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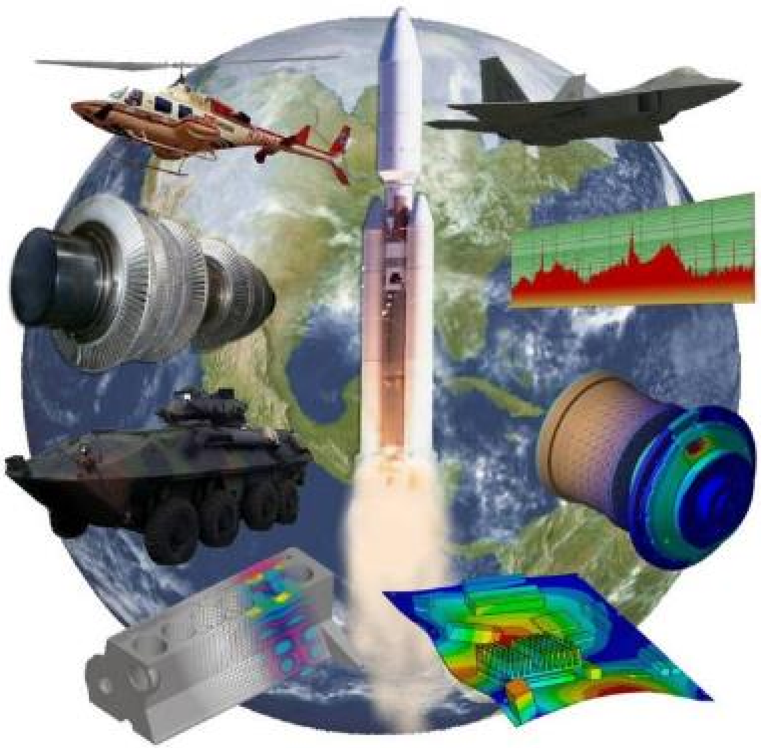
Engineering Analysis, Test & Technology

Advanced Gas Foil Bearing Design for Supercritical CO_2 Power Cycles



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Blacksburg, VA

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Today's Presentation

- Project Background
- Overview of foil bearings:
  - A primer on various types, typical applications, etc.

- Application in sCO_2 Power Cycle Machines
  - Design Considerations:
    - Fluid properties
    - Material selection
    - Load Capacity, Damping
    - Power Loss

- Progress to Date
- Ongoing Work

Project Background

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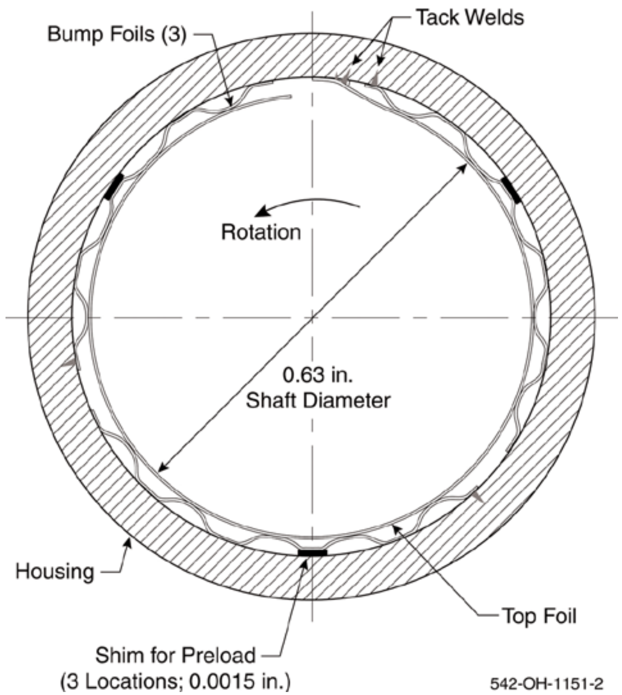
- Funding provided by the Department of Energy (DOE) Office of Fossil Energy
  - Phase 1: June 2015 – March 2016
  - Phase 2: August 2016 – July 2018
- Goal: develop a reliable, high performance foil bearing system using sCO_2 as the working fluid
  - Temperatures up to 800°C
  - Pressures up to 300 bar
- Key elements of the design:
  - An advanced hydrostatically-assisted hydrodynamic foil bearing with higher load capacity
  - An integral gas delivery system to distribute flow throughout the bearing
  - Addition of overload protection to handle large shaft excursions during severe system transients
  - Use of high temperature materials and coatings to prolong life and enabling sufficient start/stop cycles

Why Foil Bearings?

- High speed
- Extreme-temperature and/or oil-less environment
- Permits a hermetically-sealed system (eliminate end seals)
- Insensitive to system pressure
- Applicable to high energy density turbomachinery
  - Motors and generators are being designed to run faster and with more torque, with reduced size & weight
  - Direct drive is a trend
- Long, maintenance-free life

General Features of a Bump-Style Radial Foil Bearing

- Smooth top/inner foil – one or several segments
- Support foil contains cylindrical bumps
  - One or several segments
  - One or several layers
  - Sometimes slotted for improved edge loading, misalignment tolerance, etc.
- Unidirectional, with shaft rotating from free end to fixed end
- Is a hydrodynamic bearing – gas or liquid film OK
- Compliant – reduces the need for high dimensional accuracy & roundness



Bump Style Radial Foil Bearing with Preload

Application Spectrum for Foil Bearings

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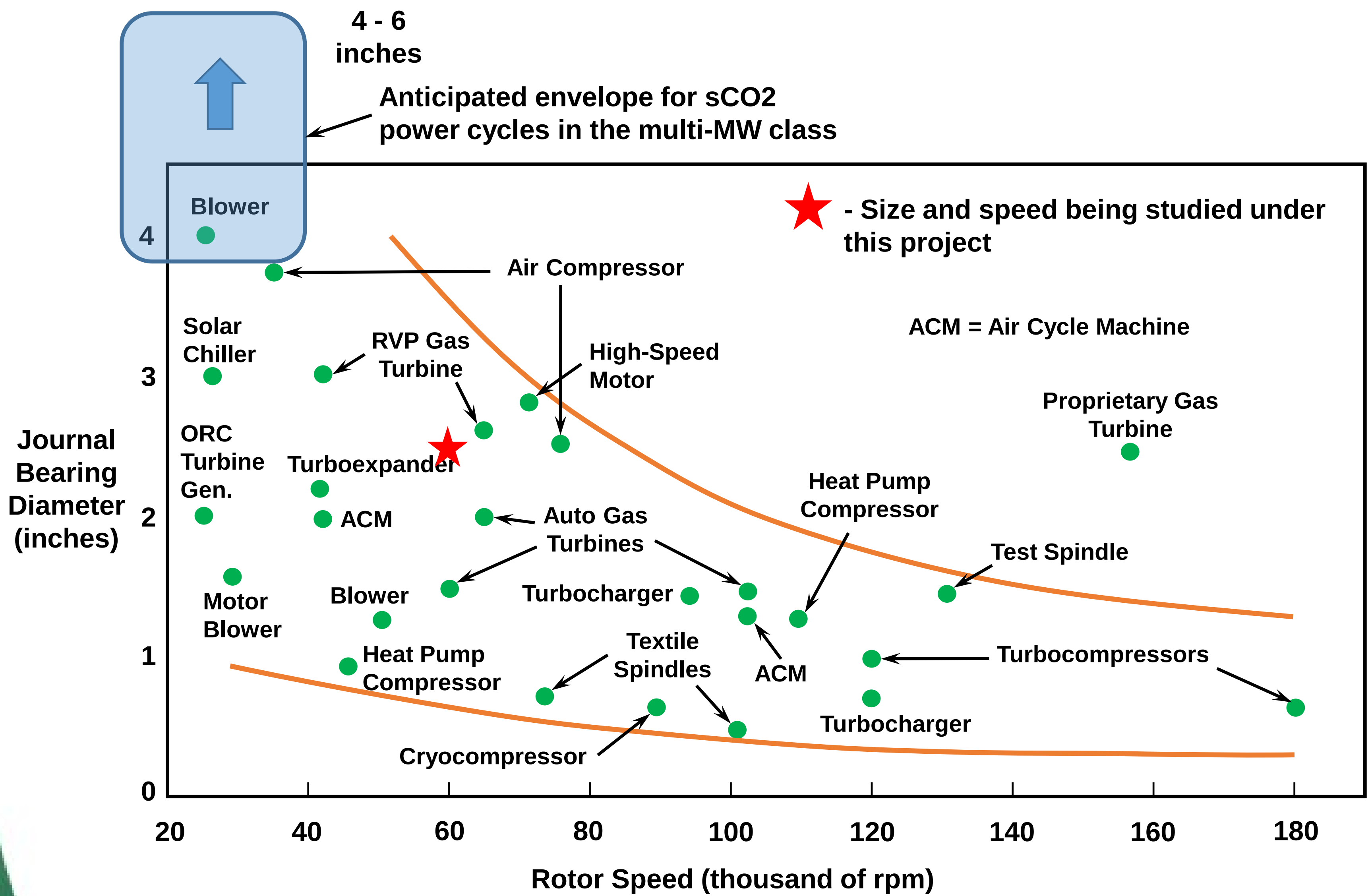
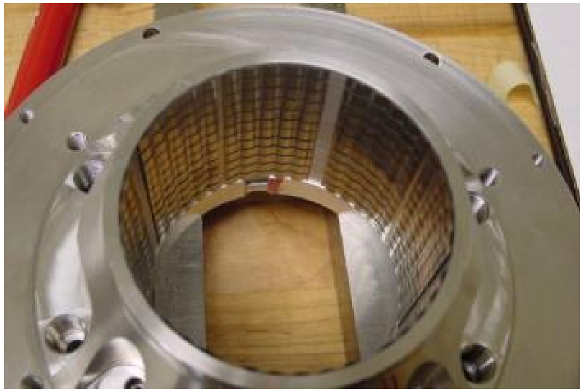


