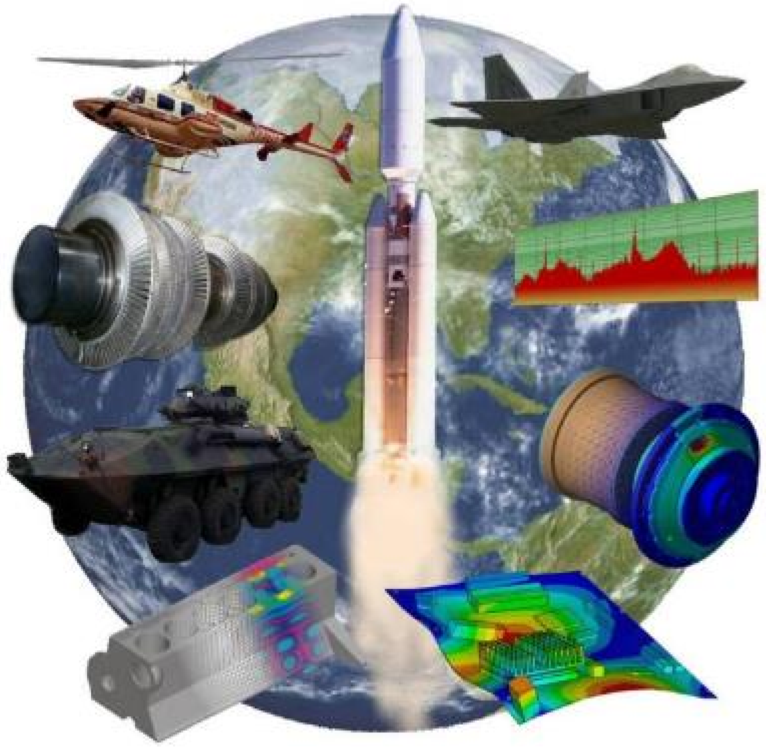
Mechanical Solutions, Inc.
Engineering Analysis, Test & Technology

Advanced Gas Foil Bearing Design for Supercritical CO_2 Power Cycles



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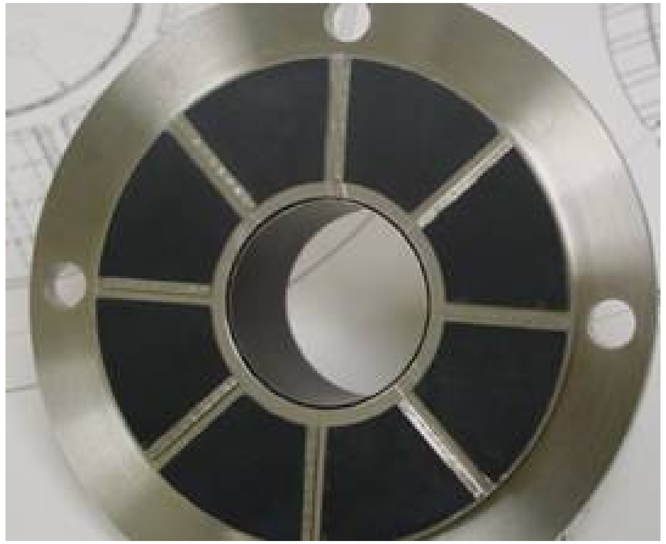
Daytona Beach, FL

18P3

Today's Presentation

- Project Background
- Overview of Hybrid Bearing Designs
  - Simple Concept
  - Radial Bearing
  - Thrust Bearing
- Fabrication of Test Bearings
- Design of Test Rig
- Test Rig Facility Installation
- Test Results
- Conclusions



Project Background

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- Completed Phase II of Small Business Innovative Research (SBIR) Program
- Funding provided by the Department of Energy (DOE) Office of Fossil Energy
- Program goal: develop a reliable, high performance foil bearing system using sCO_2 as the working fluid
  - Temperatures up to 800°C
  - Pressures up to 300 bar
- Key elements of the design:
  - An advanced hydrostatically-assisted hydrodynamic (or hybrid) foil bearing with higher load capacity
  - An integral gas delivery system to distribute flow throughout the bearing
  - Combined hydrostatic and hydrodynamic portions of the bearings to limit the leakage of the fluid fed to the bearing (a big problem for classical hydrostatic bearings)
  - Addition of overload protection to handle large shaft excursions during severe system transients
  - Use of high temperature materials and coatings to prolong life and enable sufficient start/stop cycles

Why Foil Bearings?

Advantages

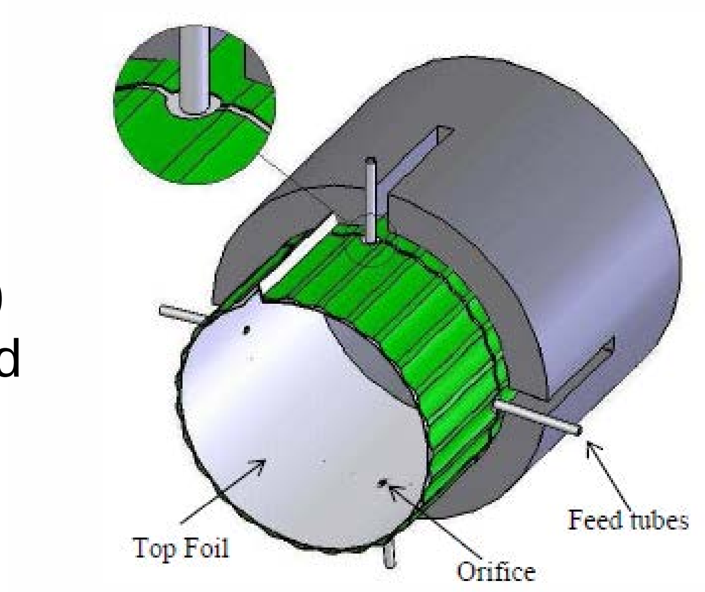
- High speed capability
- Extreme-temperature and/or oil-free environment
- Permits a hermetically-sealed system (eliminate end seals)
- Insensitive to system pressure
- Long, maintenance-free life

Disadvantages

- Low load capacity
- Relatively low direct stiffness
- Low damping
- Often need supplemental cooling
- Rubbing wear during start-up/shut-down

Hybrid Bearing Concept

- Hydrodynamic load capacity often limits gas foil bearing use in some equipment, particularly larger machines running at lower speeds
- Supplementing load capacity and stiffness could enable broader use of gas foil bearings
- Adding a hydrostatic component is one method of enhancing a gas foil bearing
- Pressurized gas is injected directly into the bearing gap
- Evaluation of a simple orifice design (as shown on right) did not generate a significant amount of pressure around a large enough area
- Minimal force benefit gained, potential instability at high eccentricities
- Must also include mechanisms to limit leakage of the hydrostatic fluid



Source: Texas A&M University (Kumar[1])

1. Kumar, M., "Analytical and Experimental Investigation of Hybrid Air Foil Bearings," A Thesis submitted to the Office of Graduate Studies of Texas A&M University, August 2008.

