2024 ICEC-ICMC

100 K Performance of a Modified Collins Cycle Cryocooler for In-space Applications

In this talk:

1. Modified Collins Cycle & Floating Piston Innovation
2. Projected Cycle Efficiency & Prior Effort Challenges
3. Expander Construction Materials & Enabling Technologies
4. Experimental Results & Control System Performance

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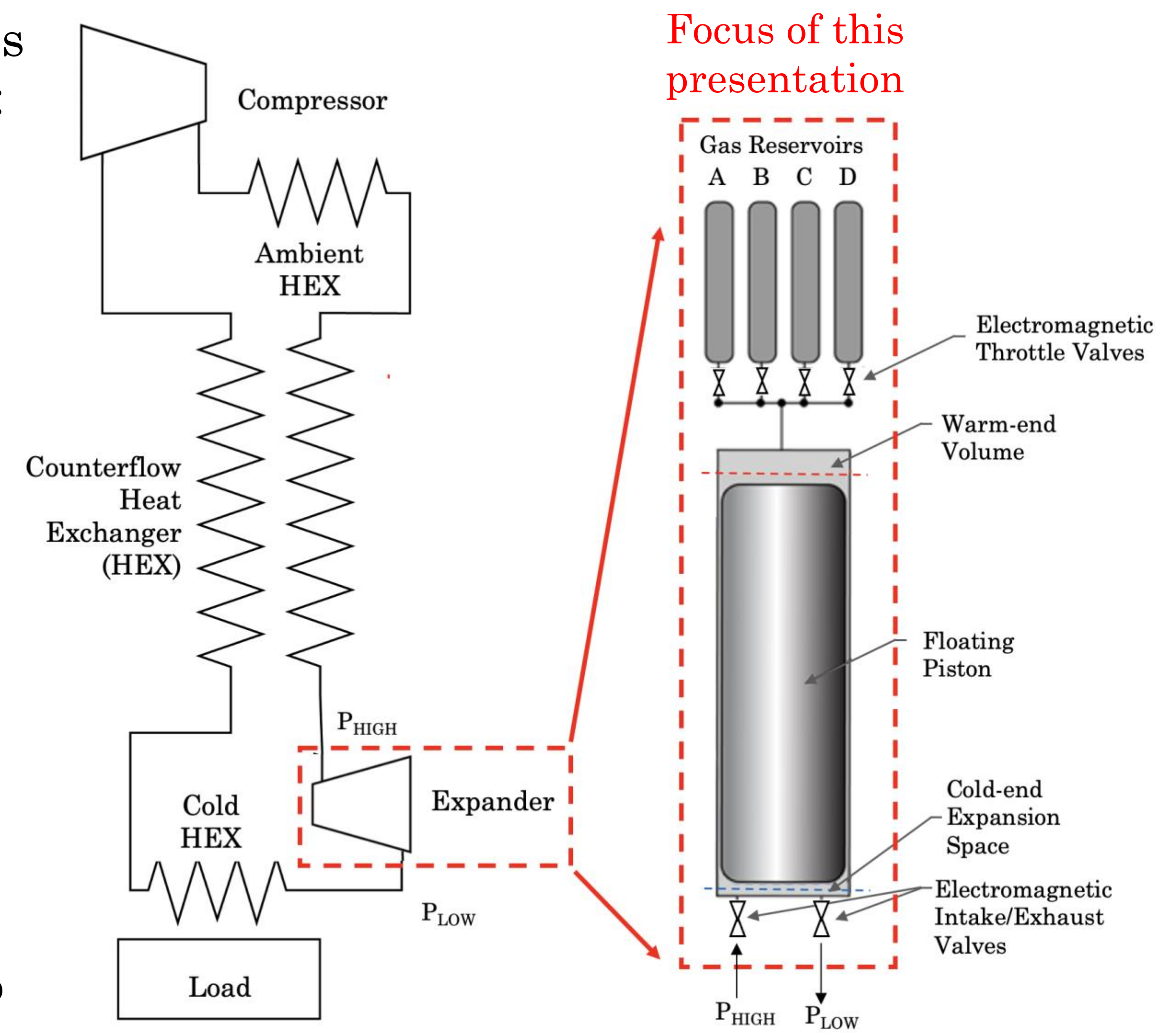
Modified Collins Cycle & Floating Piston Innovation

Medium-scale, continuous flow cryocooler featuring:

- Floating piston architecture
- Active control system
- Gas reservoir throttles dissipate the mechanical energy transferred from cryogenic temperature to room temperature by the floating piston

This approach:

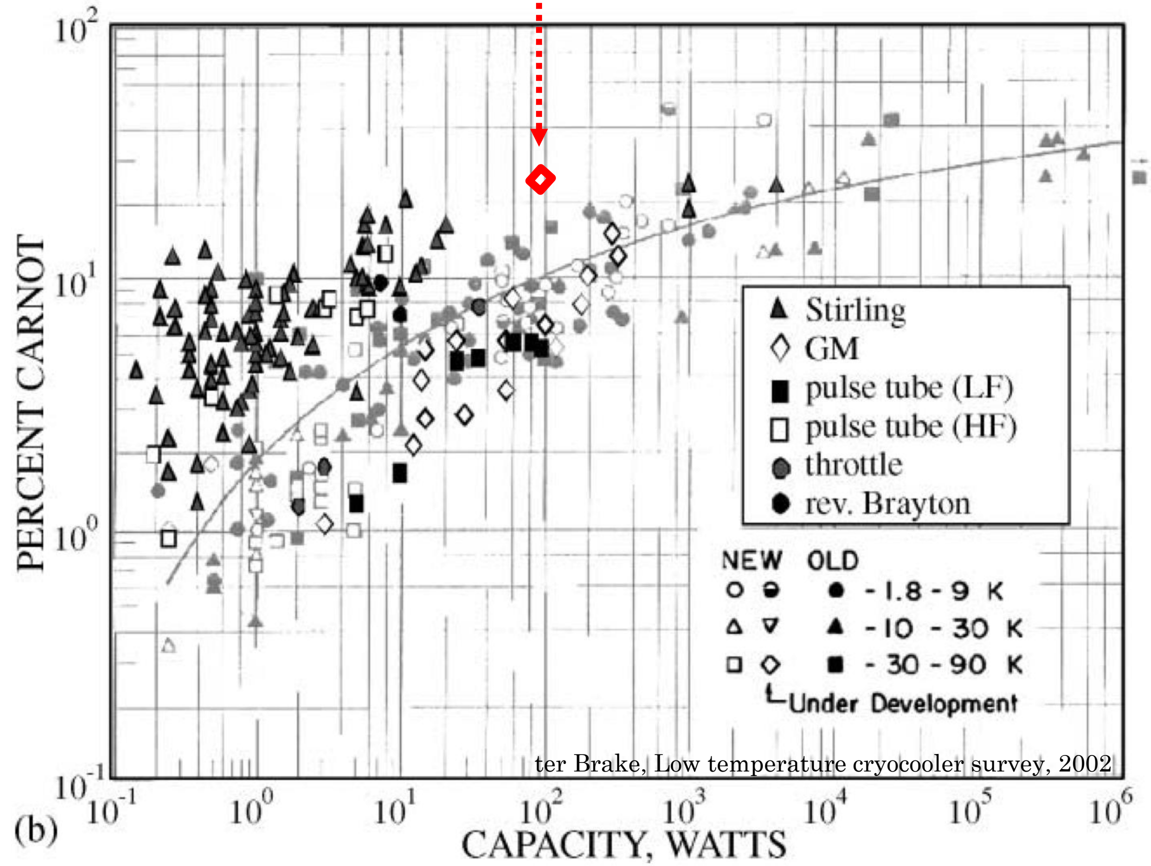
- Enables high expander efficiency (75%+)
- Allows high-pressure-ratio operation (10:1 to 15:1)



Demonstrated operation reported at 2023 CEC-ICMC

Projected Cycle Efficiency & Prior Effort Challenges

2nd law efficiency projection: 20-25% [1]



→ Projected efficiency: ~2.5x mean Strobridge efficiency curve

Prior efforts:

- Hannon demonstrated 10 K cycle operation (with pre-cooling @ 30 K) [2]

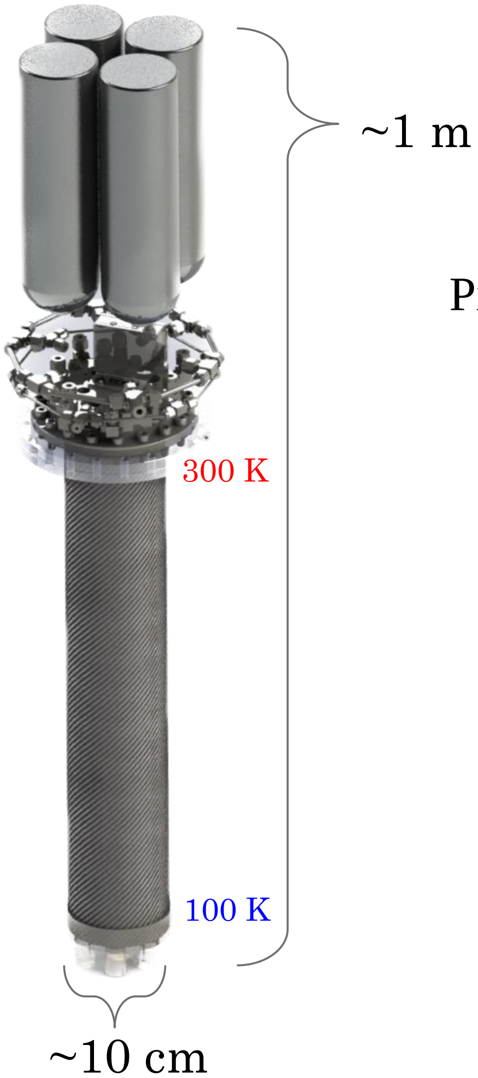
Identified improvement areas:

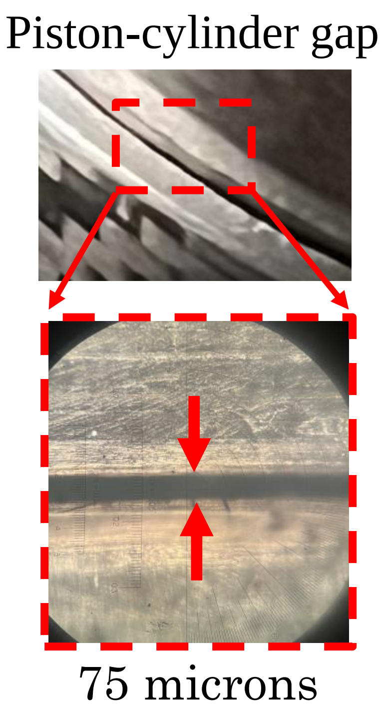
- Mechanical reliability
- Real-time control hardware
- Reservoir pressure stabilization

[1] M. Segado, Masters Thesis, MIT "Analysis and Mitigation of Key Losses in a Multi-Stage 25–100 K Cryocooler", 2014.
[2] C. Hannon et al., "Development of a 4K-10K Collins-type cryocooler for space", 2005.