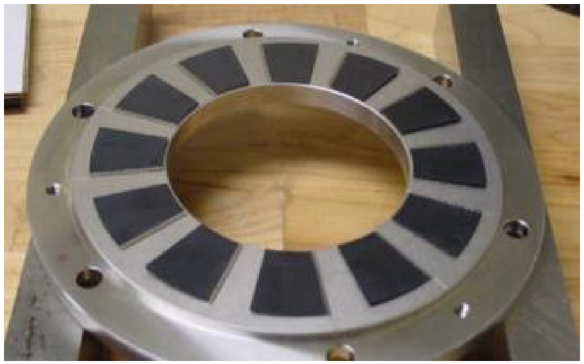
Foil Bearing Sizes

Foil Bearings for Centrifugal Air Compressor

- 93 mm journal diameter
- 45,000 rpm



Journal Bearing
Top foil removed



Thrust Bearing

Foil Bearings for Miniature Gas Turbine Engine

- 160,000 rpm
- 66 mm journal diameter

Journal Bearings | Combination Bearings | Thrust Bearings

Foil Bearings for Turbocompressor

- 180,000 rpm
- 16 mm journal diameter

Radial Foil Bearing

Applying Foil Bearings to Supercritical CO_2 Machinery

CO_2 Fluid Properties

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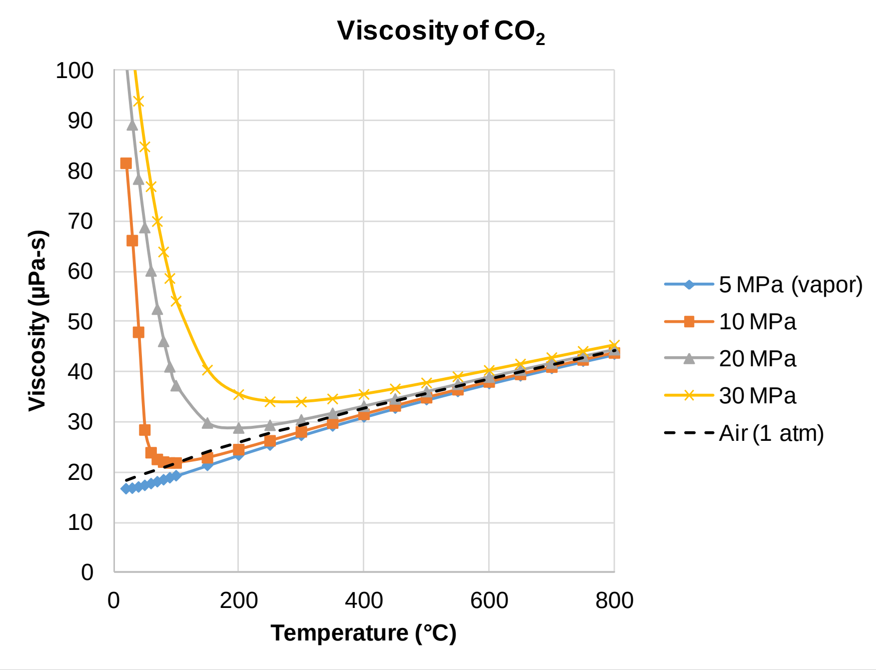
Viscosity

- Hydrodynamic lubrication simplified by using the Reynolds equation
- Viscosity is the only property taken into account
- Above 200°C, viscosity increases as temperature increases
  - Characteristic of gases
  - Insensitive to pressure variations
  - Similar to air
- Below 200°C, viscosity decreases as temperature increases
  - Characteristic of liquids
  - Very sensitive to pressure variations
  - A potentially unstable thermal condition
  - Start-up sequence may be critical for proper performance



Source: National Institute of Standards and Technology (NIST)
http://webbook.nist.gov/chemistry/fluid/

CO_2 Fluid Properties

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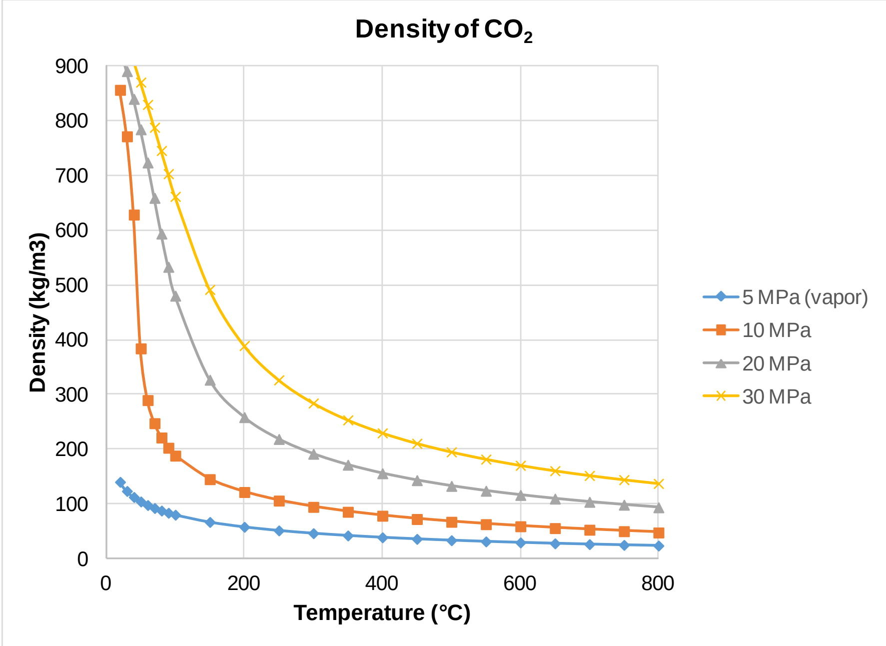
Density

- The more compressible the fluid, the more other fluid properties influence bearing design
- As flow exits the laminar regime, density becomes an important parameter
- Studies have shown a significant increase in power loss as pressure (density) increases (Bruckner and Dellacorte[1], Milone[2])
- The additional power loss must be accounted for in overall system efficiency
- The heat generated must be managed to avoid overheating and potential thermal instability

