

# Technology Readiness of 5<sup>th</sup> and 6<sup>th</sup> Generation Compliant Foil Bearing for 10 MWE S-CO<sub>2</sub> Turbomachinery Systems

H. Heshmat, J. F. Walton<sup>‡</sup> and J. L. Cordova

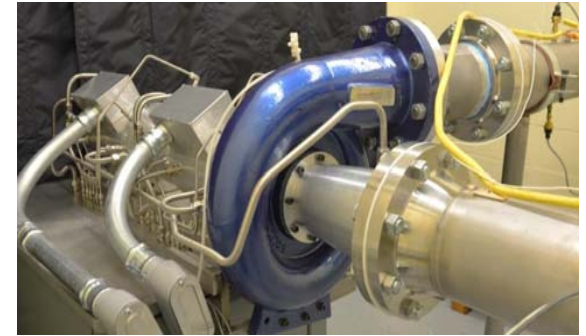
The 6<sup>th</sup> International Supercritical CO<sub>2</sub> Power Cycles Symposium  
March 27 - 29, 2018, Pittsburgh, Pennsylvania

<sup>‡</sup> Presenting Author

# Overview

- Objectives
- Background
- Technology
- Summary and Conclusions

# MITI Oil-Free Turbomachinery - Compressors



**Hydrogen Blower**

**Fuel Cell Compressor**

**Air Cycle Machine**

**Hydrogen Pipeline Compressor**

**1 kW**

**12 kW**

**30 kW**

**200 kW**

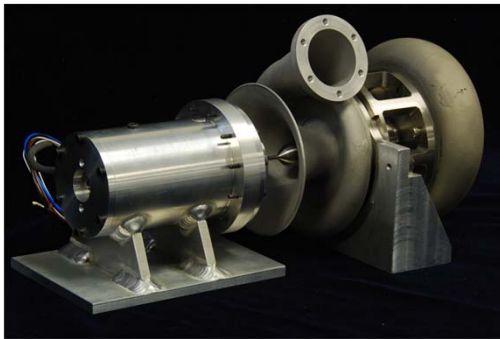
**360,000 rpm**

**120,000 rpm**

**120,000 rpm**

**60,000 rpm**

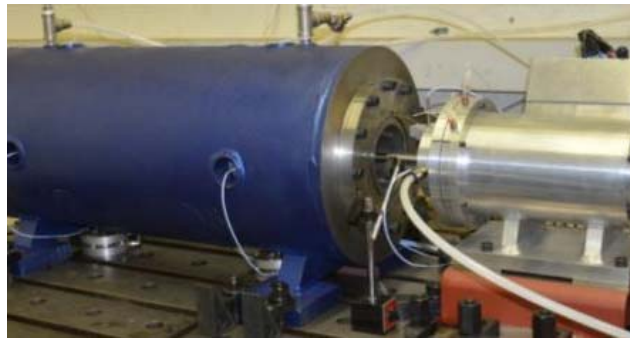
# MITI Oil-Free Turbomachinery - Energy



**Gas Turbine Generator**

**8 kWe**

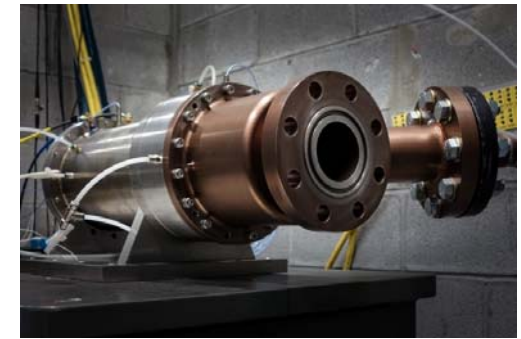
**180,000 rpm**



**Flywheel Electromechanical Battery**

**60 kWe**

**60,000 rpm**



**ORC Turbogenerator**

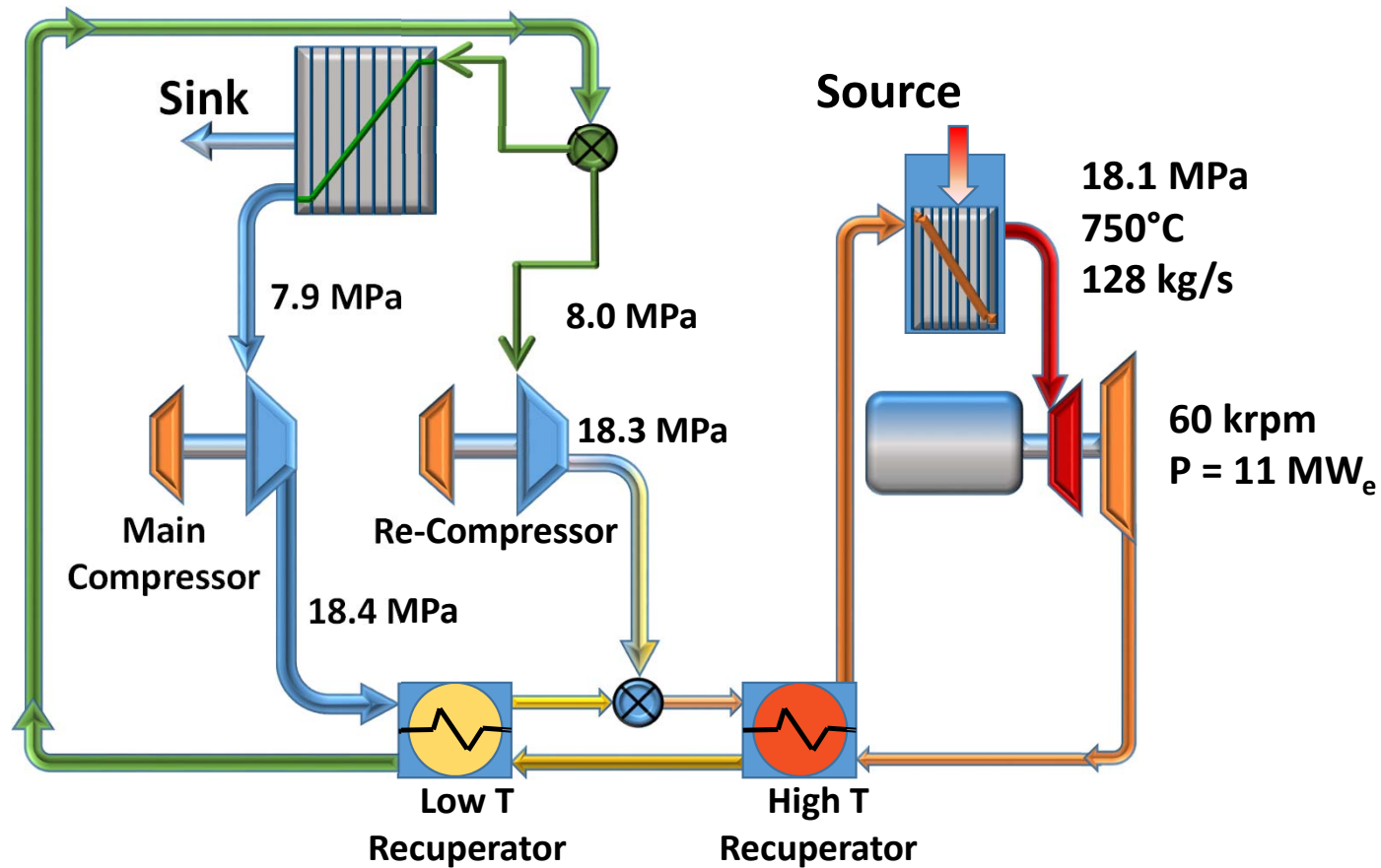
**65 kWe**

**30,000 rpm**

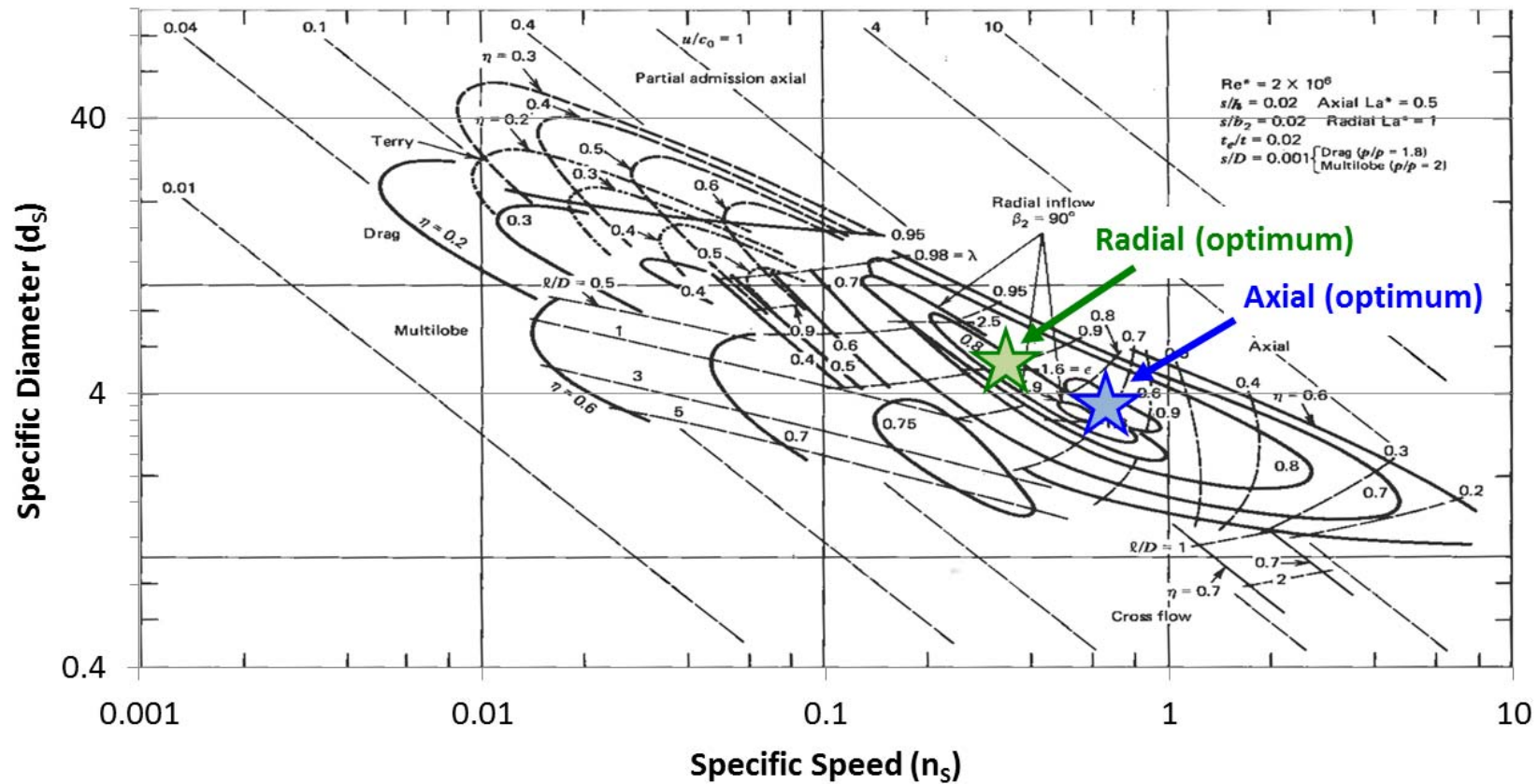
# Objectives

- Identify Turbomachinery Concepts Capable Of Operating Efficiently With s-CO<sub>2</sub>
- Identify Key Enabling Bearing Technology
  - Oil-Free Compliant Foil Bearings
  - Use s-CO<sub>2</sub> Process Fluid for Hydrodynamics and Thermal Management
  - Scalable For Multi-Megawatt Turbomachinery Applications from kW to 100s of MW