Enhanced Hydrostatic Design

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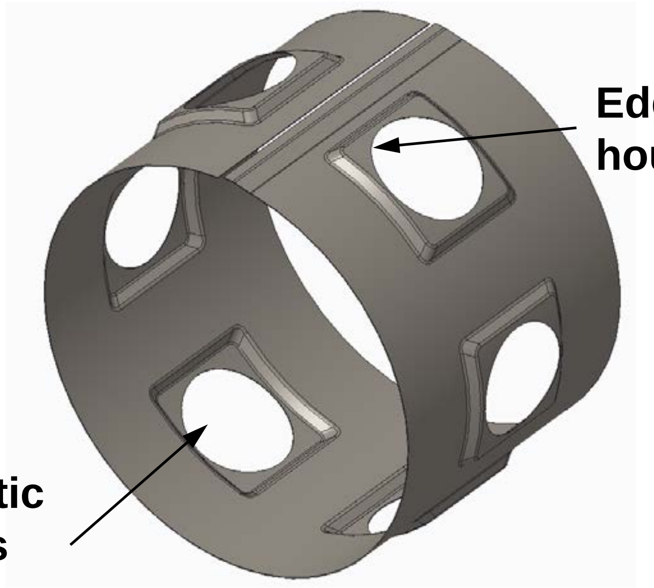
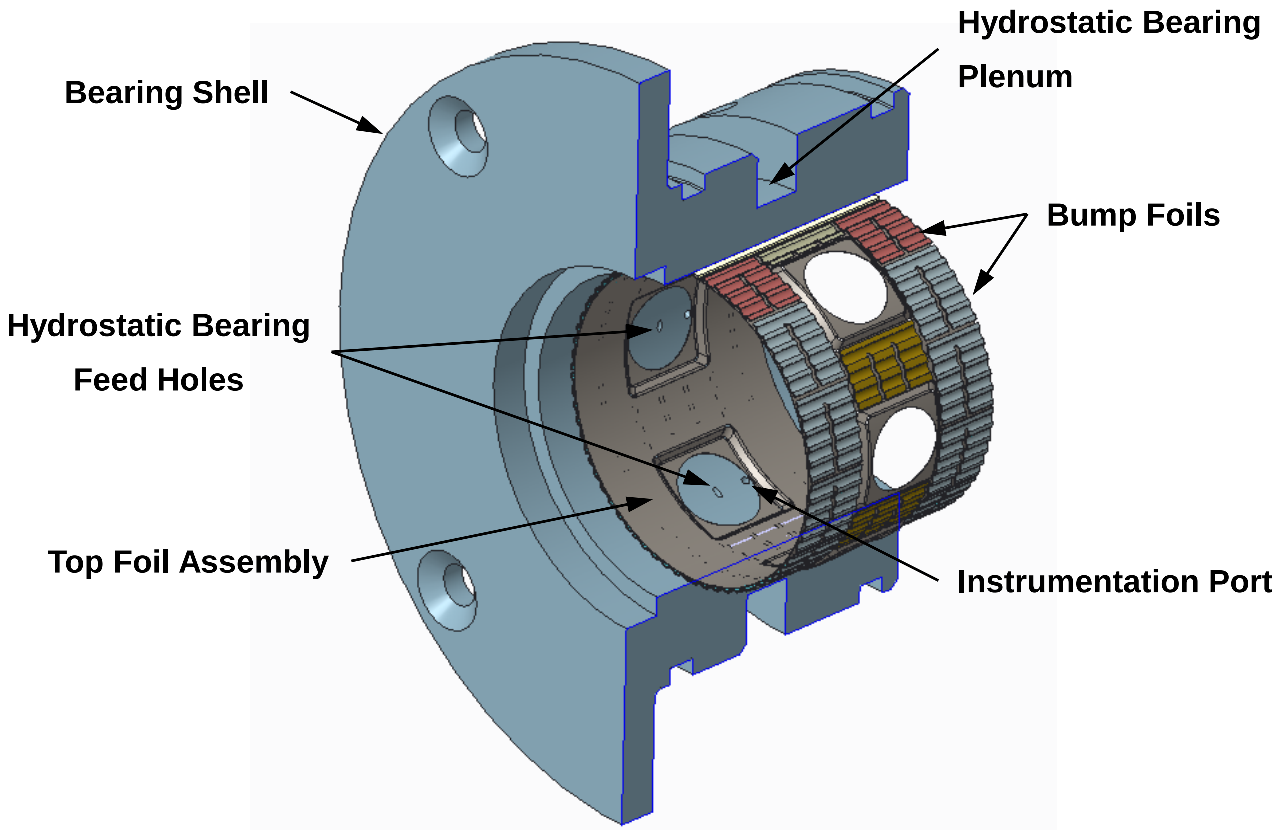
- Discrete pockets were added to the top foil to enhance the hydrostatic benefit
- The working fluid (sCO_2) is supplied to each pocket through an orifice
- The pockets provide larger pressure areas to be created
- Significantly larger hydrostatic force can be generated
- Must be aware of and avoid pneumatic hammer
- Foils and pumping grooves can significantly reduce end leakage



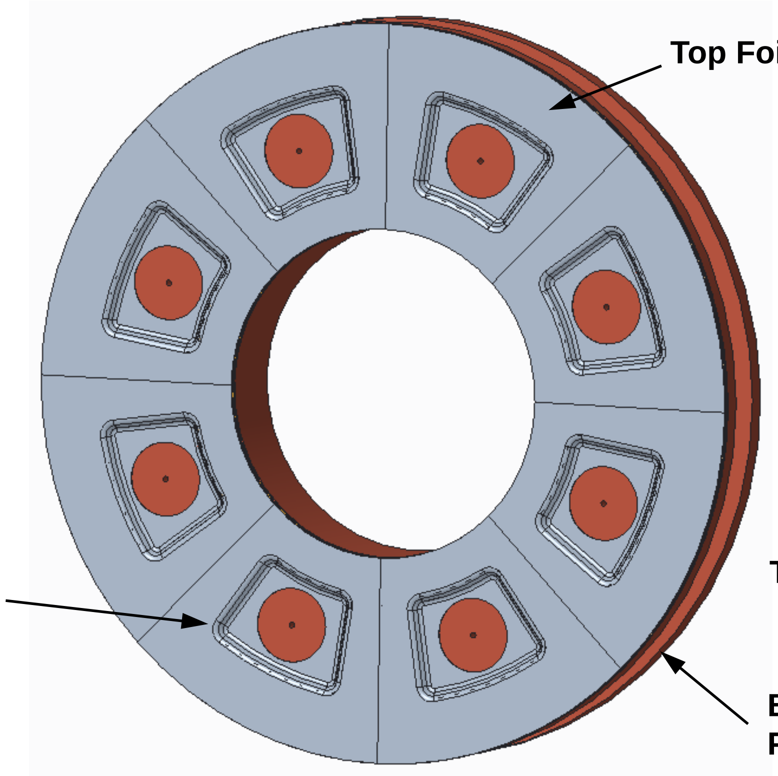
Radial Bearing Design

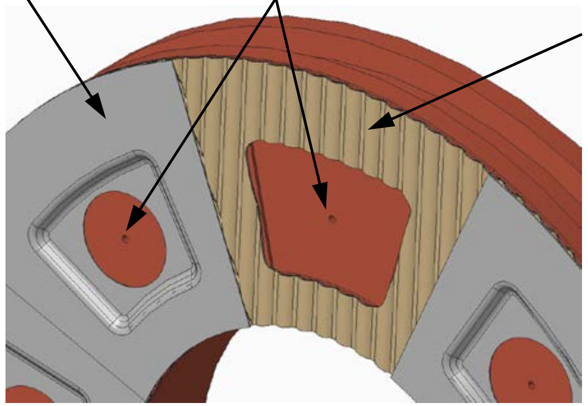
- Radial bearing consists of:
  - A top foil containing the hydrostatic pockets
  - A multi-layered array of bump foils
  - A bearing shell
- An annular plenum supplies each pocket through an orifice
- Pumping grooves (not shown) were added in strategic locations



Thrust Bearing Design

- Similar to the radial bearing, the thrust bearing consists of:
  - A top foil containing the hydrostatic pockets
  - A multi-layered array of bump foils
  - A backing plate
  - Strategic surface grooving
- An annular plenum supplies each pocket through an orifice





Top foil removed to show bump foil detail

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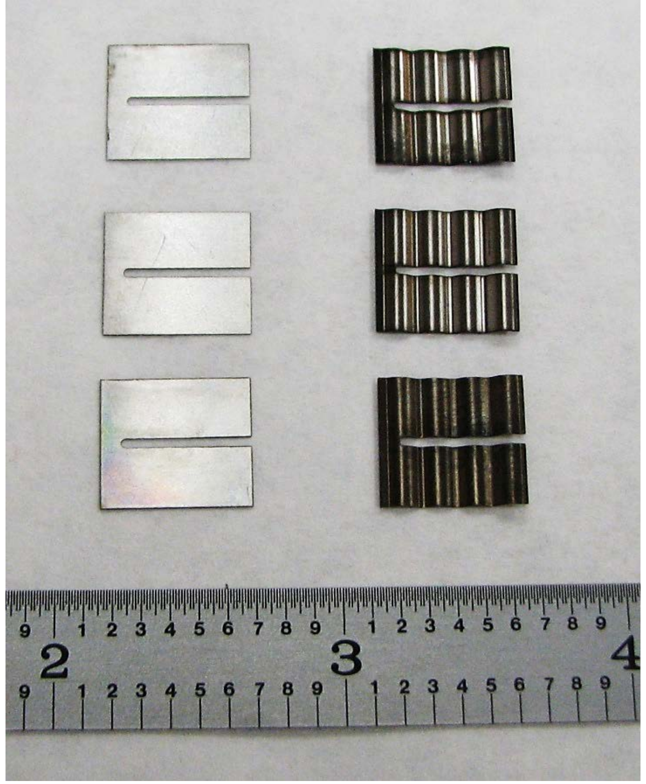
Fabrication of Test Bearings

