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# Development of a 10 K Pulse-Tube Cryocooler Stage

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# Intro

- Many missions that are planned or currently in development require sub 20 K cryocoolers
- Flight cryocoolers (to ~6 K) have been converging over the past decade to two classes of pulse tube:
  - -Single stage pulse tube (typical low temp ~55 K, as low as 35 K)
  - -Multi stage pulse tube (lowest temps ~ 3 K)
- Cryocoolers to ~35 K are readily available from industry, lower temperature coolers have limited availability and are one-offs and expensive.
- The efficiency of sub 20 K cryocoolers is limited by available regenerator designs and materials.
  - -We're focusing on developing capability to design and build pulse tube stages in the 4 to 15 K range

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# Applications and Requirements

- Earth Science
  - Detector temperatures as low as 4 K
  - Mission lifetimes 2-3 years (longer desired)
- Astrophysics
  - Temperatures as low as 50 mK
  - ~4 K stage would provide precooling for the additional stages (e.g. ADR)
  - Some applications with 4 to 10 K as the coldest stage
  - Mission lifetimes 1 to 3 years (up to 10 years for flagship missions)
- Planetary
  - Temperatures to 10 K
  - Lifetime 2-3 years
- Cost is a major driver for all categories
  - Cost-capped competed missions can't pay for development
  - TRL 5-6 is typically required prior to mission selection
  - Small efficiency improvements can lead to significant cost savings

# Focus on Optimized Regenerator Development

- Pulse tubes are typically built with homogeneous regenerators (e.g. Pb pellets, steel screens).
- At higher temperatures ($T \geq 35$ K), heat capacity variations of the regenerator with temperature do not significantly limit performance.
- At lower temperatures ($T < 20$K), regenerator materials are strongly peaked and limit performance over the range of the regenerator
  - Low temperature regenerator materials are typically brittle intermetallics and hard to work into geometries other than spheres
- We're investigating alternative regenerator designs:
  - Heterogeneous (layered) regenerators
  - ErPr felts and screens

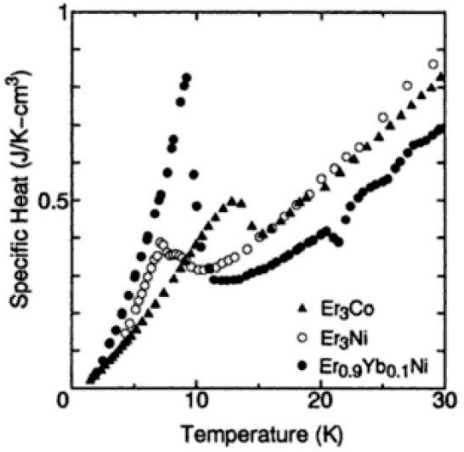
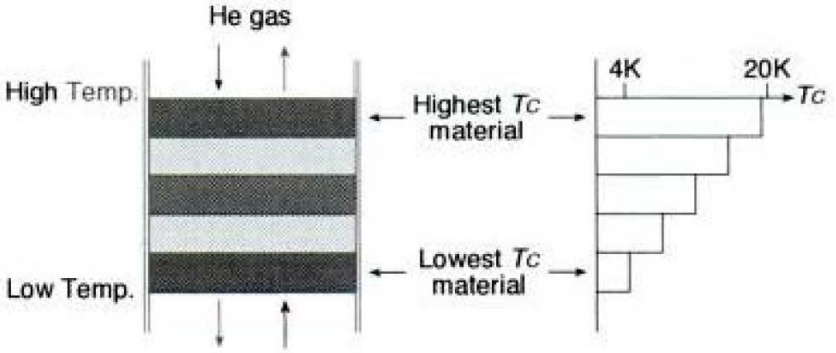