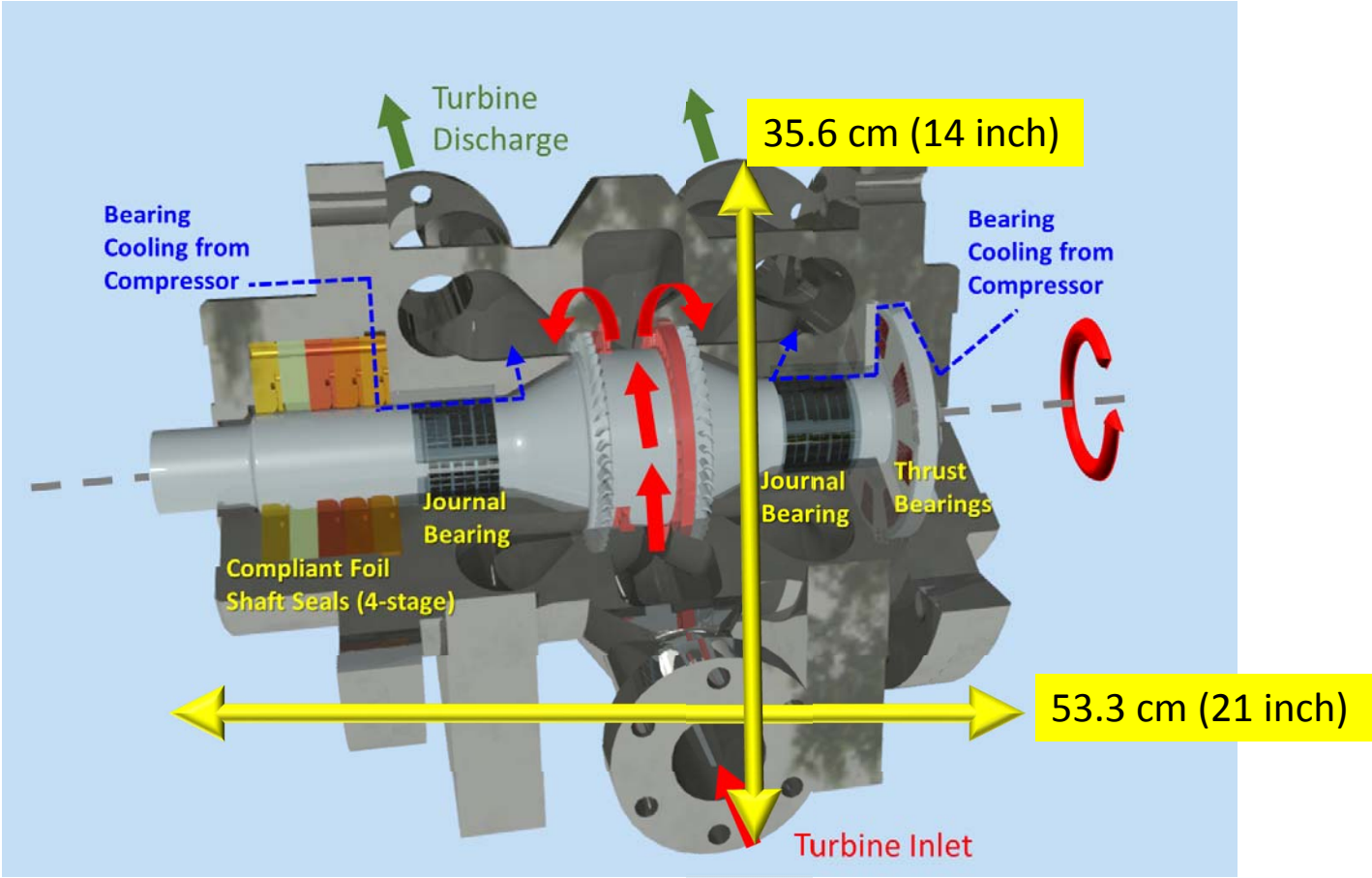
# Preliminary Cycle Analysis for Net 10 MW System



# Preliminary 1<sup>st</sup> Order Aero Analysis

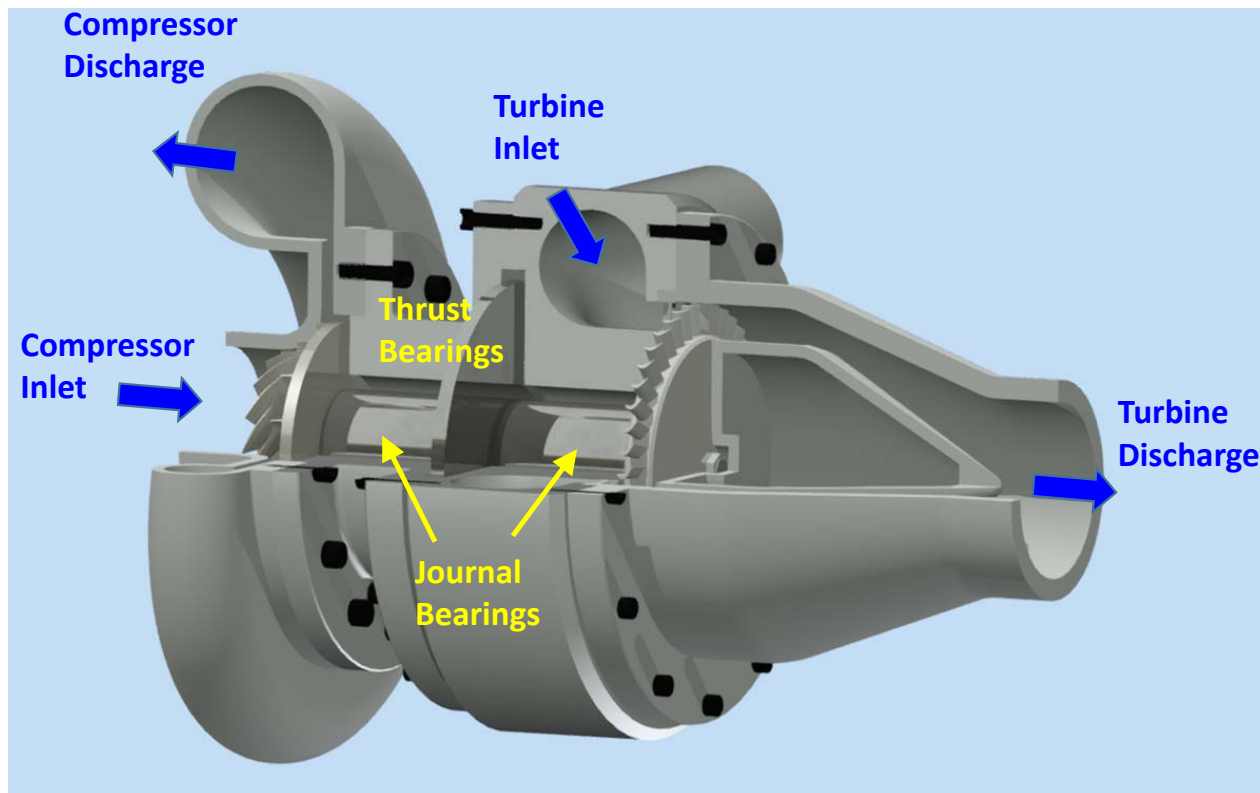


# Turbine Rotor Concept



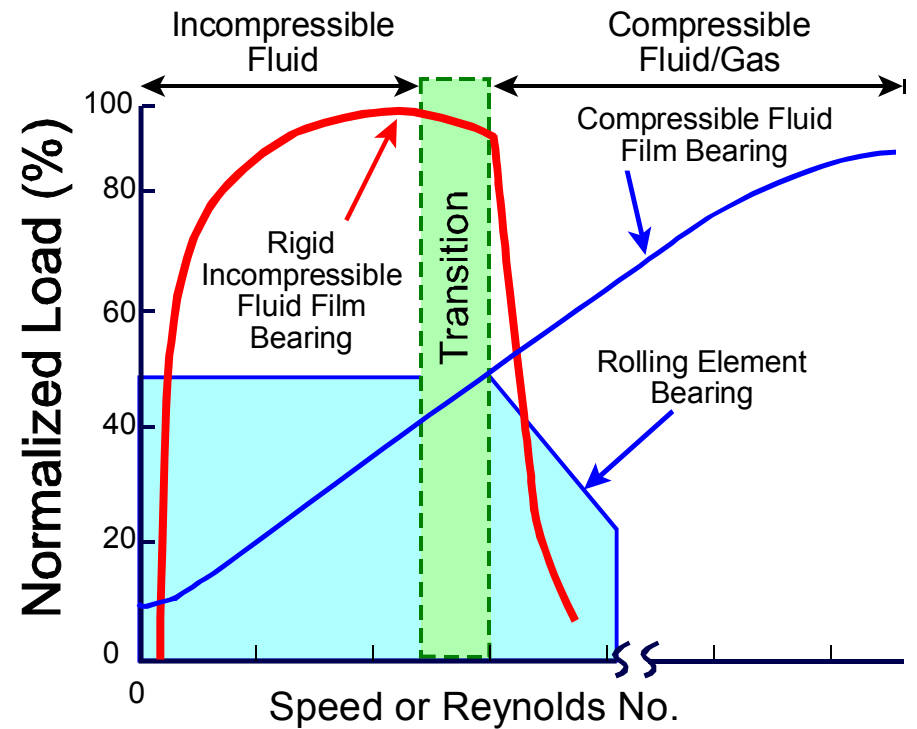
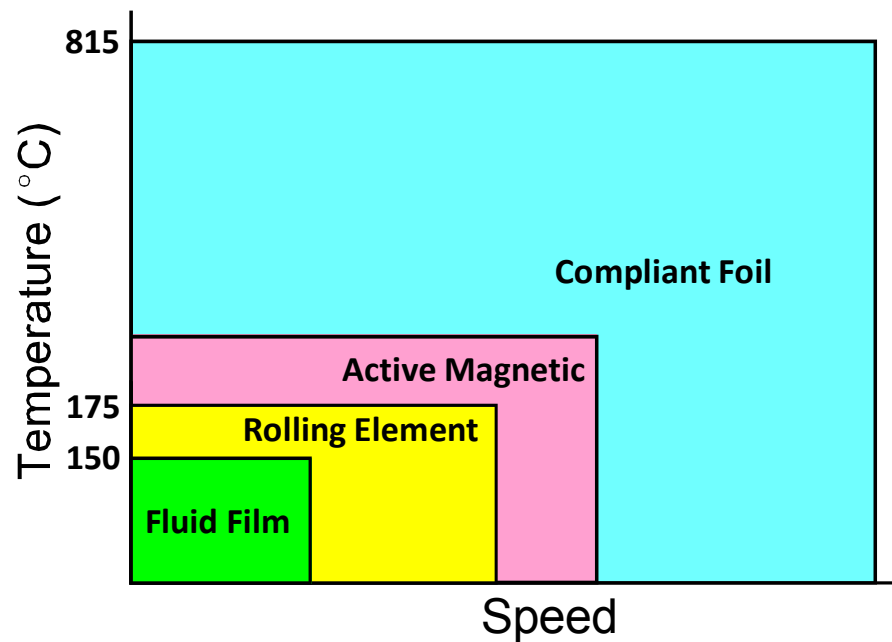


