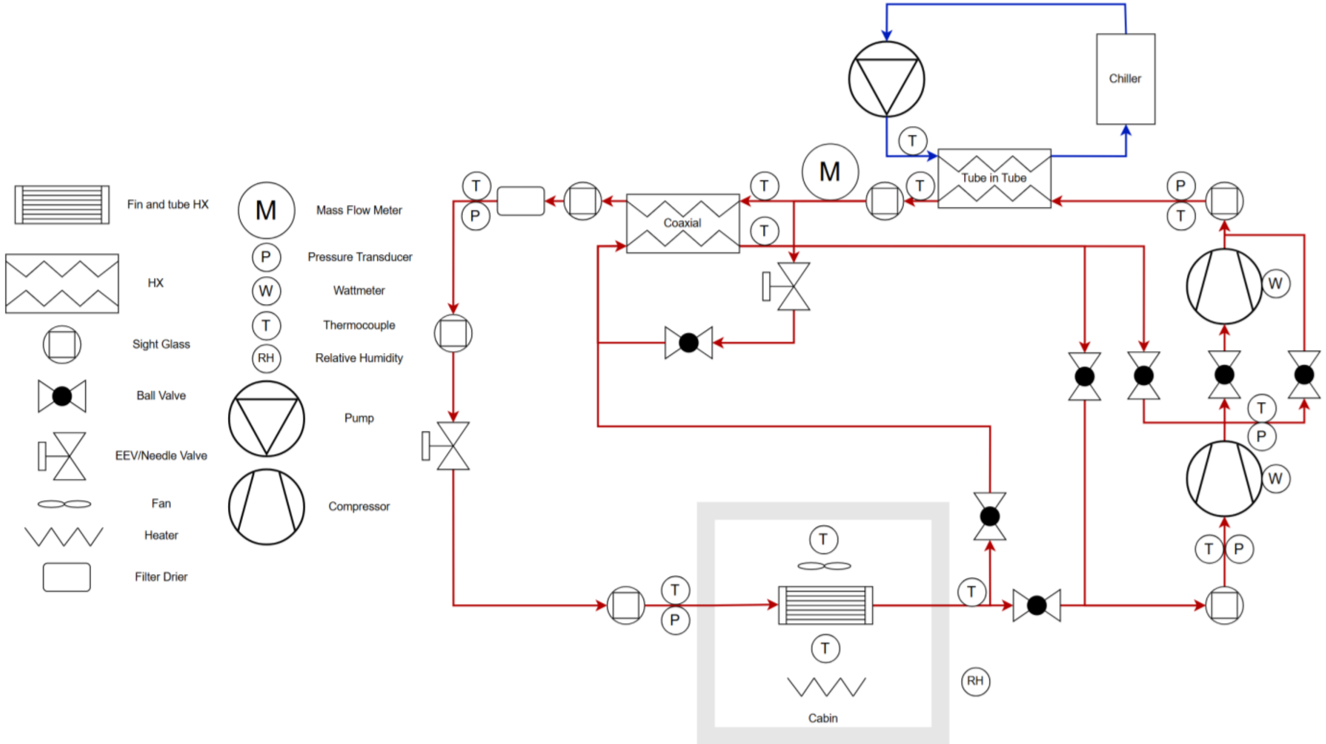
Experimental Plan and Objectives

1. Collect performance data under range of operating conditions
2. Confirm linear compressor efficiency → support modeling/design
3. Evaluate effectiveness of cycle enhancements on efficiency
4. Evaluate pumpdown procedure for reliability
5. Evaluate performance under frost/defrost

	Test No.	Te [°C]	Tc [°C]	Configuration	Compressor	Notes
baseline	1	-5	25	4-component basic	Embraco (1 @60Hz)	Characterize compressor/cycle performance in refrigerator configuration
	2	-25	25	4-component basic	Embraco (1 @ 60Hz)	Characterize compressor/cycle performance in freezer configuration
Repeatability	3	-5	25	4-component basic repeat	Embraco (1 @60Hz)	Determine repeatability of compressor in refrigerator configuration
	4	-25	25	4-component basic repeat alternative compressor	Embraco (1 @ 60Hz)	Determine repeatability of another Embraco compressor in freezer configuration
Other operating conditions	5	-25	25	4-component basic repeat	Embraco (1 @ 60Hz)	Determine effect of superheat in freezer configuration
	6	-35	25	4-component basic	Embraco (1 @ 60Hz)	Characterize compressor/cycle performance at higher pressure lift and superheat
	7	-5	45	4-component basic	Embraco (1 @ 60Hz)	Characterize compressor/cycle performance at different operating point
Cycle enhancements	8	-5	25	Add LL-SLHX	Embraco (1 @ 60Hz)	Demonstrate efficiency benefit of SLHX in refrigeration cycle
	9	-5	17.6	Pseudo 2-stage, Stage 1	Embraco (1 @ 60Hz)	Demonstrate efficiency gains from cycle enhancements at different operating point
	10	17.6	45	Pseudo 2-stage, Stage 2	Embraco (1 @ 60Hz)	Demonstrate efficiency gains from cycle enhancements at different operating point
Other compressor prototype	11	-5	25	4-component basic	Bosch Prototype	Evaluate prototype performance - refrigerator
	12	-25	25	4-component basic	Bosch Prototype	Evaluate prototype performance – freezer
Procedural tests	13	-5*	25*	4-component basic*	Embraco (1 @ 60Hz)	Pumpdown procedure test and hold
	14	-25	25	4-component basic*	Embraco (1 @ 60Hz)	Frost/Defrost Evaluation