**Figure 2.** Specific heat of magnetic regenerator materials.



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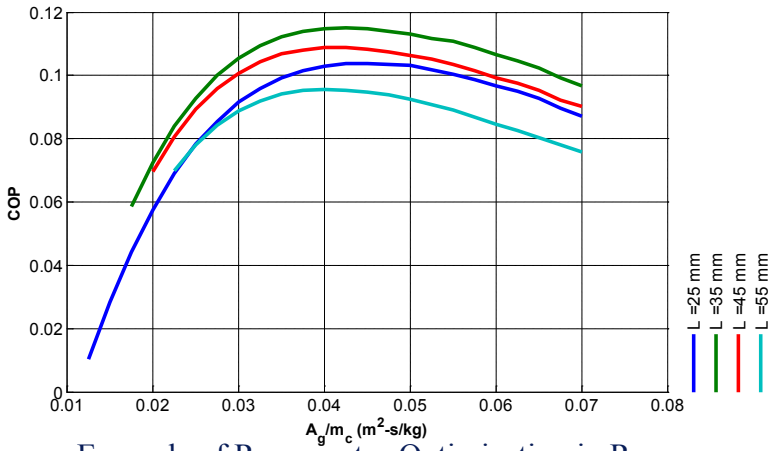
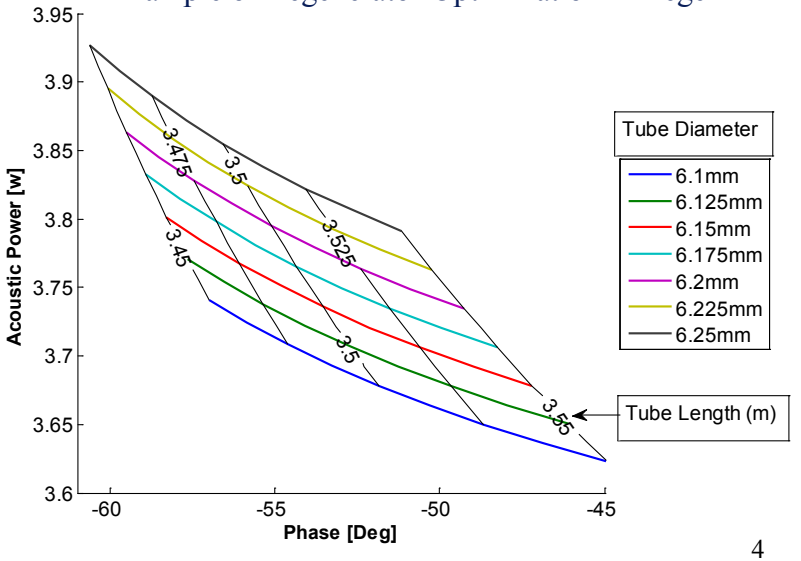
# Cooler Modeling and Analysis

- Cooler Design Process
  - Cooler design process used the previously mentioned analysis tools and follows the "Approximate Design Method for Single Stage Pulse Tube Refrigerators" (Pfotenhauer et al.) as described below:
    - Specify Cooler Lift and Temperatures
    - Find optimal Regenerator Geometry and operating parameters using Regen
    - Use equations and the Optimal Regenerator Geometry and Operating parameters to size pulse tube
    - Size inertance tube and reservoir to provide appropriate phase shift using Schunk's Model.
    - Use Sage to evaluate performance of resulting geometry (ongoing)




Example of Regenerator Optimization in Regen




Example of Inertance Tube Sizing with Schunk Model

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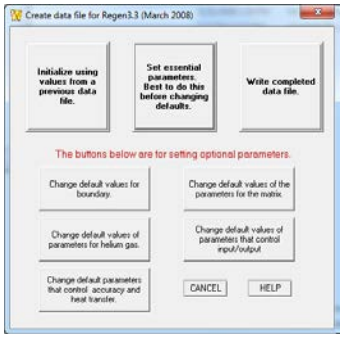
# Cooler Modeling and Analysis