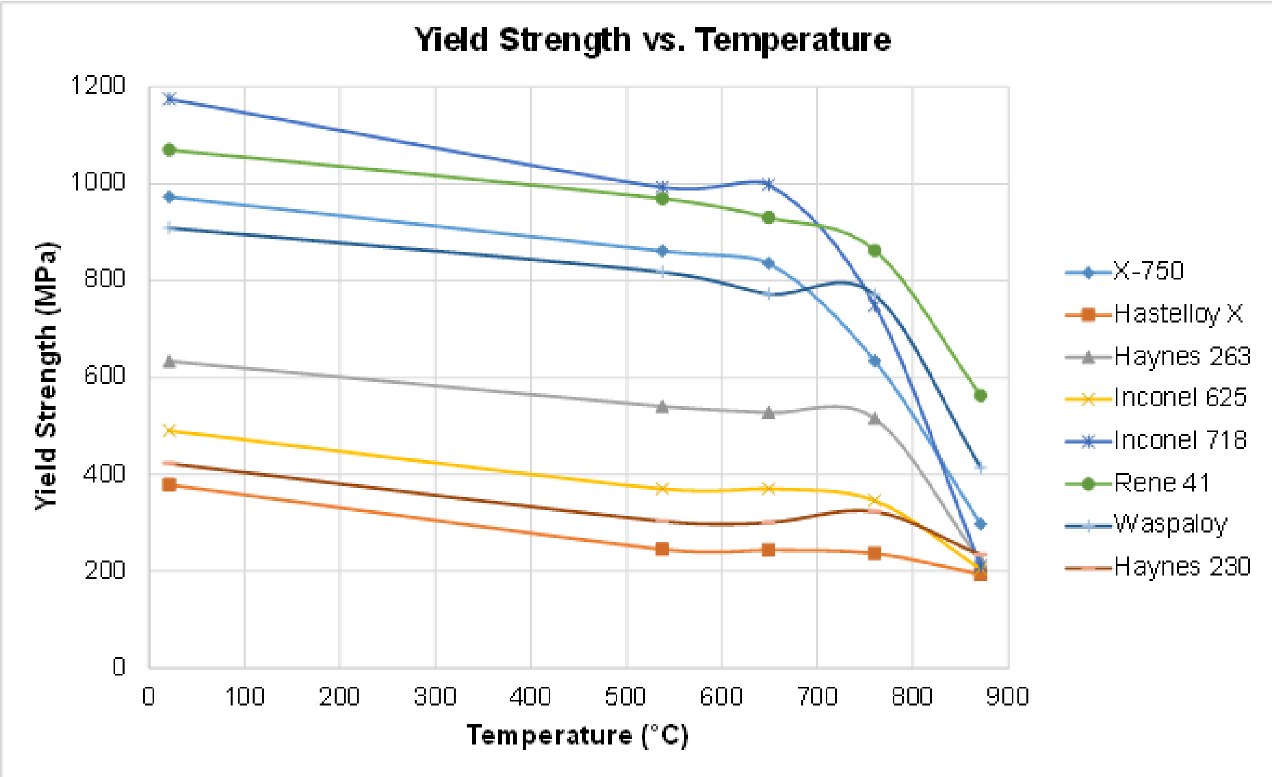


Source: National Institute of Standards and Technology (NIST)
http://webbook.nist.gov/chemistry/fluid/

1. Bruckner, R.J. and DellaCorte, C., “Windage Power Loss in Gas Foil Bearings and the Rotor-Stator Clearance of High Speed Generators Operating in High Pressure Carbon Dioxide Environments”, Supercritical CO2 Power Cycle Symposium, Rensselaer Polytechnic Institute, April 29-30, 2009, Troy, NY.
2. Milone, D., "Windage and Gas Foil Bearing Losses in a Supercritical Carbon Dioxide Turbine Generator;" Supercritical CO2 Power Cycle Symposium, May 24-25, 2011, Boulder, CO.

Material Considerations - Strength

- Inconel X-750 commonly used foil material
  - High strength at elevated temperatures
  - Good fatigue and corrosion resistance
  - Available in a variety of foil thicknesses
- René 41 a potential alternative



Strength of Several Nickel Alloys (Courtesy Haynes International, Inc.)

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- Under normal, steady-state operating conditions, there is no contact between the shaft and bearing
- During start-up and shut-down, contact is inevitable
  - This is most often the life-limiting aspect of foil bearings
  - By energizing the hydrostatic feature, rubbing during start-up/shut-down may be avoided
- Characteristics of a good coating include
  - Low friction
  - Resistance to wear
  - Good adhesion to the substrate

Advanced Coatings

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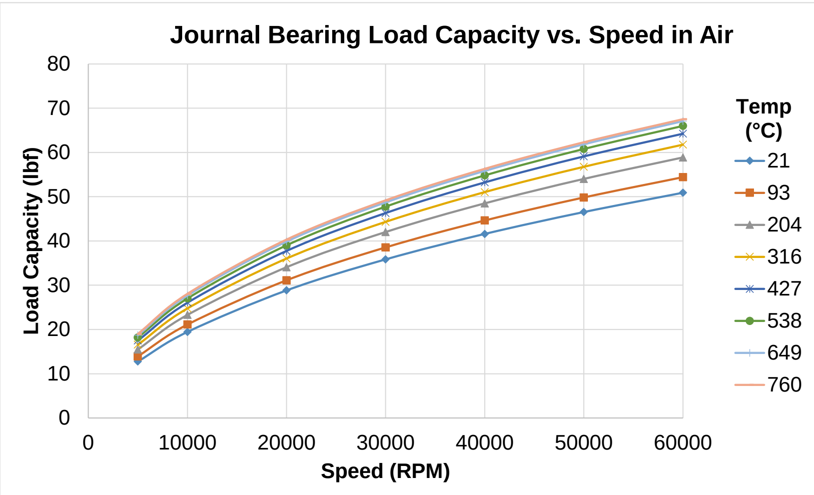
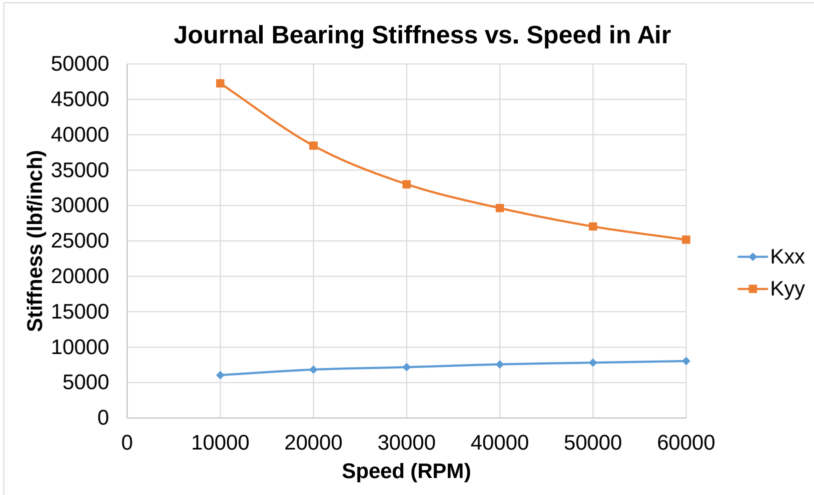
- A number of high temperature coatings were previously evaluated up to 650°C, with promising results
- The best candidates were then evaluated up to 800°C
- A new family of coatings is starting to become available, known as Adaptive coatings, or “chameleon” coatings
  - Named due to their ability to adapt to changing temperature by preserving good tribological properties from 25°C to 1000°C
  - Due to higher expense and long lead times, these will be evaluated in Phase 2

Bearing Performance

- Project focused on developing a journal bearing
  - Diameter: 63.5 mm (2.50 inches)
  - Length: 44.5 mm (1.75 inches)
  - Speed: 60,000 rpm
  - D·N: 3.81 million
- Phase 1 testing was performed in air



