Oil-Free Rotor-Bearings For Hydrogen Transportation & Delivery

A Centrifugal Compressor Operating Beyond Its Bending Critical Speed

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DOE Hydrogen Program

Overview

Timeline

- June 27, 2006
- March 27, 2009
- 95 Percent Complete

Budget

- Total proposed project funding
  - $750,000 DOE SBIR
  - $0 (SBIR – No Cost Share)
- $350,000 FY07 Funding
- $350,000 FY08 Funding

Barriers

- Hydrogen Delivery Compressor
  - Reliability
  - System Cost
  - Efficiency of H2 Gas Compression

Partners

- Lead: Mohawk Innovative Technology, Inc. (MiTi®)
- Mitsubishi Heavy Industries

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Relevance

Objective:

- **Demonstrate key technologies needed to develop reliable and cost effective centrifugal compressors for hydrogen delivery**
  - **Flow to 1,000,000 kg/day**
  - **Pressure rise from 300-500 up to 1200-1500 psig**
  - **Contaminant-Free/Oil-Free**

Category	2005 Status	FY2012 (Project Target)	FY2017
Reliability	Low	Improved	High
Energy Efficiency	98%	98%	>98%
Capital Investment ($M) (based on 200,000 kg of H2/day)	$15	$12	$9
Maintenance (% of Total Capital Investment)	10%	7%	3%
Contamination	Varies by Design		None

Objectives

- Assess feasibility of centrifugal compressors for hydrogen transmission and delivery
  - Demonstrate full-scale oil-free foil bearings in compressor simulator rig hardware
  - Test candidate bearing/shaft materials and coatings

Approach/Project Plan

Preliminary System Design

Refine System Configuration

- Multi-Stage Sizing
- Compressor Stage Flow & Pressure
- Shaft Speed
- Bearing & Seal Requirements

Detailed Design & Fabrication

Single Stage Compressor

- Single-Stage Compressor, Inlet, Diffuser & Return Channel
- Shaft, Seals & Bearings for High-Speed Operation

Test, Evaluate & Refine Design

Single Stage Compressor

- Verify High-Speed Dynamics
- Measure Compressor Performance
- Refine and Scale Design

Demonstrate feasibility of very high speed hydrogen centrifugal compressor through component test

Project Milestones

Month/Year	Milestone or Go/No-Go Decision
Sept/06	**Project Milestone:** Update preliminary modular centrifugal compressor design to achieve pressure and flow
Jan/07	**Project Milestone:** Complete bearing & test rig designs
Mar/07	**Project Milestone:** Complete tribological testing
Jul/07	**Project Milestone:** Fabricate foil bearings and rig mods
Mar/09	**Project Milestone:** Complete simulator testing

Oct/09	**DOE Milestone:** Down select novel compression technology for hydrogen delivery

Project Plan

- Demonstrate Feasibility of Oil-Free Hydrogen Centrifugal Compressor
  - Refine Compressor System Concept
  - Design Rotor-Bearing Dynamic Simulator
    - Full Size Rotor and Bearings
    - Simulate Dynamics and Bearing Loads
  - Validate Bearing Capability and Shafting Design Through Dynamic Testing in Air
    - Rotor-Bearing Operation Above Bending Critical Speed
    - Operation with Side Loads
    - Identify Impact of Hydrogen
  - Identify Candidate Bearing and Shafting Coatings with Appropriate Friction and Wear Life

Project Plan - Seals

- Demonstrate Feasibility of Oil-Free Hydrogen Centrifugal Compressor
  - Design Compliant Foil Shaft Seal
    - Full Size - 2.5” Diameter
    - Differential Pressures to 200 psig
  - Validate Seal Capability through Testing in Air and with Helium Gas
    - Test Statically and At Speeds to 54,000 rpm
    - Pressures to 100 psi in Air, 200+ psig in He