- Modeling Tools

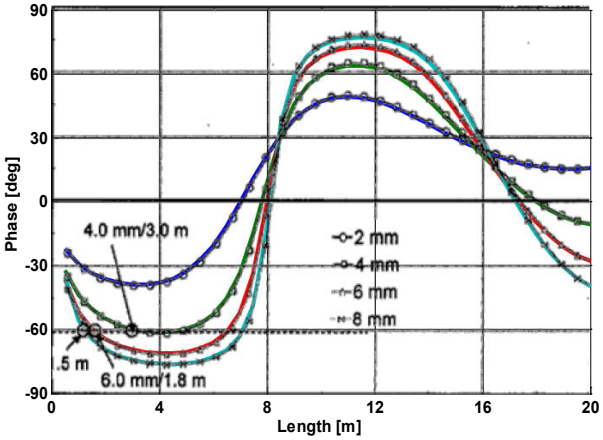
  - Regen 3.3
    - A Fortran program that models helium flow and heat transfer in regenerators of the type used in cryocoolers. Developed by NIST and widely used in Industry and Academia
    - Additional matlab code written to allow multiple Regen cases to be run in parallel (allows 1000's of cases to be run in short order)

  - Inertance Tube Modeling
    - A matlab implementation of the distributed component model described by Schunk et al. in "Experimental Investigation and Modeling of Inertance Tubes" is used to predict inertance tube phase shift.

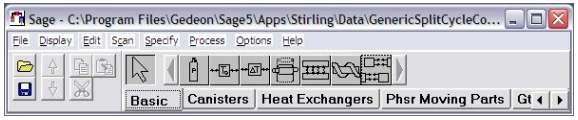
  - SAGE 8.0
    - SAGE is used to model overall cooler performance. SAGE has been used by industry and universities throughout world to models all types of cryocoolers.



Regen 3.3



Verification of matlab implementation of Schunk Model



SAGE 8.0

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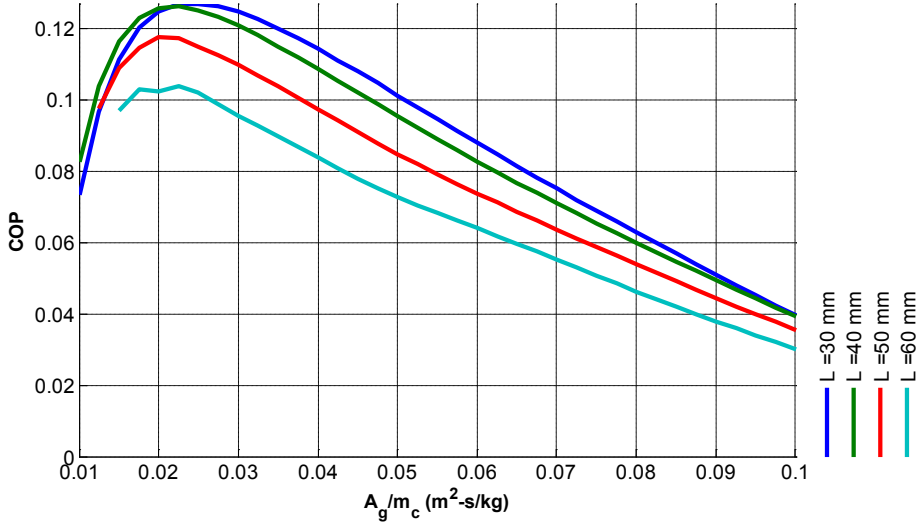
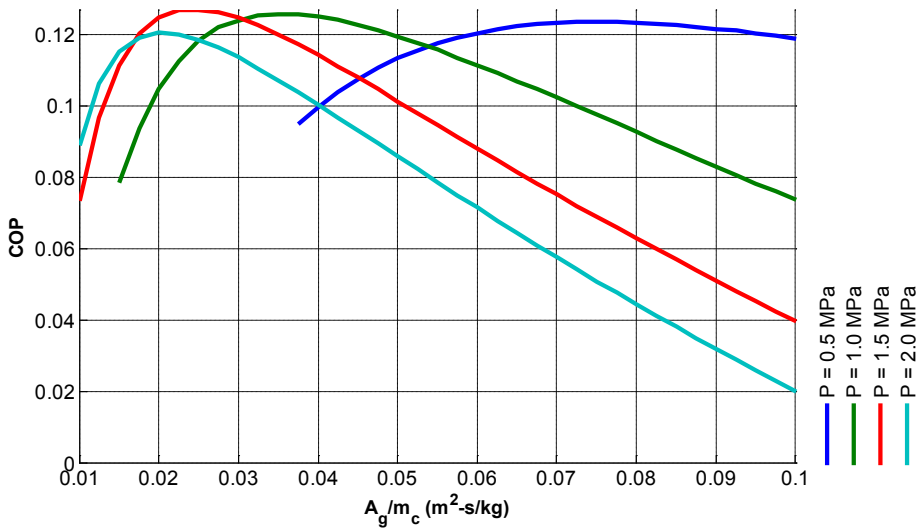
# Example Coefficient of Performance vs. Design

