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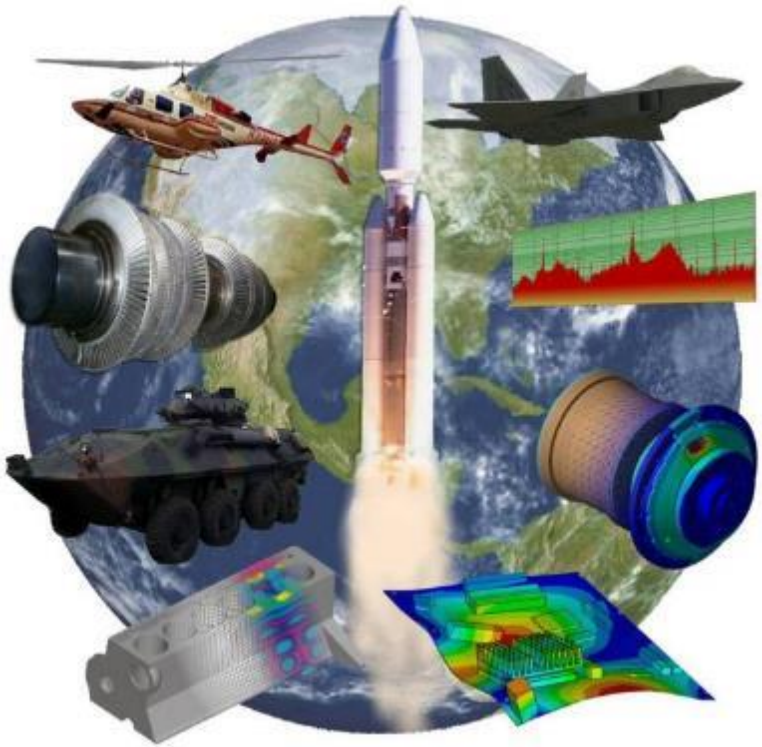
Engineering Analysis, Test & Technology

Advanced Gas Foil Bearing Design for Supercritical CO_2 Power Cycles



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The 5th International Symposium

Supercritical CO_2 Power Cycles

March 28-31, 2016

San Antonio, TX

Today's Presentation

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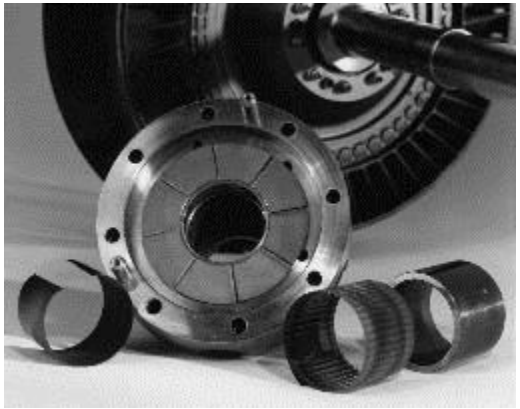
- Project Background
- Overview of foil bearings:
  - A primer on various types, typical applications, etc.
- Application in sCO_2 Power Cycle Machines
  - ***Design Considerations:***
    - Fluid properties
    - Material selection
    - Load Capacity, Damping
    - Power Loss
- Progress to Date
- Future Work



Project Background

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- Funding provided by the Department of Energy (DOE) Office of Fossil Energy
- 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?

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- 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

Traditional Foil Bearing Drawbacks

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- Low load capacity
- Require thermal management (cooling)
- Relatively low direct stiffness
- Low damping (but low cross-coupling also)
- Difficult to quantify rotordynamic coefficients analytically
- Intolerant of low frequency overloads
- Rubbing wear during start-up/shut-down

Foil Bearing Styles

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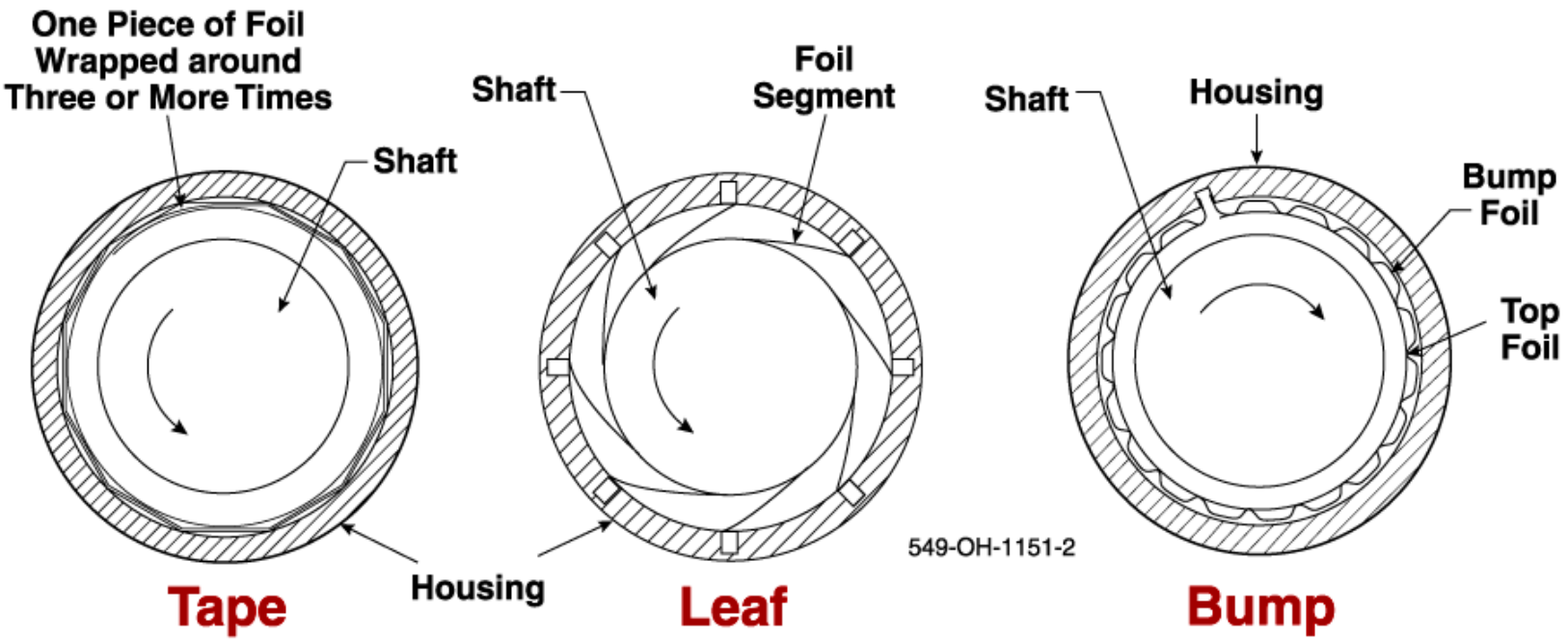
Three Most-Common Types