Radial Bearing Components

Bearing Shell



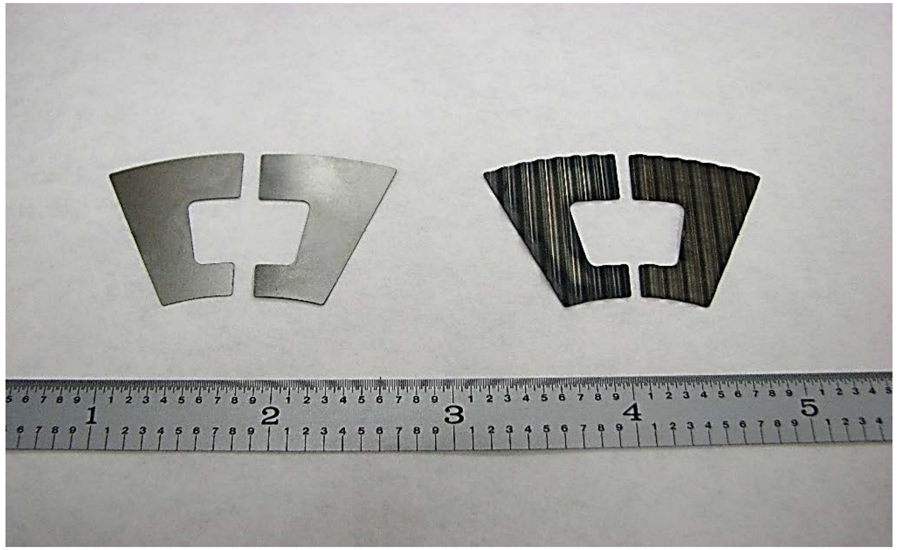
Bump Foils

Top Foil w/ Pockets

Fabrication of Test Bearings

Thrust Bearing Components

Bearing Plate



Bump Foils

Top Foil
w/ Pockets

Fabrication of Test Bearings

- First attempt at fabricating top foils
  - Started with heat treated material
  - Significant amount of spring back
  - Significant residual stresses remained
- Second attempt
  - Used annealed material instead
  - Manufactured fixtures to restrain the parts
  - Ran an annealing cycle (stress relief) followed by a precipitation hardening step
- Greatly improved product form (10x)
- Had to deal with residual stresses and distortions from laser welding

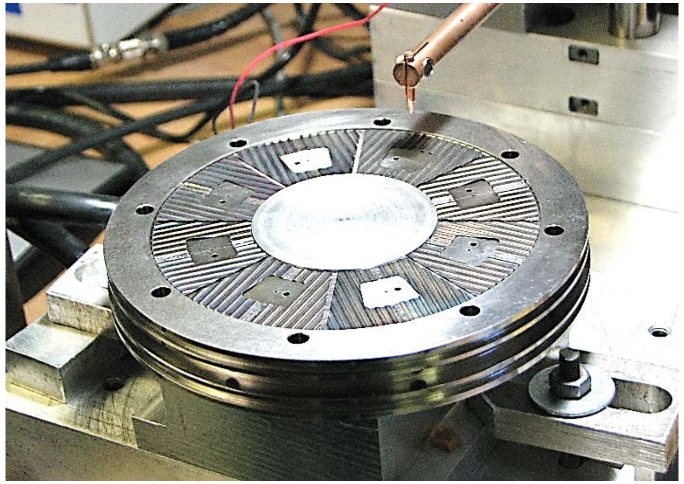
Radial Top Foil H.T. Mandrel

Finished Top Foil

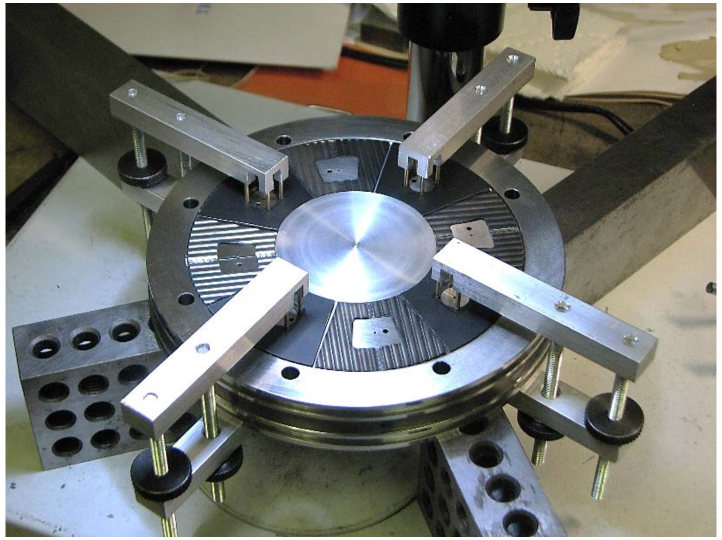
Heat Treat Plates with Processed Thrust Top Foils