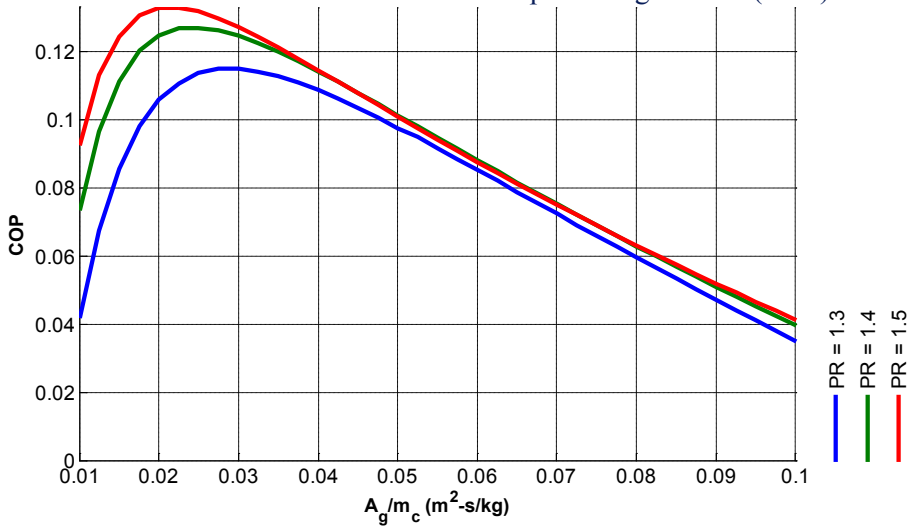
COP for Various Lengths with Packed Sphere Regenerator (ErNi)



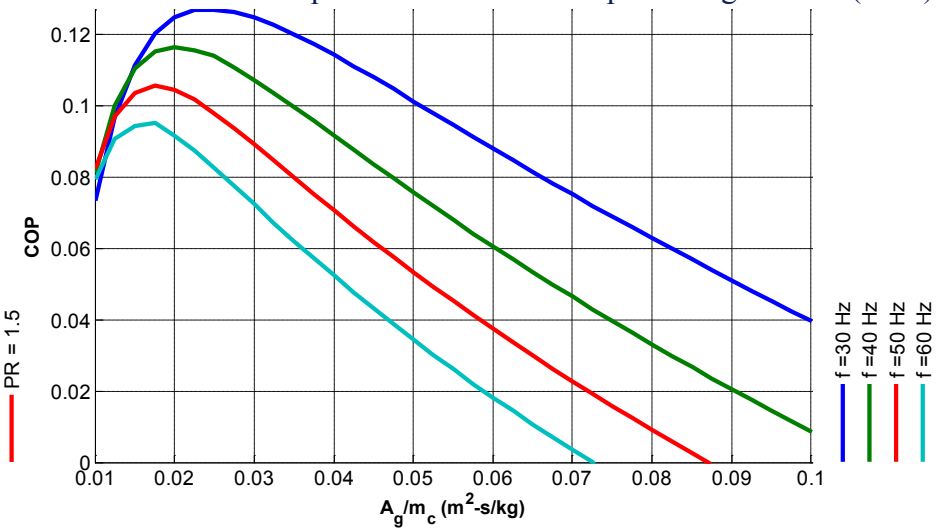

COP for Various Charge Pressures with Packed Sphere Regenerator (ErNi)




COP for Various Pressure Ratios with Packed Sphere Regenerator (ErNi)