Estimated Hydrodynamic Load Capacity



Estimated Stiffness under Constant Load

Hydrodynamic Performance

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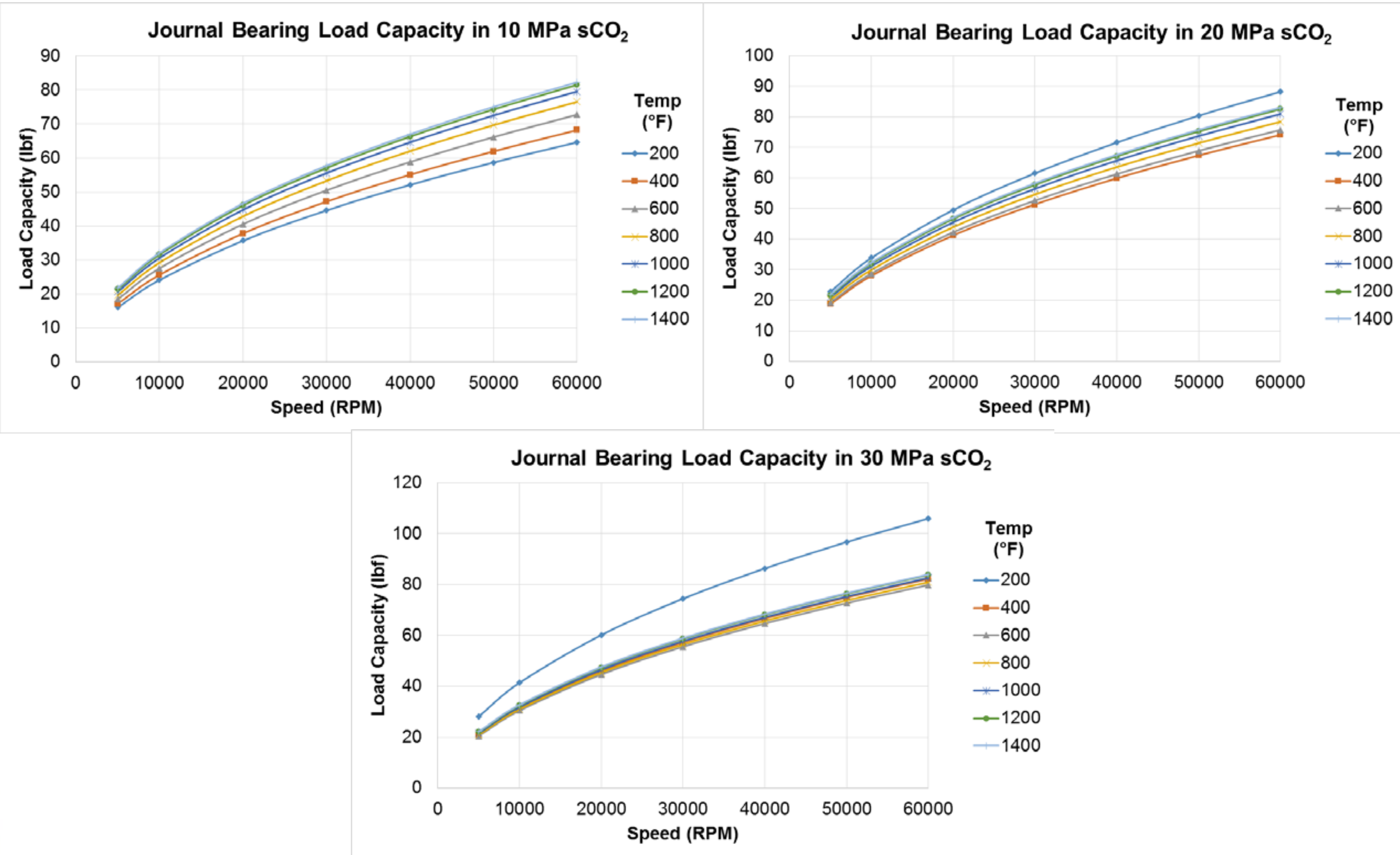
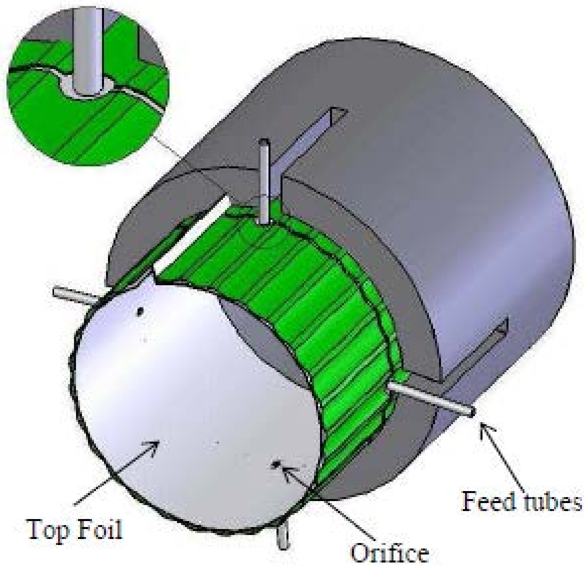
- Phase 2 testing will be in sCO_2



Estimated Hydrodynamic Load Capacity

Hydrostatic Performance

- 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 cavity



Source: Texas A&M University (Kumar[3])

3. 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.

Hydrostatic Performance

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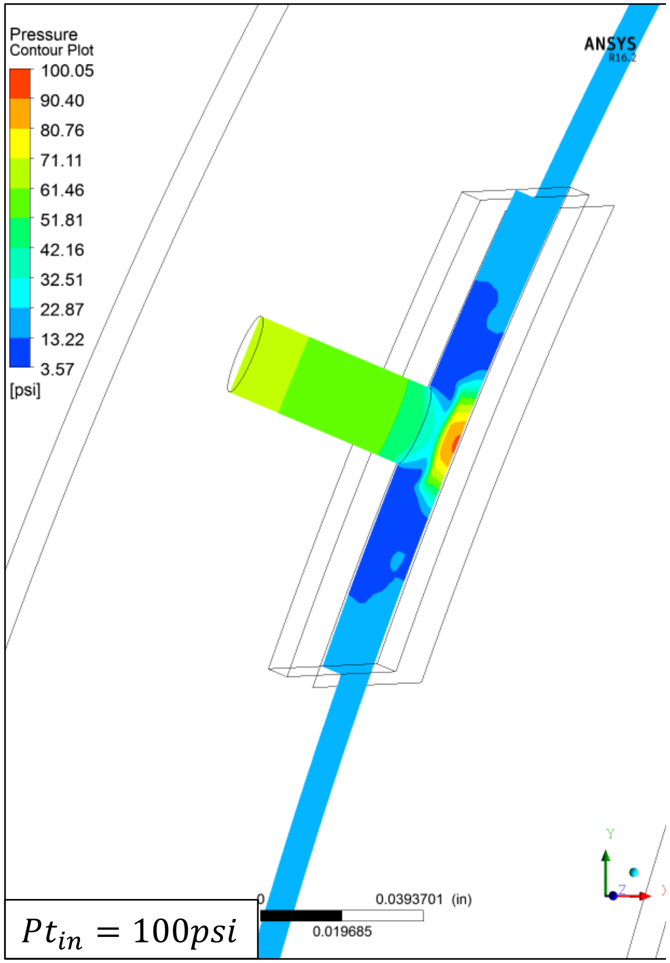
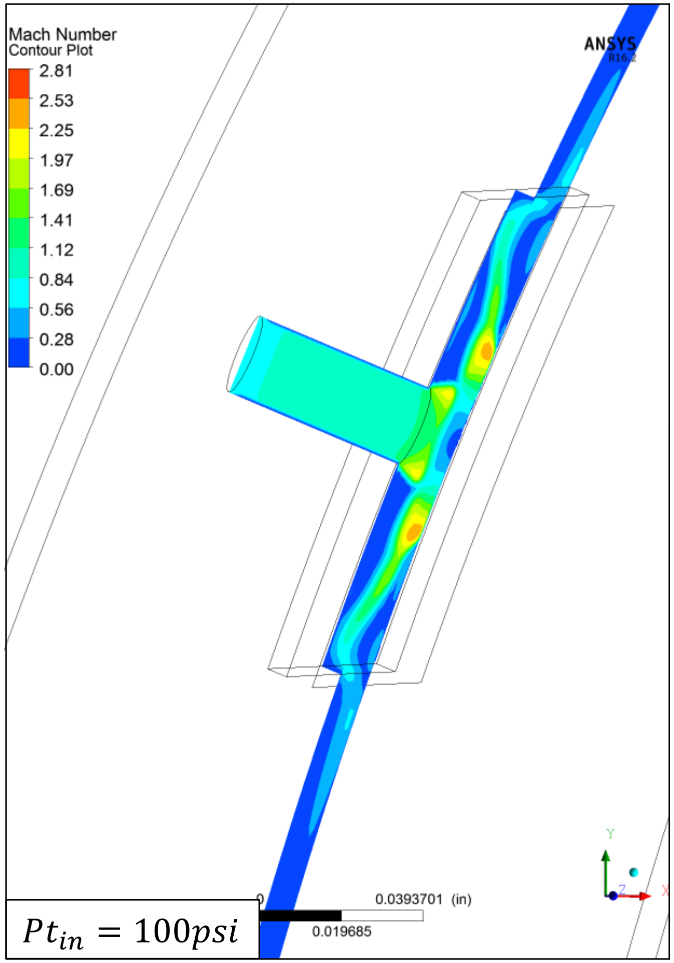
- MSI is studying a proprietary design using CFX (ANSYS, Inc.)