# 5 MW Turbo-Compressor (2x)

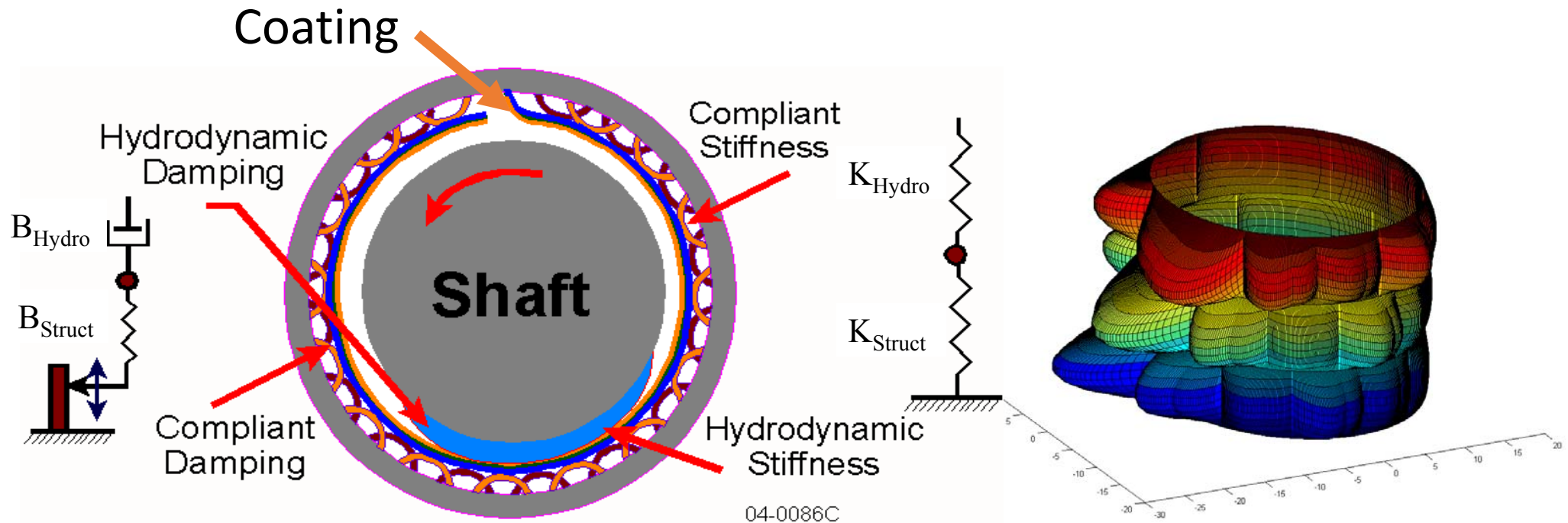


50-80 krpm

# General Bearing Characteristics



# Foil Bearing Fundamental Mechanisms



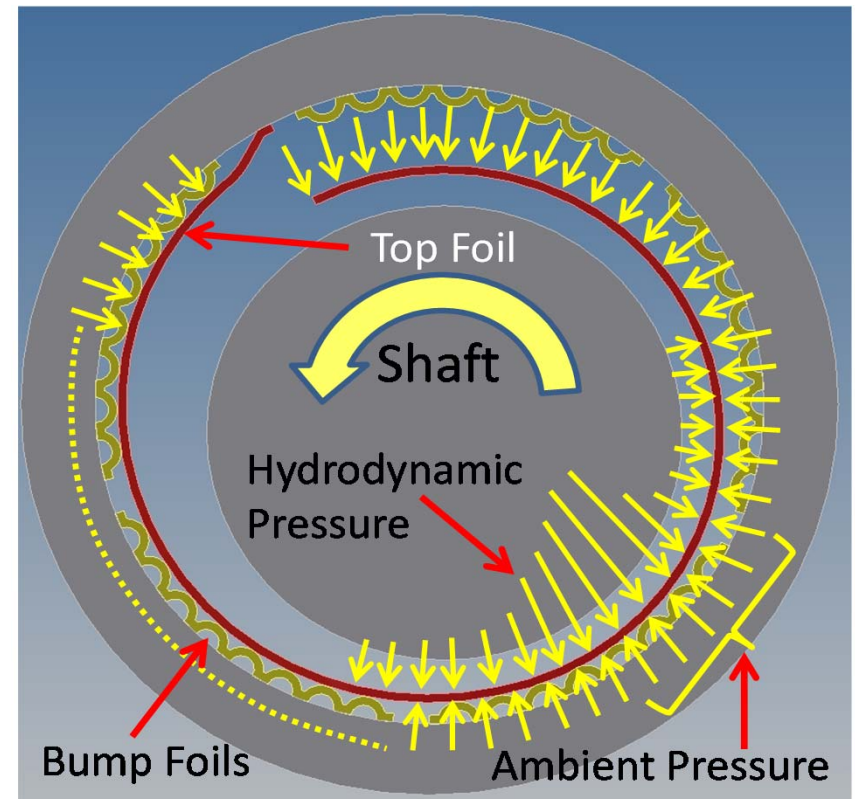
# MiTi Korolon Coated Foil Bearings Demonstrated with Different Process Fluids

**Air, H<sub>2</sub>, He  
(H<sub>2</sub>+H<sub>2</sub>O)**

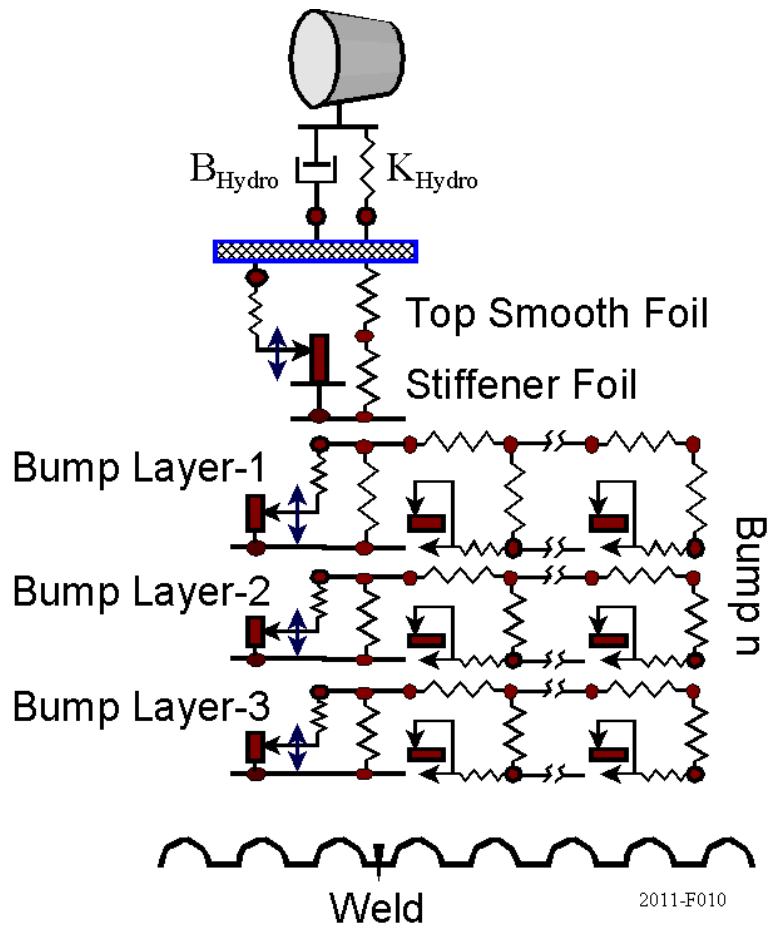
**R134a, 245fa,  
R1233zd & R1234yf,**

**s-CO<sub>2</sub>**

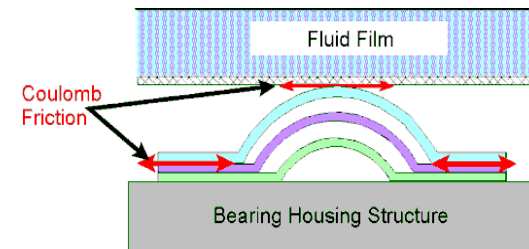
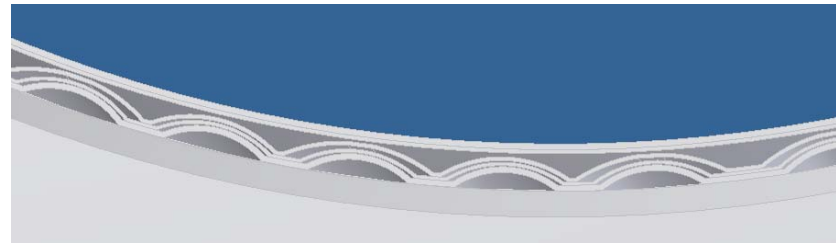
**2-Phase Flow**