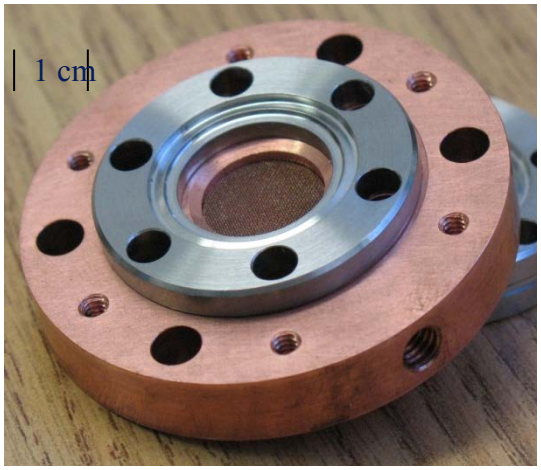



COP for Various Frequencies with Packed Sphere Regenerator (ErNi)



# Cooler Development: Heat exchangers & Pressure sensors

- HX bodies include flow channels for pressure sensors on both sides of flow
  - Currently investigating Kulite piezoelectric sensors: similar to Endevco, certified to 77 K (and we have approaches for using with much colder components);
  - Plan to calibrate as mass flow sensors
  - Pressure sensors yield relative phase of flow at different locations, which is vital for investigating phase shift across regenerator and phase shifter



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# Assembly, with path to flight designs

- Components are assembled using modified CF flanges vacuum-brazed to each, with teflon gaskets for sealing (to be tested: metal gaskets are fallback)
  - All fabrication techniques are available in-house: major advantage in a development phase
  - Sequence of fabrication matters: some materials cannot tolerate brazing temperature
  - Components can easily be interchanged
  - Minor leaks can be tolerated: this is not a UHV device yet

- For flight assembly, expect to replace the CF flanges with weldable design:
  - possibly orbital-tube or other arc method
  - maybe laser, or e-beam (not available in-house so far as I know)

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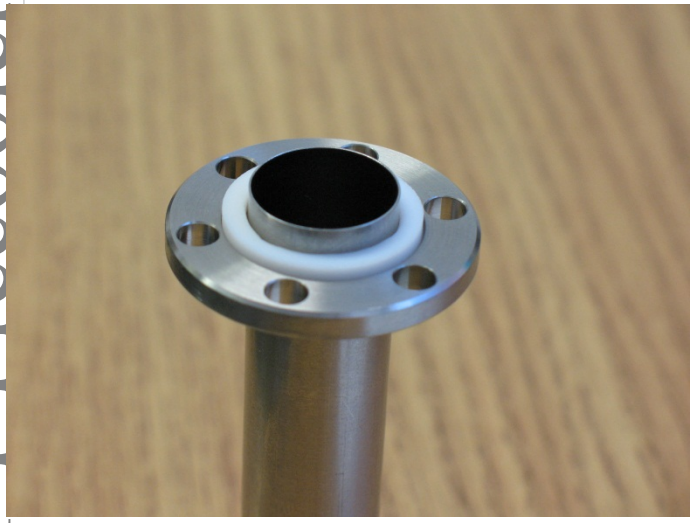