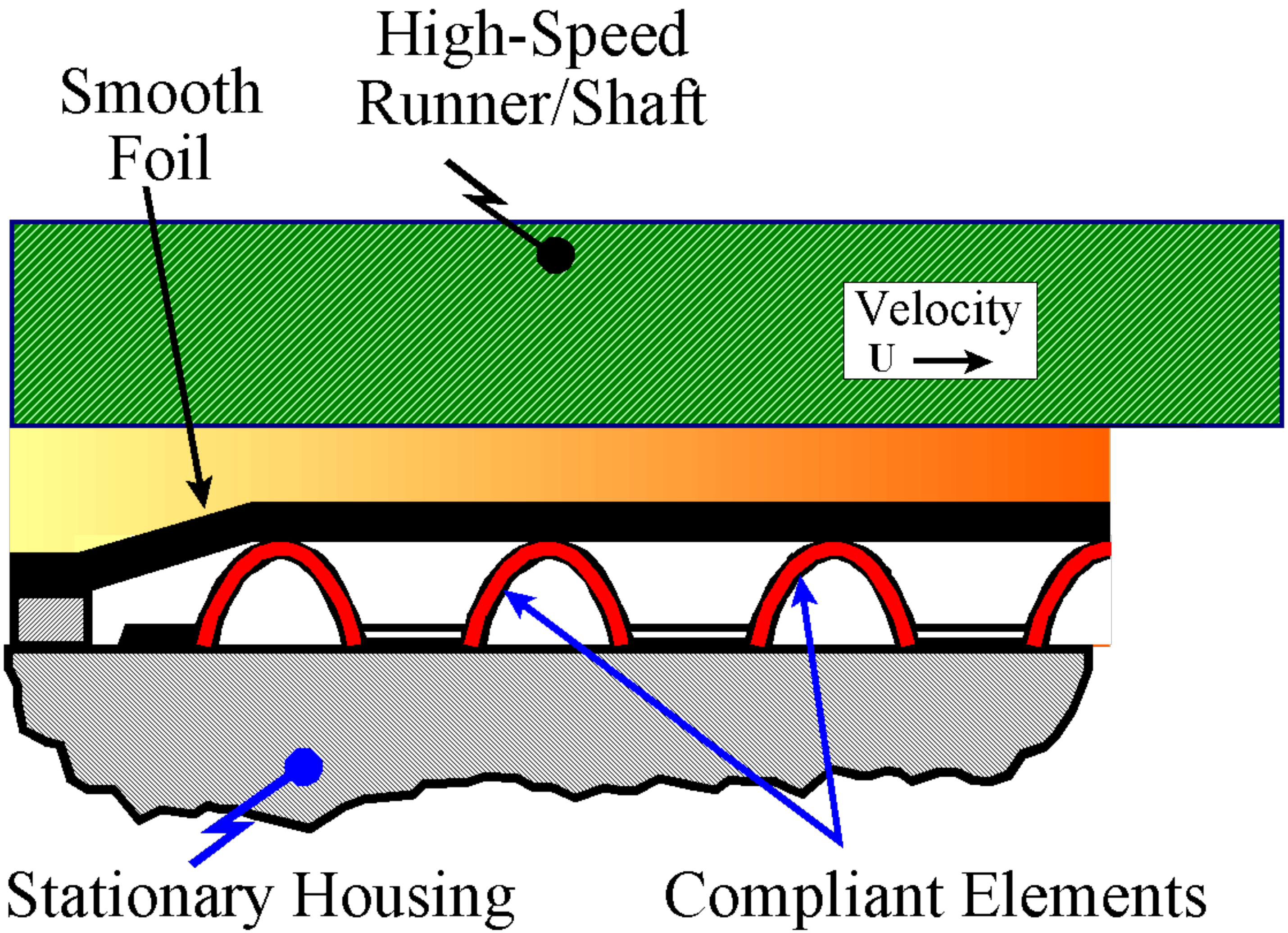
Progress

- System Configuration Assessment Complete
- All Bearing Design and Fabrication Tasks Complete
- Bearing and Shaft Coating Tests Complete
- Rotor-Bearing Simulator Testing In Progress
  - Operation Above Bending Critical Speed on Gas Foil Bearings Demonstrated
  - Impact of Hydrogen Embrittlement Demonstrated
  - Requirements for High-Speed Shafting Identified
  - Foil Bearing Capabilities Demonstrated
- Dynamic Seal Design Analysis in Progress
- Static Testing of Preliminary Dynamic Seal Design Conducted

Bearing Selection

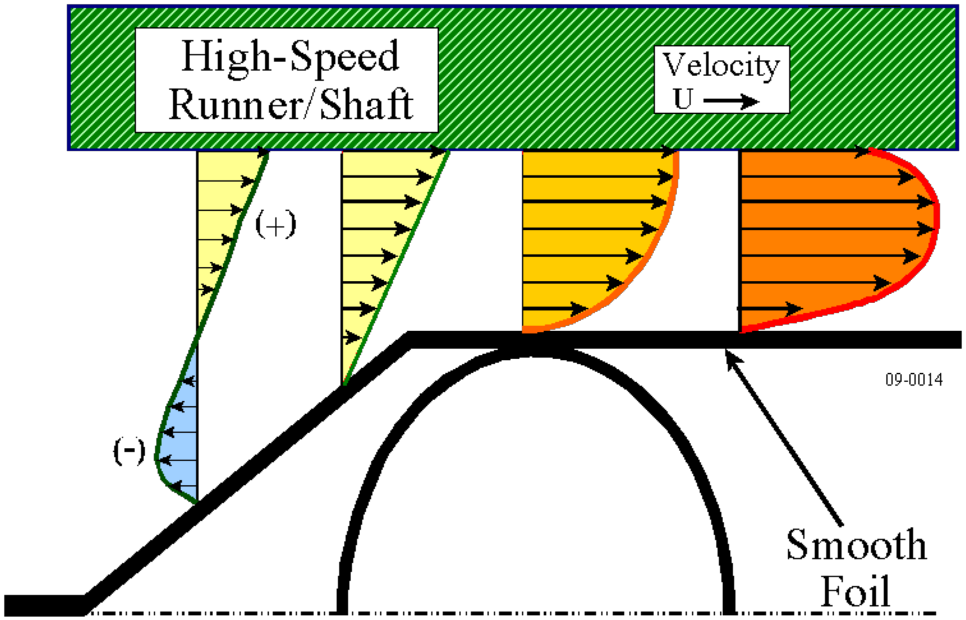
Bearing	Pro				Con			
	Efficiency	Total Load Capacity	Life	Speed	Contaminate Hydrogen	Auxiliaries	Cost	Other
Fluid Film	med-low	high	high	medium	Yes	Many	Operating	MisAlign
Magnetic	high	high	med-high	high	No	Electronics Backup Brg	Purchase	Failure Modes
Hydrostatic	medium	high	med-high	med-high	No	Hi-Press Gas	Precision Mfg & Operating	MisAlign Stability Debris
Foil	high	med-high	high	high	No	None	Low	Startup & Low Speed, Debris Filter
Hybrid	high	high	high	high	No	Electronics	Purchase	Hi-Press Gas Debris Filter