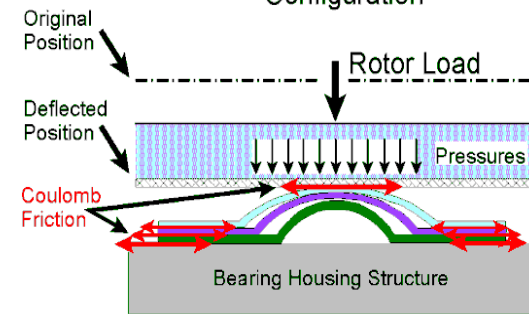
# Complexities of Mechanisms



2011-F010



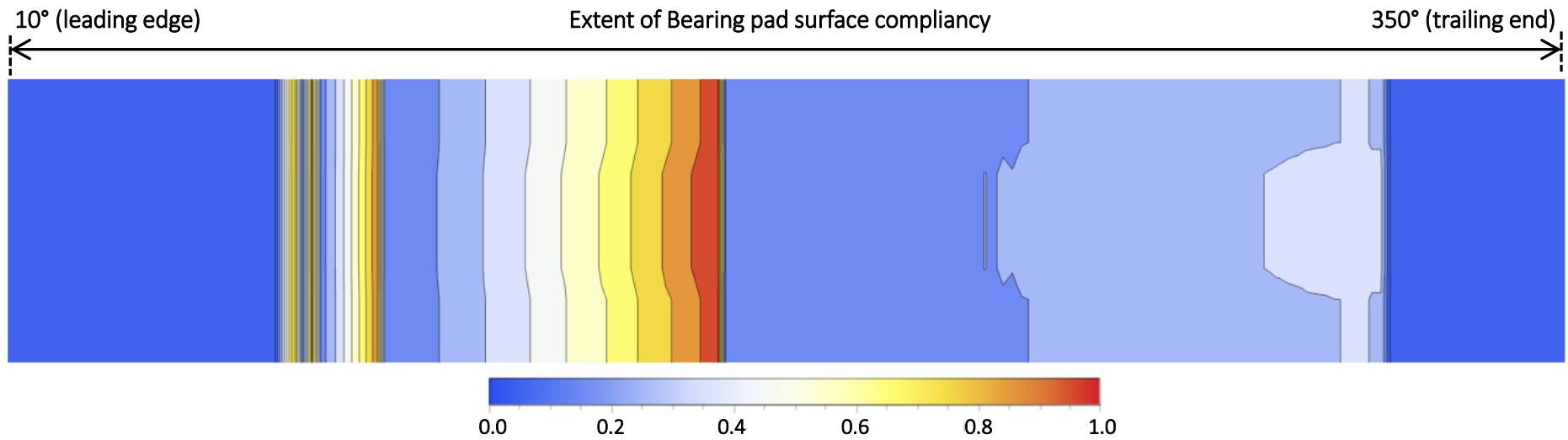
a.) Unloaded & Low Load Configuration



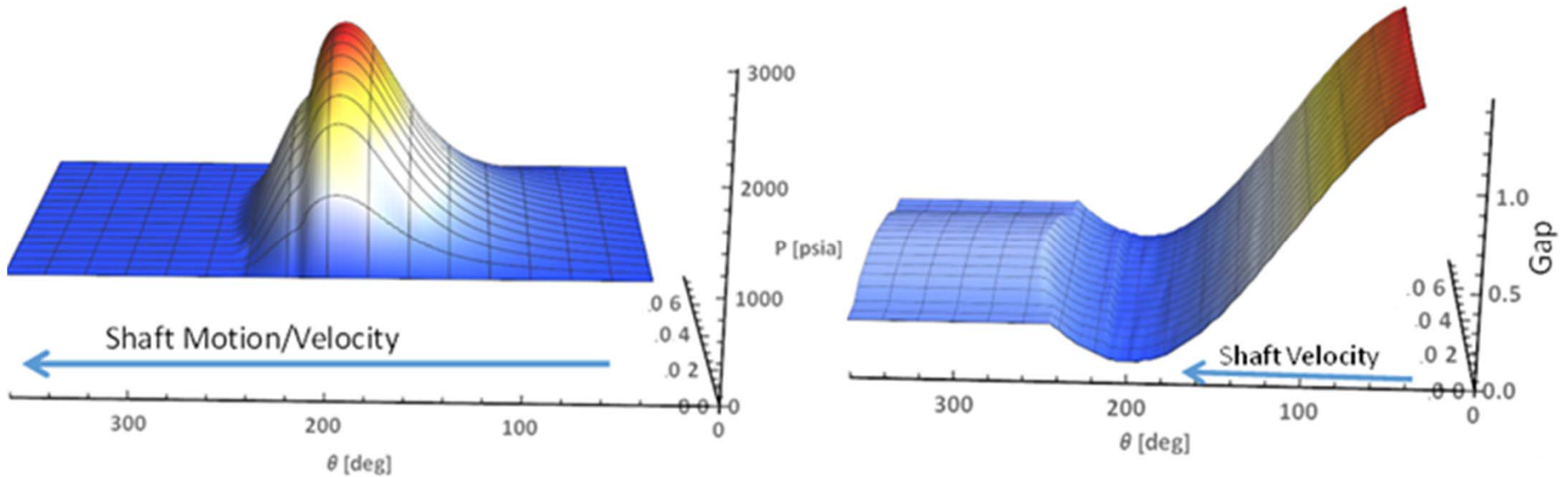
b.) High Load Configuration

96-0187a

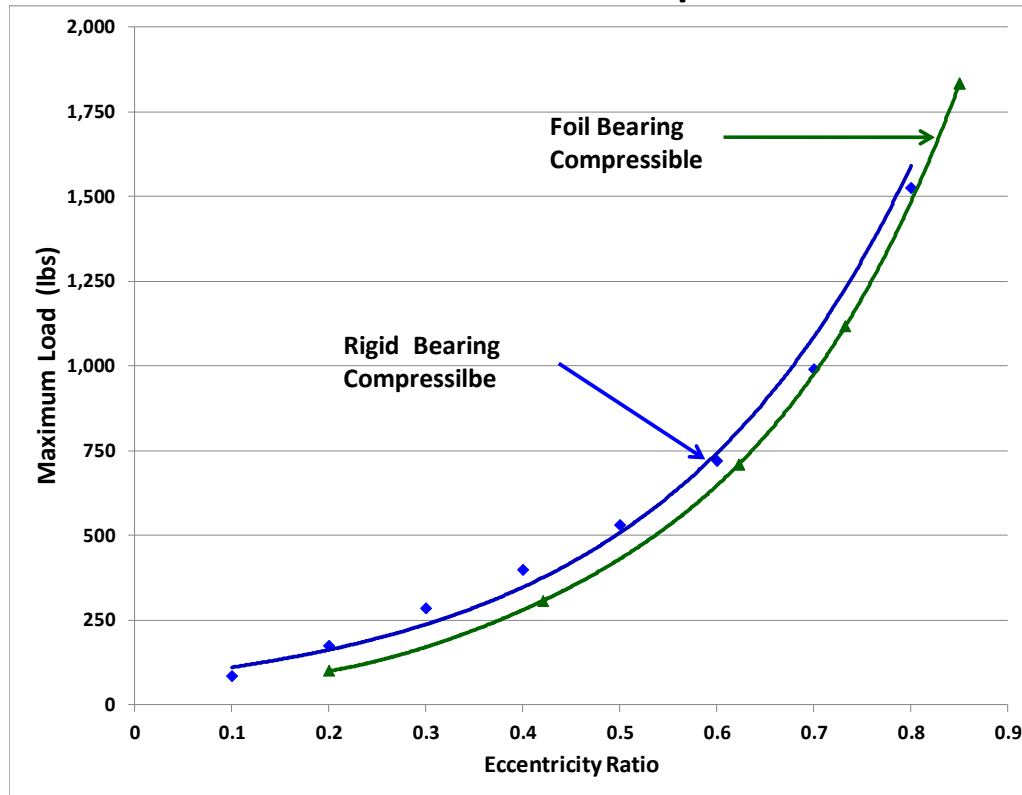
# Normalized Foil Compliance Matrix



# Foil Bearing Film Pressure and Height



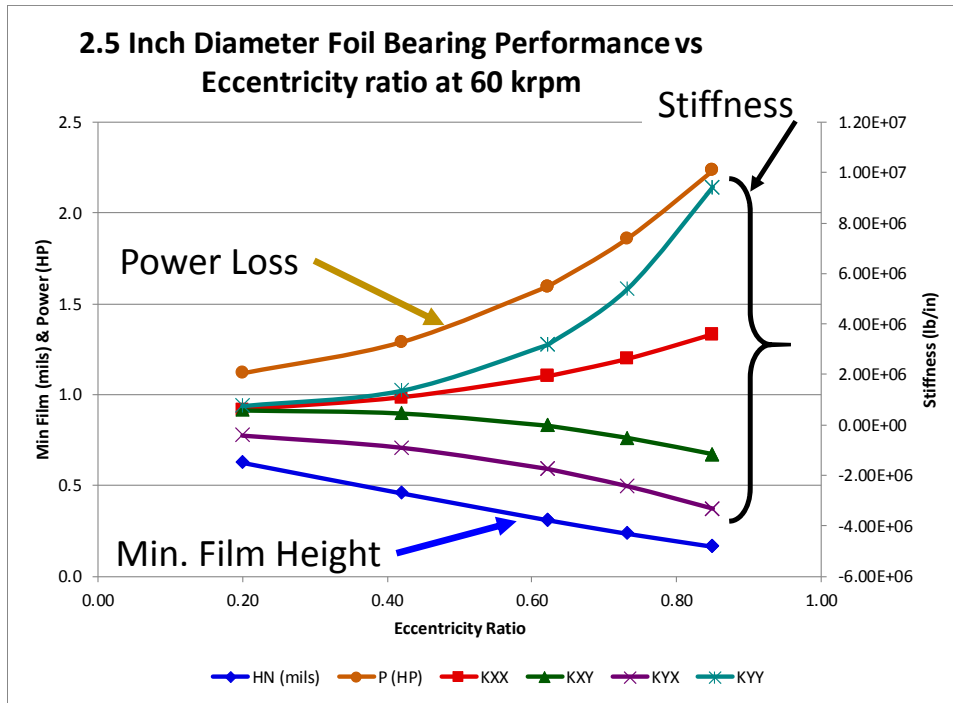
# Comparison of Rigid vs Compliant Bearings at 60,000 rpm