Bump type most publicized and common

General Features of a Bump-Style Radial Foil Bearing

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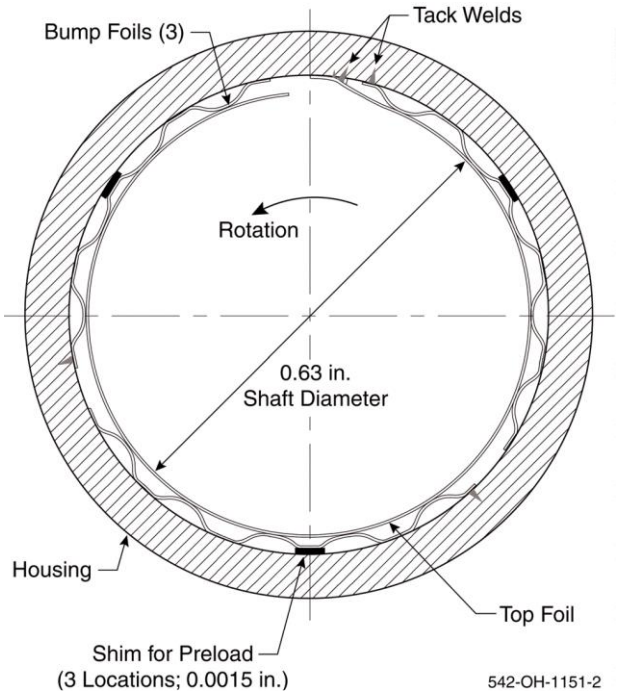
- Smooth top/inner foil – one or several segments
- Support foil contains cylindrical bumps
  - One or several segments
  - One or several layers
  - Sometimes slotted for improved edge loading, misalignment tolerance, etc.
- Unidirectional, with shaft rotating from free end to fixed end
- Is a hydrodynamic 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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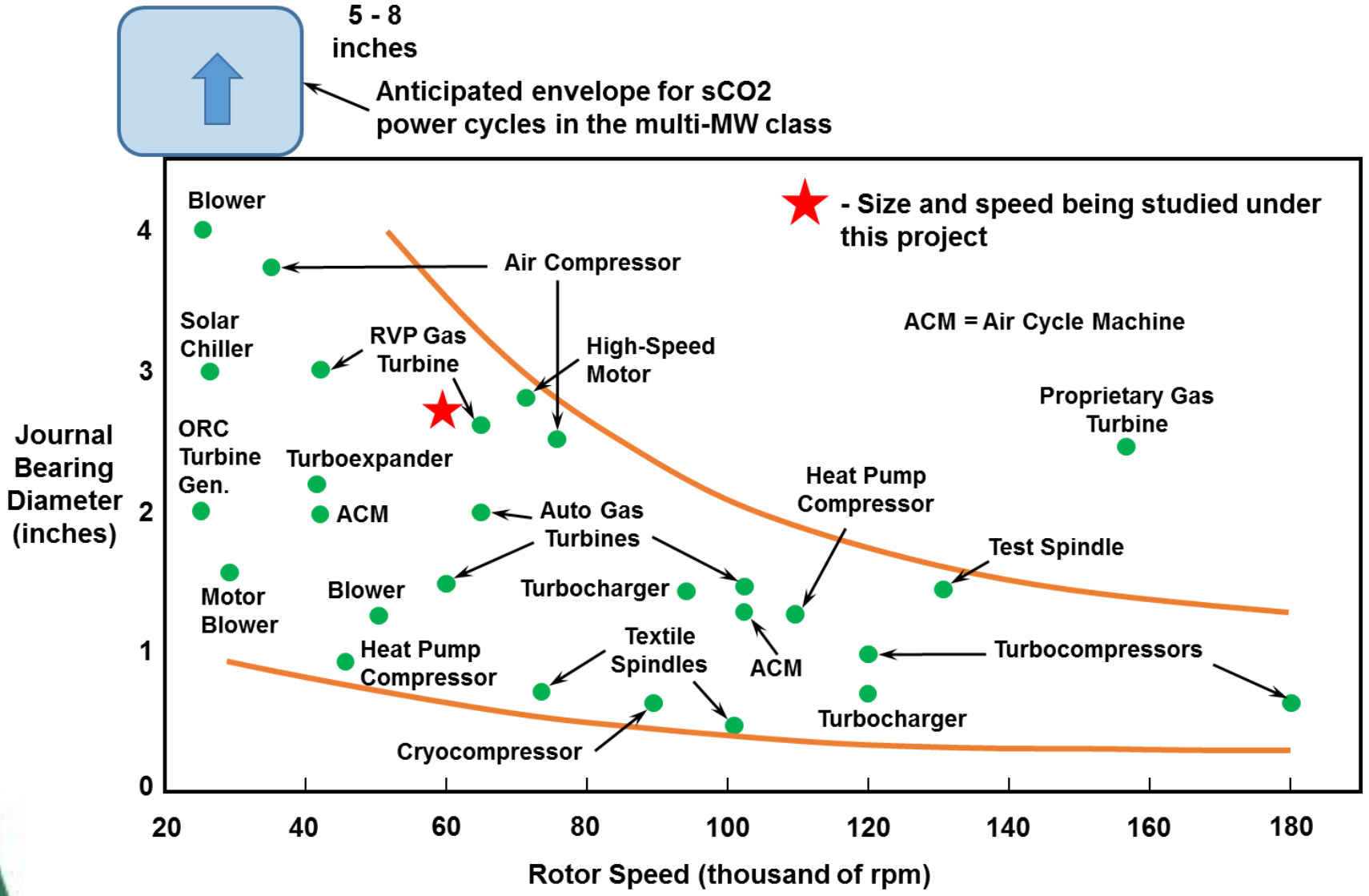