New Floating Piston for High Reliability

- First time demonstration of vacuum-insulated lightweight piston
  - Hollow graphite-epoxy composite with Invar coating (helium barrier)
  - Previous work with G10 piston had reliability issues
- Lightweight piston eliminates warm end seal and minimizes blowby
- CTE matched piston-cylinder to avoid jamming
- Composite material system minimizes heat leak due to large axial temperature gradient (300 K to 90 K)

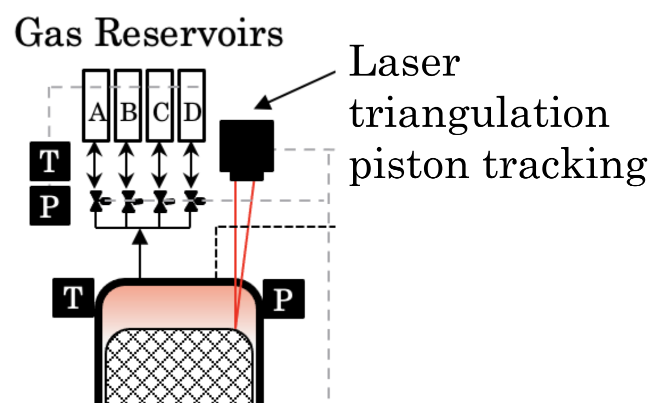




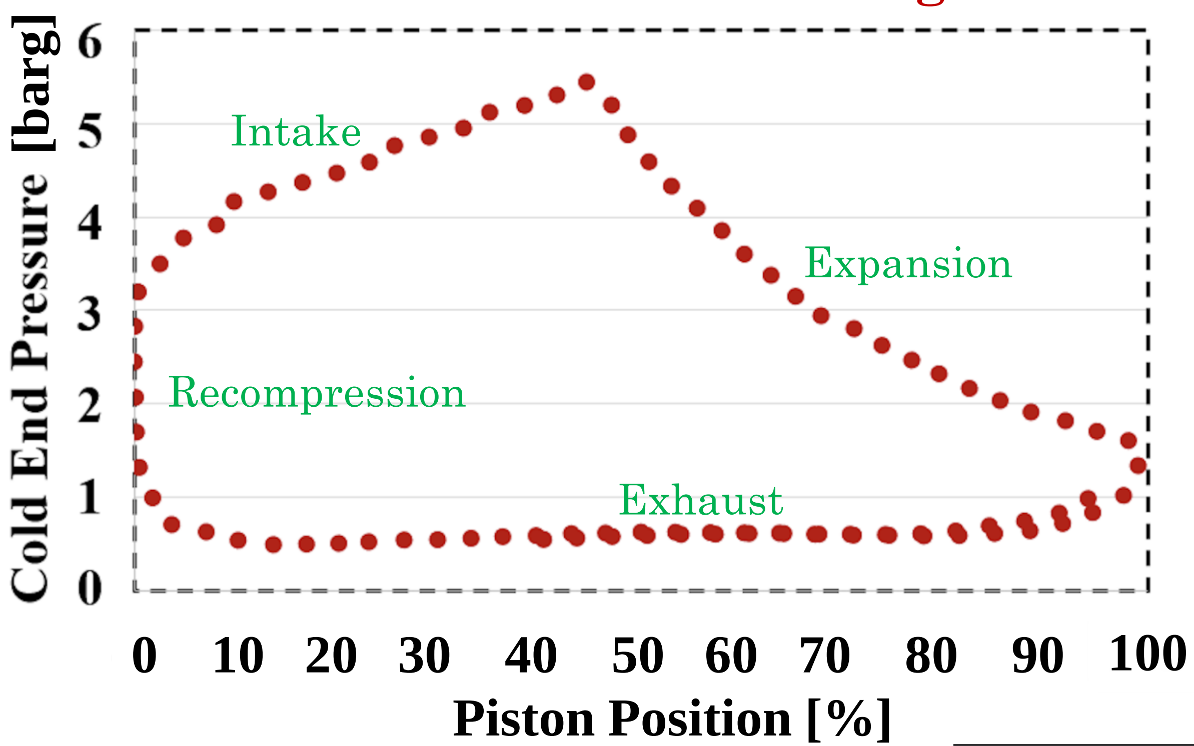
Result: High reliability (in-space applications)

Enabling Technologies

- Laser triangulation piston tracking input
  - ± 60-micron accuracy to minimize clearance volume
- Real-time control unit (FPGA)
  - Sequential reservoir opening/closing based on pressure and piston position data [3]
- Fast acting commercial solenoid valves
  - Low flow resistance
  - ~1 billion cycle lifetime