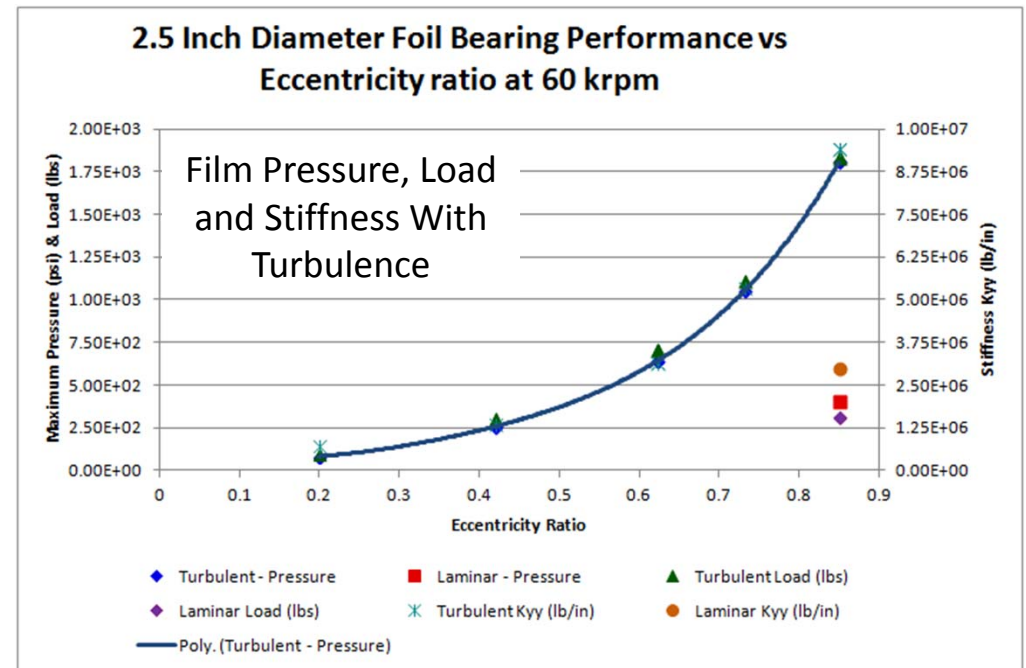


# s-CO2 Foil Bearing Characteristics

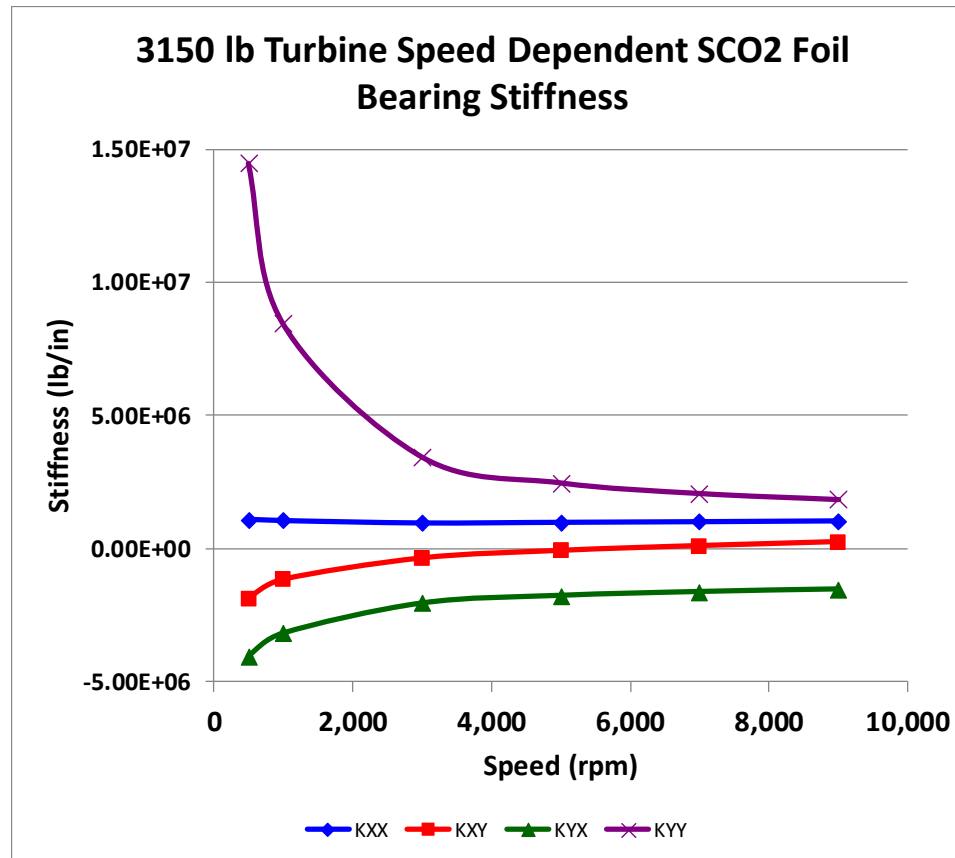
## Dynamic Characteristics



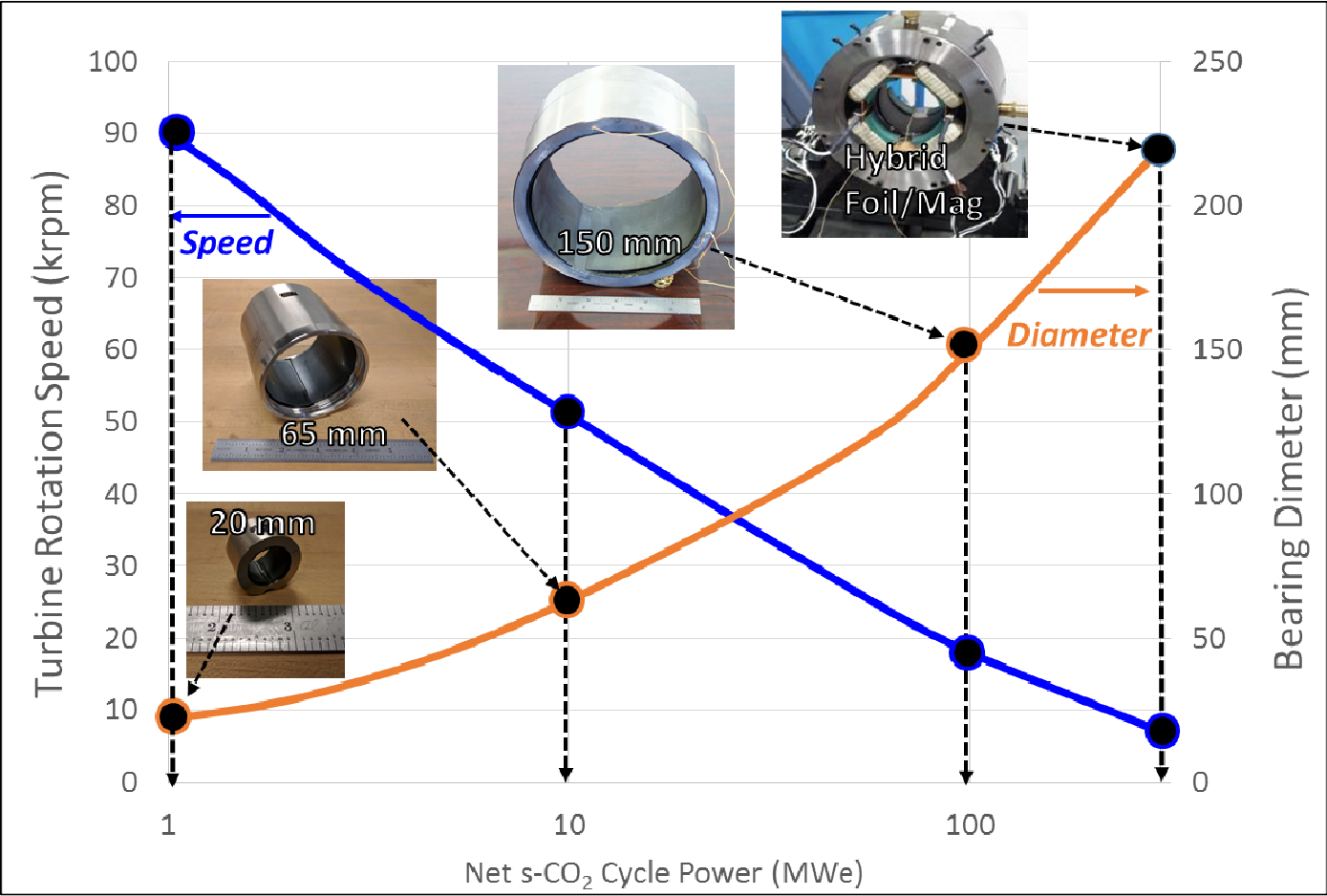
## Load Performance



# Foil Bearing for 100 MW Scale

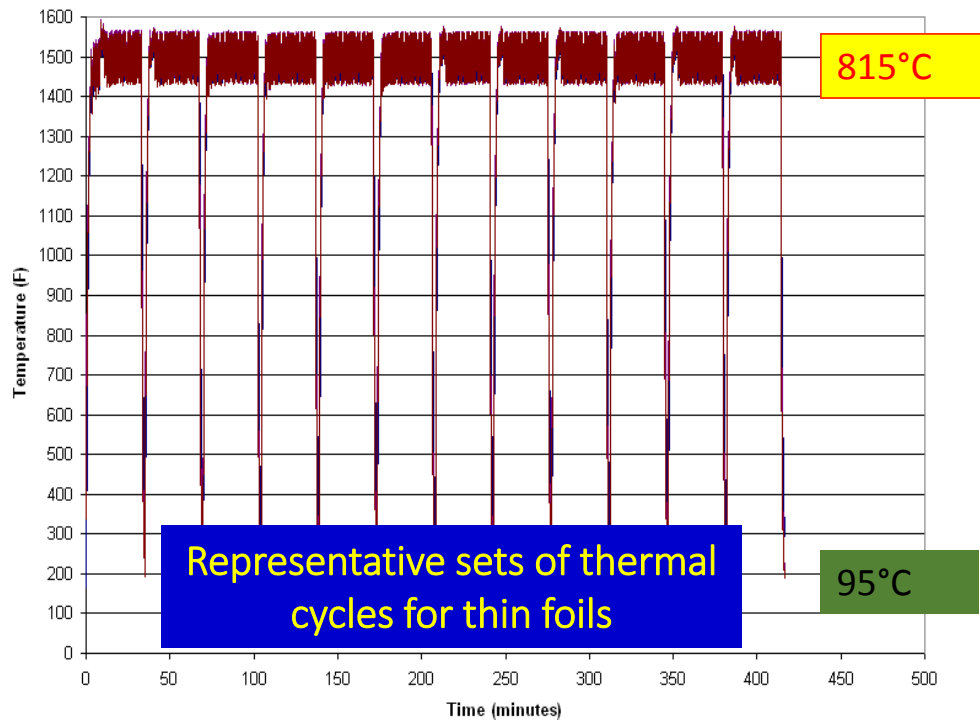


# Scalability of Foil Bearings from 1 to 100s MWe



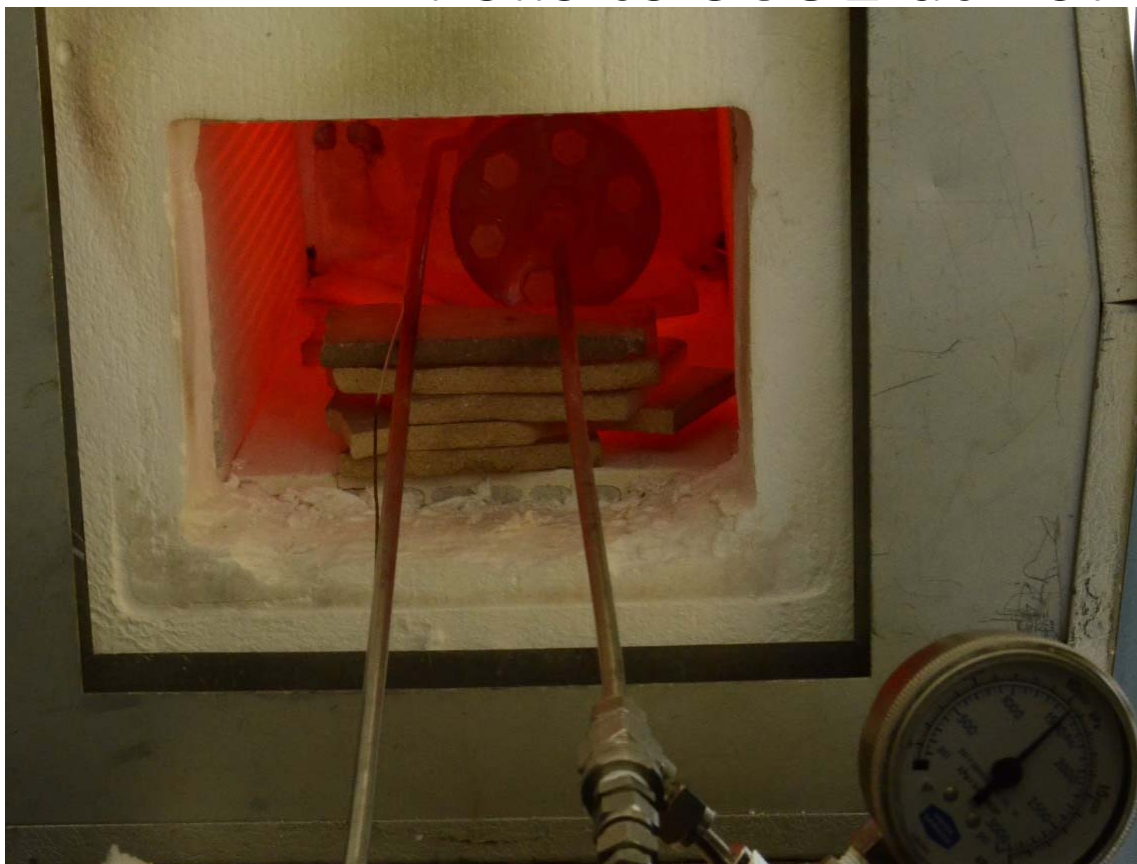
# Bend Testing After 815°C Thermal Cycling