Foil Bearing Sizes

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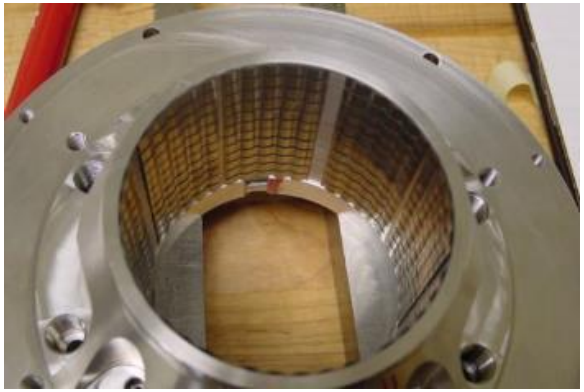
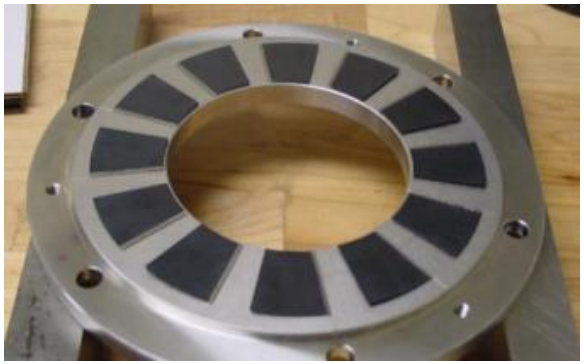
Foil Bearings for Centrifugal Air Compressor

- 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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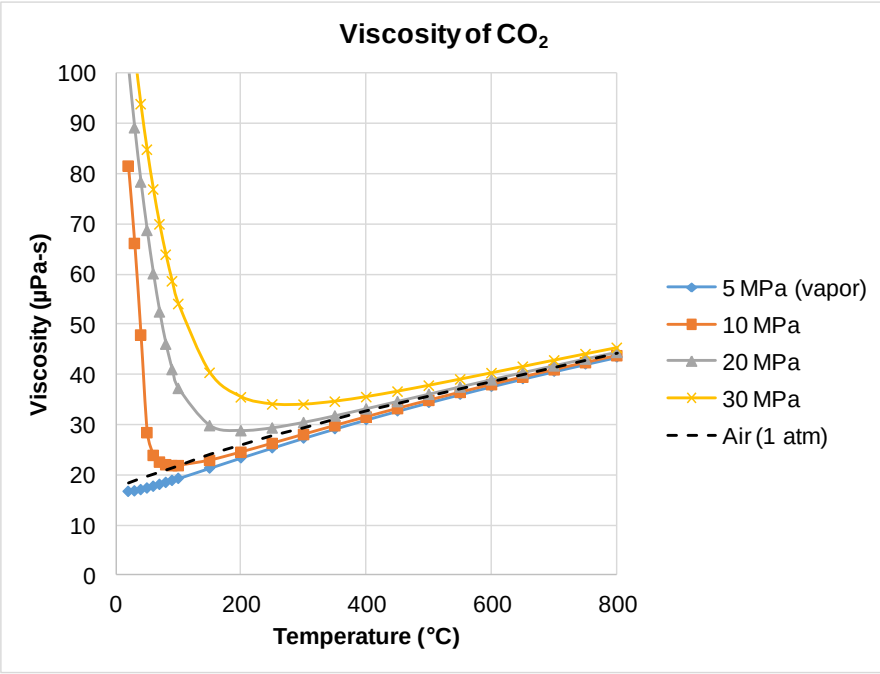
Viscosity