Near ideal measured P-V diagram

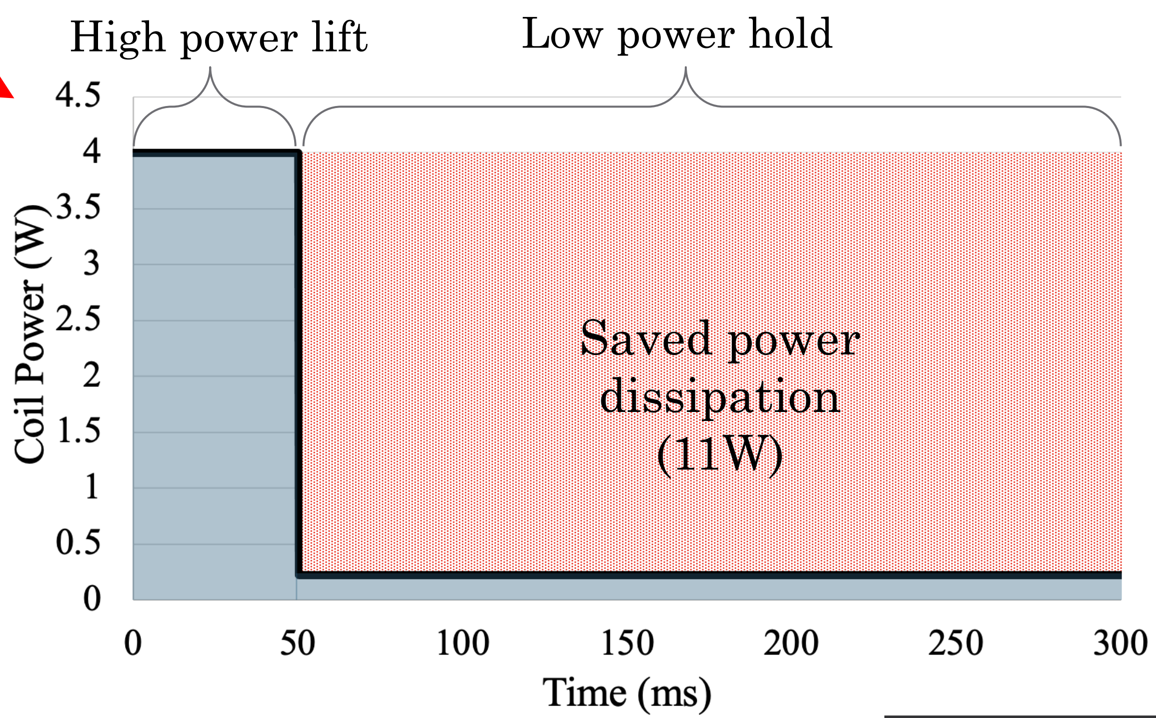


[3] J. Hogan, Masters Thesis, MIT "Development of a Floating Piston Expander Control Algorithm for a Collins-Type Cryocooler", 2011.

Reducing Power Dissipation in the Cold Valves is Key

- Fixed voltage valve actuation does not allow efficient operation
- System controls valves using a short "high" voltage lift pulse followed by a longer low voltage hold pulse
- Current implementation results in a 4-fold decrease in power dissipated by the valves
- FPGA control unit allows real-time valve control