Bearing Technology

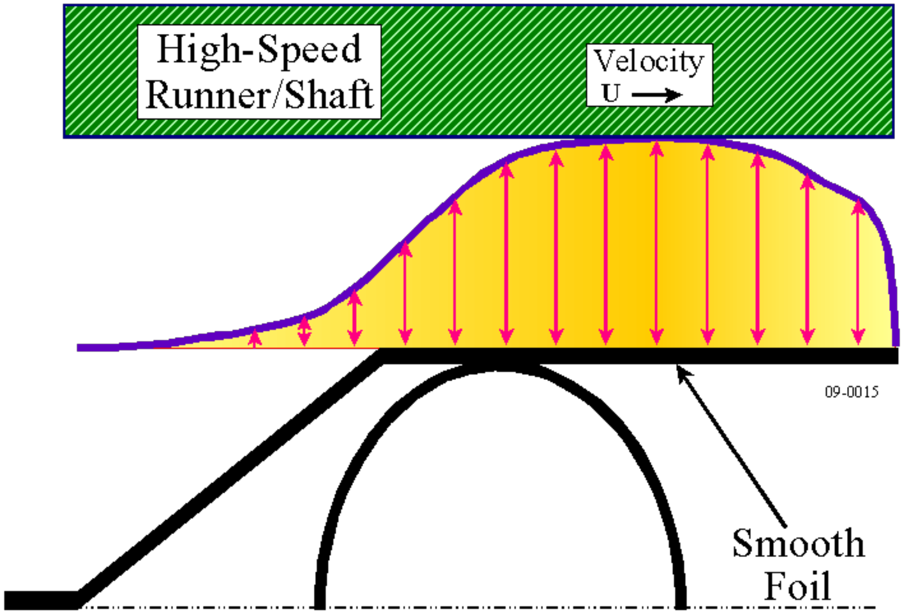


Bearing Technology

Velocity Profile

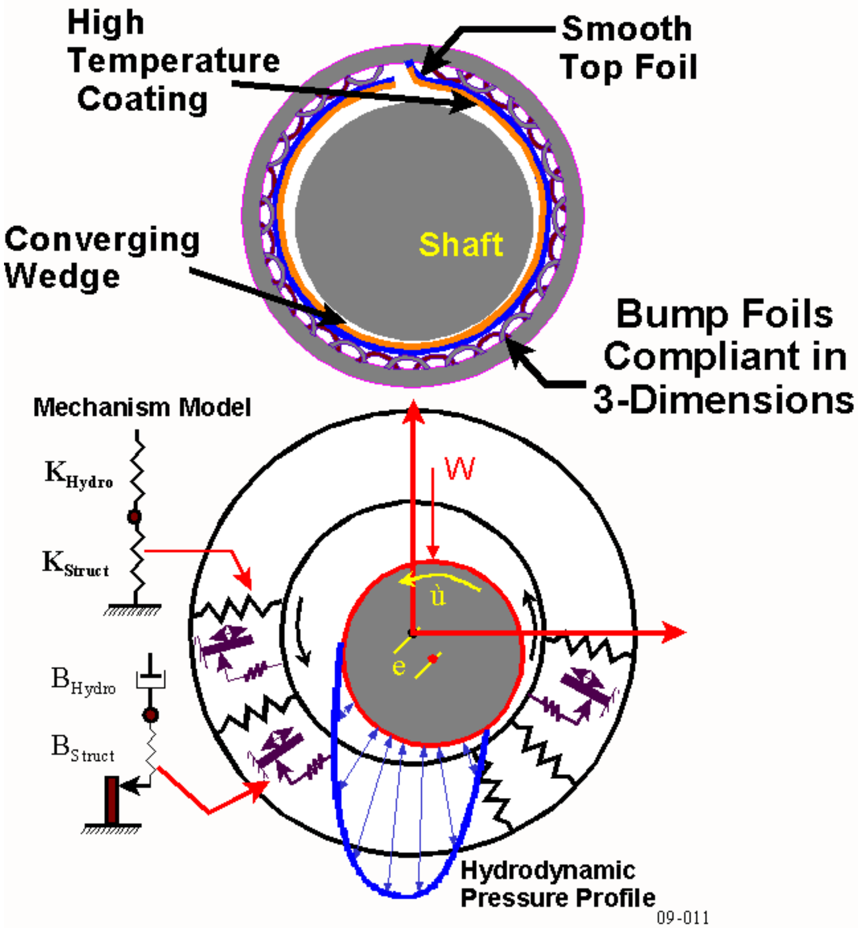


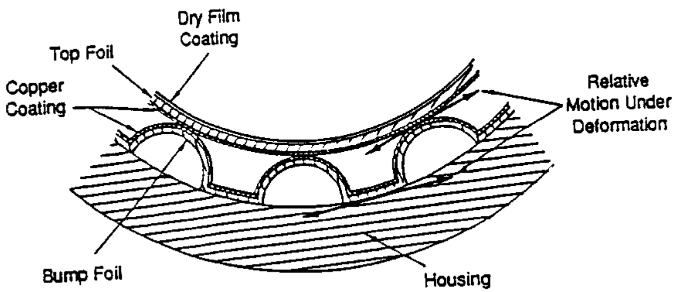
Pressure Profile



Air Foil Bearing Concept

- Air bearings have a thin, smooth inner surface supported on compliant bump foils. When a shaft spins at high speed, a thin high pressure air film is generated, which lifts and supports the shaft.
- Structural and hydrodynamic mechanisms exist simultaneously to produce stiffness and damping.