Korolon™ 1350A coated foil after 50 thermal cycles and bend testing



YSZ coated foil fractured after thermal cycling and bend testing

# MiTi Bomb Setup to Expose Korolon Coated Foils to SCO<sub>2</sub> at >675°C and >80 Bar



# Korolon Coated Bearing Foil Before & After Exposure to SCO<sub>2</sub>

## Pretest Bend

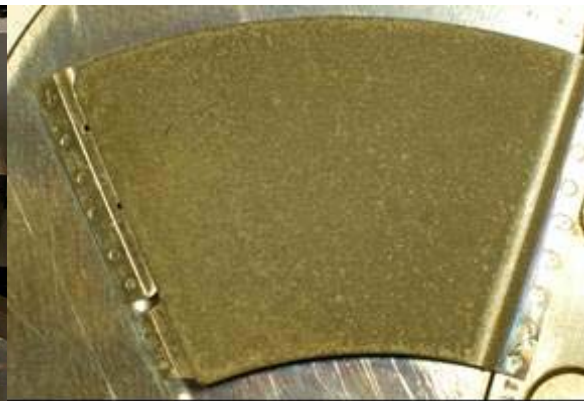
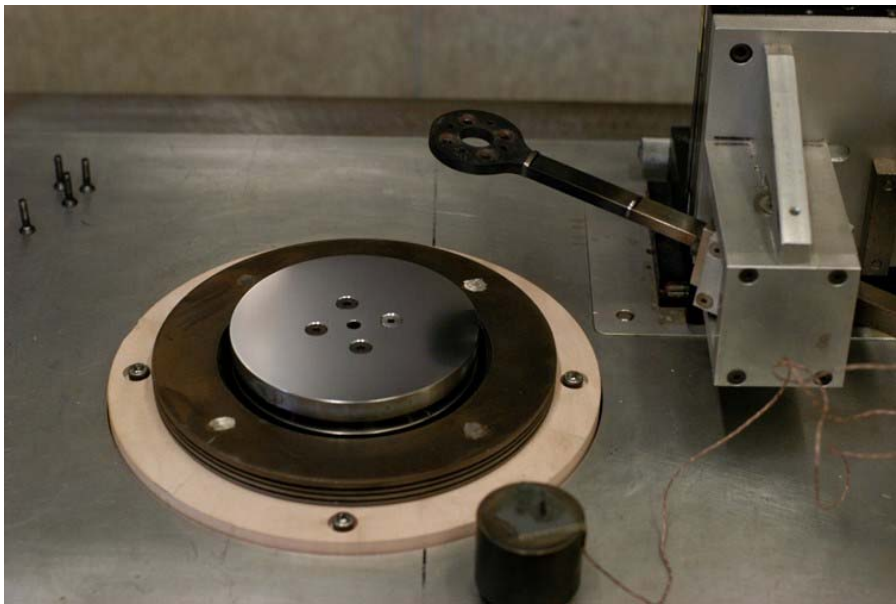


## Posttest Bend

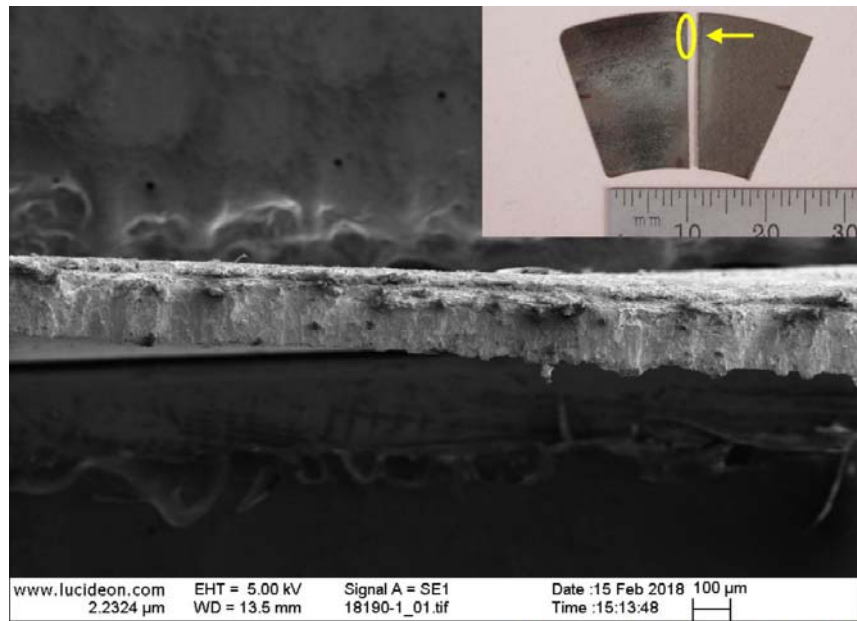




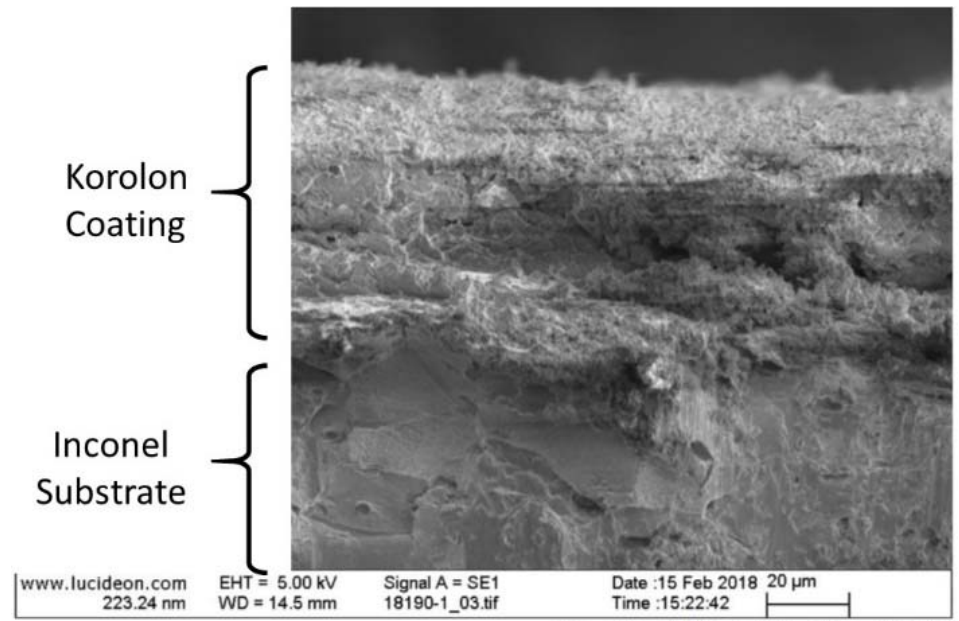
# Post Exposure Tribological Test



# MiTi Korolon™ Coated Foil Sample After Exposure to 650°C SCO2 and 500 Start/Stop Cycles



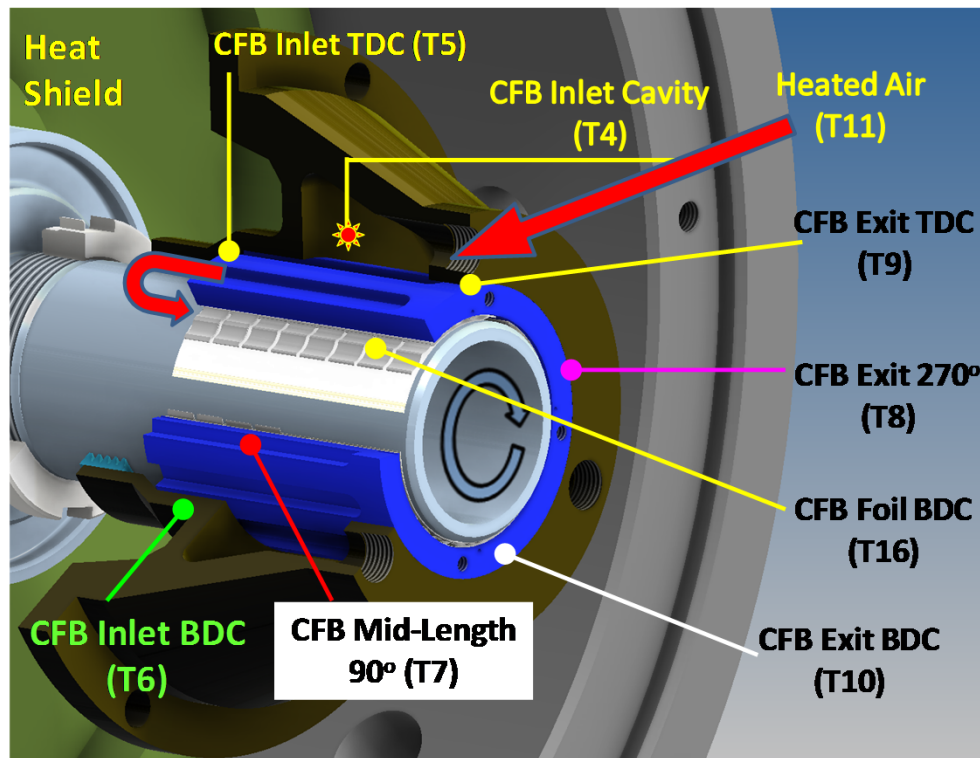
Nominal Magnification 50X



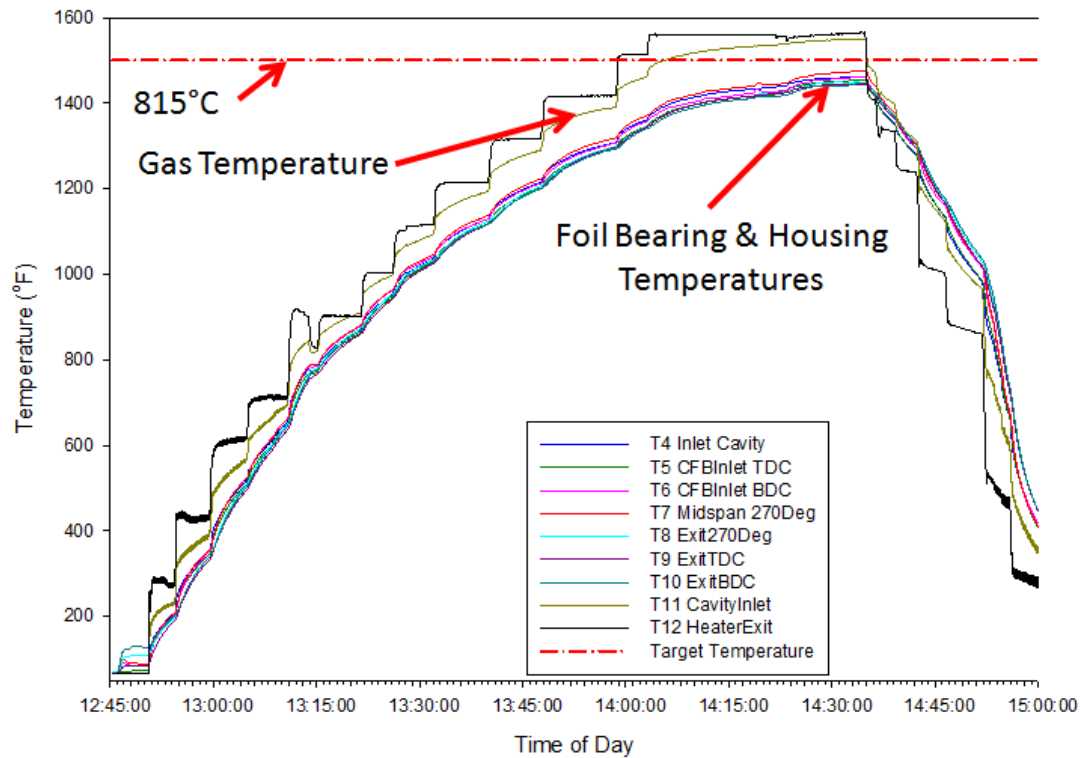
Nominal Magnification 500X



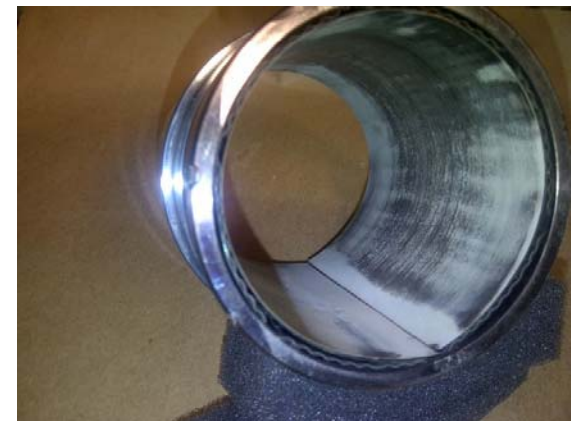
# Measured High Temperature Foil Bearing Performance