- 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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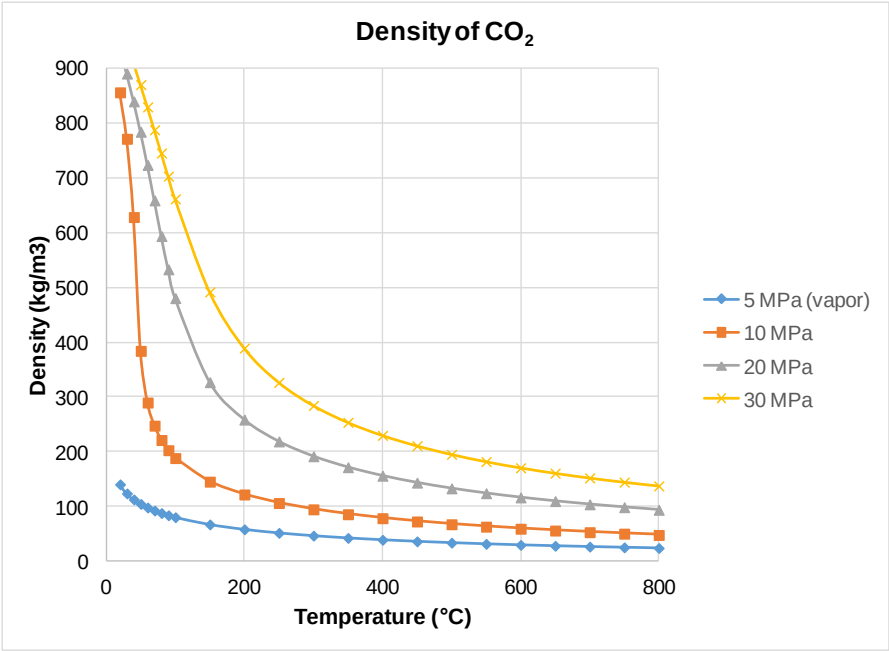
Density

- 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

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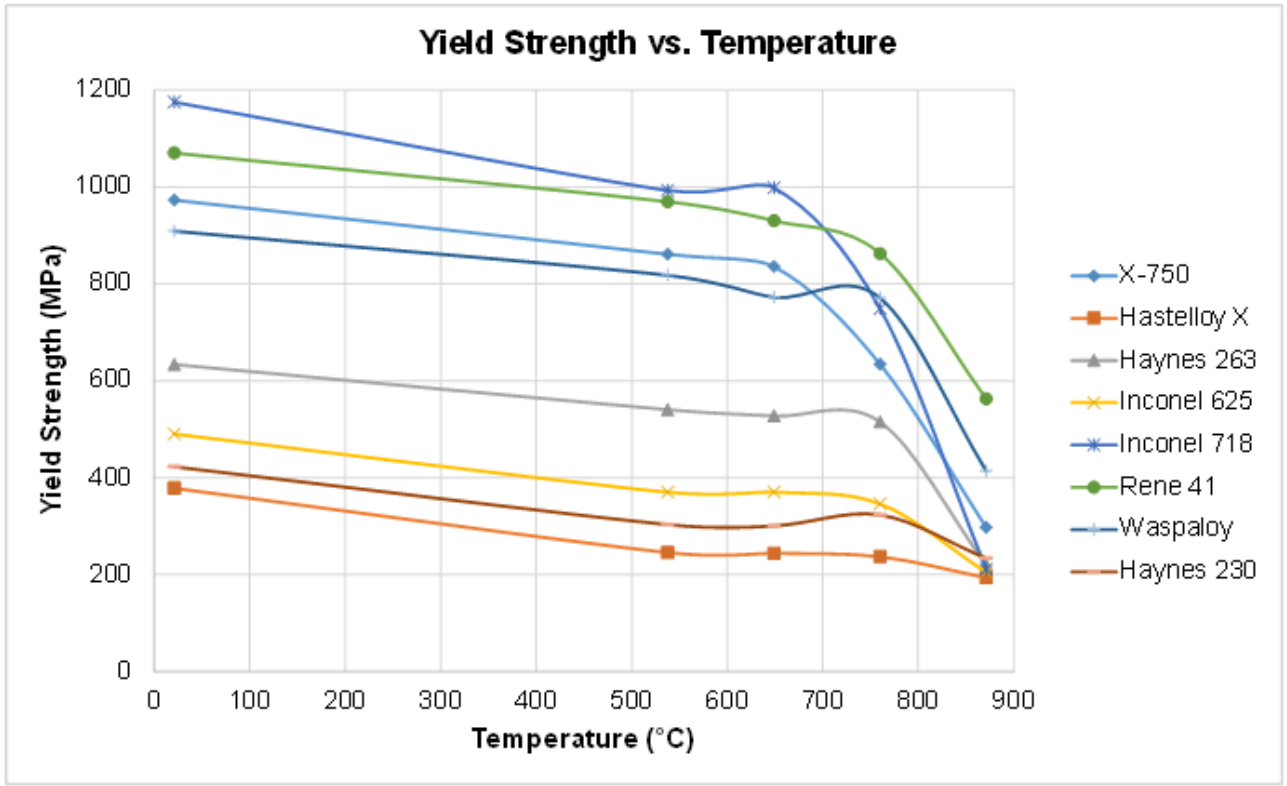
- Inconel X-750 commonly used foil material
  - High strength at elevated temperatures
  - Good fatigue and corrosion resistance
  - Available in a variety of foil thicknesses
- René 41 a potential alternative



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

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Material Considerations - Corrosion

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Corrosion in sCO_2 is a potential problem

- High strength steels exhibit severe corrosion in sCO_2 environments[3]
- Nickel alloys exhibit resistance to sCO_2 corrosion
  - Typically used for foil material
- Some austenitic stainless steels are OK
  - Typically used for bearing housings
  - Grade 316 has been shown to be susceptible to sCO_2 corrosion
  - Grades 310 and 347 demonstrate resistance similar to nickel-based alloys[4]

3. Cao, G., Anderson, M., Sridharan K., Tan, L., and Allen, T., "Corrosion of Candidate Alloys in Supercritical Carbon Dioxide," presented at the Supercritical CO_2 Power Cycle Symposium, Rensselaer Polytechnic Institute, April 29-30, 2009, Troy, NY.