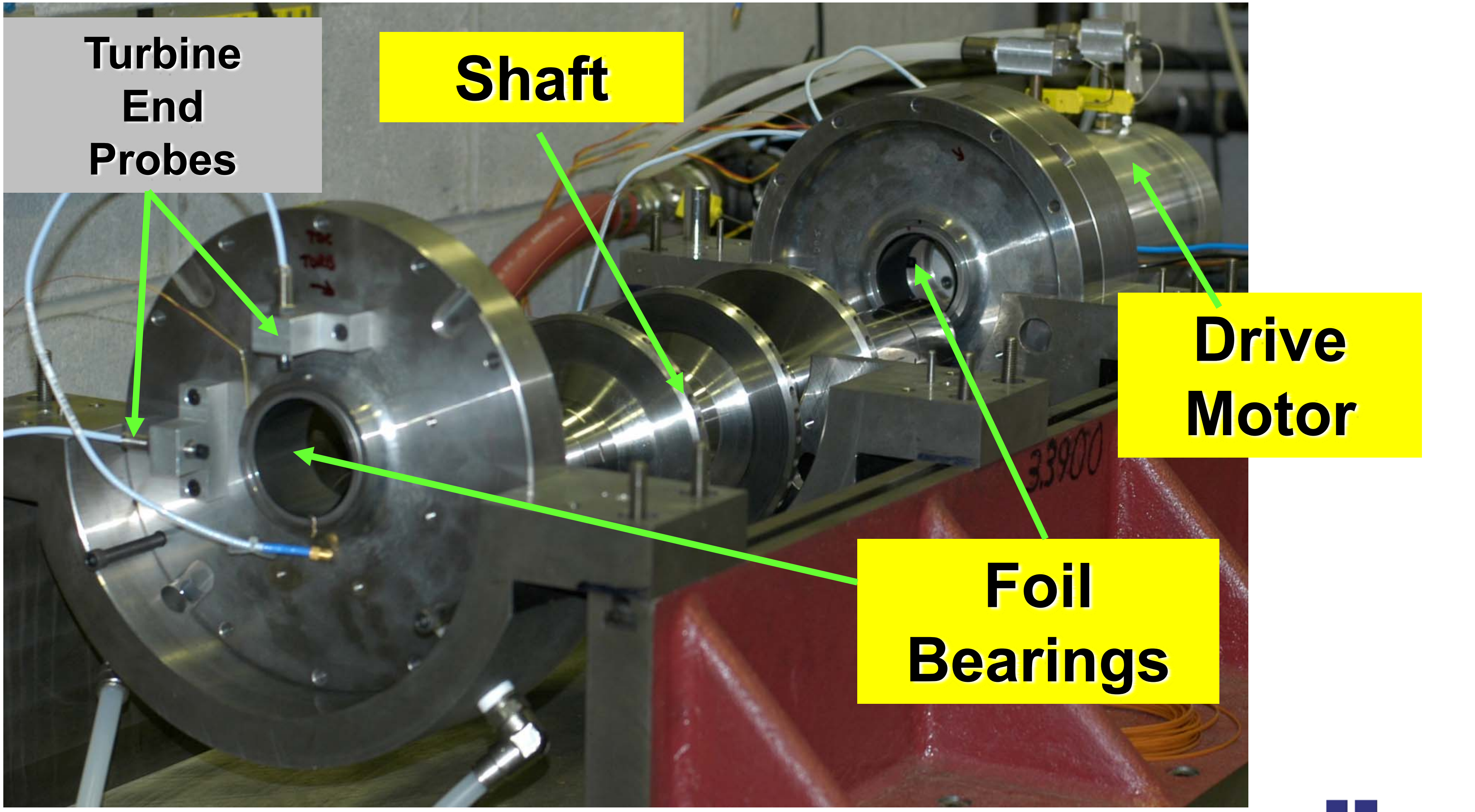


Foil Bearings for H_2 Compressor

- Foil Bearing Dimensions
  - Journal Bearings
    - Diameter = 2.5" (63 mm)
    - Length = 2.0" (50 mm)
    - Projected Area = 5 in^2
  - Thrust Bearings
    - Outer Radius = 3.265" (83 mm)
    - Pad Radial Length = .915" (23 mm)
- Bearing Coating
  - MiTi® Korolon™ 900
  - 25 lb Load Capacity @ Start Up (N=0)
- Bearing Stiffness
  - 20-30k lb/in/in
- Theoretical Load Capacity
  - 500 lb @ 800 fps