CFD Results of a Single Nozzle

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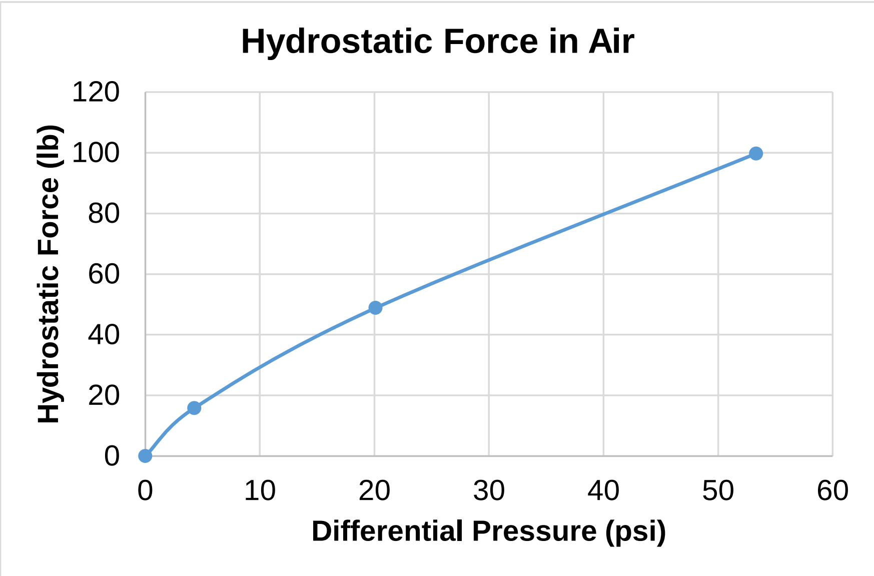
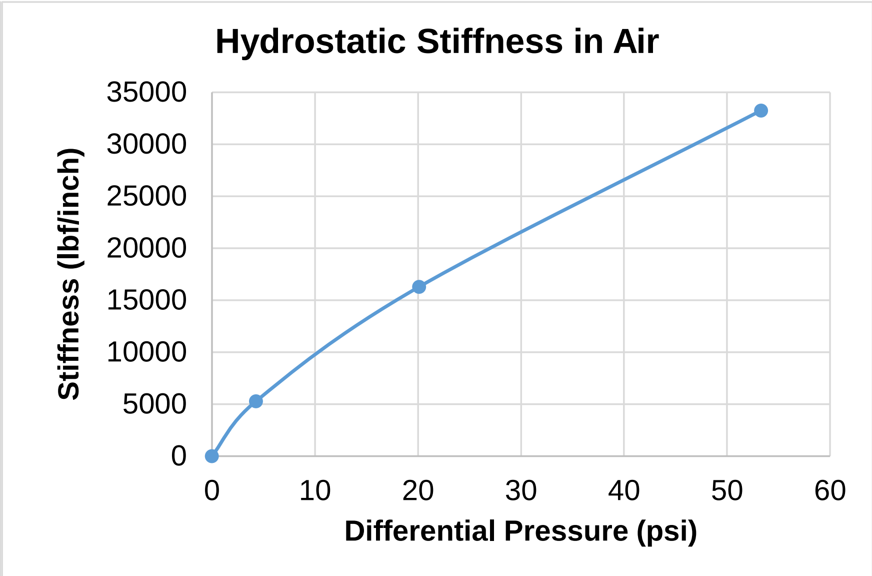
Generated Hydrostatic Force and Stiffness vs. Differential Pressure for the Journal Bearing

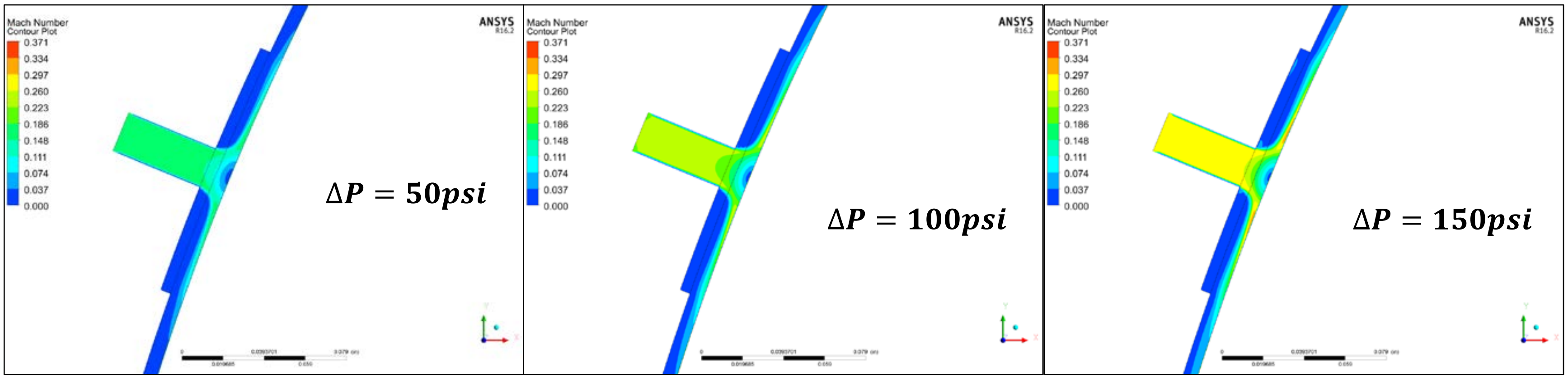




Hydrostatic Bearing Performance

Same CFD model used to predict performance in sCO_2

- Nature of sCO_2 required the use of a Real Gas Properties (RGP) table
- Table consists of a matrix of fluid properties as a function of pressure and temperature
- Unlike the air case, high flow velocities are not present due to much higher density, tending to keep the Mach number low.



Validation Testing

Static Testing – Hydrostatic Bearing

Dynamic Testing – Hybrid Bearing

Coating Evaluation

Static Testing – Hydrostatic Bearing

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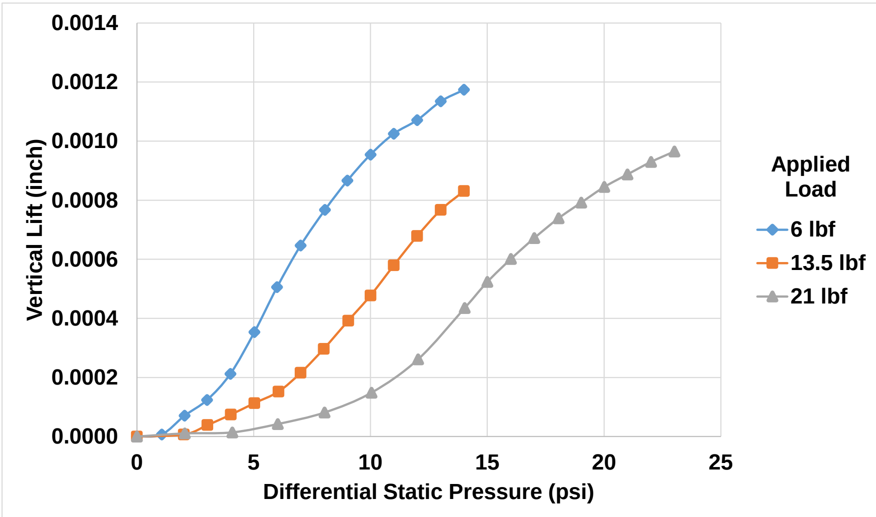
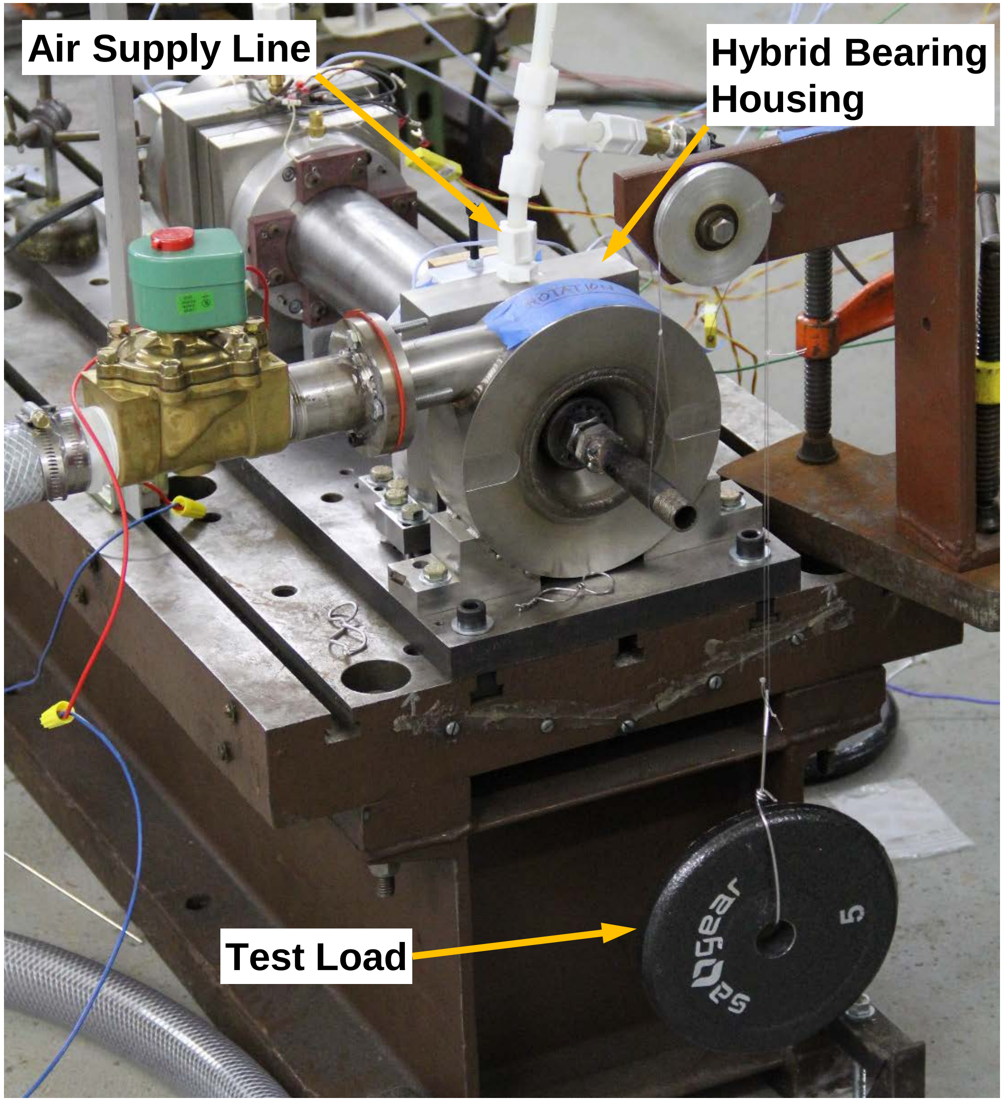
- Prototype hybrid bearings were constructed for both static (zero speed) and high-speed (50,000 rpm) testing
- The bearings were installed in MSI’s high-speed test rig
- Initial static load testing was conducted by varying the load, applying supply pressure, and measuring the vertical levitation of the shaft
- Stiffness was measured by incrementally changing the load and recording the change in shaft position