4. Mahaffey, J., Anderson, M., Kalra, A., and Sridharan, K., "Materials Corrosion in High Temperature Supercritical Carbon Dioxide," 4th International Symposium - Supercritical CO2 Power Cycles, September 9-10, 2014, Pittsburgh, PA.

Advanced Coatings

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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
  - Tens of thousands of cycles might be required over the life of a device
  - 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
  - The required initial pressure source may not be available
- 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 have been evaluated up to 650°C, with promising results
- The best candidates are currently being 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 the next phase

Bearing Performance

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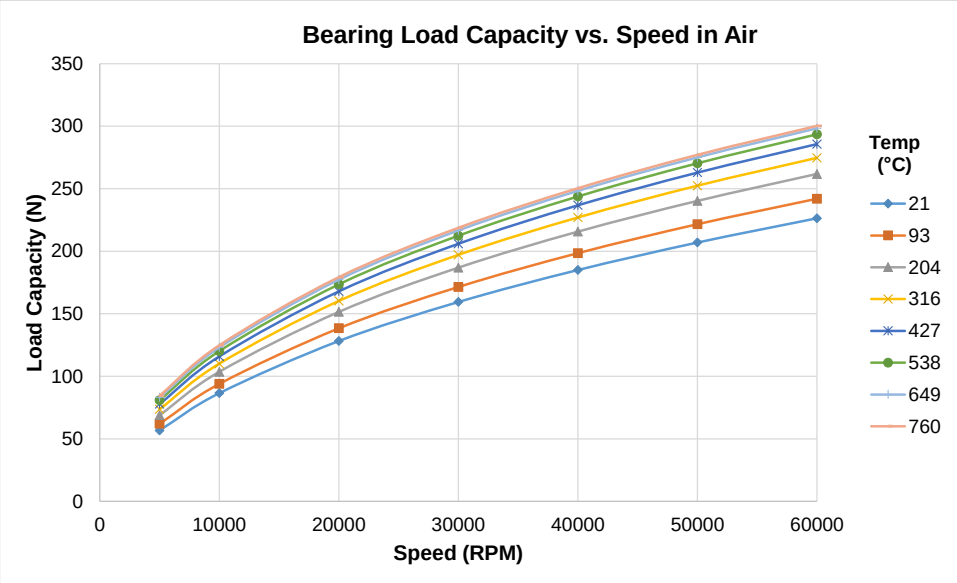
- Project focused on developing a journal bearing
  - Diameter: 63.5 mm (2.50 inches)
  - Length: 44.5 mm (1.75 inches)
  - Speed: 60,000 rpm
  - D·N: 3.81 million
- Phase I testing is in air



Estimated Hydrodynamic Load Capacity

Hydrodynamic Performance

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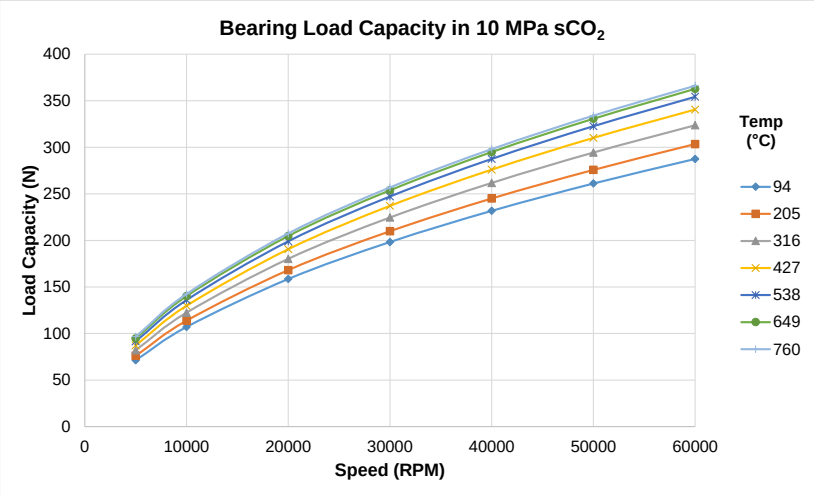
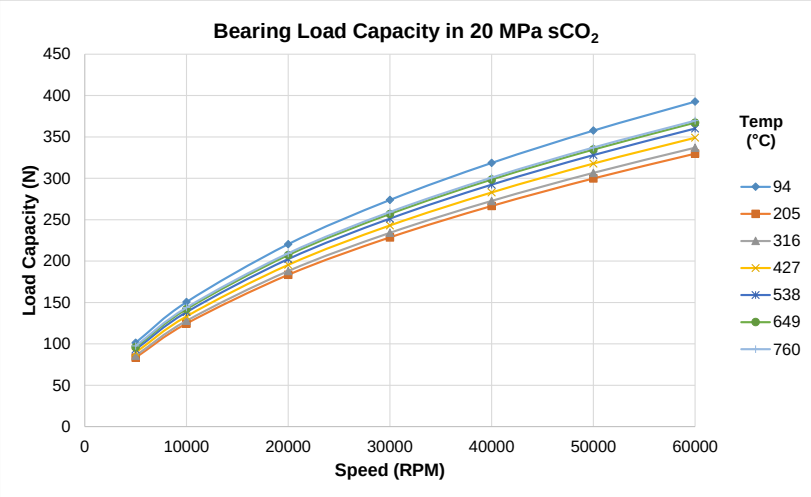
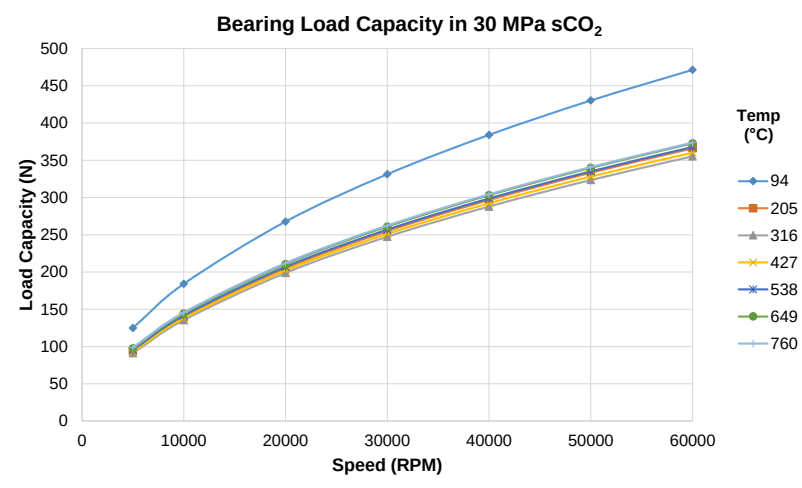
- Phase II testing will be in sCO_2