Design Based on Previous Compressor Concept Sizing

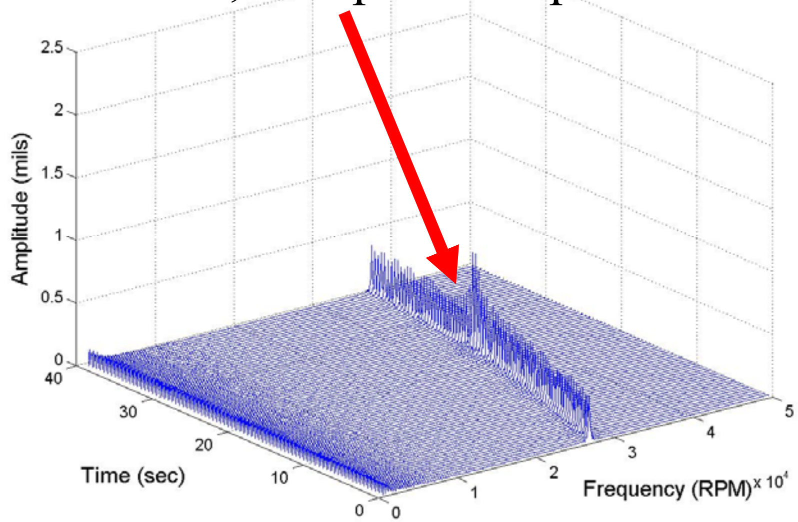
Hydrogen Compressor Simulator



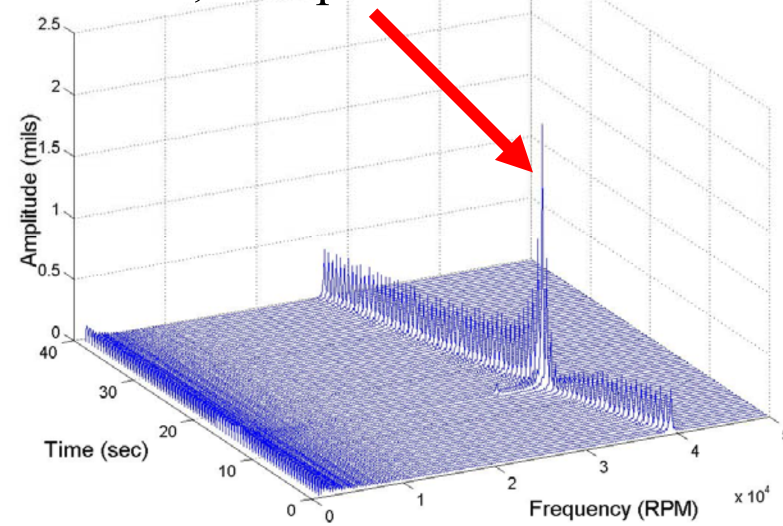
Supercritical Operation

♦ Experimental plots of rotor run-up and coast down through bending critical speed