Valve power management board



11 W cooling power savings (11% at 100 W total lift)

Cryogenic Apparatus Overall Setup

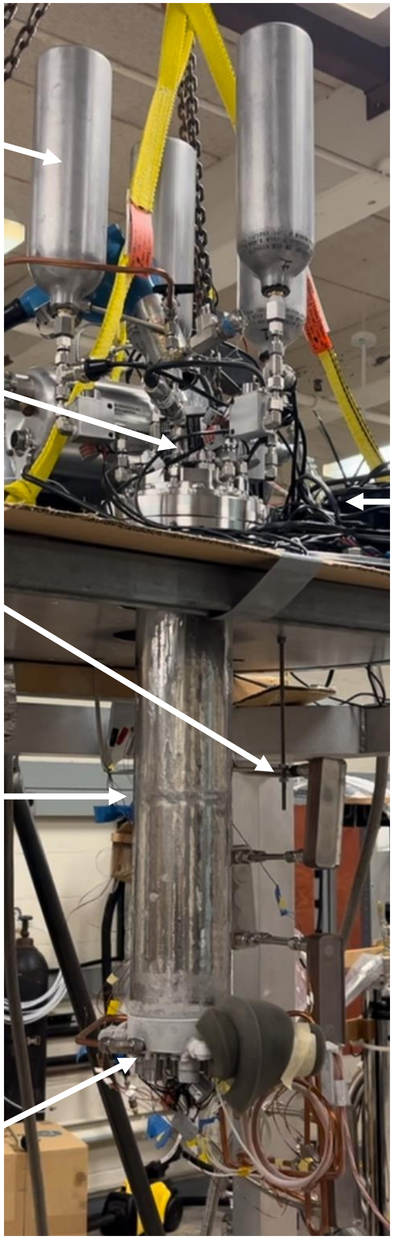
Gas Reservoirs & Instrumentation

Warm End Valves

Counterflow HEX

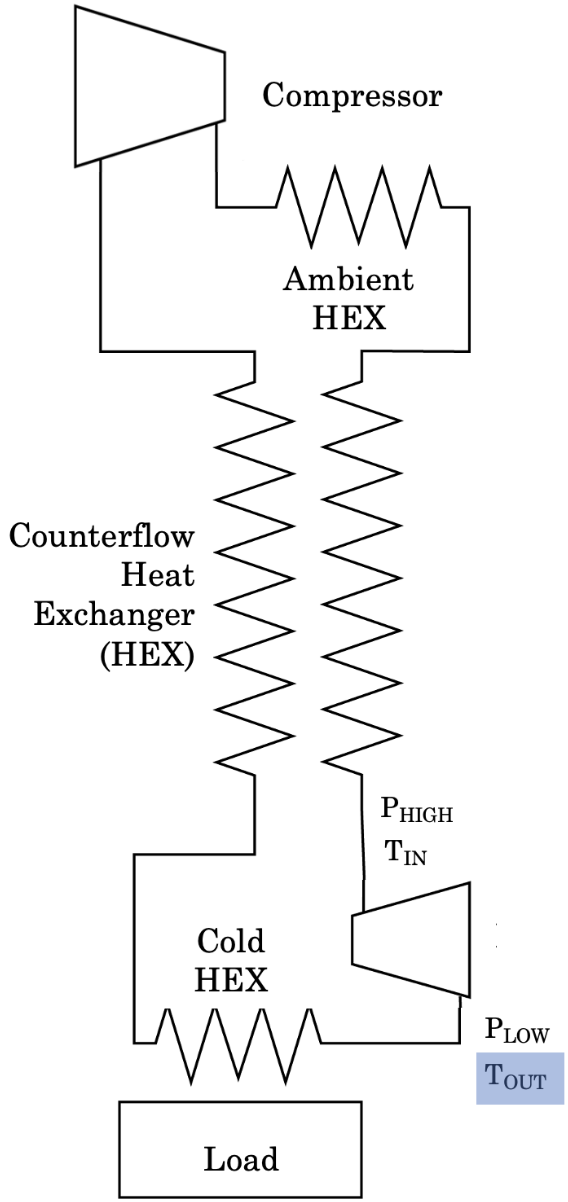
Invar covered carbon fiber cylinder & piston