Estimated Hydrodynamic Load Capacity

Hydrostatic Performance

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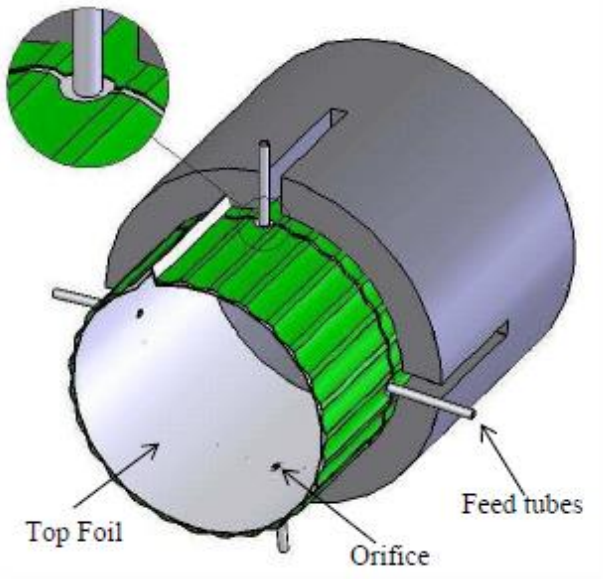
- Hydrodynamic load capacity often limits gas foil bearing use in some equipment, particularly larger machines running at lower speeds
- Supplementing load capacity and stiffness could enable broader use of gas foil bearings

- 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[5])

5. 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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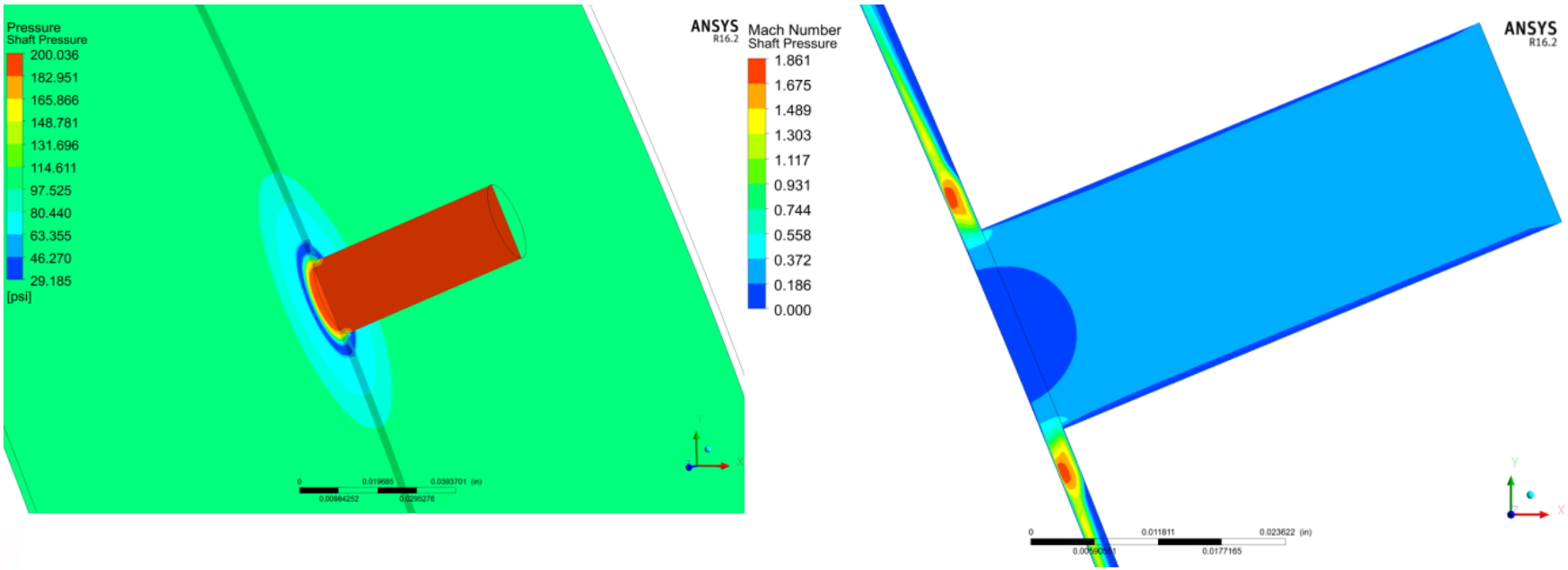
- MSI is studying a proprietary design using CFX (ANSYS, Inc.)
- An additional load capacity of 120 N is estimated for 20°C air with a supply pressure of 4.5 bar