Experimental Setup



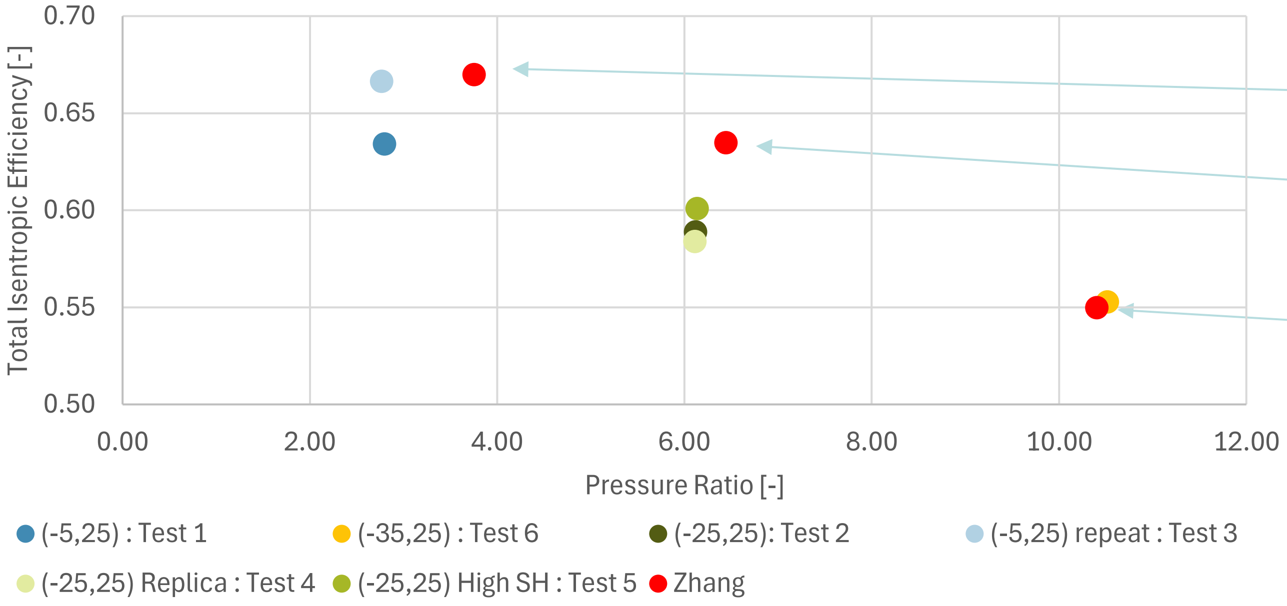


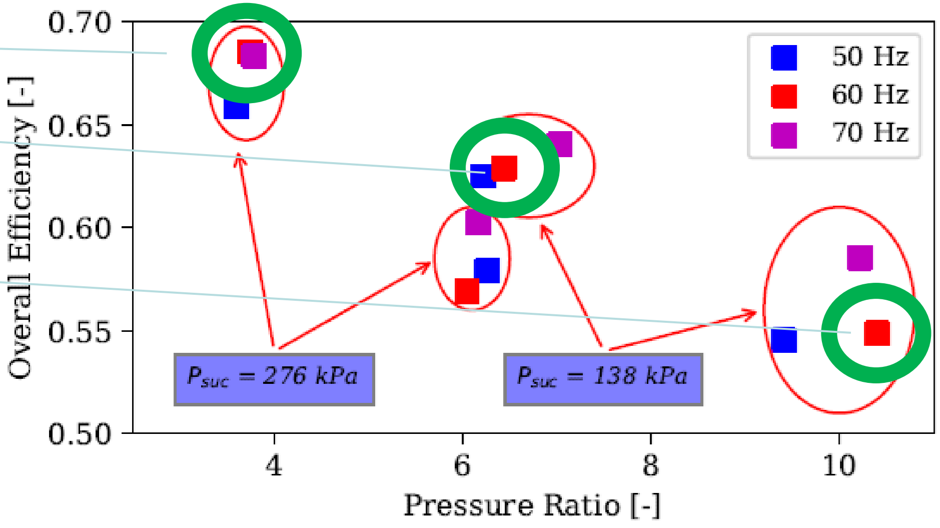
Parameter	Device	Manufacturer	Model No.	Uncertainty
Temperature	Thermocouple	Omega	TT-T-24	±0.5 C
Refrigerant Flow Rate	Coriolis Flow Meter	Emerson	CMFS025M319N2BAEKZZ	± 0.1% *
Pressure	Pressure Sensor	Omega	PX429-500AI	±1.38 kPa
Pressure	Pressure Sensor	Setra	ASM1300PA2M11B3A01	±1.03 kPa
Pressure	Pressure Sensor	Omega	PX559-250AC2IS	±17.24 kPa
Pressure	Pressure Sensor	Wika	S-10	±2.76 kPa
Pressure	Pressure Sensor	Setra	ASM1300PA1M11B3A01	±1.03 kPa
Coolant Flow Rate	Ultrasonic Flow Meter	Keyence	FD-H32	± 3%
Power	Wattmeter	Ohio Semitronics	GH-131E	±0.2%
Relative Humidity	RH Sensor	Rotronic	HC2A-S3	±0.8%

*Uncertainty increases to ~1-2% at specified flow range

Refrigerator/Freezer Baseline – Comp. Eff.