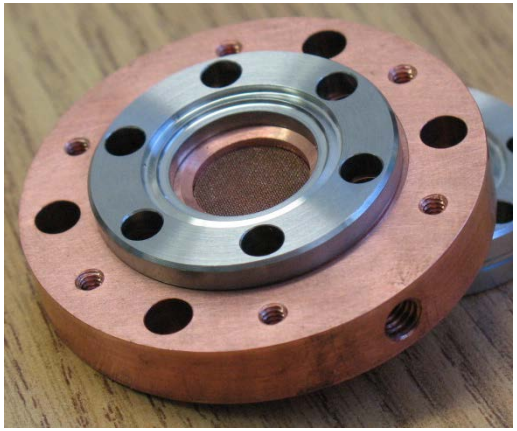

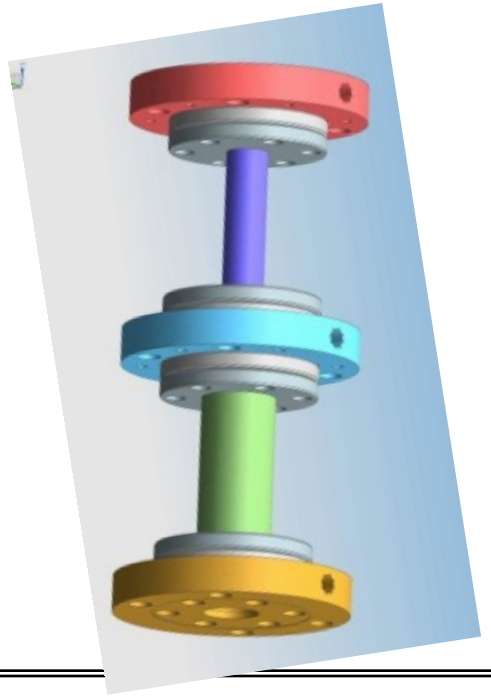

# Test facility

- 24” vacuum chamber with 2-stage GM cryocooler
  - Capable of precooling to <20 K for 10 K stage development, component testing
  - Water chiller & circulator (not shown) for higher-T, higher-P operation
- NI data collection modules for dynamic pressure sensors, LakeShore and Cryocon temperature controllers, other standard equipment
- Q-drive 2S132 and 2S175 available

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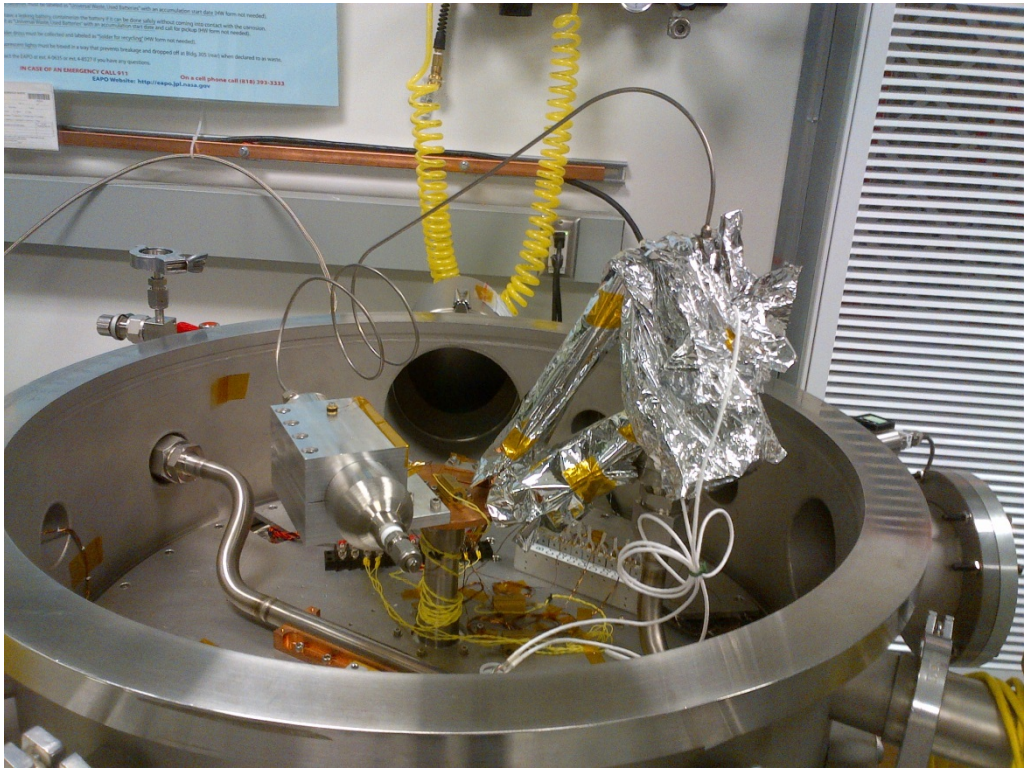
# S70 steel Cold Head in Chamber

- Cold head AC and WHX attached to 2nd stage of GM cooler
- Gas flow precooled by 1st stage of GM cooler
- Radiation shield at ~60 K (not shown)
- Calibrated thermal straps measure heat flux