Fabrication of Test Bearings

Installed Radial Bump Foils



Spot Welding Thrust Bump Foils



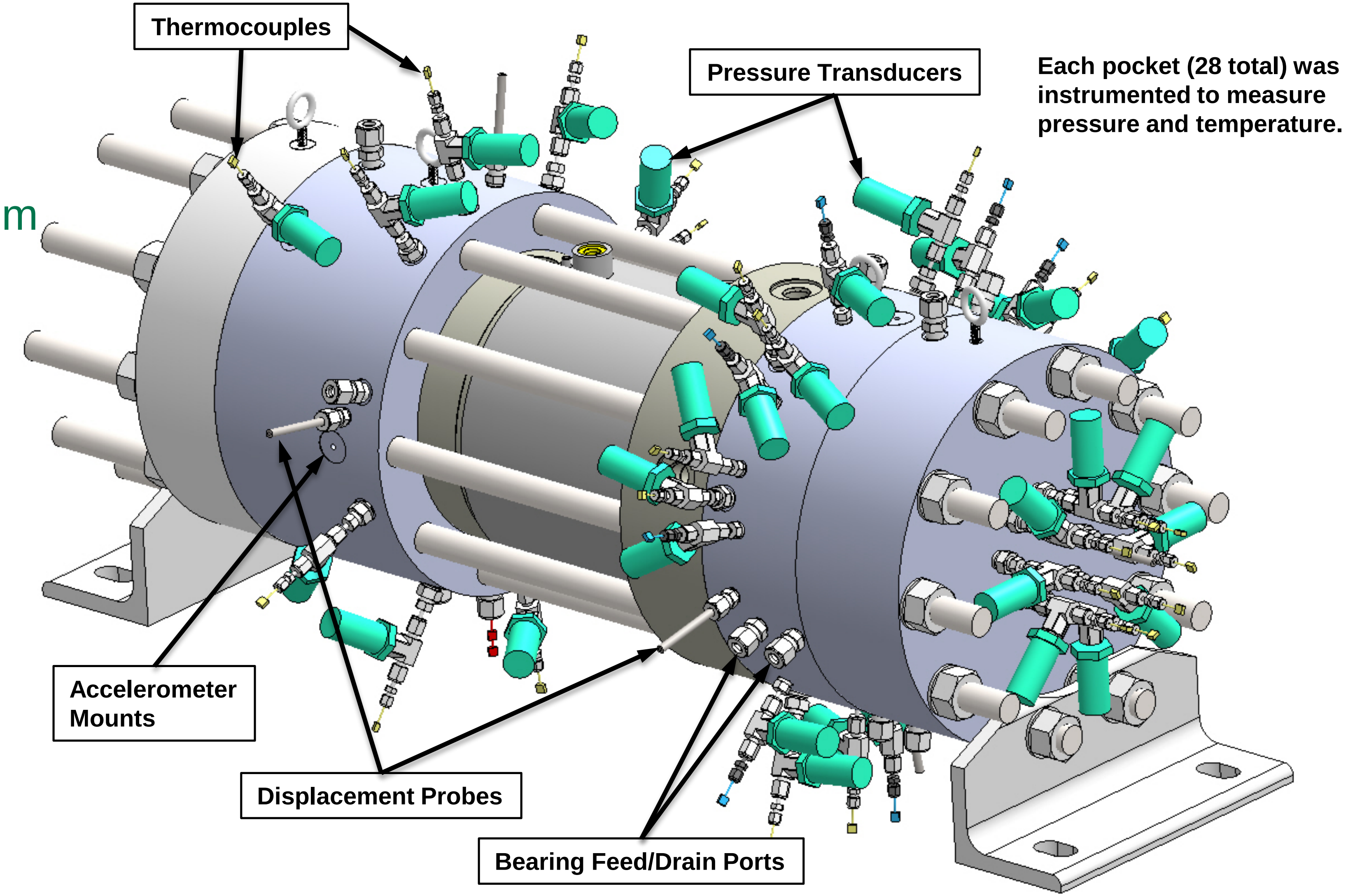
Laser Welding Thrust Top Foils

Finished
Radial Bearing

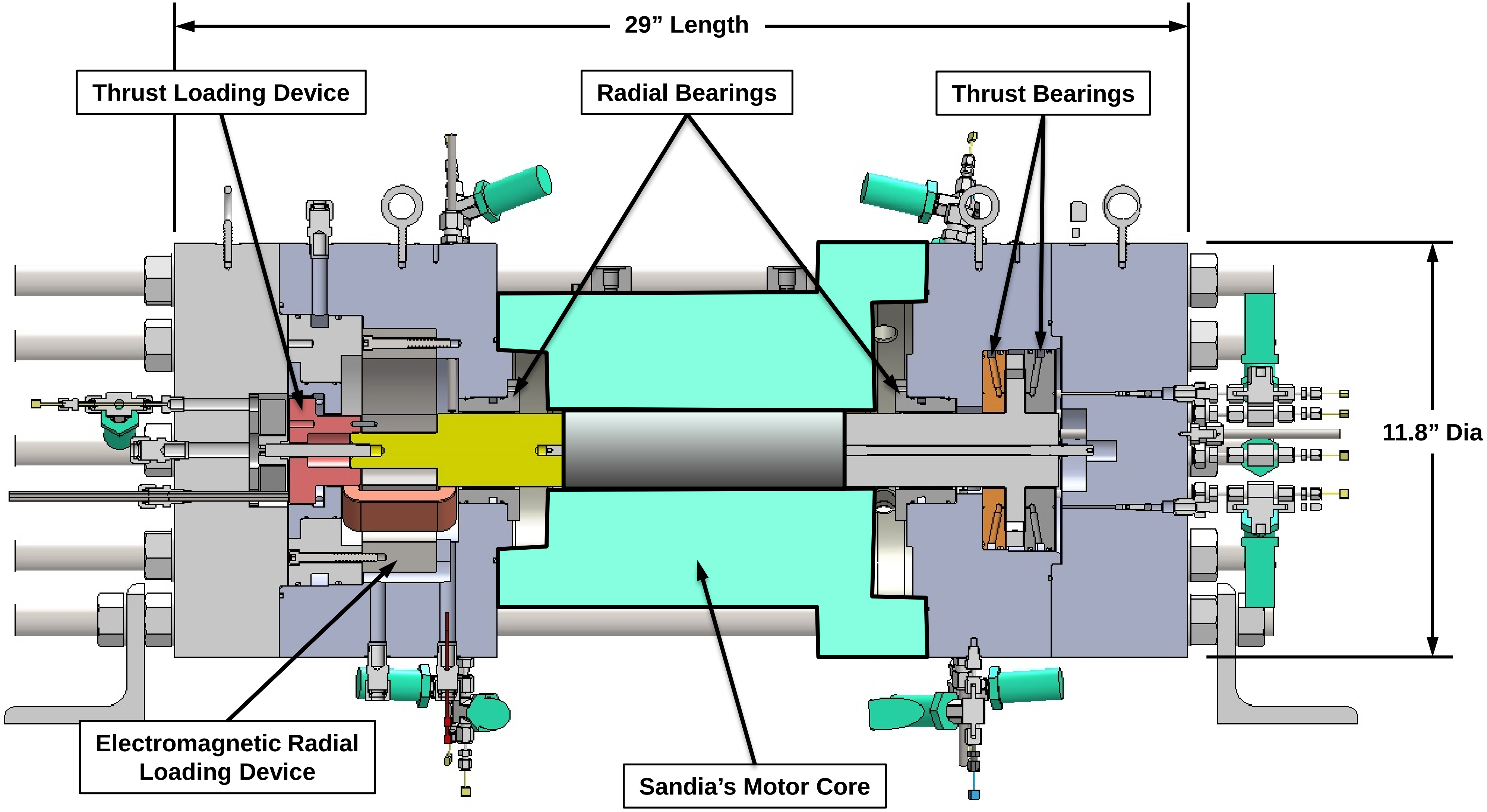
Finished
Thrust Bearing

Test Rig Design

- Capabilities
  - Rated Pressure: 2300 psi
  - Rated Temp.: 300°F
  - Max. Speed: 50,000 rpm
  - Max. Power: 40 Kw
- Instrumentation
  - Thermocouples: 40
  - Pressure transducers: 40
  - Accelerometers: 5
  - Displacements: 5
  - Key phasor: 1
  - Current transducers: 3
  - Flowmeters: 3



Test Rig Design



Test Rig Assembly

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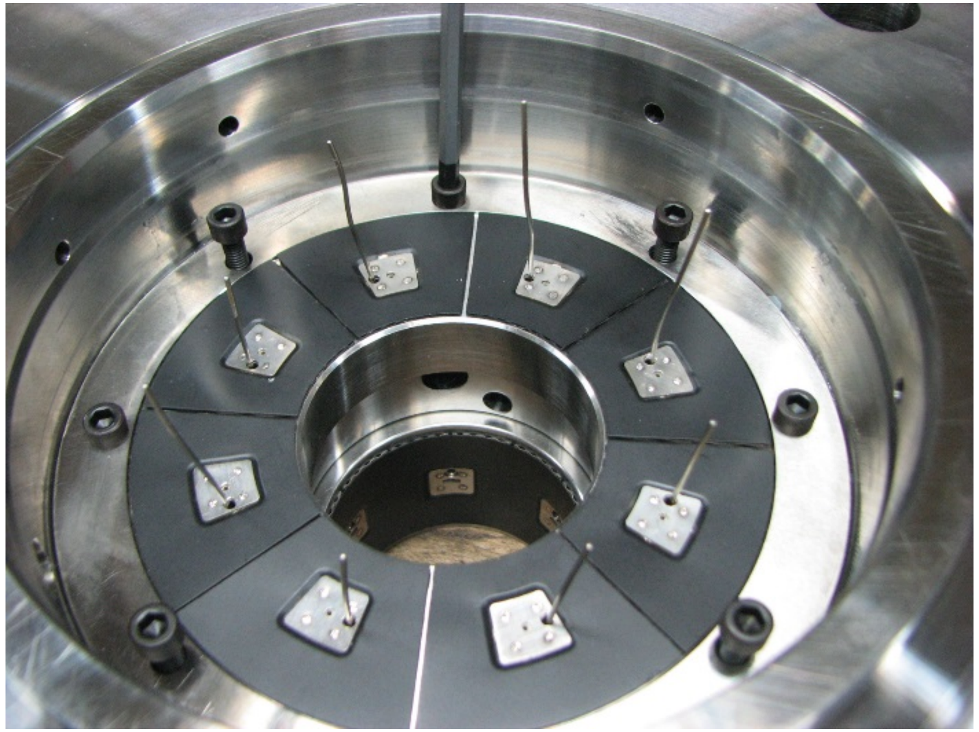
Vessel first assembled at MSI

Tie rods were hydraulically tensioned to 28,300 lbf each

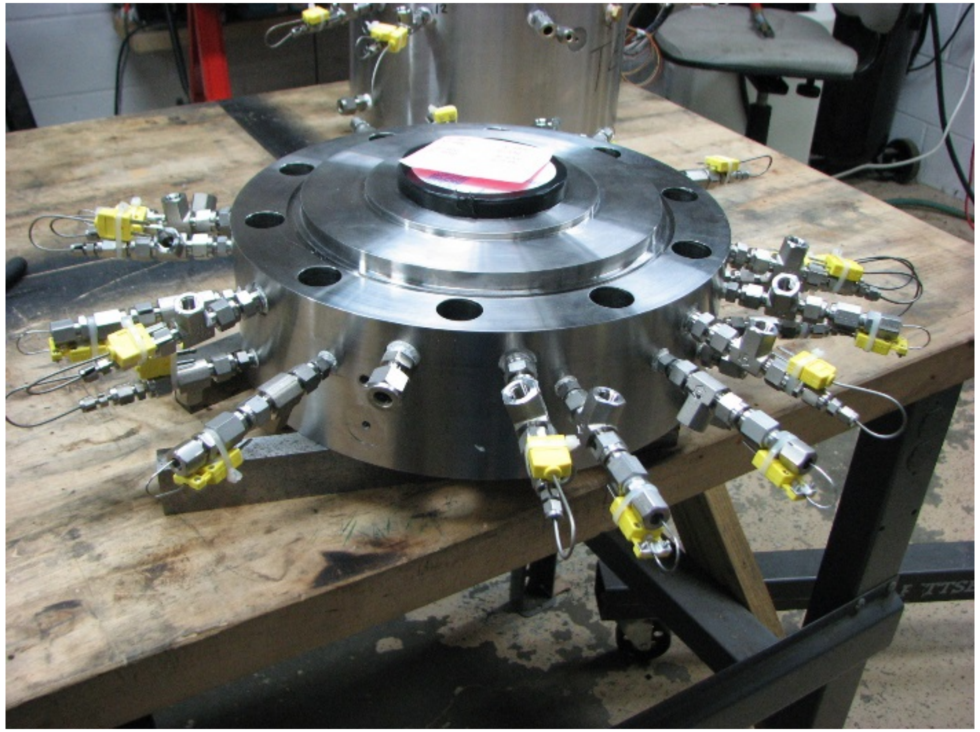
Vessel was hydro-tested to 3000 psi

Test Rig Assembly

All of the fine assembly work was done at MSI prior to shipping to Sandia for testing