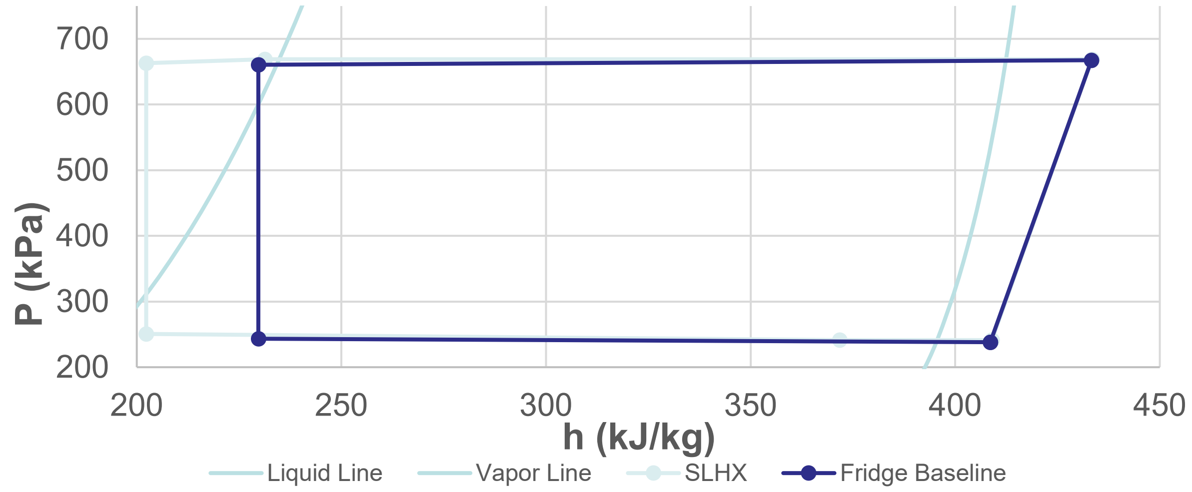
- Refrigerator condition (-5,25) has 4% absolute difference with repeat test and average of two tests has 2% absolute difference with Zhang at similar point
- Freezer condition (-25,25) has 1% absolute difference with repeat test and average of two tests has 5% absolute difference with Zhang at similar point
  - Higher superheat condition with slightly higher efficiency
  - Uncertainty ~3-7% absolute
- Higher pressure ratio freezer condition (-35,25) closely matched with Zhang



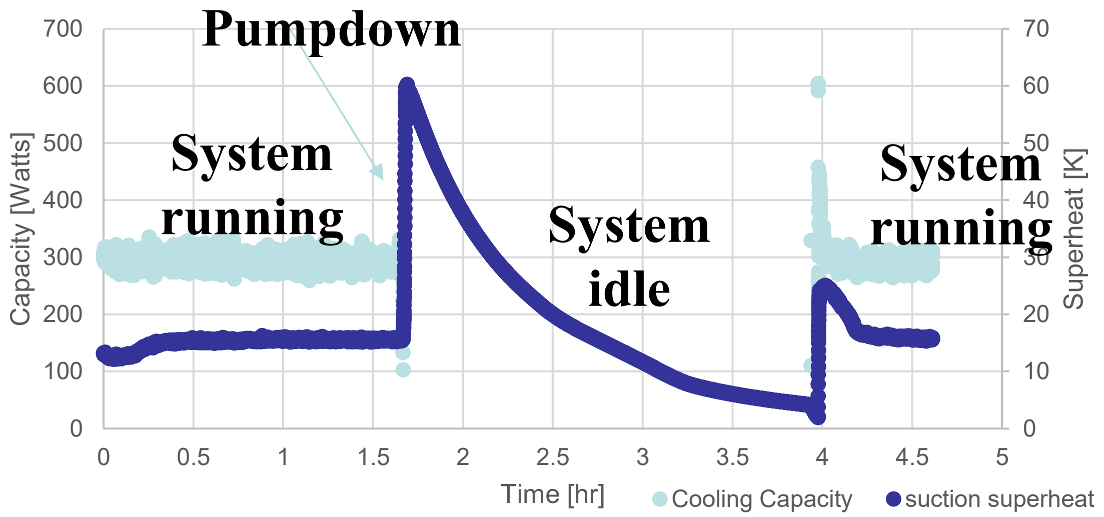


Specialty Testing: SLHX, Pumpdown, Frost

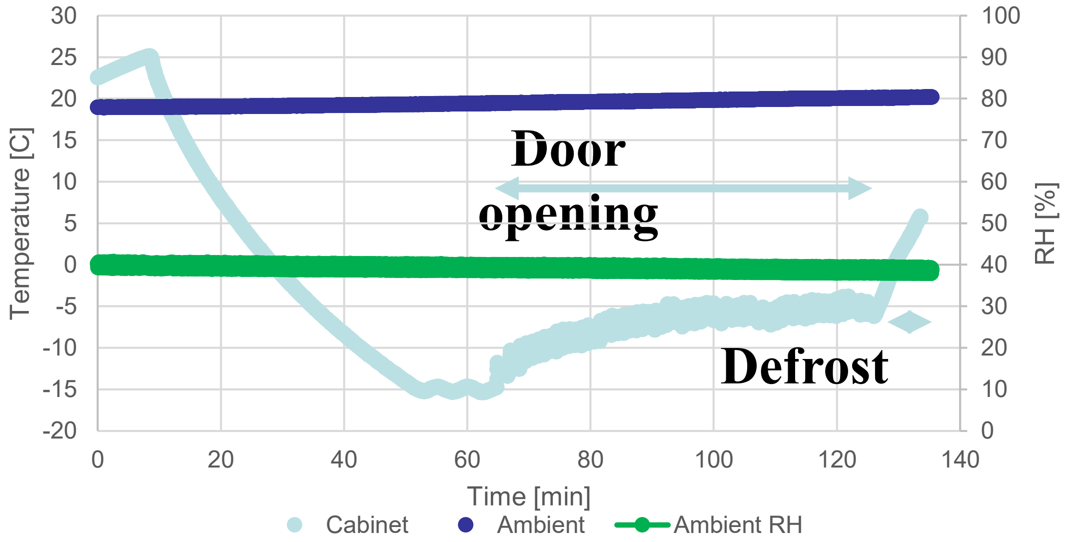
- 3.6% improvement in COP at the same superheat
  - 49% vs 51% of Internal (Refrigerant) Carnot COP