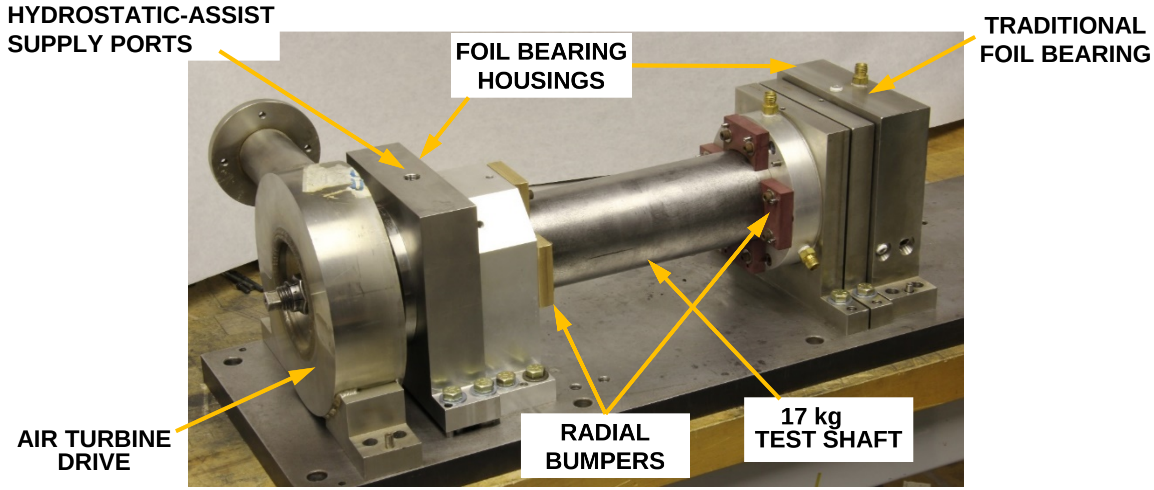
Hydrostatic Lift vs. Applied Static Pressure

Static Testing – Hydrostatic Bearing



Dynamic Testing – Hybrid Bearing

- The same test rig was used to perform high-speed testing to 50,000 rpm
- A hybrid foil bearing was installed on the drive end
- A conventional foil bearing was installed on the opposite end
- Rotor weight: 17 kg (37 lbm)
- Rig is driven by an air turbine



Dynamic Testing – Hybrid Bearing

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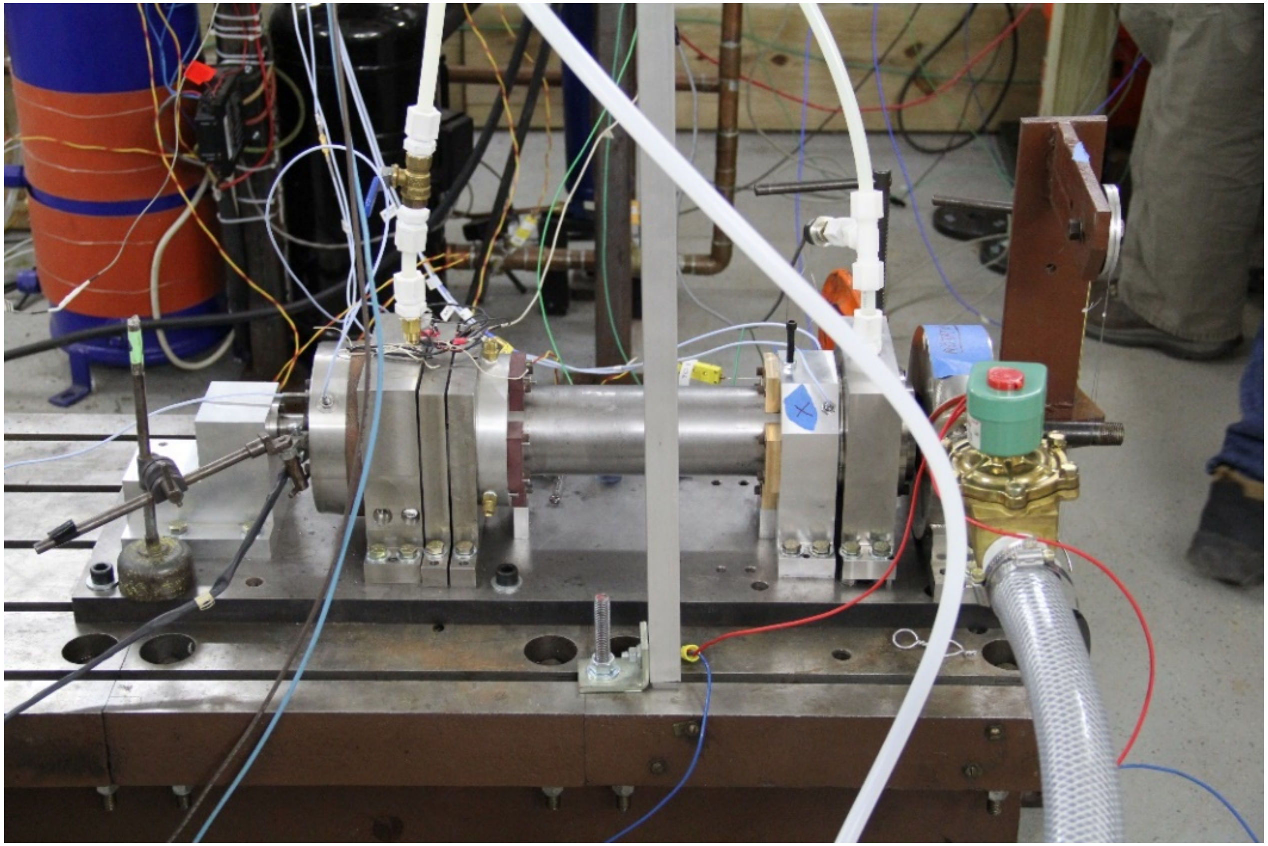
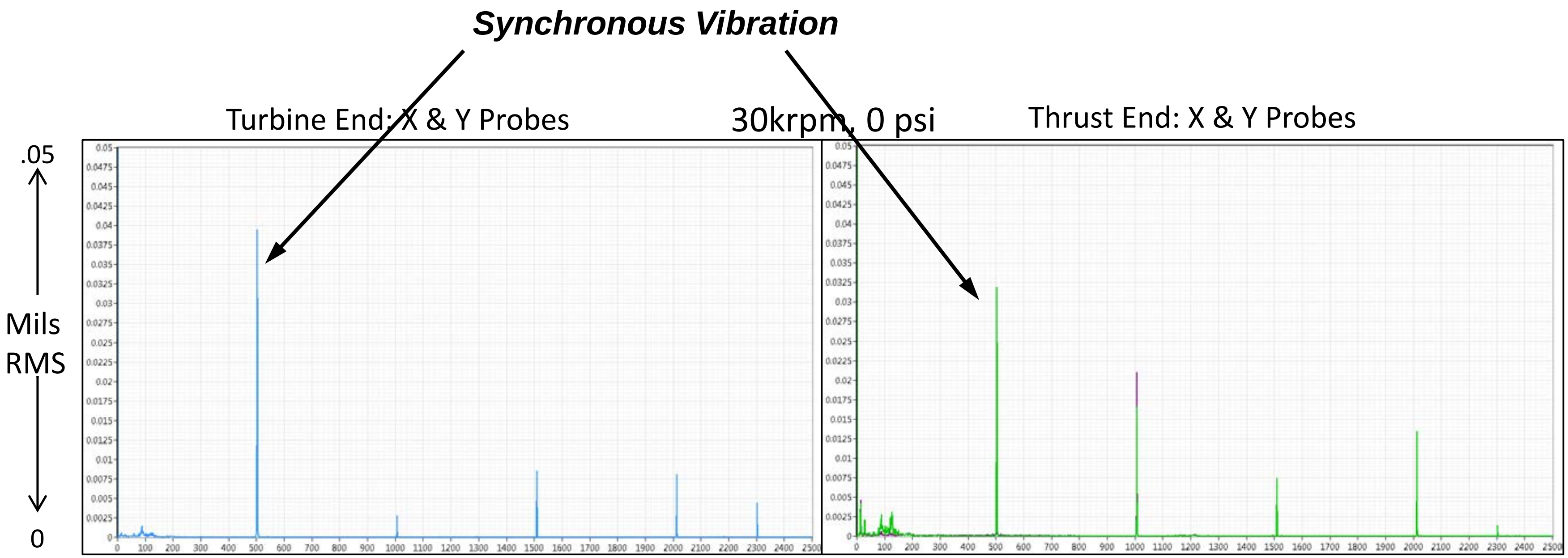
MSI's High Speed Foil Bearing Test Rig Installed in Test Cell