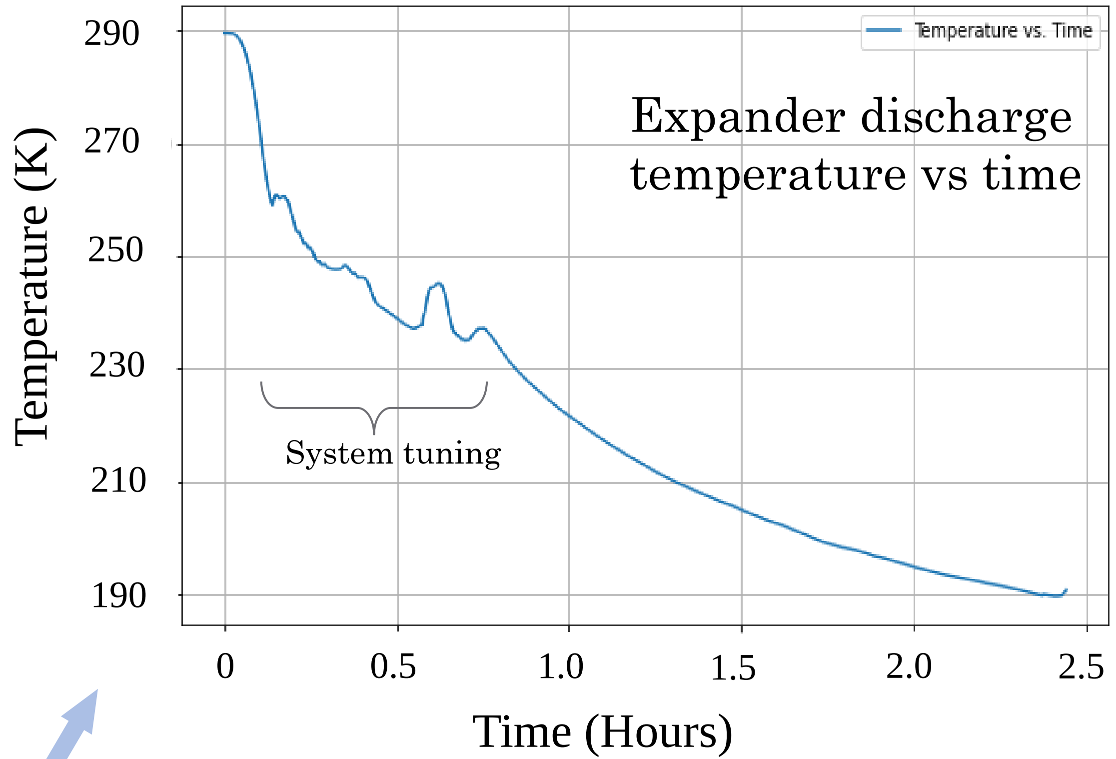
Cold End Valves



Control System Hardware

Prototype Cooldown Test



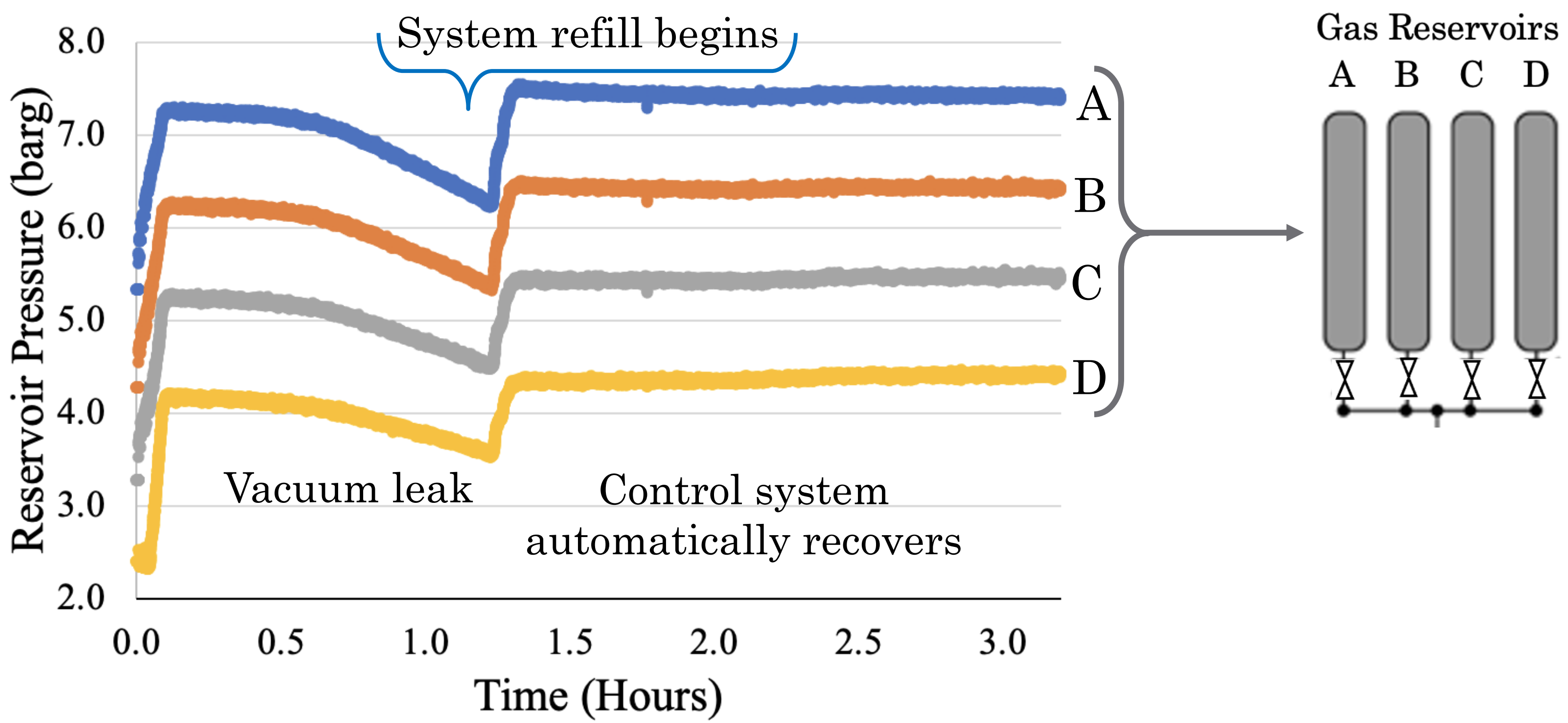


Operating Conditions:

- Pressure ratio of 2.5 : 1
- 3 Hz operating speed
- Ultimate temperature limited by leak into the vacuum space

Robust Control and Operation

- Stable and distributed reservoir pressures and automatic system recovery are critical to efficient operation
  - Previous work did not achieve this in a closed system



Current control system is robust and stable in both steady state and against adverse events