Bearings were installed in the housings and thermocouples fed through and terminated

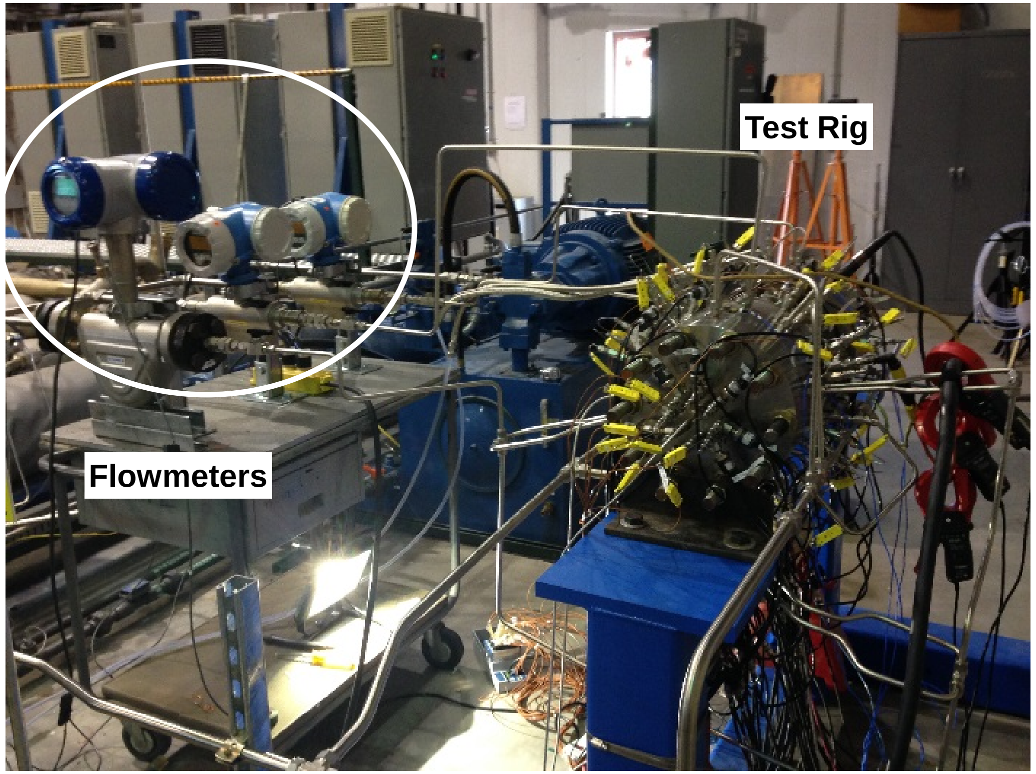


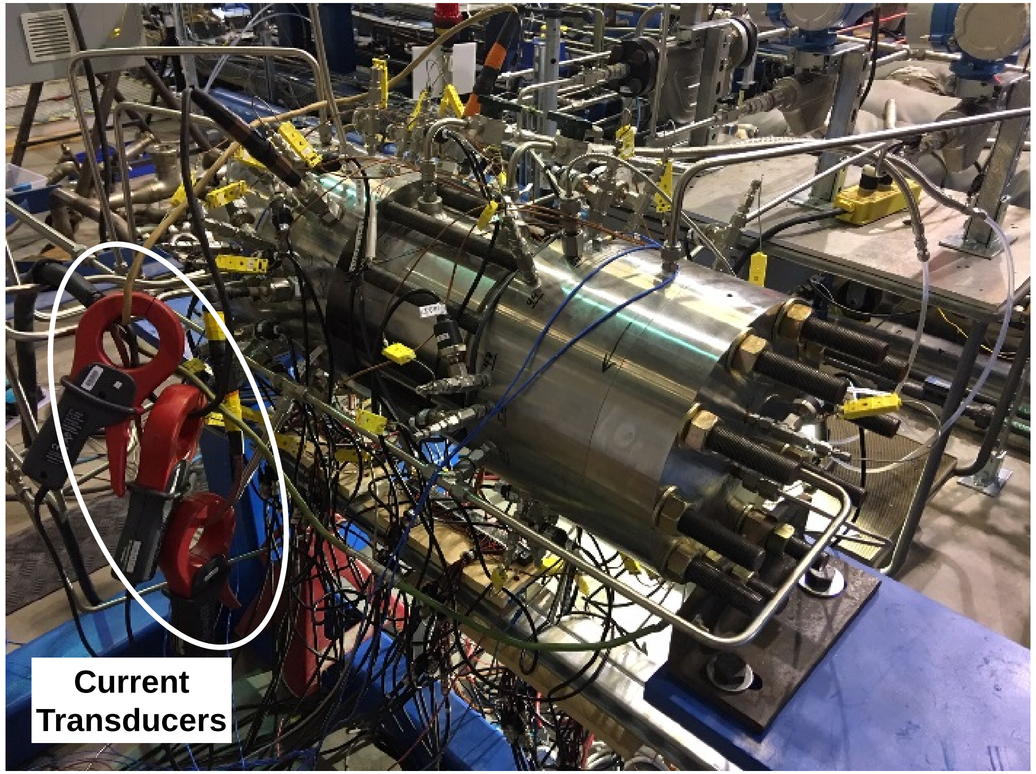
Fittings for the gas supply, drains, and pressure transducers were installed

Test Rig Assembly

Final assembly was conducted at Sandia's facility

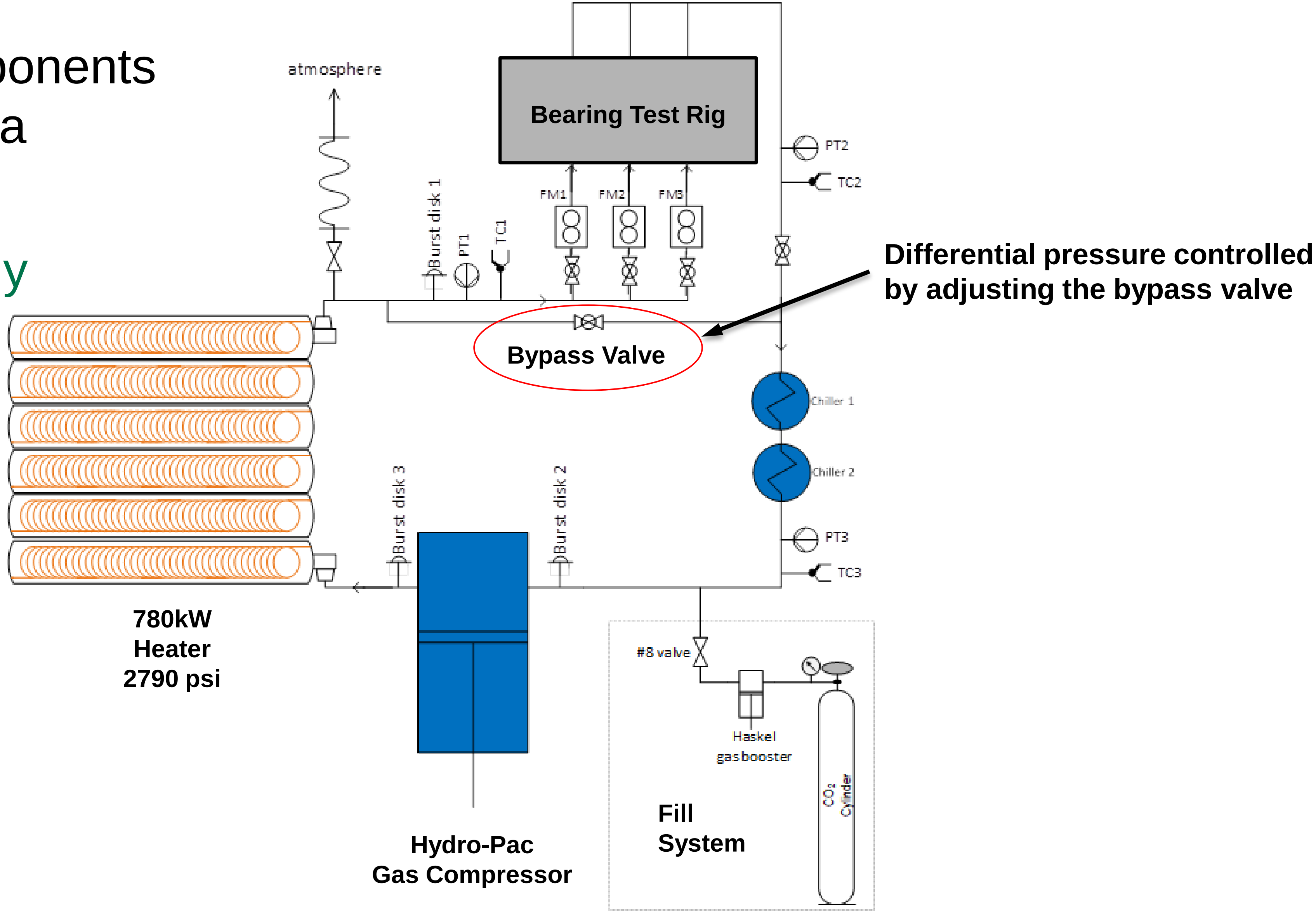
The test rig was then connected to their sCO_2 flow loop





sCO$_2$ Flow Loop

- All flow loop components supplied by Sandia
- Test conditions
  - 1600 psi supply
  - 257°F
  - 300 psi dP