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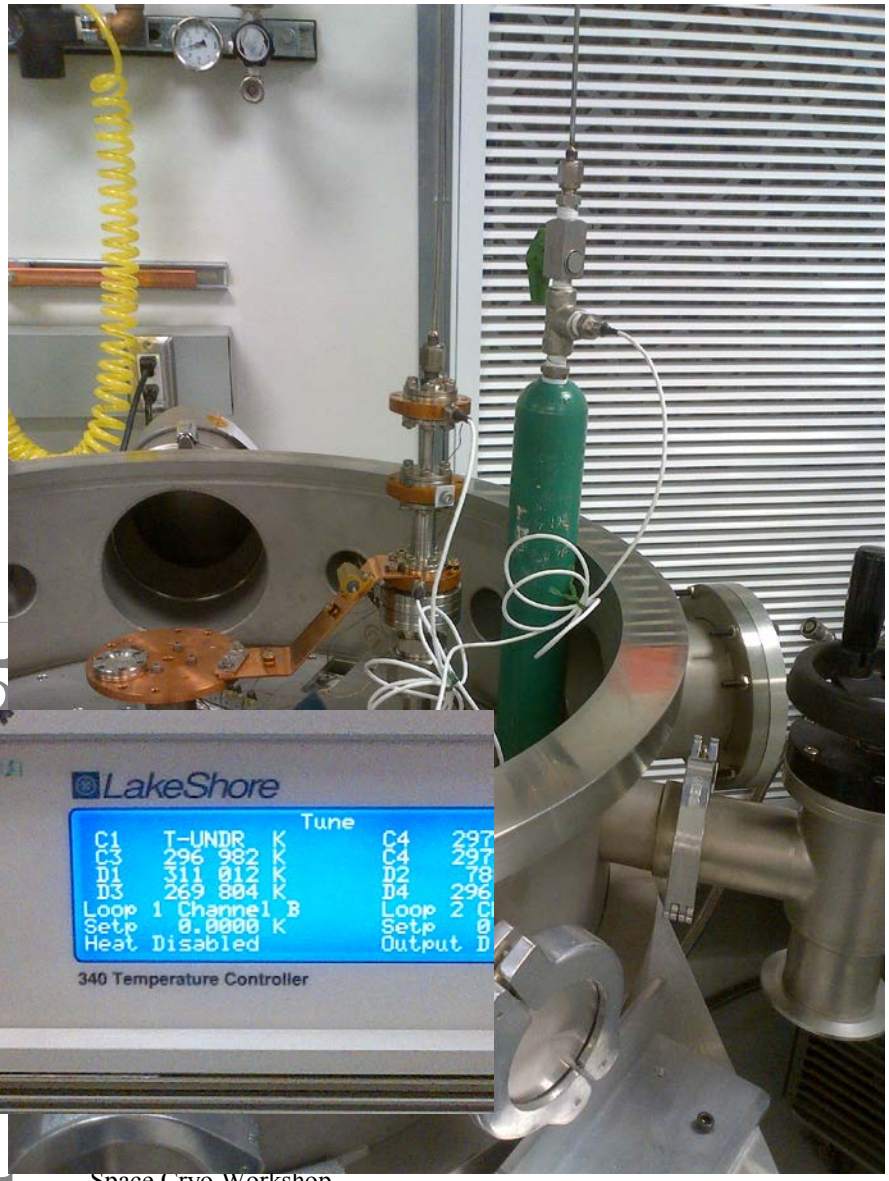
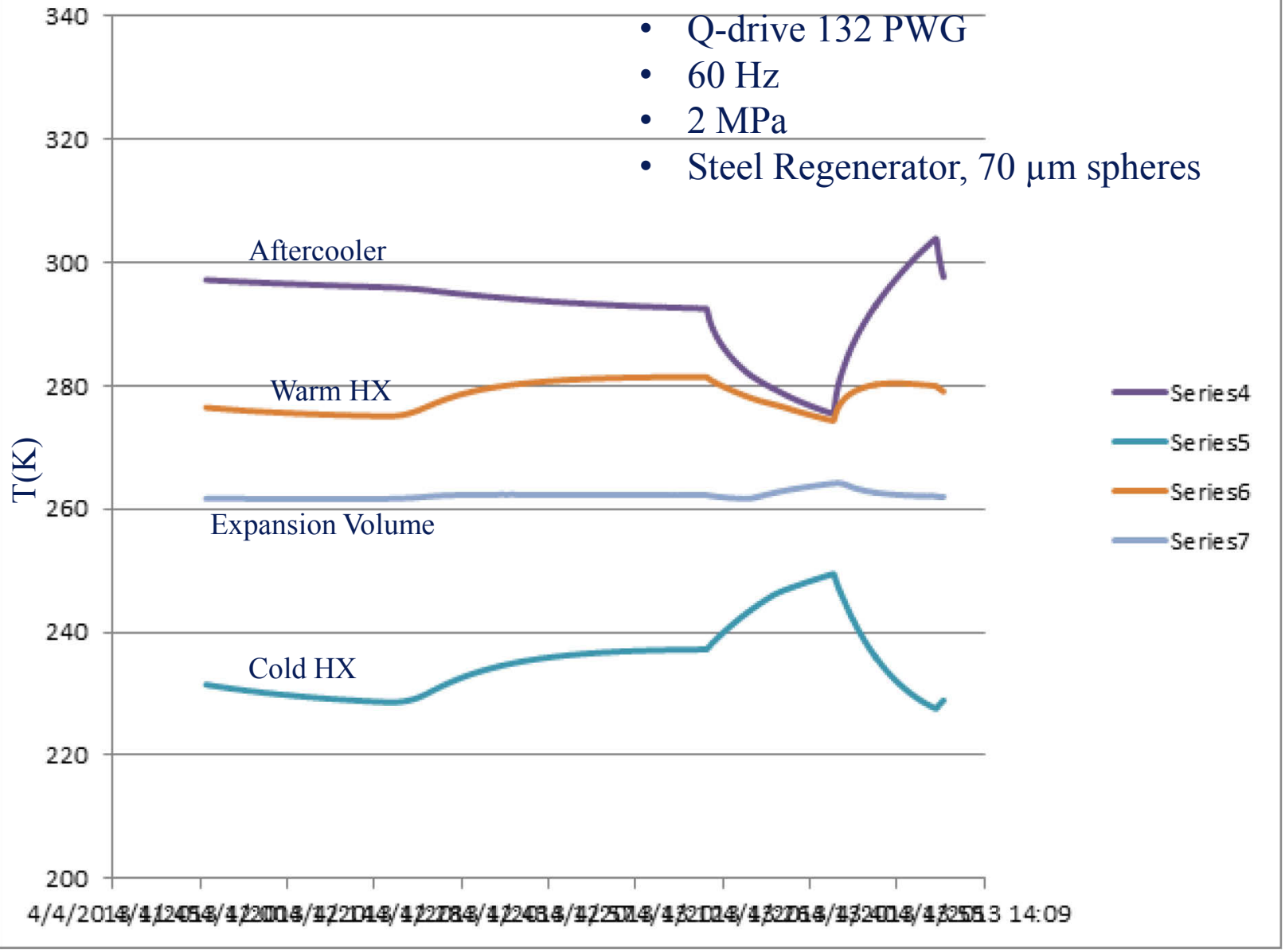
# First Frost


LakeShore
Tune
C1 T-UNDR K
C3 296 982 K
D1 311 012 K
D3 269 804 K
Loop 1 Channel B
Setp 0.0000 K
Heat Disabled
C4 297
C4 297
D2 78
D4 296
Loop 2
Output
340 Temperature Controller

# Experimental Results – Steel Spheres

- Q-drive 132 PWG
- 60 Hz
- 2 MPa
- Steel Regenerator, 70 µm spheres

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# Conclusions & Acknowledgement

- We're making progress toward development of a sub-20 K pulse tube stage.
  - Initial build using low-cost 70 micron steel spheres in the regenerator provides expected cooling
  - We have a modeled design for a 15 K cooler that should be running this month
- We have near term plans to work on alternative regenerator designs and modeling of those designs
  - Heterogeneous regenerators
  - ErPr felt and screens
  - Novel construction approaches

This work was performed at the California Institute of Technology, Jet Propulsion Laboratory, under contract with the National Aeronautics and Space Administration