34,400 rpm run-up



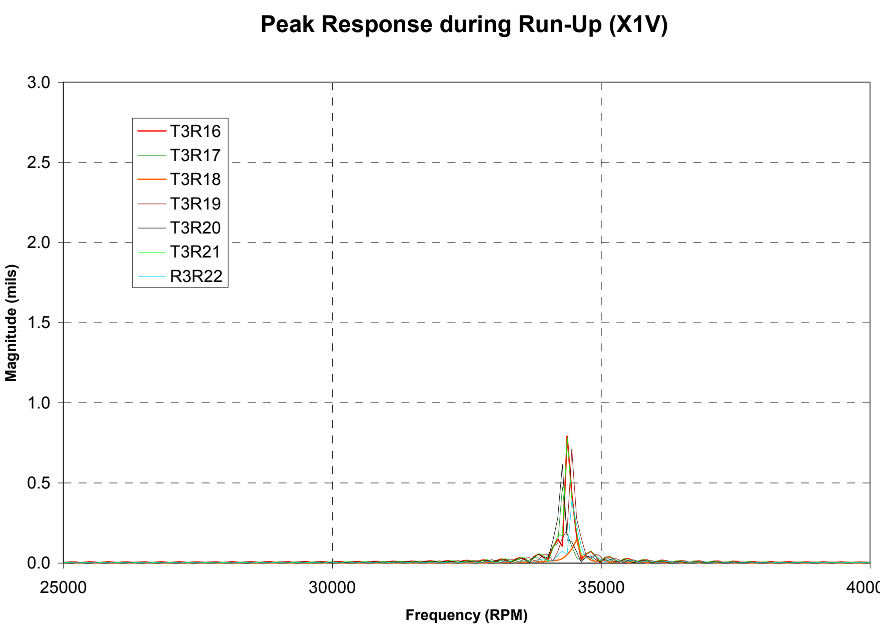
34,300 rpm coast down

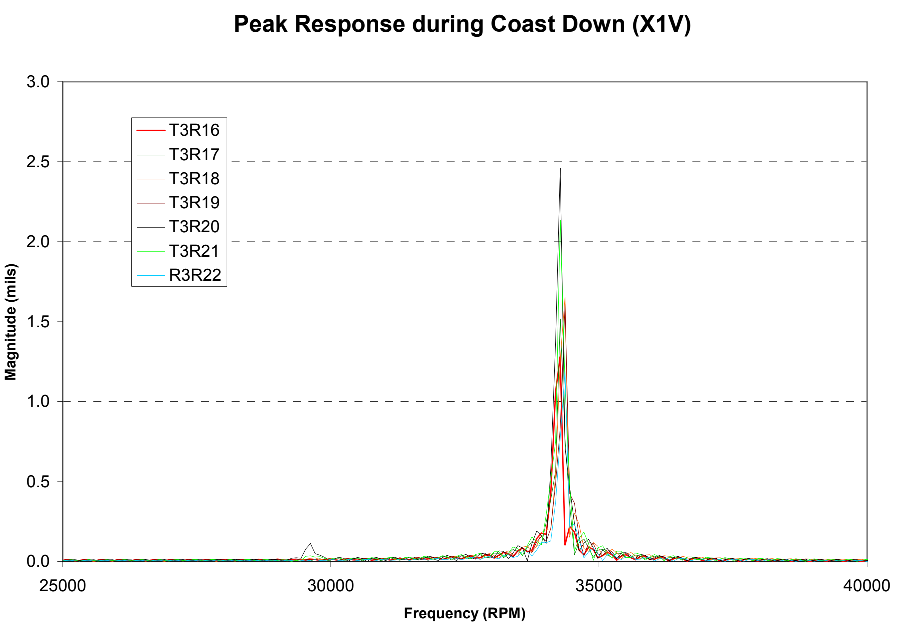


❖ Excellent correlation between prediction and experimental results

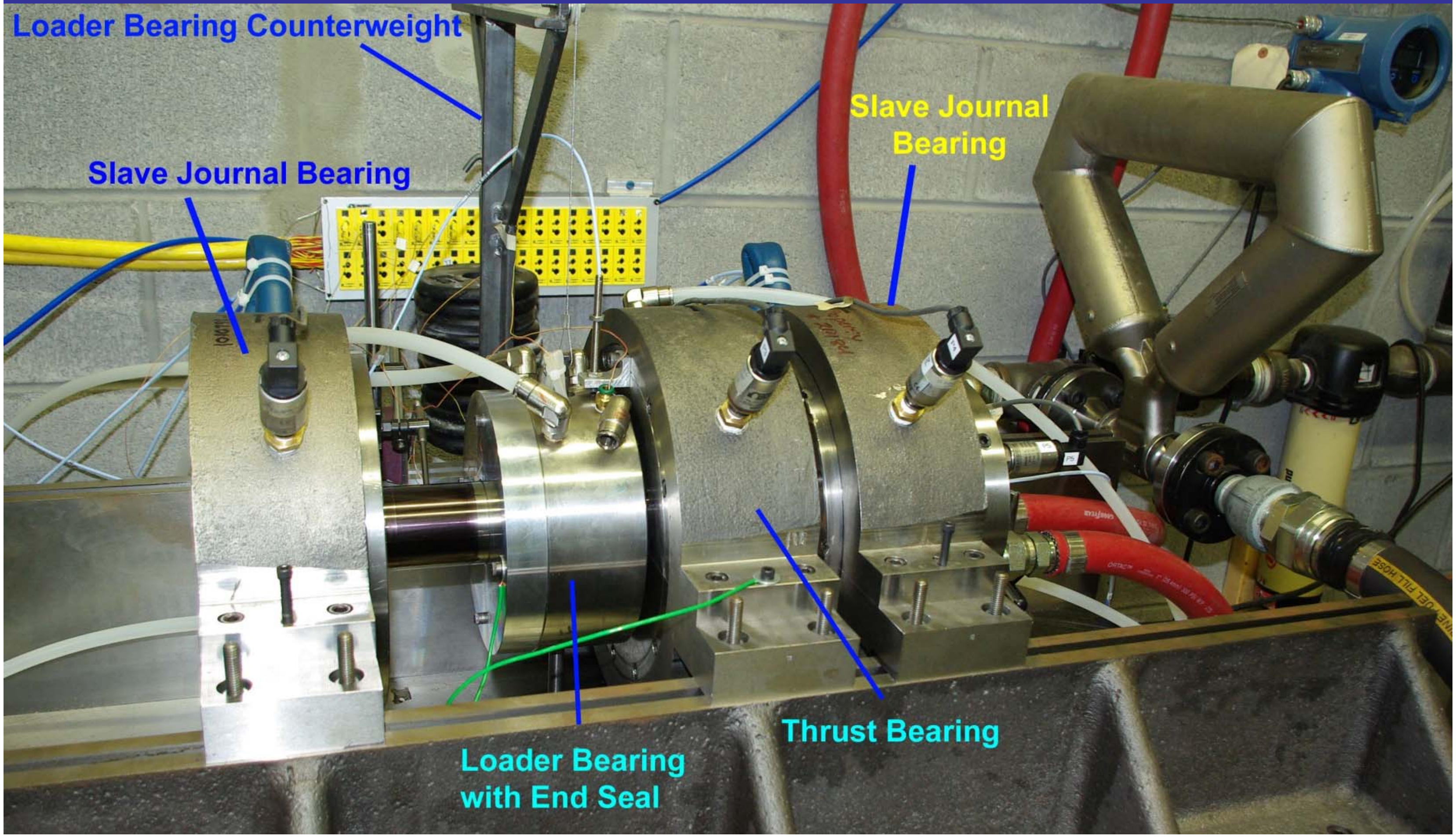
Repeatable Response Through Bend

- Peak rotor response shown for 8 consecutive runs
  - –Bending Critical Speed – Run-Up = 34.4 ± 0.1 krpm
  - –Bending Critical Speed – Coast Down = 34.3 ± 0.1 krpm
- Bending speed imposes ~93 lb dynamic load/bearing