- Pumpdown was effective at preventing liquid slugging



- Impacts of door openings measured
- Assessed time required for defrost



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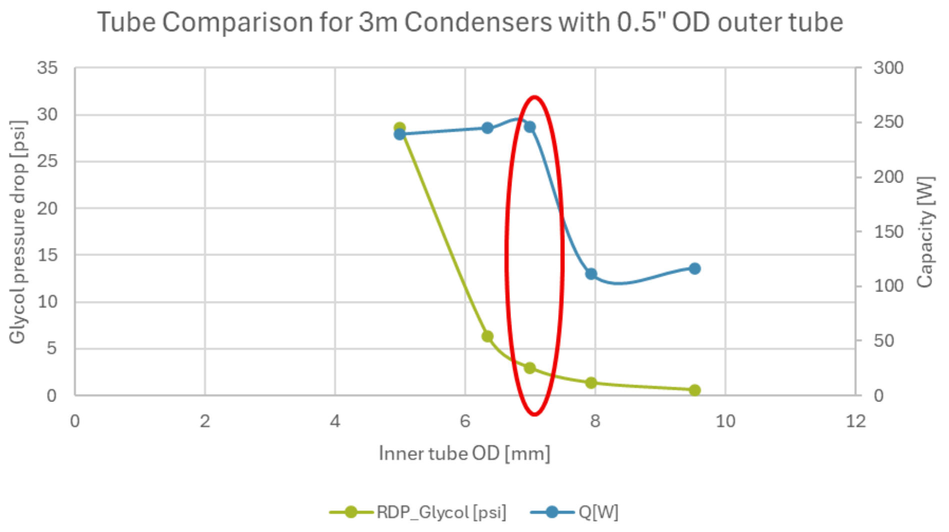
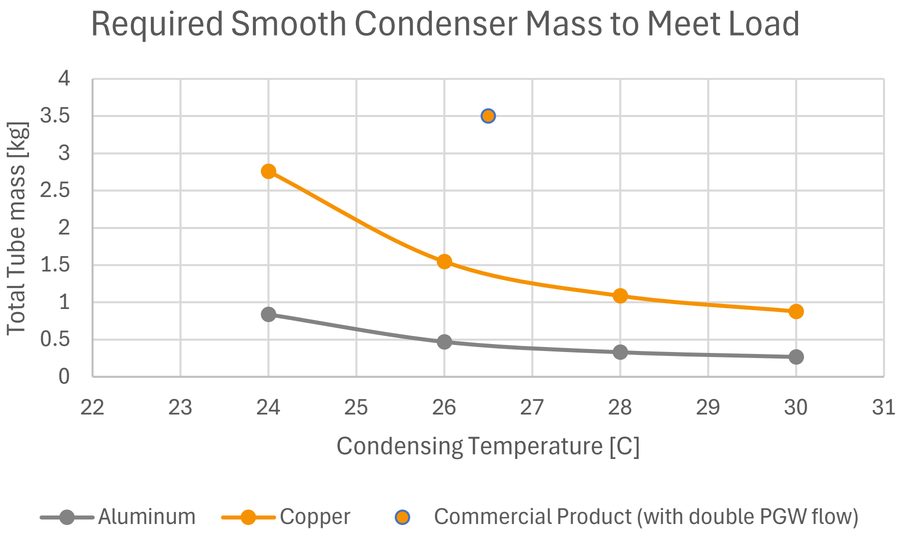
Design Refinement

Condenser Design

- Coaxial style HX design

- Tailoring tube diameters to available flows to balance thermal-hydraulic performance





- Potential mass reduction through diameter reduction and copper→ aluminum (if inhibited PGW)