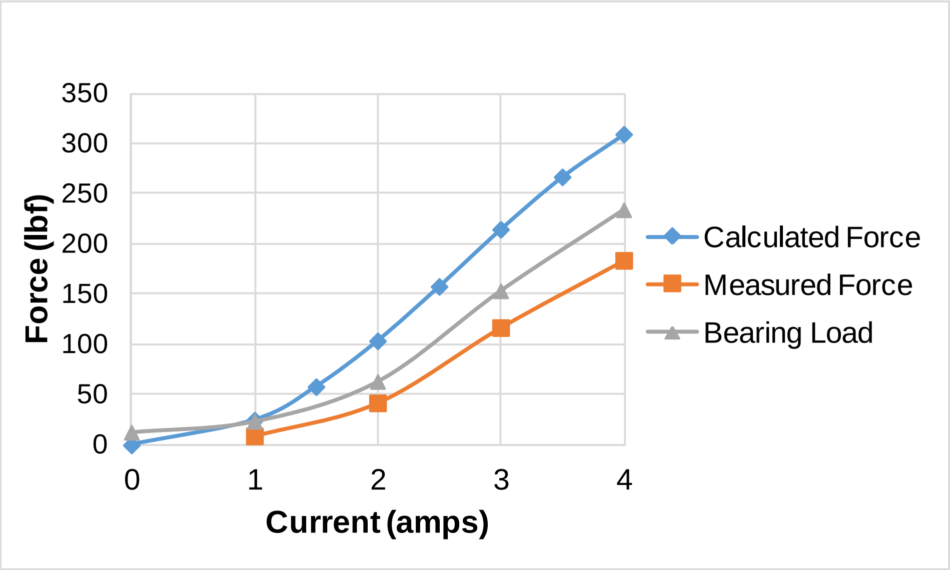


Bearing Tests - Objectives

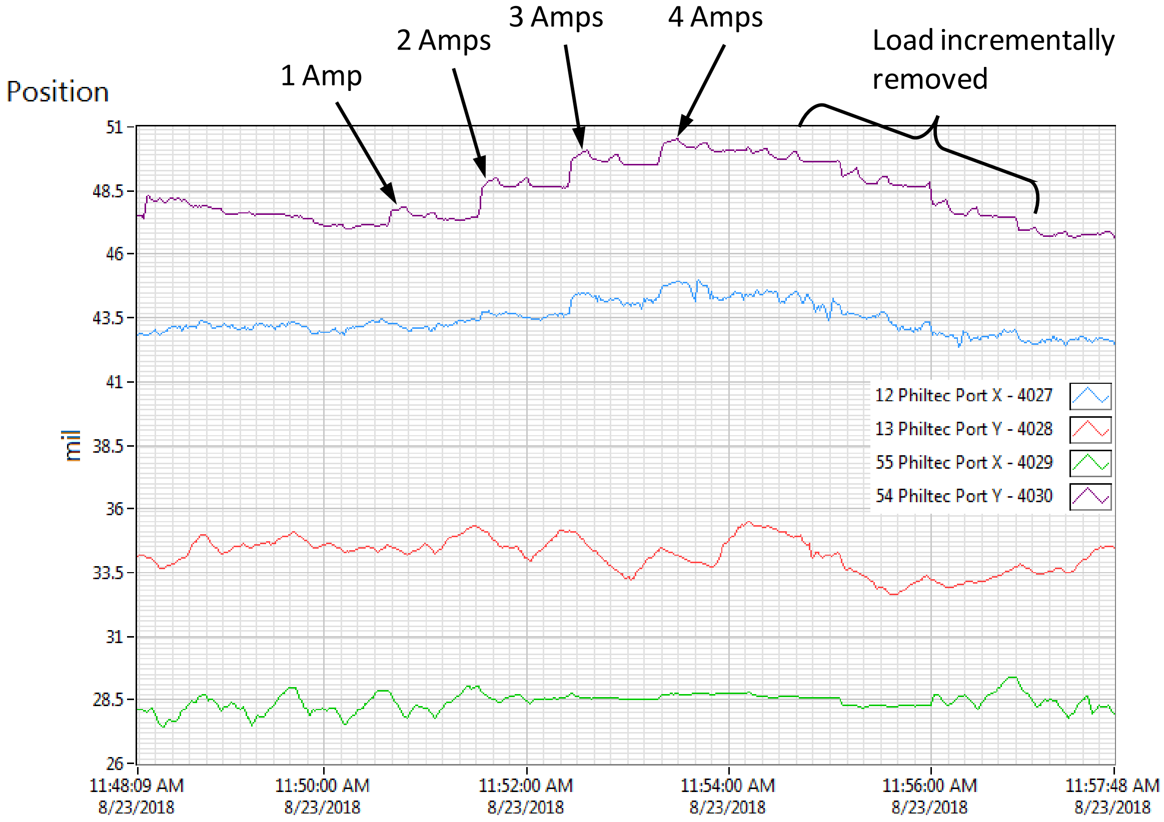
- Static Tests
  - Observe lateral shaft motion in response to radial load
  - Observe axial shaft motion in response to an axial load
  - Measure the static stiffness of the radial bearings
  - Measure the static stiffness of the axial bearings
- Dynamic Tests
  - Identify the rotor critical speeds to determine safe operating speeds
  - Run the test rig stably up to 50,000 rpm
  - Measure the dynamic stiffness and damping of the bearings
- Coatings Evaluation
  - Continue the Phase I effort to identify high temperature, wear-resistant coatings
  - Perform start-stop cycle testing in a CO_2 environment up to 800°C