Dynamic Testing – Results

- At 30k rpm the rig experienced very stable operation
- Vibration levels were very low



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Dynamic Testing – Results

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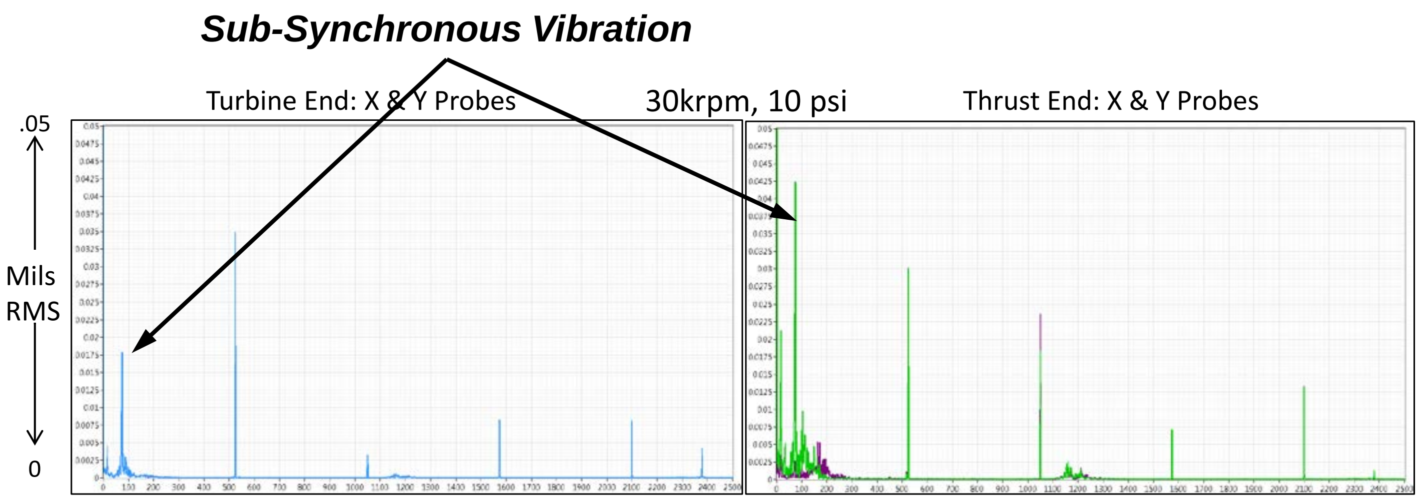
- At 30k rpm the rig experienced very stable operation
- Vibration levels were very low
- As hydrostatic air pressure was added (10 psi), a small sub-synchronous vibration (~79 Hz) was present
- The sub-synchronous vibration grew as pressure was increased to 15 psi, but diminished at 20 psi



Advanced Coating Testing

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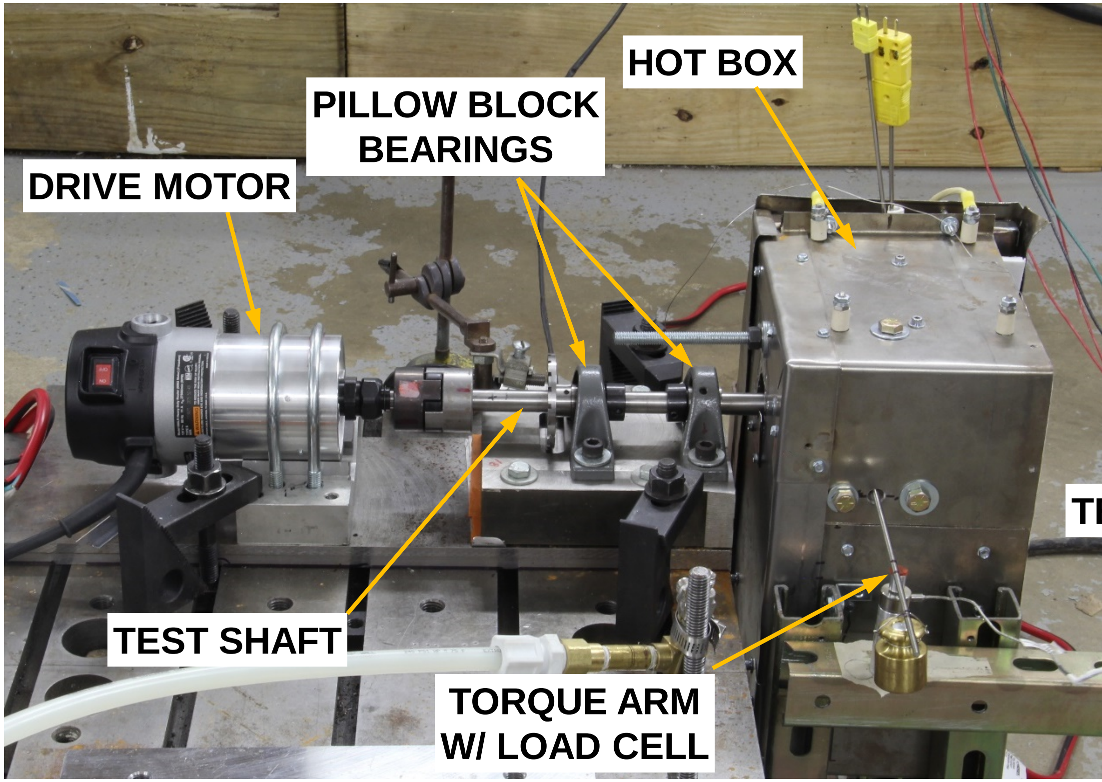
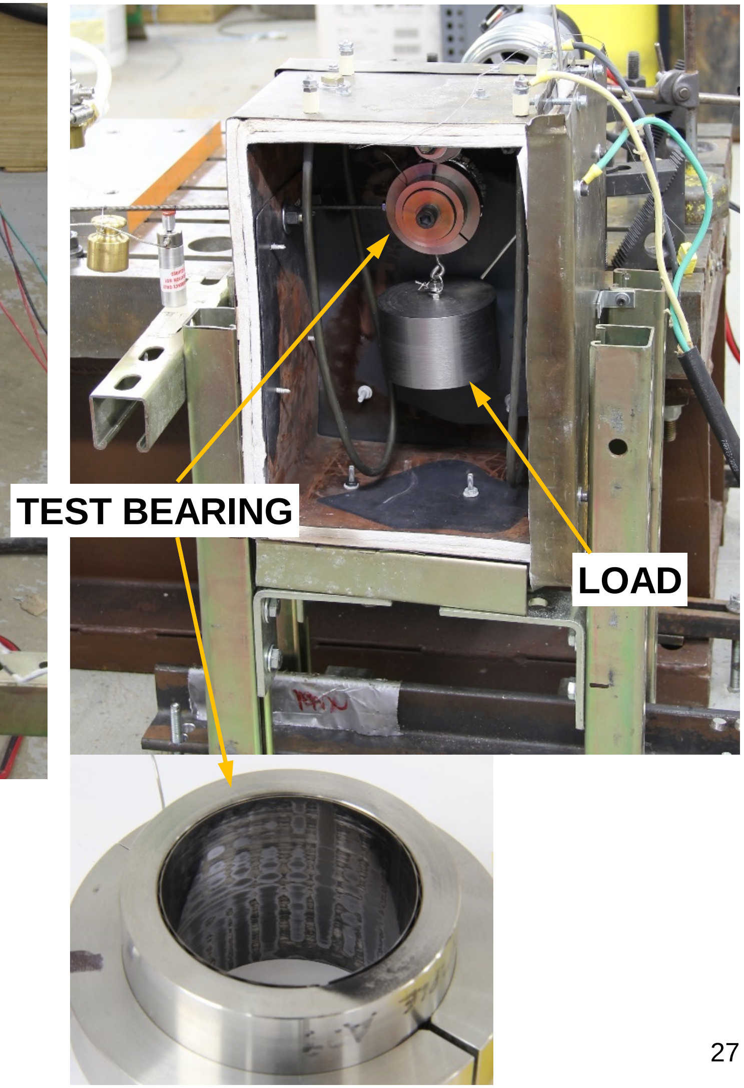
High Temperature Start/Stop Cycle Testing