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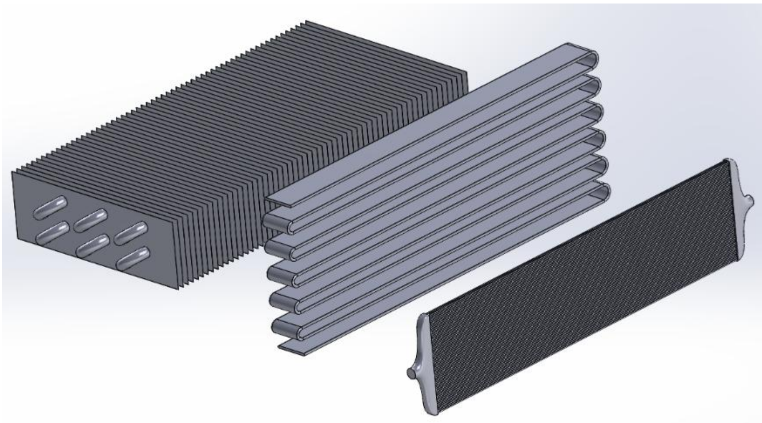
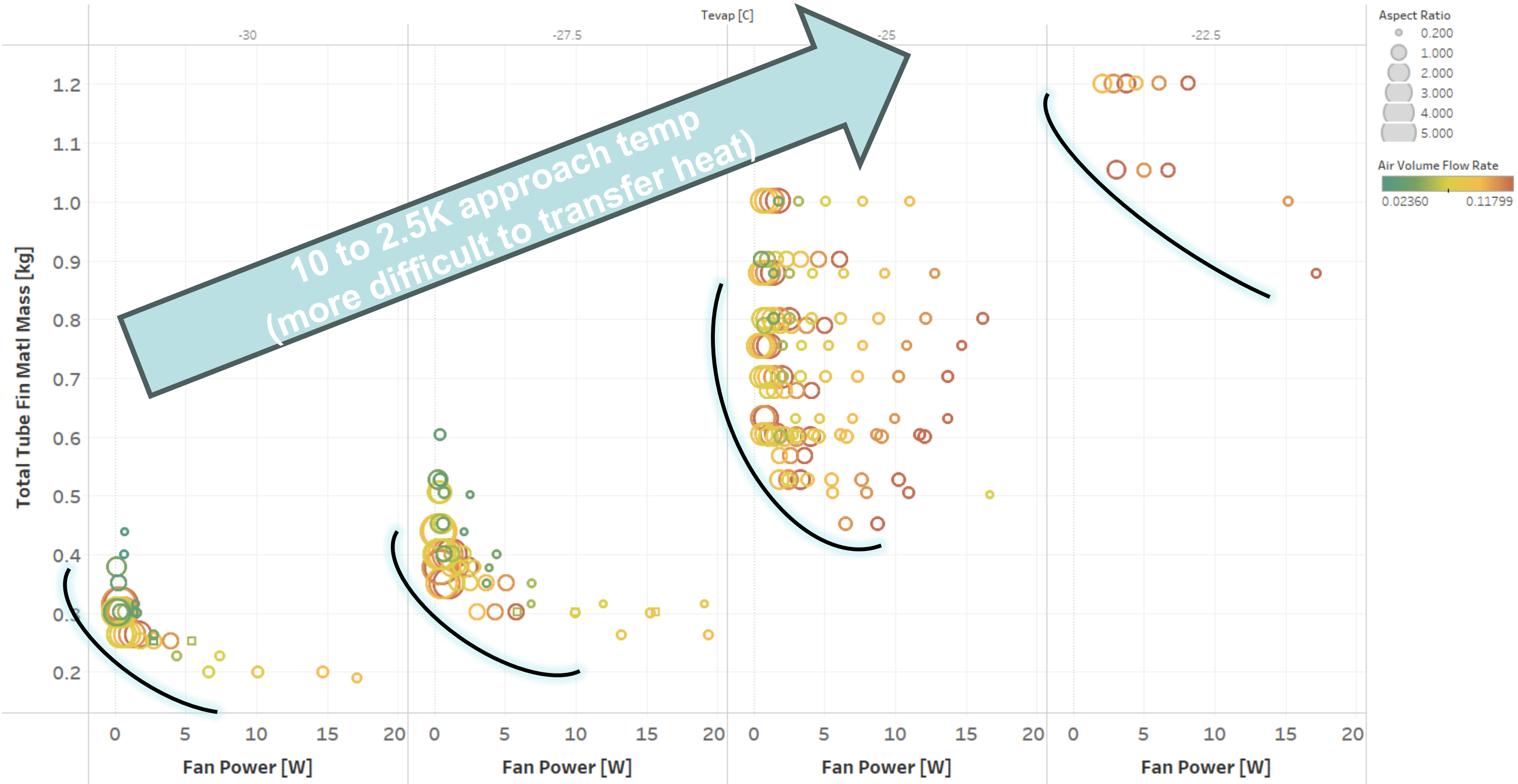
Evaporator Optimization

- Tube fin, microchannel, bare tubes: over 100,000 simulations run



- Tube fin results (freezer conditions, 250W)
- Designs with large aspect ratio (taller transverse to airflow) have lower fan power
- Achieving lower approach temperatures requires more mass and/or air flow rate

Fan Power vs Heat Exchanger Mass



Fan Power [W] vs. Total Tube Fin Matl Mass [kg] broken down by Tevap [C]. Color shows details about Air Volume Flow Rate. Size shows details about Aspect Ratio. Shape shows details about Baseline. Details are shown for various dimensions. The data is filtered on Air Velocity, which ranges from 1 to 7.741945820. The view is filtered on Heat Load, Tevap [C], Overall Outlet Saturation Delta, Avg Saturation Temperature Drop and Fan Power [W]. The Heat Load filter ranges from 240.000 to 252.000. The Tevap [C] filter keeps 8 members. The Overall Outlet Saturation Delta filter ranges from 2.000 to 9.537. The Avg Saturation Temperature Drop filter ranges from 0.533 to 2.000. The Fan Power [W] filter ranges from 0.16 to 20.00.

Note: *Ideal* Fan Powe

System Evaluation

- Simplified system model used to evaluate all combinations of selected components. Estimates power consumption and equivalent system mass

Evaporator + Fan

45 options:
8 TF
3 MC
4 Bare Tube
X 3 fan speeds each

Compressor
4 Options:

1. 10% lower η than Embraco
2. Equivalent to Embraco
3. 2 Embraco compressors in series
4. Theoretical: VI with 5% higher efficiency

Insulation

Polyimide AC-550H
3 Thicknesses:

1. 2”
2. 3”
3. 4”