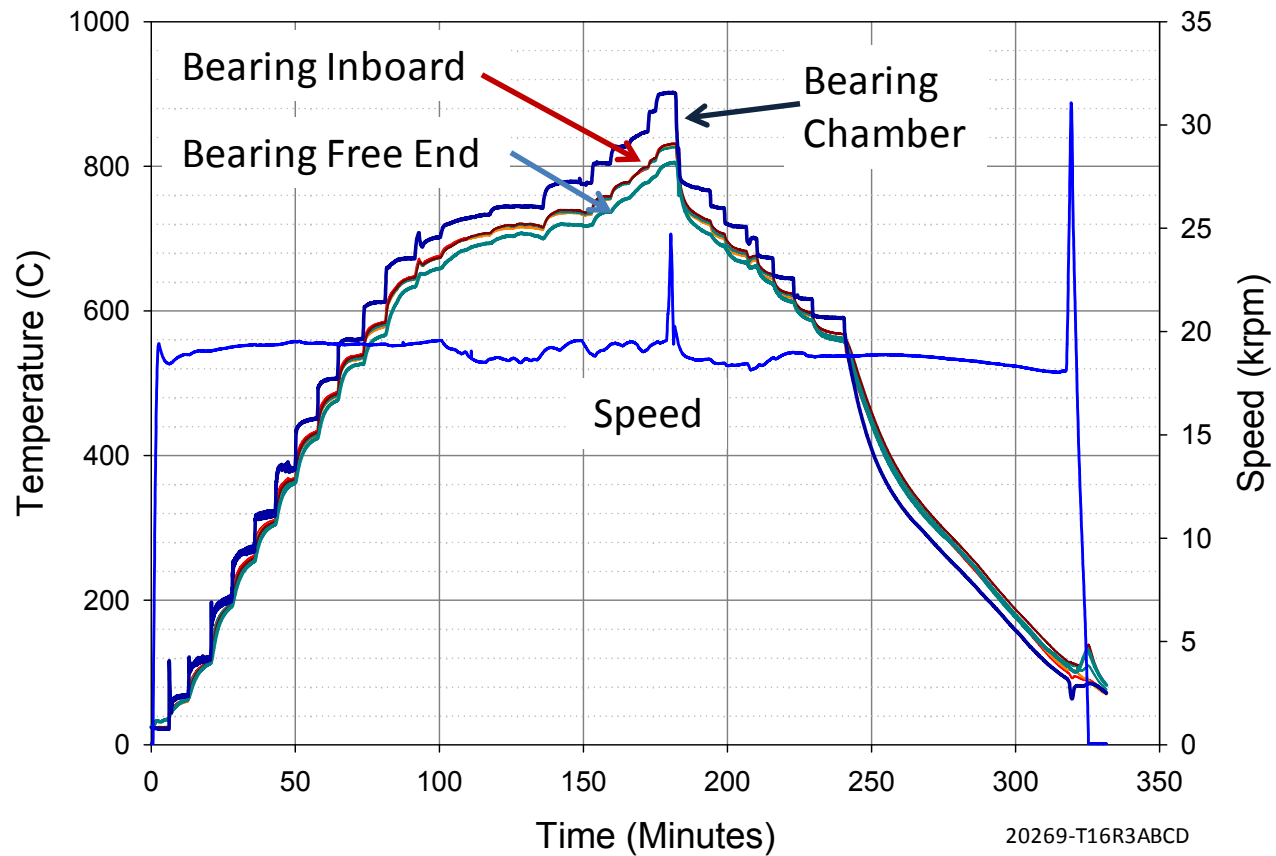
# Thermal Performance of Foil Bearing Gen IV



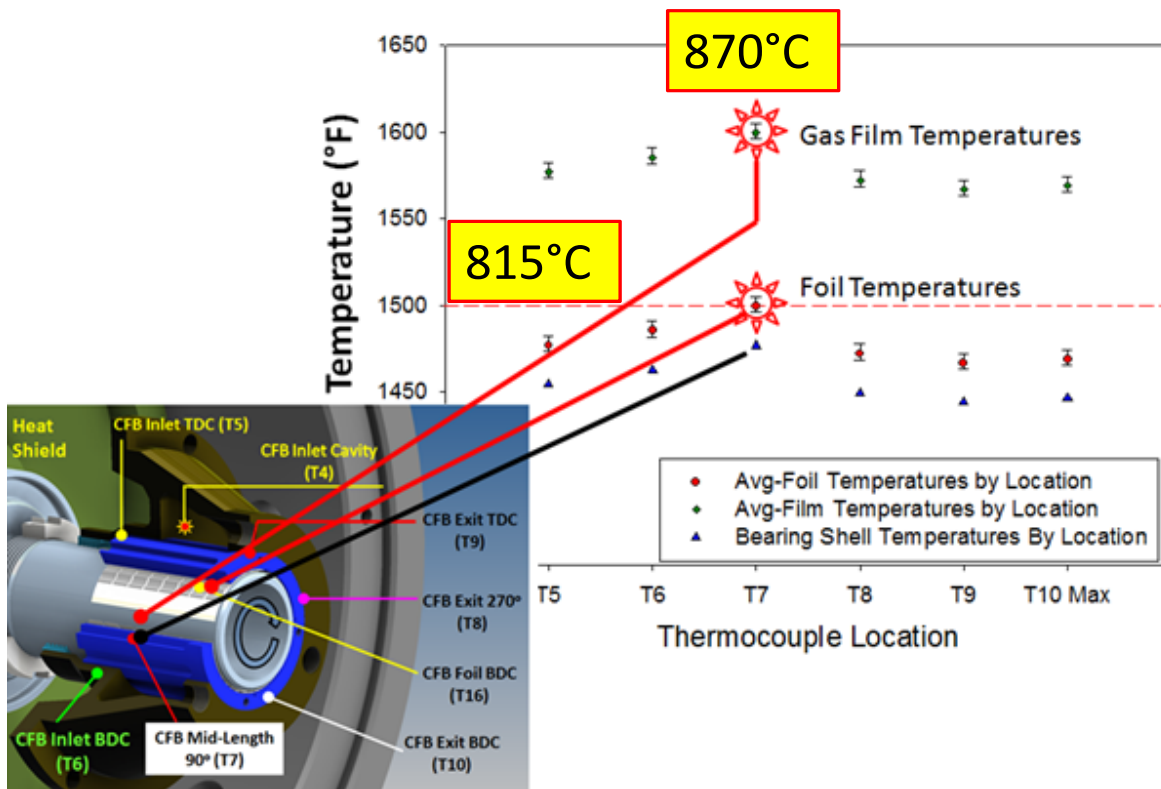
Bearing Len x Diam = 100 x 75 mm<sup>2</sup>