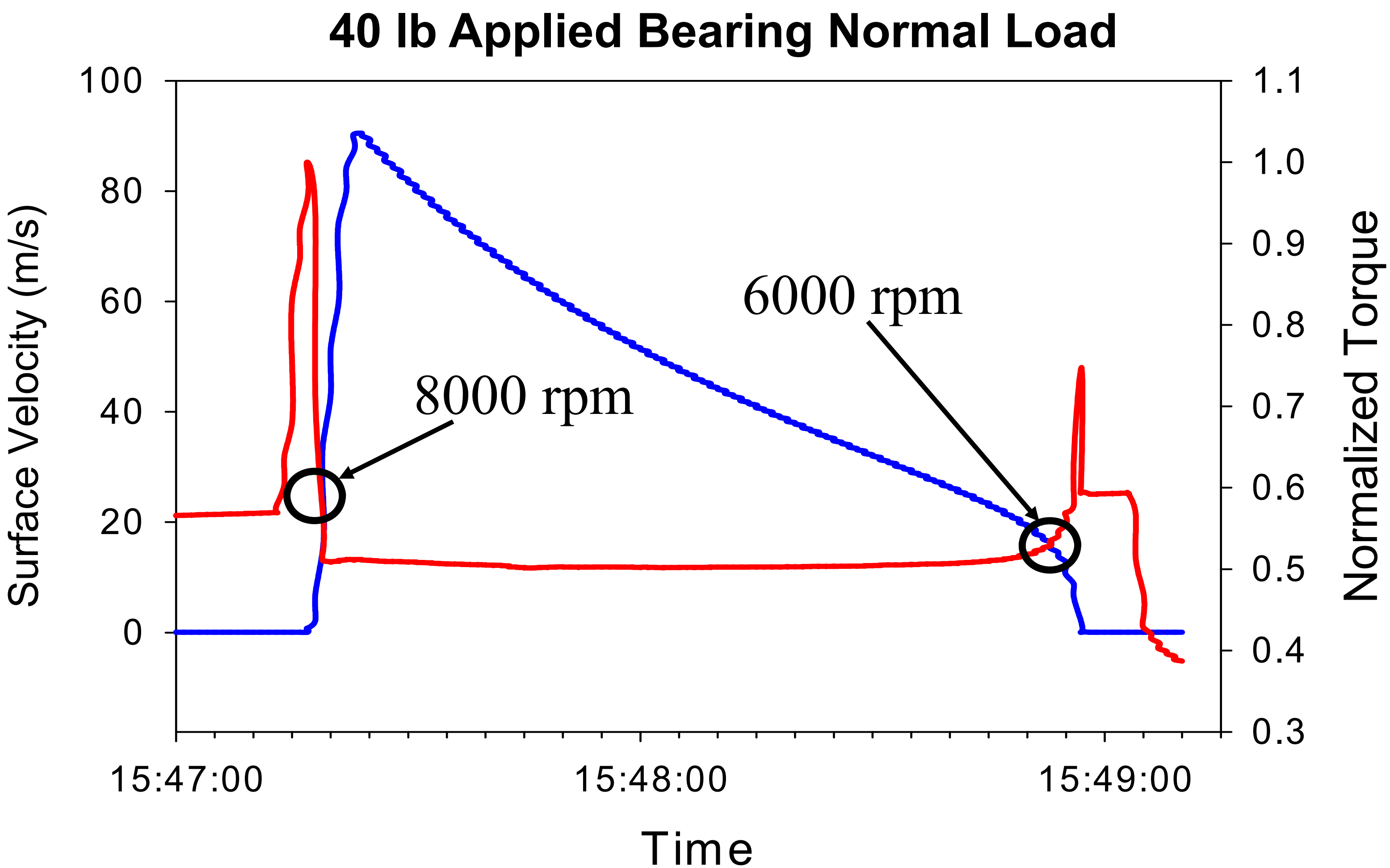




Bearing Loader Test Rig



Typical Lift-Off Test



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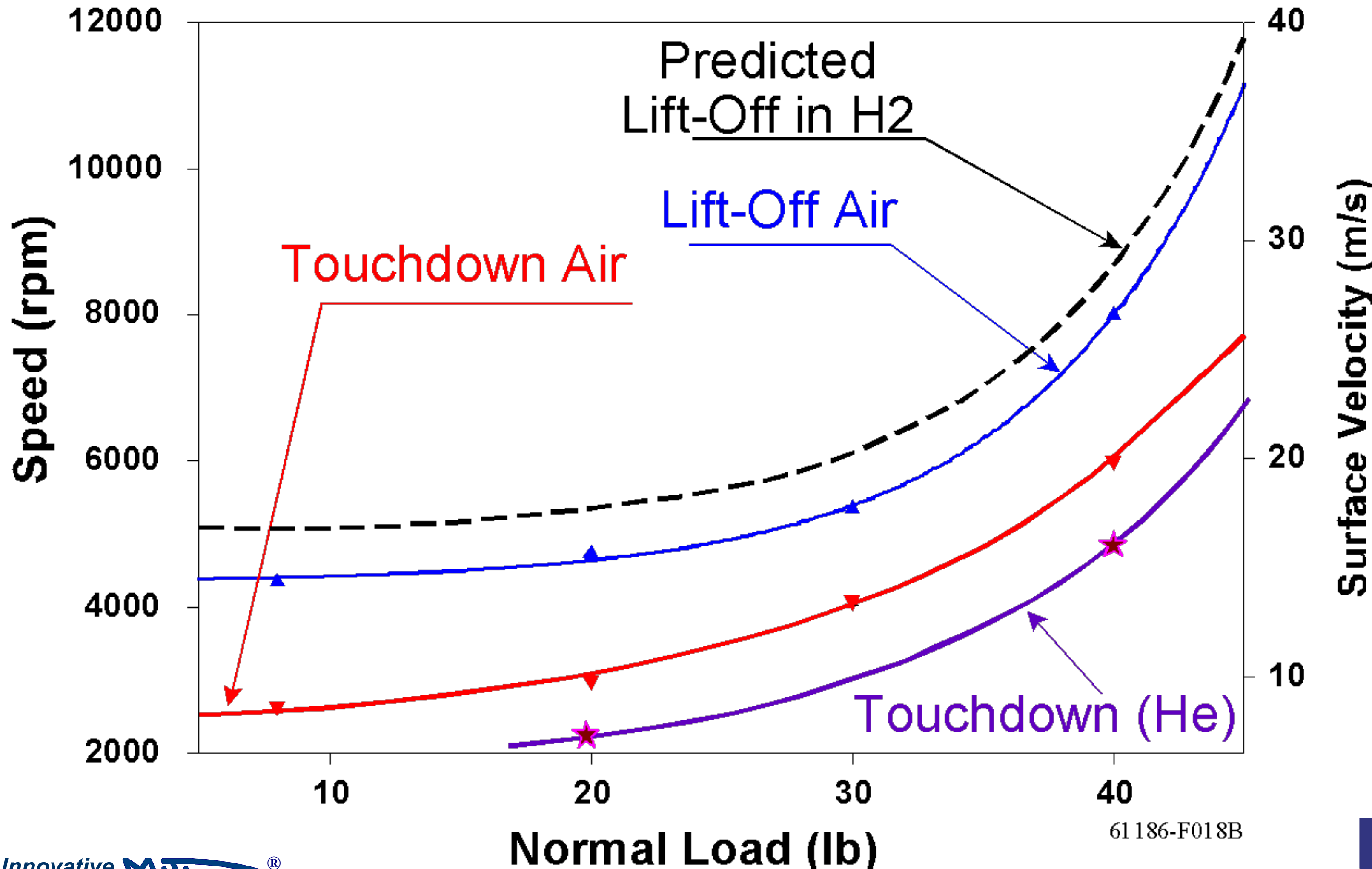
Lift-Off Test Under Various Conditions