Suction Line HX

2 Options:

1. With
2. Without

Condenser

4 Options:

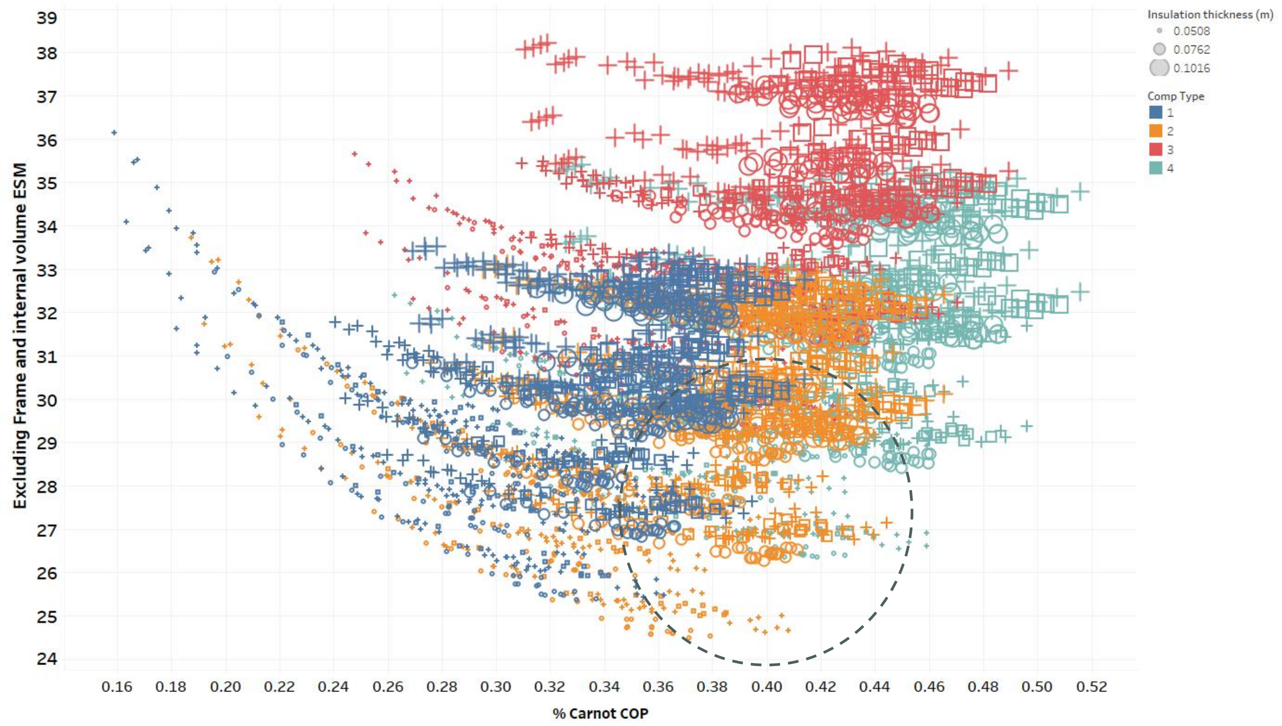
1. Commercial option
2. Al with 3K approach
3. Cu with 3K approach
4. Cu with 5K approach

ESM: 1 kg/kg + 18 kg/m^3 + 69 kg/kW

4320 Combinations to evaluate

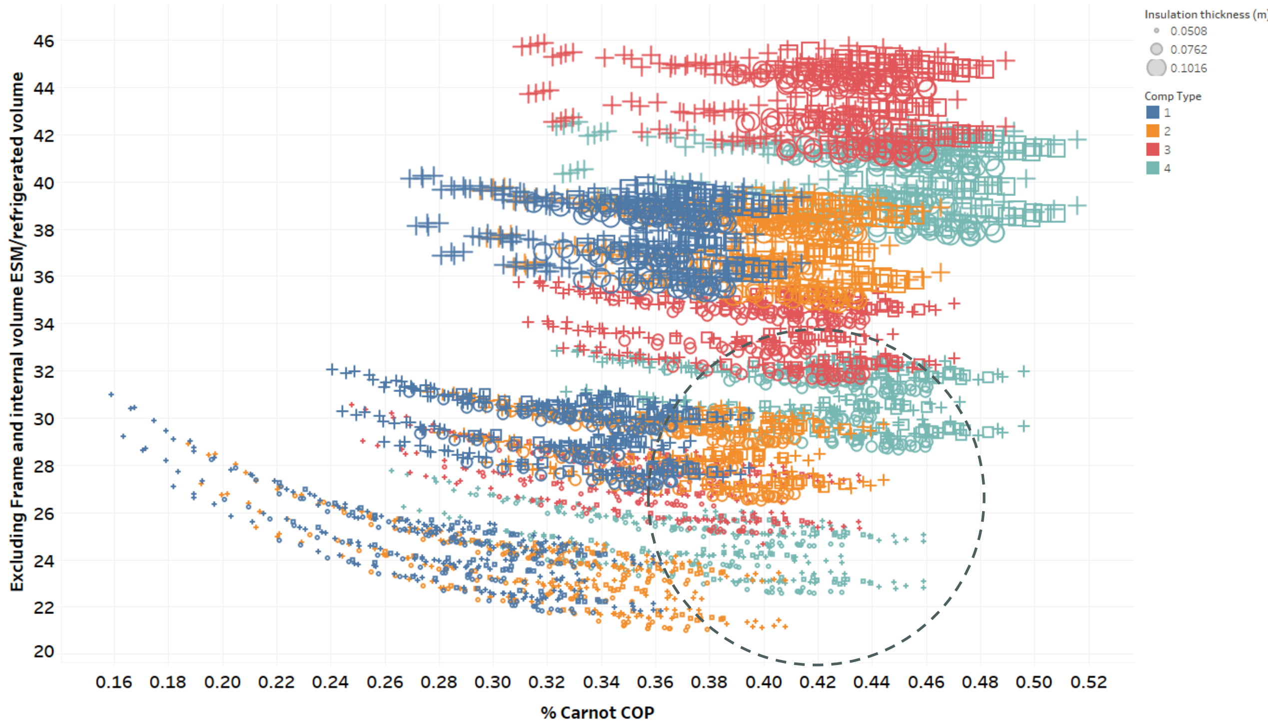
System Selection

ESM vs % Carnot COP



% Carnot COP vs. Excluding Frame and internal volume ESM. Color shows details about Comp Type. Size shows details about Insulation thickness (m). Shape shows details about Evaporator Type.