# 5+ Hour Elevated Temperature Test

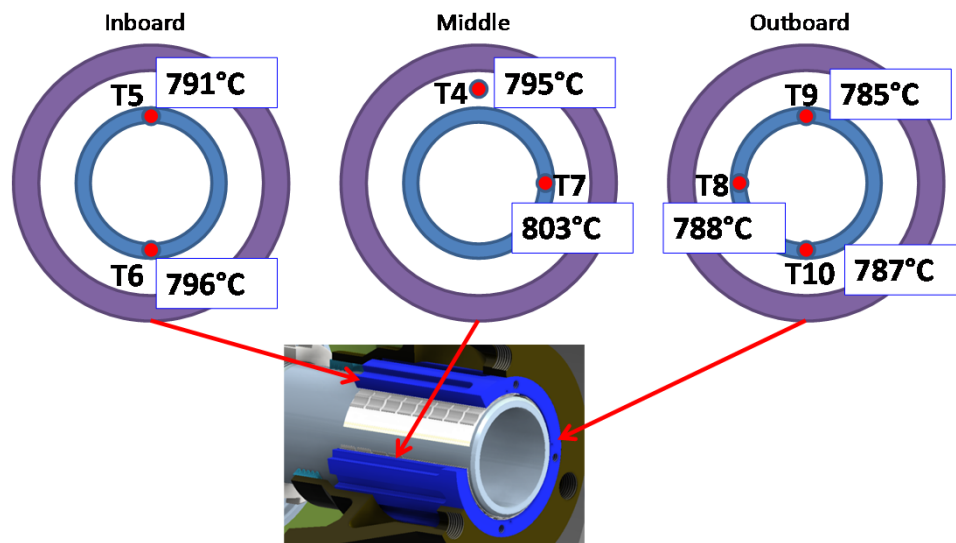


# High Temperature Foil Bearing

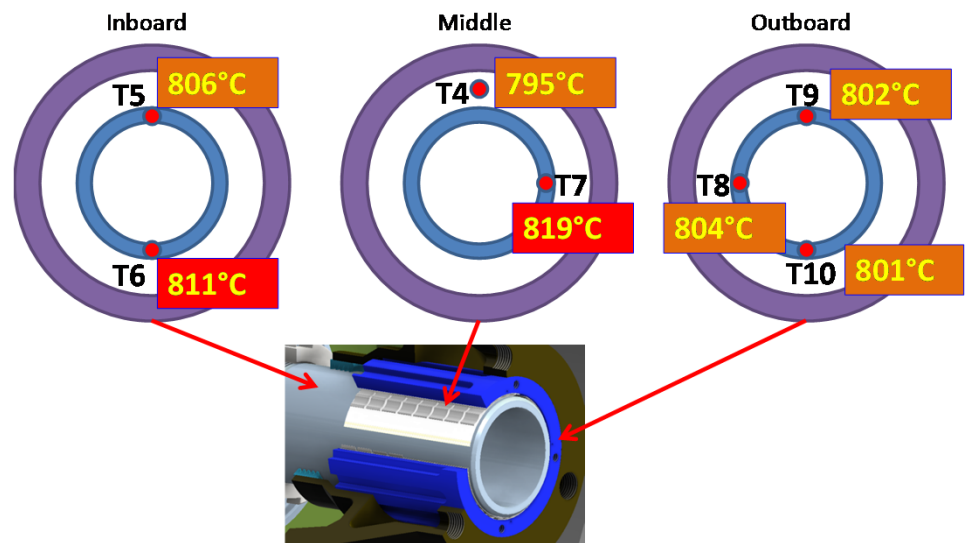


# Bearing Housing and Foil Temperatures

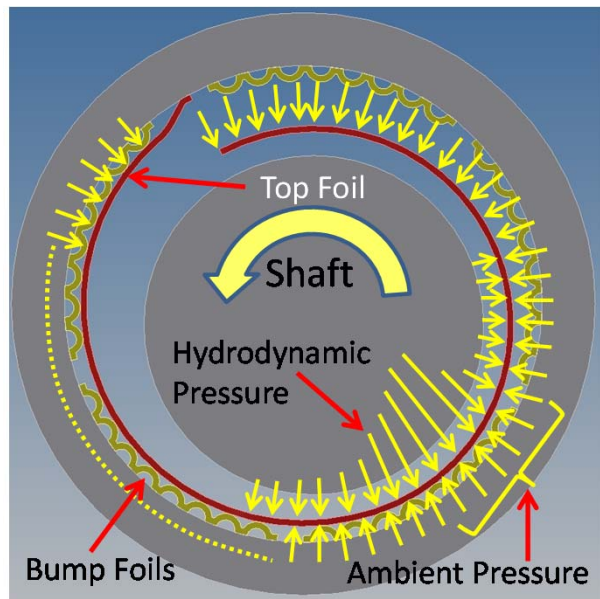
## Bearing Shell Temperatures



## Bearing Foil Temperatures



# Foil Bearing Generations/Classes



Class	Load Capacity (psi/MPa)	Stiffness	Damping	Speed Limit	Shock Tolerant	Size (mm)	Misalign Capable	≤ 175°C	≤ 370°C	≤ 480°C	≥ 650°C	≥ 815°C
I	15/.103	Low	Very Low	Low	No	30-50	Very Low	✓				
IIA	33/.23	Low	Low	Med	No	30-50	Low	✓				
IIB	50/.35	Med	Low	M-H	Med	25-75	Low-Med	✓	✓			
III <sup>1</sup>	100/.69	Med	Med	High	Yes	15-100	Med	✓	✓			
IV <sup>2-4</sup>	100/.69	High	High	Unlim	Yes	6-240	Med-High	✓	✓	✓		
V <sup>5</sup>	100/.69	3-D	High <sup>+</sup>	Unlim	Yes	6-240	High	✓	✓	✓	✓	
VI <sup>6</sup>	100/.69	3-D	High <sup>+</sup>	Unlim	Yes	6-240	High	✓	✓	✓	✓	✓

1.DellaCorte (2000), 2-4.Heshmat (2005), (2006), (2004), 5.Salehi (2007), 6.Heshmat (2018)



# Summary & Conclusions

- s-CO<sub>2</sub> Turbomachinery is Compact and Operates at High-Speed
- High Temperature s-CO<sub>2</sub> Environment Restricts Use of Conventional Bearing Technologies and Lubricant Systems
- Compliant Foil Gas Bearings Are an Enabling Technology
- Preliminary Testing Shows Korolon Coated 6<sup>th</sup> Generation Foil Bearings Have Capabilities to Meet Needs for s-CO<sub>2</sub> Systems From kW to 300 MW
  - High Temperature Testing to 870°C
  - High Load Capacity
  - High Speed with Low Power Loss
- Further Verification and Demonstration of Korolon Coated Foil Bearing Performance and Durability in High Temperature s-CO<sub>2</sub> is Underway

# Acknowledgements

- U. S. Department of Energy under Award No. DE-SC0015811.
- The authors particularly acknowledge the support of Mr. Brian K. Robinson at DOE.

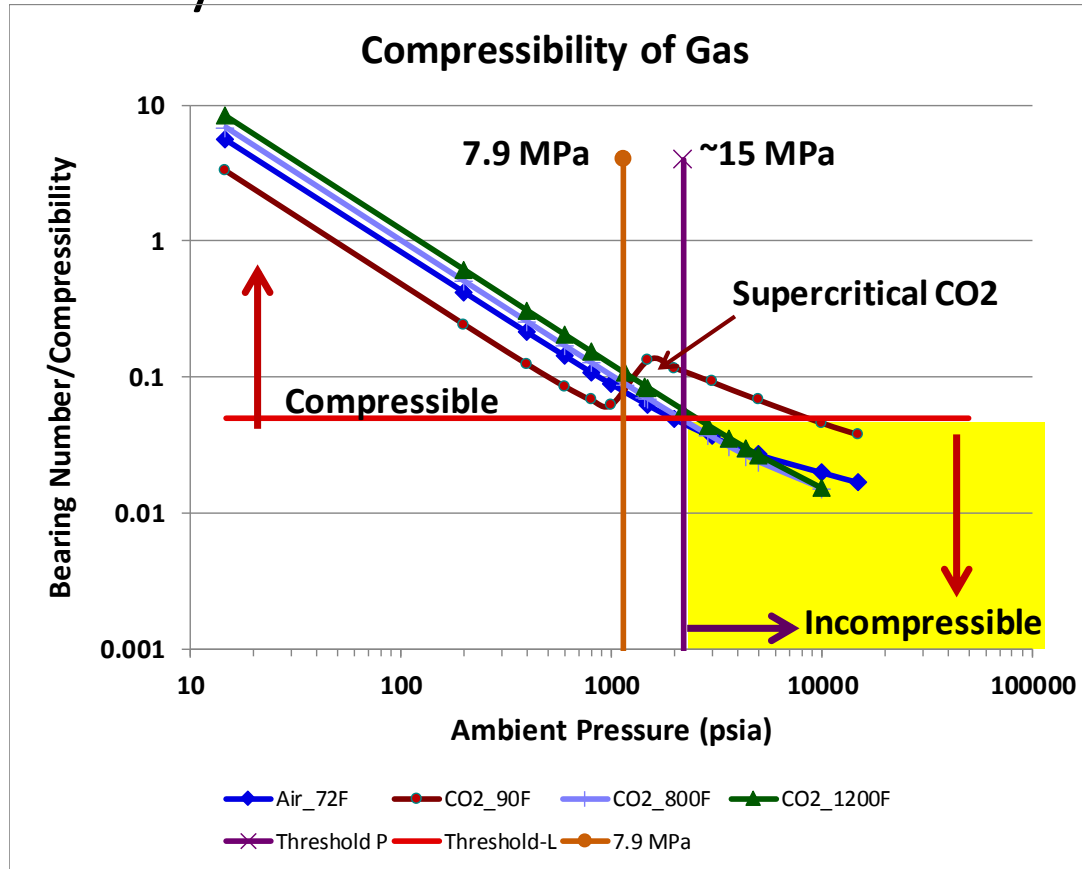
Thank you!

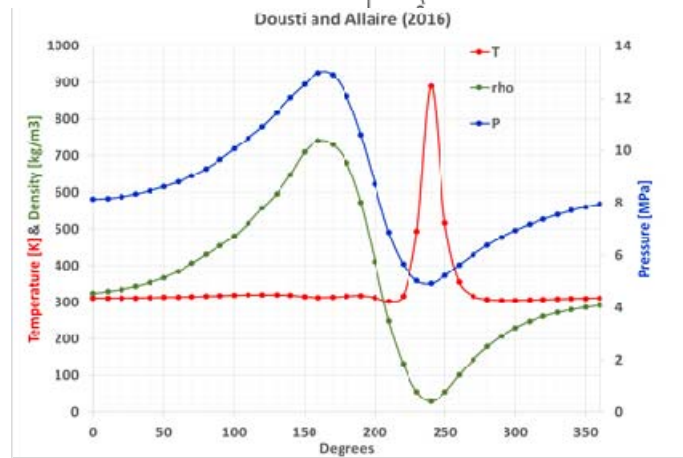
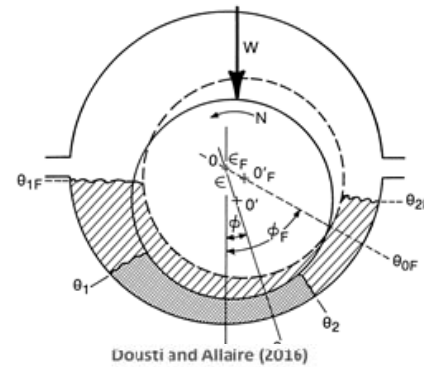
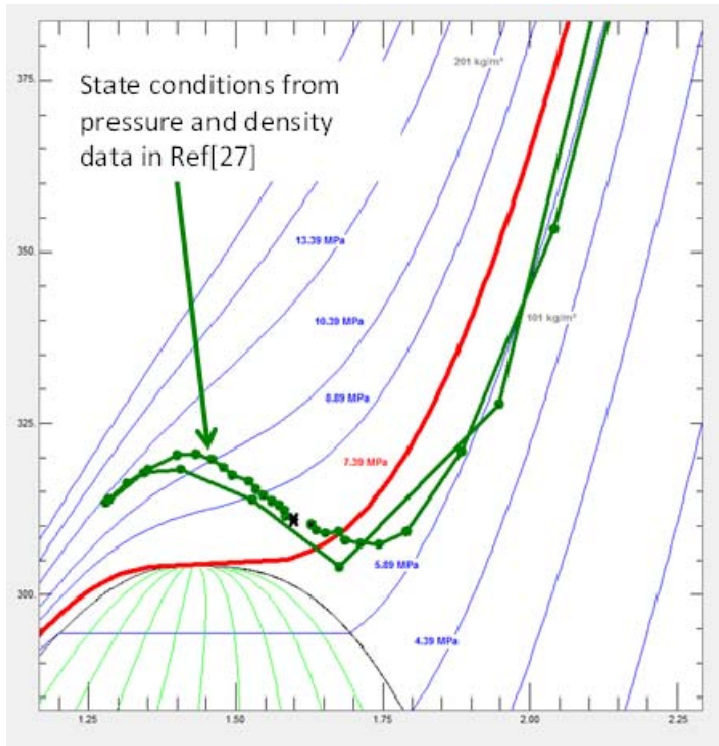


# Backup

# Compressibility of s-CO2

$$\Lambda = (6\mu\omega/p_a)(R/C)^2$$





# Bearing Requirements/Environment - Scaling

Power	Pressure	Temperature	Weight	Speed
(MW)	(MPa)	(°C)	(kg)	(rpm)
1	7.8 - 30	650 - 750	1-2	120,000
10	7.8 - 30	650 - 750	100	50,000
100	7.8 - 30	650 - 750	1500	10,000
300	7.8 - 30	650 - 750	>5,000	5,400

# MITI Oil-Free Bearings and Seals



**Journal Foil  
Bearing**

**Thrust Foil  
Bearing**

**Foil Face  
Seal**

**Foil Radial  
Seal**

6-150 mm

15-250 mm

25-1300 mm

20-250 mm

100 psi / 870°C

80 psi / 650°C

>80 psid / 650°C

>100 psid / 870°C

# Korolon Coated Foil Bearing Life Test