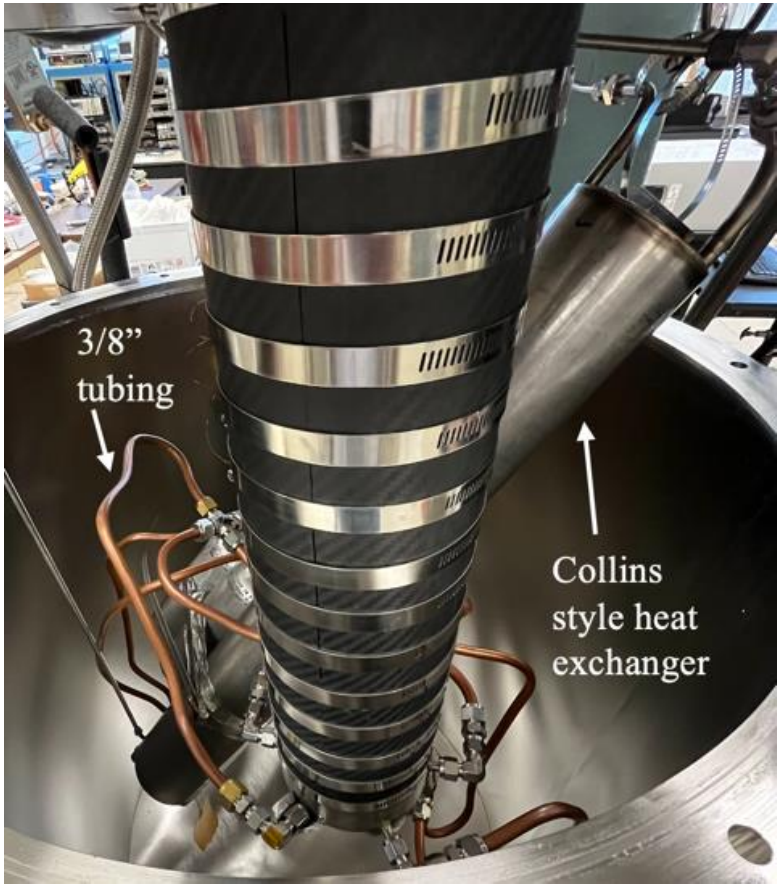
Summary

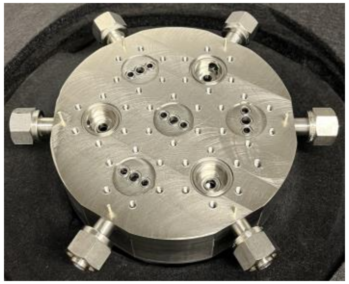
- Cooling to 189 K despite an ambient heat leak
- Stable operation with new control system architecture
- Invar-jacketed graphite-epoxy floating piston developed
  - Lightweight
  - Low thermal conductivity
  - Dimensionally stable (Low CTE)
  - Hermetic

Next steps:

- Demonstrating 100 W @ 100 K
  - Increase cold port size →
  - Reservoir volume increase → Lower frequency operation
  - Fix the leak!

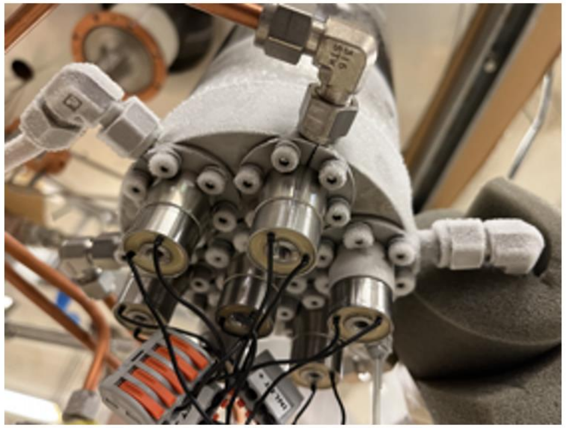
Cryogenic vacuum chamber setup





Updated cold cap

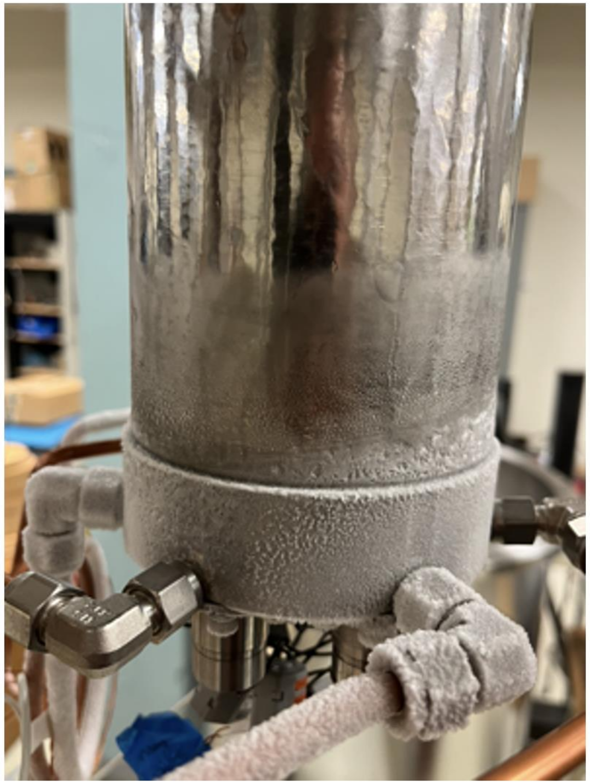
Thank you!



Acknowledgments

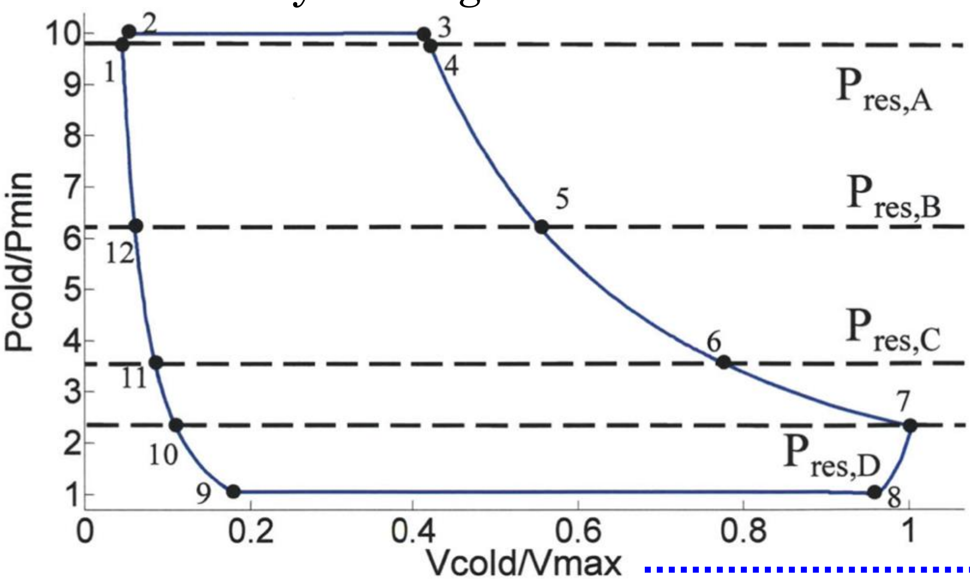
This work was funded by the **National Aeronautics and Space Administration** under project number 80NSSC21K0221.