ESM/Refrigerated Volume vs % Carnot COP



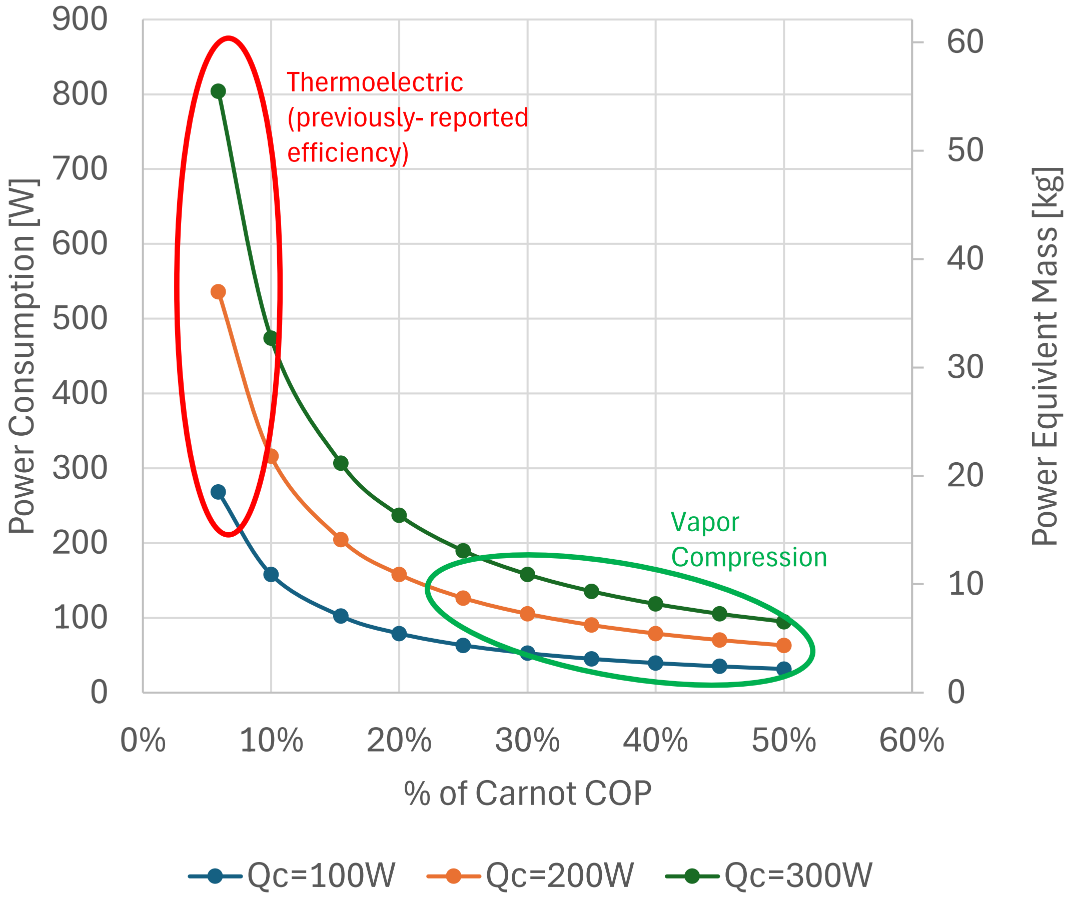
% Carnot COP vs. Excluding Frame and internal volume ESM/refrigerated volume. Color shows details about Comp Type. Size shows details about Insulation thickness (m). Shape shows details about Evaporator Type.

Synthesis

- Most important: achieving 45% of Carnot COP is possible with vapor compression, but it is not necessarily optimal in terms of ESM. High-efficiency designs require heavier components, not always justified by power savings
  - Cycle enhancements like SLHX and two-stage compression can improve efficiency and reduce power, but often increase weight more than equivalent power savings
- Larger evaporators, higher airflow rates preferred
- Largest, aluminum condenser preferred
- Insulation: increasing thickness reduces power, but power-mass penalty and insulation properties determine if it’s worthwhile
- Viable, attractive design configurations are possible with conventional / current state-of-the-art components

Key Contributions

- Holistic model-based design and optimization allows for informed decision making & component selection
- Experimental confirmations of: high efficiency of linear compressor, effectiveness of pumpdown procedure for restart reliability in variable orientation/gravity
- Achieving 45% Carnot is possible but not ESM-optimal. Transitioning from thermoelectric to vapor compression offers considerable power and ESM savings, but the difference between VCCs at 30 and 50% of Carnot COP is much smaller!



Thank you for your attention

For additional questions, please contact

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Backup Slides

Background: Recent Devices

RFR designed for ISS

- Thermoelectric-based
  - COP: 0.373 (Müller, 2002)
  - ~5% of Carnot COP (~7)
- Cancelled in 2002

	Units	Freezer Mode	Refrig./Freezer Mode
Unit Mass	kg	321.0 (1)	321.0 (1)
Secondary Structure Mass	kg	91 (2)	91 (2)
Volume, Including Rack	m³	2.00 (3)	2.00 (3)
Volume, Without Rack	m³	1.16 (3)	1.16 (3)
Power	kW	0.268 (4)	0.205 (4)
Thermal Energy Management	kW	0.297 (4)	0.228 (4)
Crewtime	CM-h/y	0 (1)	0 (1)
Logistics	kg/y	321.0 (1)	321.0 (1)
Internal Load	kg	295 (1)	295 (1)
Internal Volume	m³	0.614 (1)	0.614 (1) 81

Air-Squared/Purdue Prototype

- Vapor compression with oil-free scroll compressor
  - COP not published, >1.2 in bench tests
- SBIR project, demonstrated in parabolic flights