Radial Bearing Static Testing

A radial load was applied to the bearings with an electromagnet



Force vs. Applied Current



Radial Displacement as Load is Applied

Radial Bearing Static Testing

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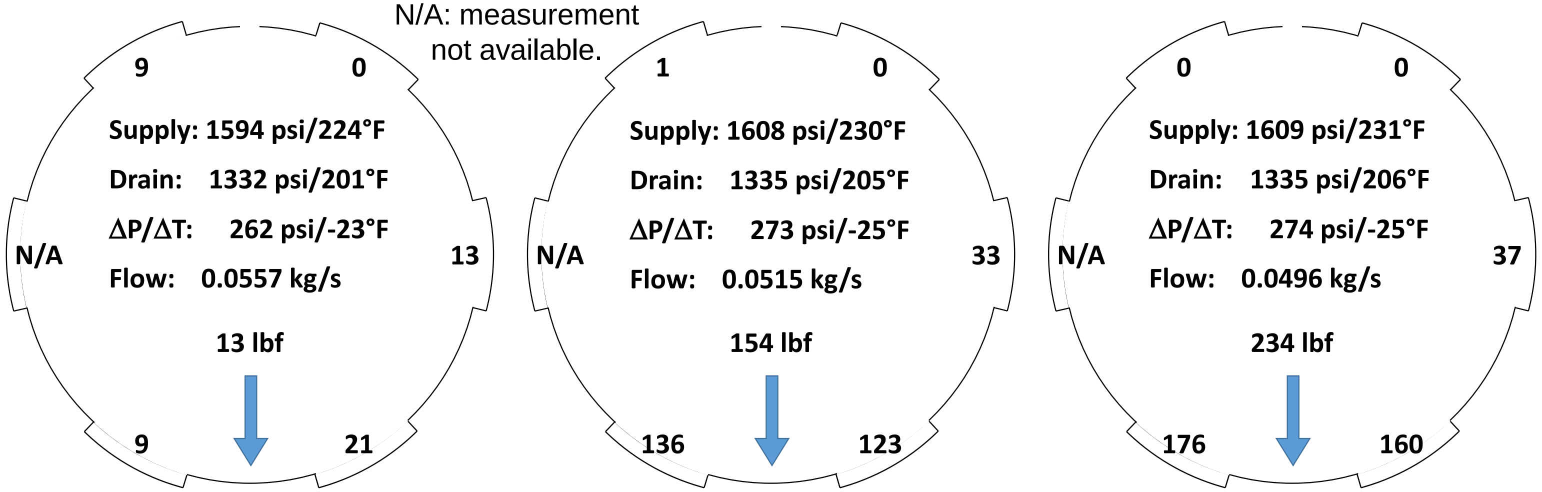
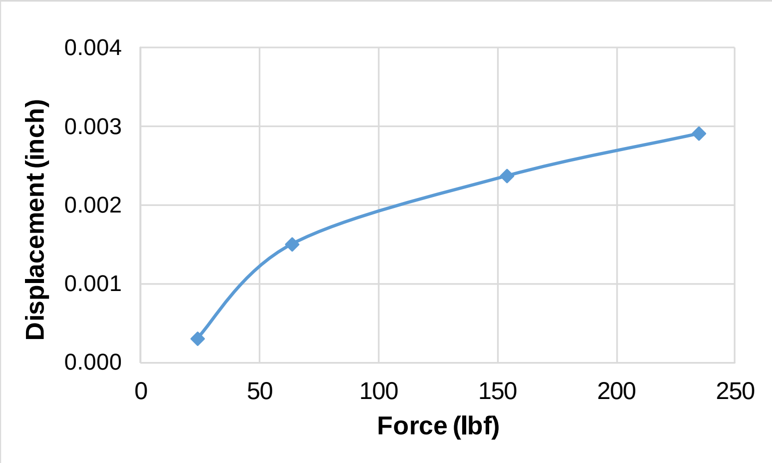
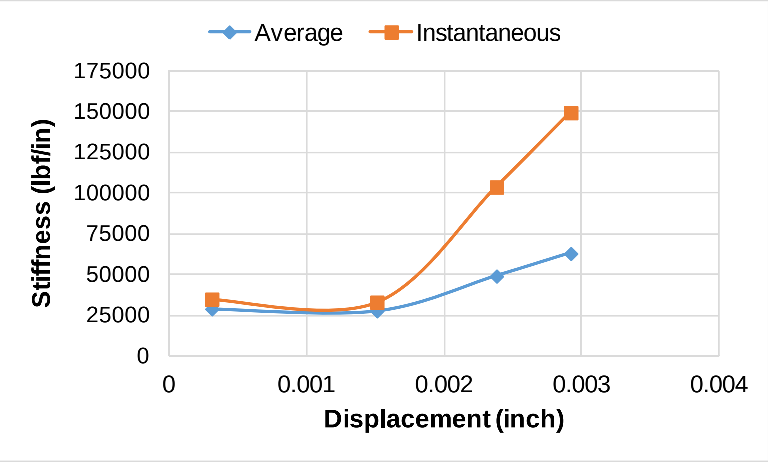
- Due to profile variations in the bore, could not develop the maximum intended pocket pressures
- As load was applied, pressures did develop on the loaded side as intended
- Resulting stiffness was highly non-linear
  - Average stiffness (total force/total displacement) was ~1/3 of prediction
  - Instantaneous stiffness ($\Delta F/\Delta D$) approached design value
- Improving bore quality should significantly improve performance

N/A: measurement not available.



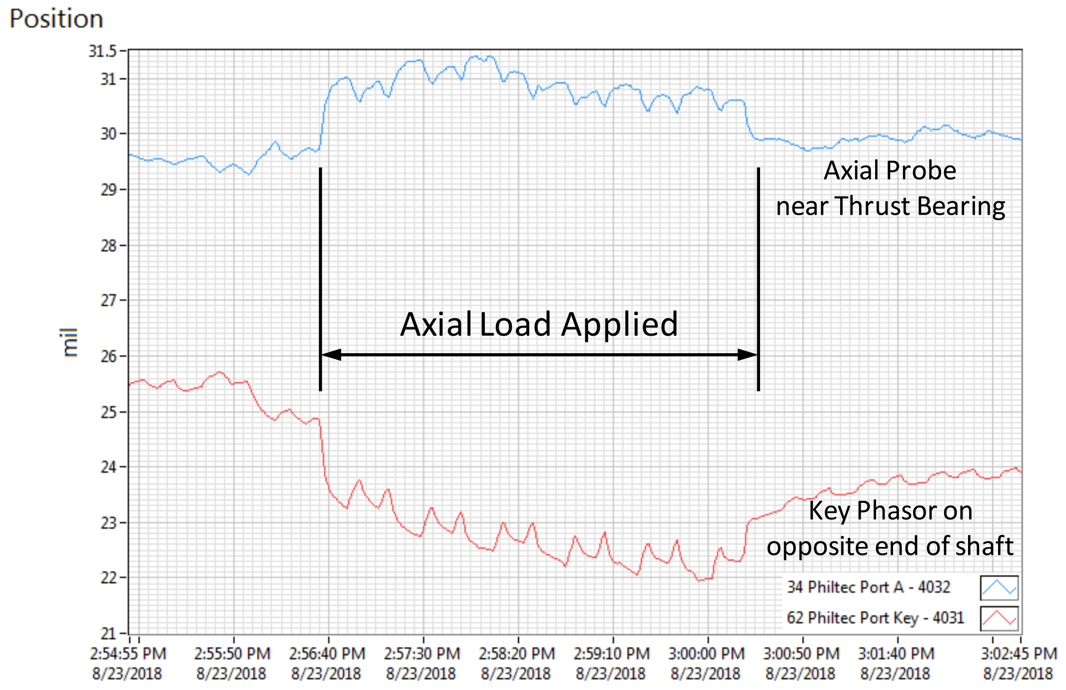
Pocket pressures relative to drain pressure. Values are in psi.





Thrust Bearing Static Testing

- Axial load was applied to the bearings with pressure acting on a shaft-mounted piston
- Could only develop 25 psi across the piston, resulting in a 98 lbf load (vs. 1100 lbf design)
- Due to profile variations in the pads, could not develop the intended pocket pressures
- Nevertheless, the classic hydrodynamic foil bearing action provided sufficient thrust capacity for functionality during the test
- Reducing pad profile variation should significantly improve performance



Axial Displacement as Load is Applied

Dynamic Testing

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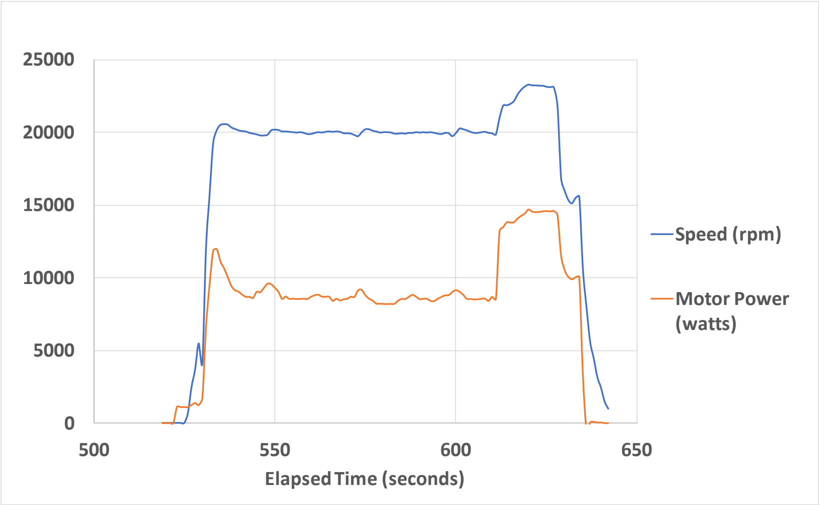
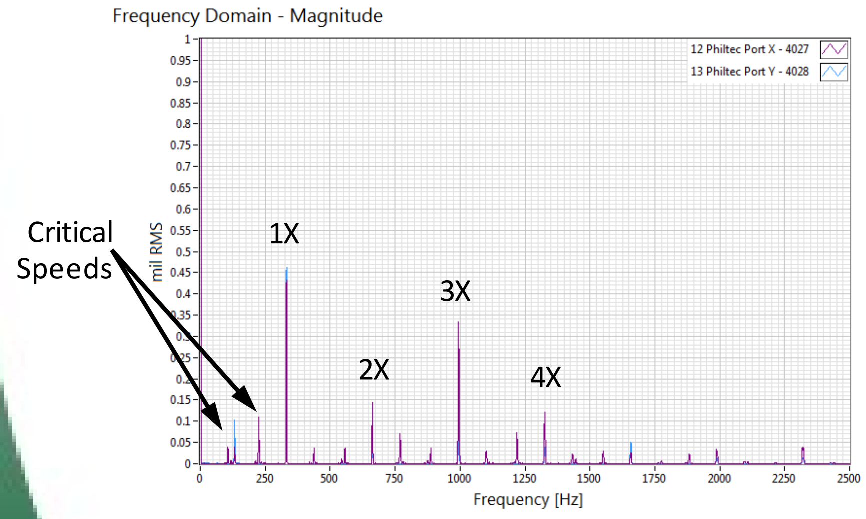
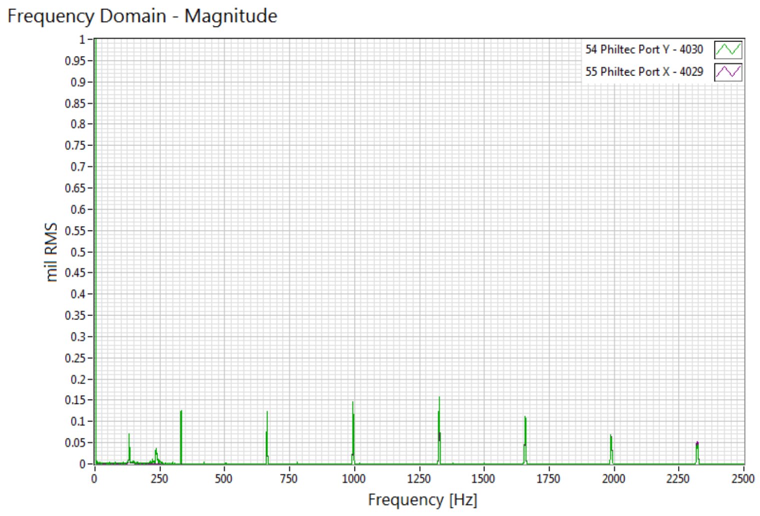
- Goal: run up to 50,000 rpm
- Initial run-up to 20,000 rpm (controller minimum speed setting)
- Very stable operation with low vibration
- Some sub-synchronous vibration, but very low amplitude
- Attempted to run up to 30,000 rpm, but encountered motor control problems and noise above 24,000 rpm