CFD Results of a Single Nozzle

Current Testing Underway

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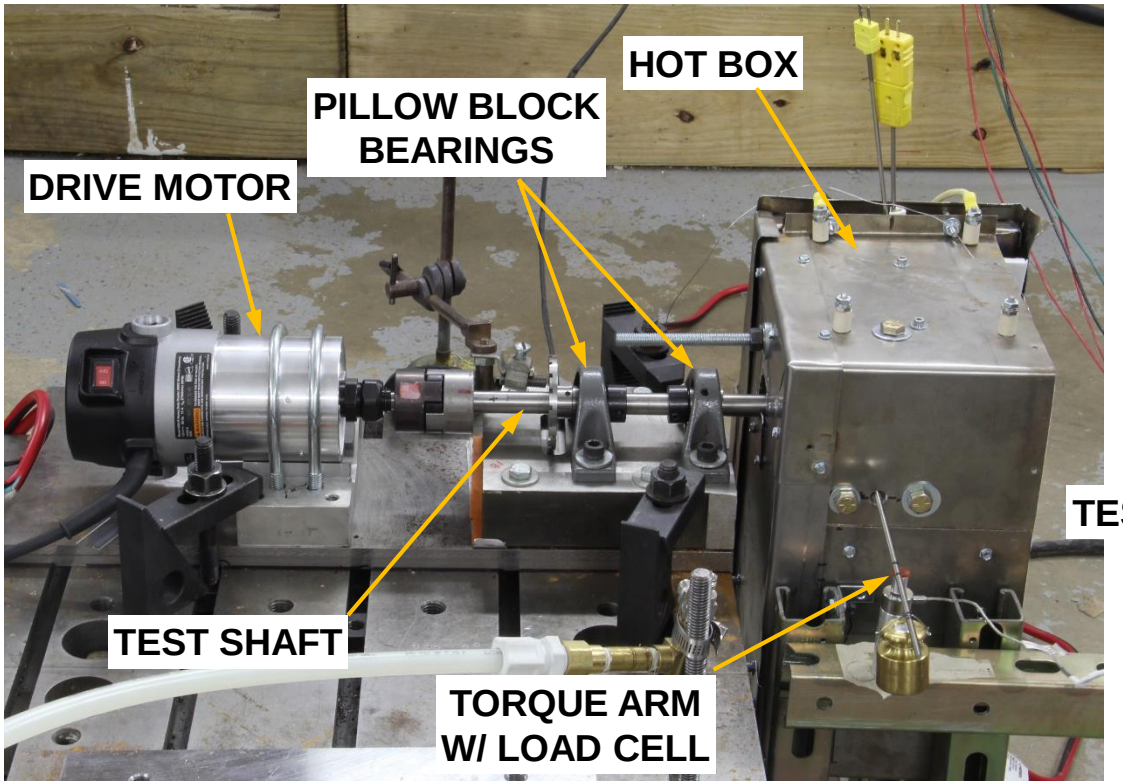
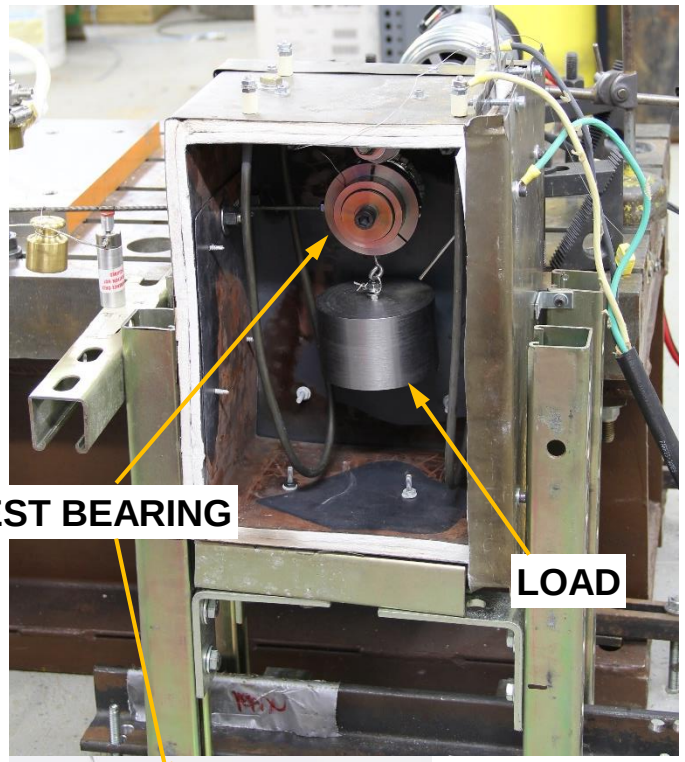
High Temperature Start/Stop Cycle Testing