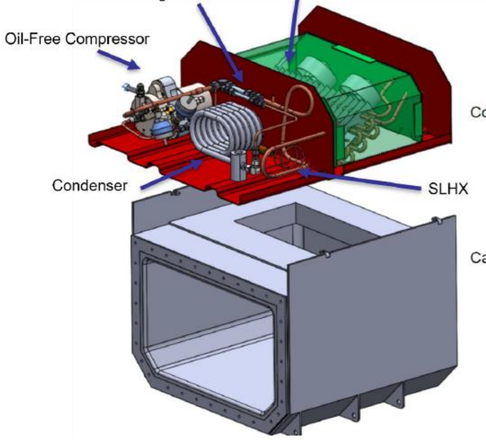


Figure 1: CAD Model of Refrigeration System Final Design

Background: Efficiency Context

- Solicitation calls for COP of 45% of Carnot Limit:
- Refrigerator 2.8/50°C: **2.63** ; Freezer -25/25°C: **2.23**
- Much higher than state-of-the-art cooling equipment of any type
  - Possamai & Todescat, 2004: analysis of domestic refrigerator: 1.85 COP (34% of Carnot 5.49)
  - Qian et al. 2016: review of not-in-kind cooling technologies: VCC 20-27% of Carnot
  - US DOE Minimum Efficiency Standards (AWEF) translate to 16~18% of Carnot

$$COP_{Carnot} = \frac{T_C}{T_H - T_C}$$

Table 3 – Quantitative comparison of NIK cooling technologies.

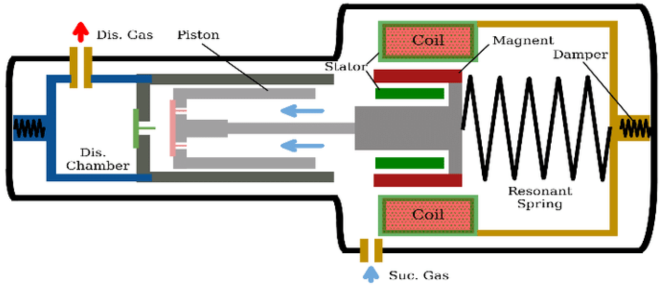
Technology	Φ_{mat}	Φ_{sys}	$\Phi_{mat} \cdot \Phi_{sys}$	$\Phi_{mat,max}$ at ΔT_{lift}	$\Phi_{sys,max}$ at ΔT_{lift}	$(\Phi_{mat} \cdot \Phi_{sys})_{max}$ at ΔT_{lift}
		at $\Delta T_{lift} = 10$ K				
Vapor compression (baseline)	0.88	0.23	0.20	0.94 at 37 K	0.30 at 23 K	0.27 at 24 K
Elastocaloric (single stage)	0.63	0.21	0.14	1.00 at ∞ K	0.22 at 13 K	0.16 at 17 K
Magnetocaloric (AMR)	0.91	0.32	0.29	1.00 at ∞ K	0.33 at 9 K	0.30 at 9 K
Electrocaloric	0.41	n/a	n/a	1.00 at ∞ K	n/a	n/a
Thermoelectric	0.20	0.53	0.13	0.21 at 5 K	0.70 at 5 K	0.15 at 5 K
Stirling	1.00	0.04	0.04	1.00	0.12 at 64 K	0.12 at 64 K
Brayton	0.08	0.27	0.02	1.00 at ∞ K	0.32 at 82 K	0.15 at 130 K

Qian et al. 2016

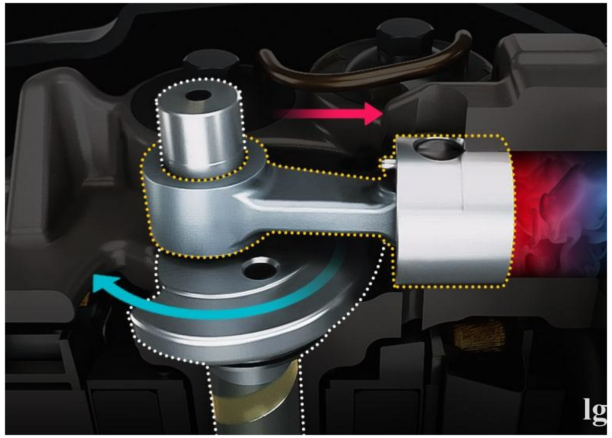
Compressors

1. Must operate reliably without oil
2. Must achieve high efficiencies

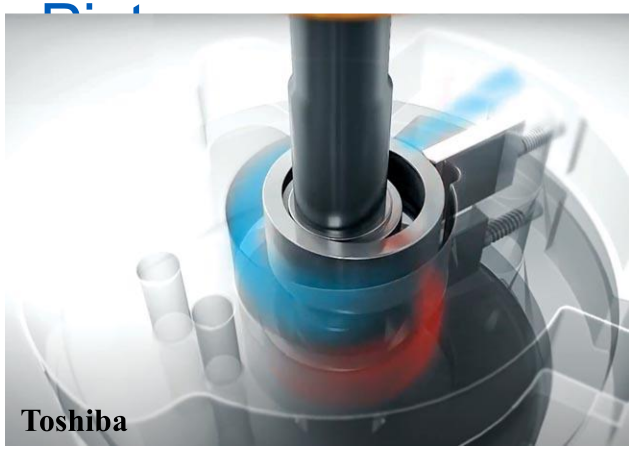
Linear



Reciprocating/Pisto



Rotary/Rolling



Scroll

Multiple moving parts, bearing surfaces; require oil, higher losses (typically)

Linear actuator, one moving part. Piston can be centered with gas bearing, spiral flexure bearings, etc.

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