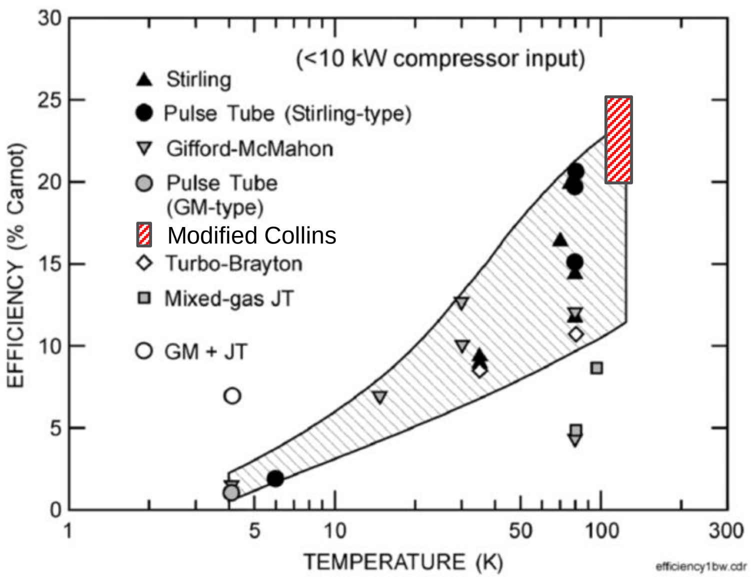
The authors would like to thank **Dr. Jeffrey Feller** for the valuable discussions and guidance in this project.



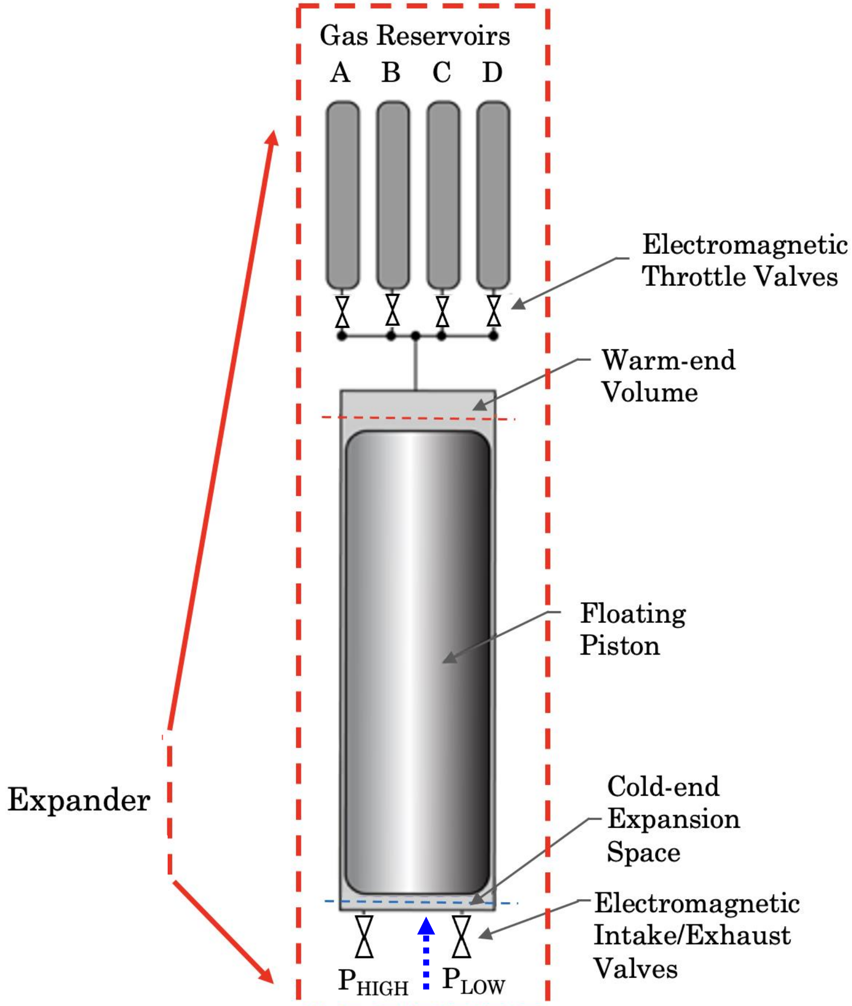
Modified Collins Cycle & Fundamentals

Ideal P-V cycle diagram:





Radebaugh, Cryocoolers, state of the art and recent developments, 2009



Overall Performance