Rig Capabilities

- Automatic start/stop cycling
- 17,000 RPM
- 650°C

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Current Testing Underway

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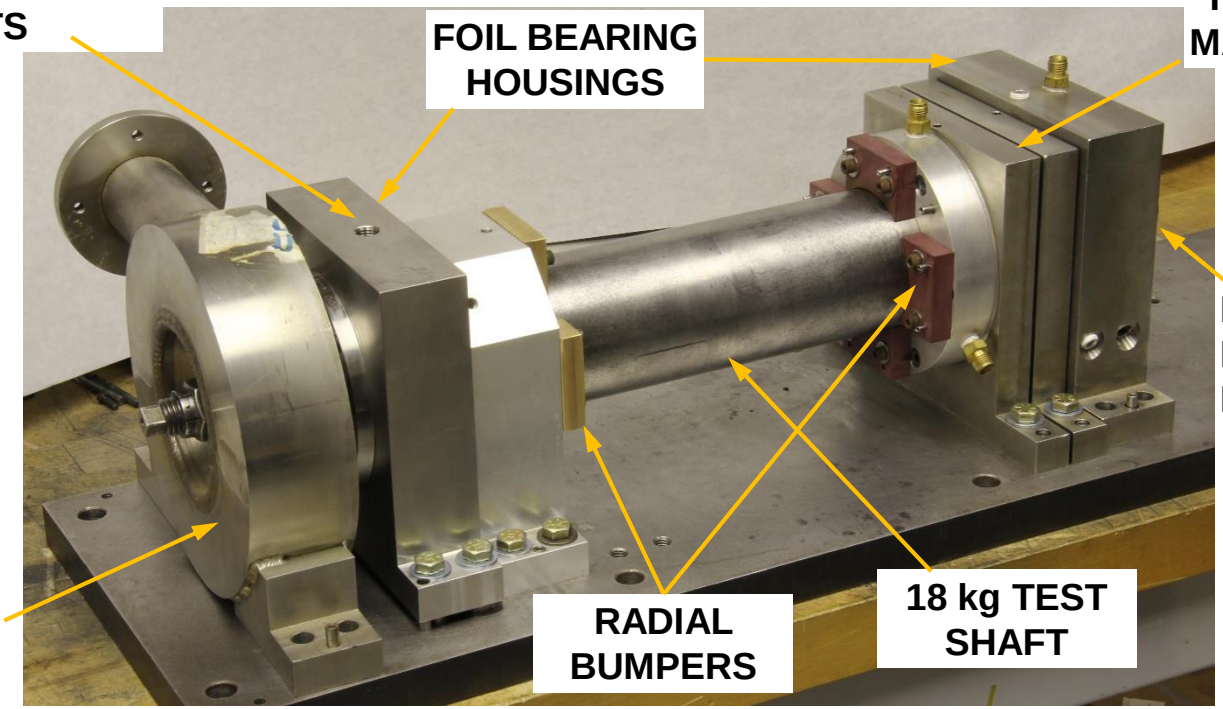
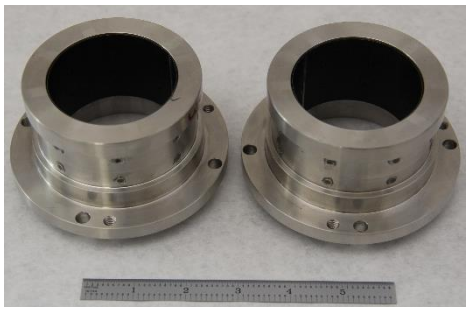
High Speed Testing – 60,000 RPM



Instrumentation (not shown)

- X-Y displacement probes
- Accelerometers
- Thermocouples



HYBRID TEST BEARINGS (RADIAL)

Future Work

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Phase I

- Complete high temperature start/stop cycle testing
- Conduct high-speed testing of hybrid bearing design

Phase II

- Generate both journal and thrust bearing designs
- Conduct bearing validation tests in hot sCO_2 environment
- Continue evaluation of high temperature, low-wear coatings

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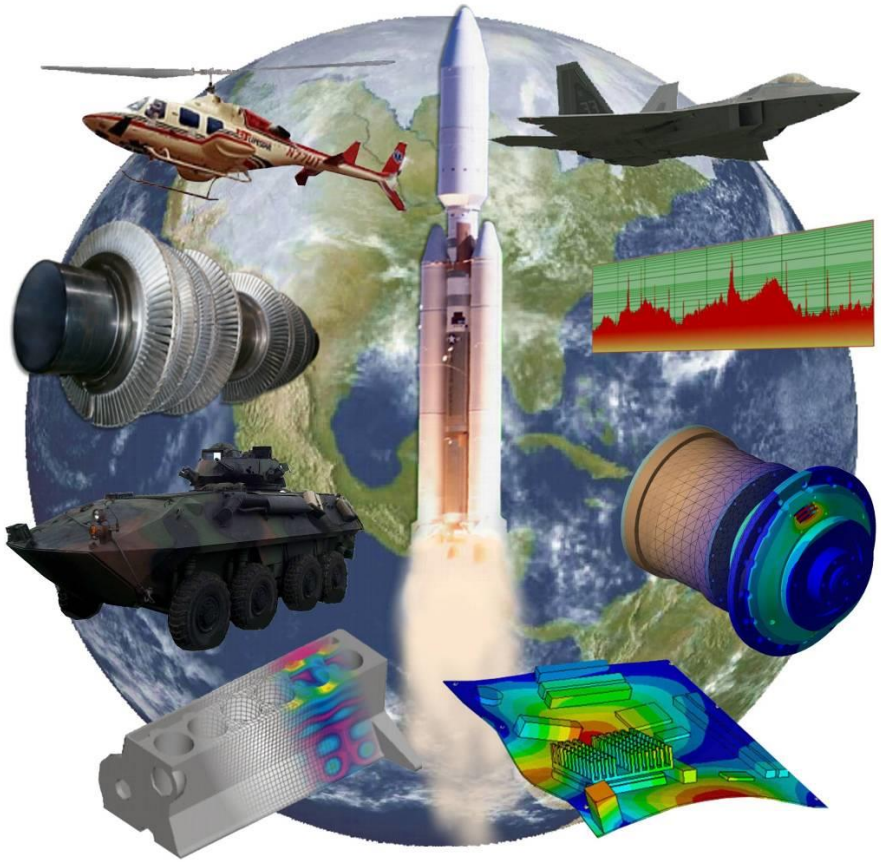

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