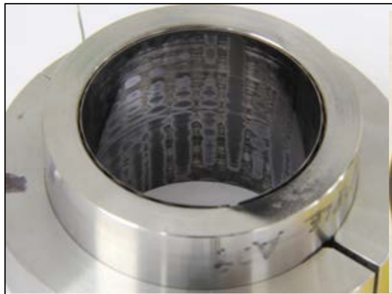


Rig Capabilities

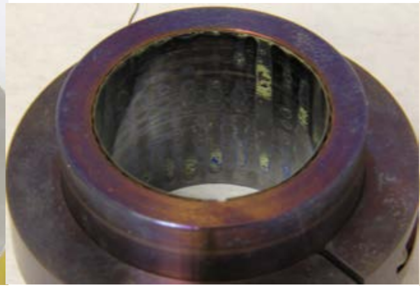
- Automatic start/stop cycling
- Constant applied load
- 17,000 RPM
- 650°C
- Continuous torque monitoring

Start/Stop Cycle Testing

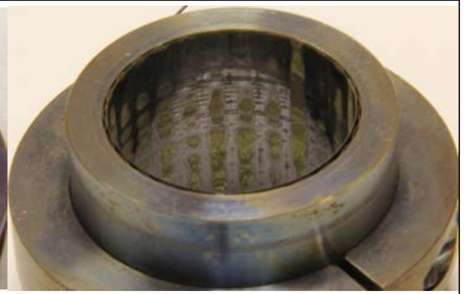
Sample Bearings and Test Shaft After Cycling



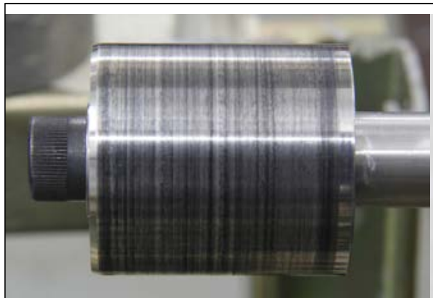
100 Cycles, 20°C



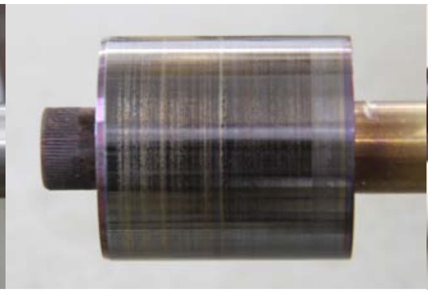
500 Cycles, 540°C



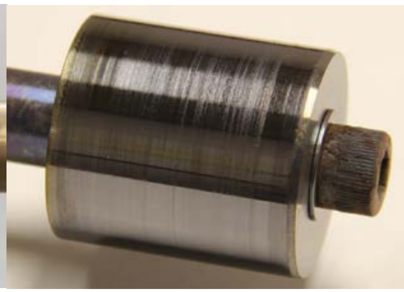
500 Cycles, 650°C



100 Cycles, 20°C



500 Cycles, 540°C



500 Cycles, 650°C

Start/Stop Cycle Testing - Results

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- Coating successfully passed the cycle testing
- Test shaft shows evidence of some coating transfer
- Shaft has appearance of a typical burnishing operation
- No evidence of adhesive wear was found
- Test shaft measured 8 microns (0.0003 inch) of wear (10% of bearing clearance) after initial room temperature run
- No measurable wear after high temperature cycles
- Wear of the top foil was 3-5 microns

Ongoing Work

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Phase 2

- Continue to optimize design and refine analytical models incorporating both hydrostatic and hydrodynamic bearing behavior
- Include intra-bearing interaction among the bearing foils
- Generate both optimized and practical (in sCO_2) journal and thrust bearing designs
- Conduct bearing validation tests in sCO_2 environment at Sandia National Labs
- Continue evaluation and improvement of high temperature, low-wear coatings

Acknowledgment

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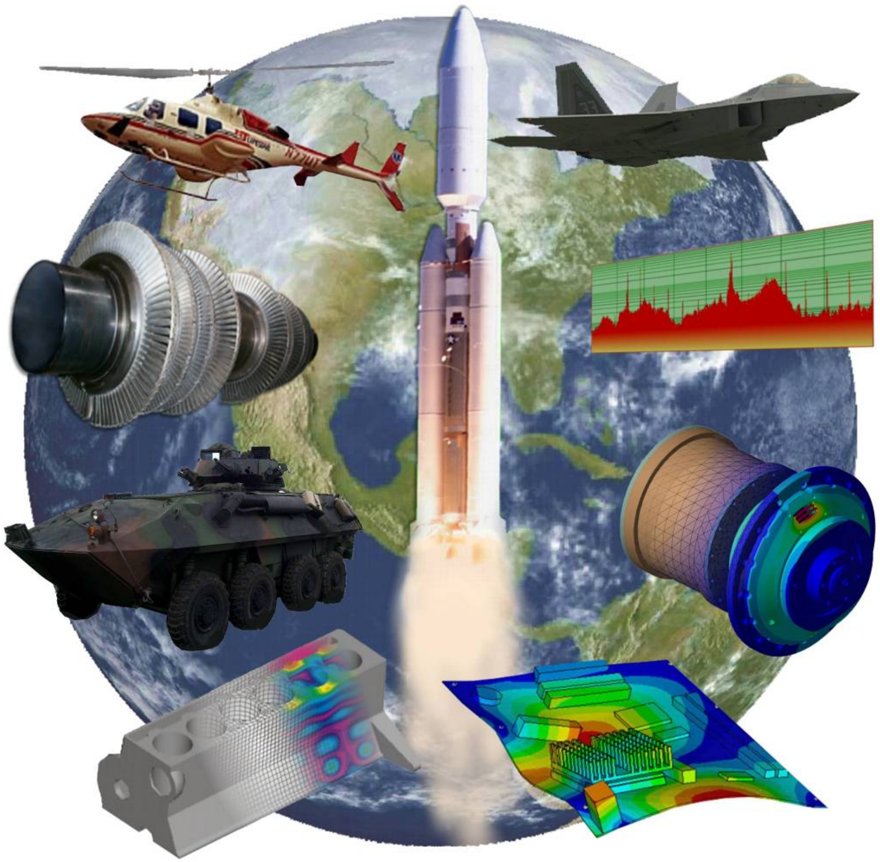

Stop By Our Poster

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