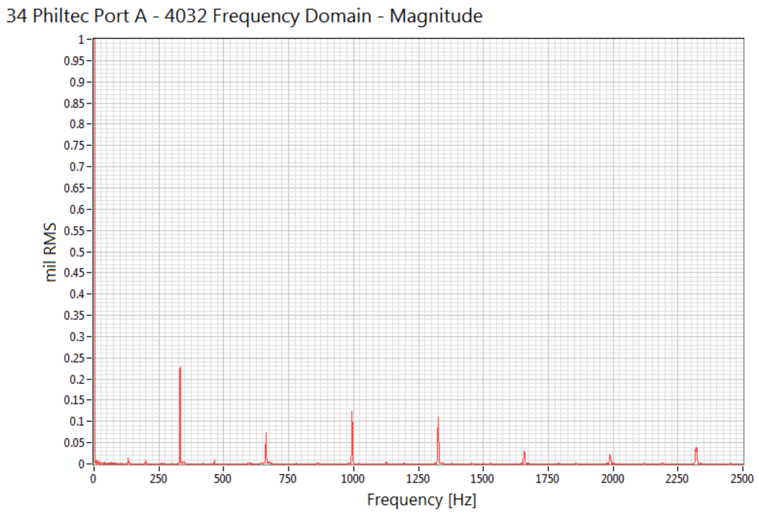




Thrust-End Radial Bearing



Free-End Radial Bearing

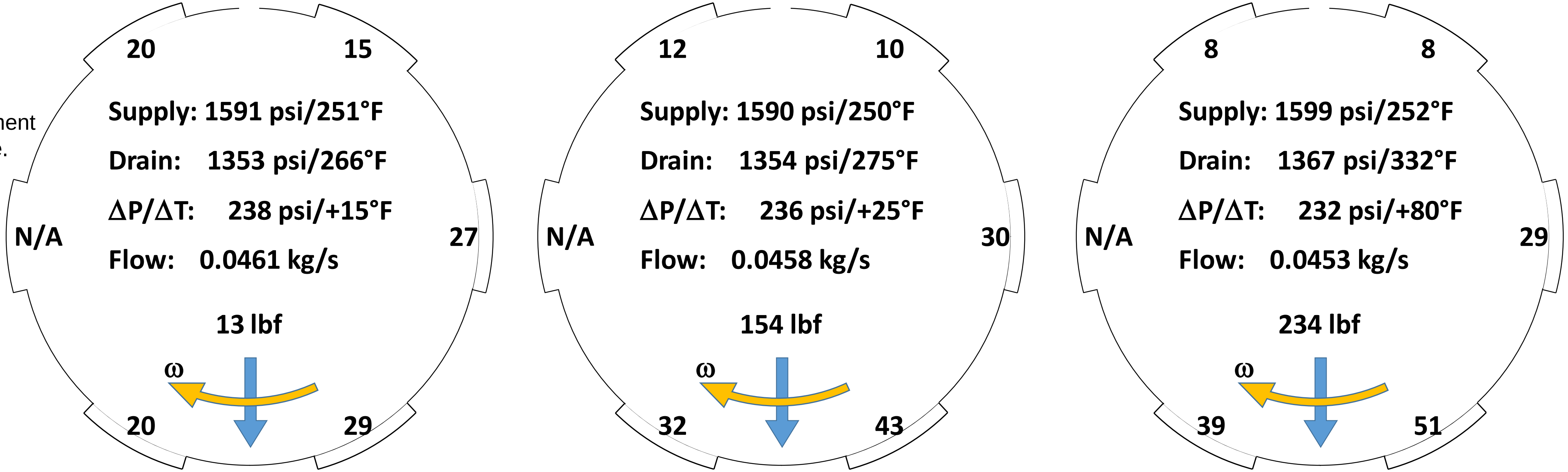


Axial Vibration

Dynamic Testing

- Applied radial load in 1 amp increments up to 234 lbf
- Higher pocket pressures developed as rotation increased
- Under load, the bottom pocket pressures increased, but not as much as non-rotating case
- Behavior was consistent with predictions, but suggested that radial clearances opened more than expected during rotation
- Bearing flow was lower than with static case (as predicted)

N/A: measurement not available.



Pocket pressures are relative to drain pressure. Values are in psi.

In Conclusion:

Summary

- Results from the testing are very encouraging
- The hydrostatic assist was shown to substantially increase load capacity and stiffness in the radial bearings
- Current limitations prevented validation of the hydrostatic performance of the thrust bearing design
- Top foil imperfections in first bearing prototypes limited their performance
- Issues within the test rig prevented achieving the desired maximum speed
- Pneumatic hammer was successfully avoided by using an acoustic based design analysis technique

Future Work

- Development of manufacturing processes to improve surface profiles is the top priority
- Investigating additional funding sources to continue the bearing development and testing
- Test rigs at MSI will be used to continue development under IR&D funding
- MSI intends to extend the design to apply to other process gases

Acknowledgment

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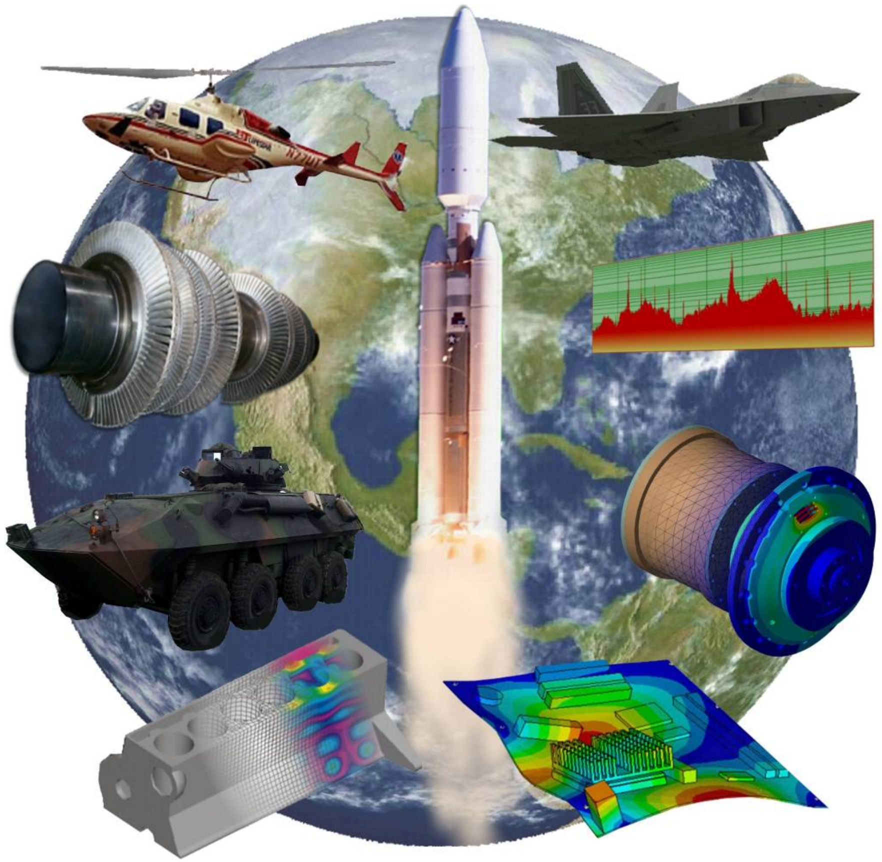

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