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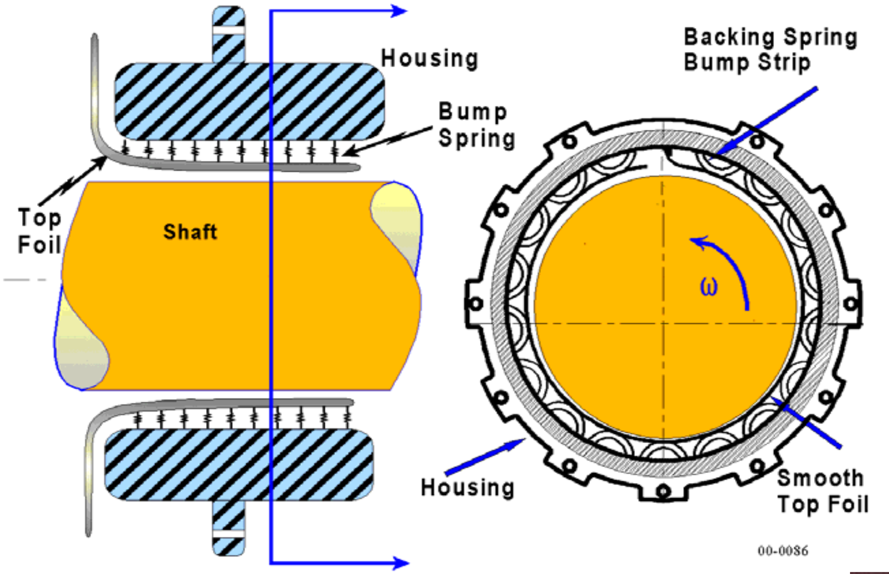
Project Summary: Bearing Test Results

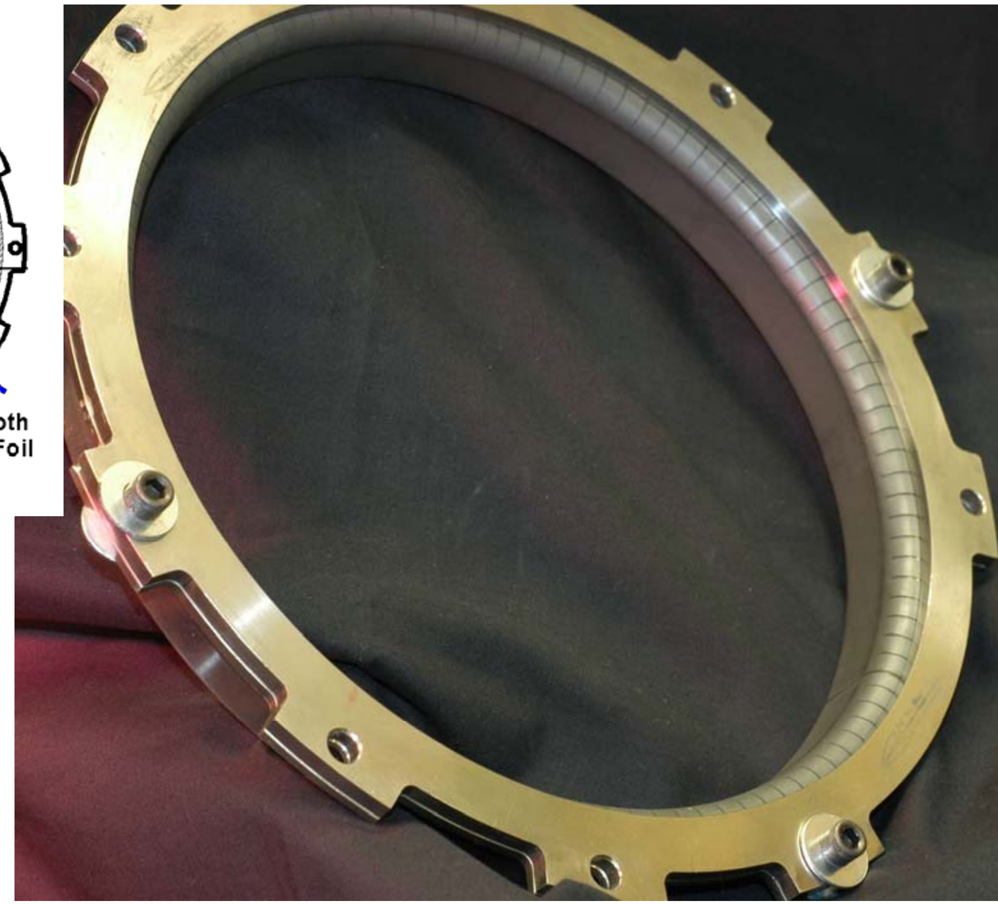
- Bearing Durability Demonstrated
  - Through multiple touchdowns under high loads
  - 100 start/stops tests
- Bearings successfully tested under following conditions:
  - Beyond required loads
  - Tested with Air, Helium and to 500^{o}F ambient temps
  - Experimentally measured bearing performance validated theoretical design predictions
  - Bearings endure high-speed labyrinth seal rub
- Simulator Rotor Super-Critical Operation Demonstrated
  - Bending critical exceeded multiple times
  - Excellent rotordynamic stability observed
- Maximum operating speed ~ 54,000 rpm (1600 fps)

Seal Selection

- Types Considered
  - Labyrinth
  - Brush
  - Honeycomb
  - Abradable
  - **Dynamic Compliant Foil**
- Issues
  - Leakage
    - Clearance
    - Differential Pressure
  - Wear Life and Debris
  - Material Compatibility

Foil Seal Concept

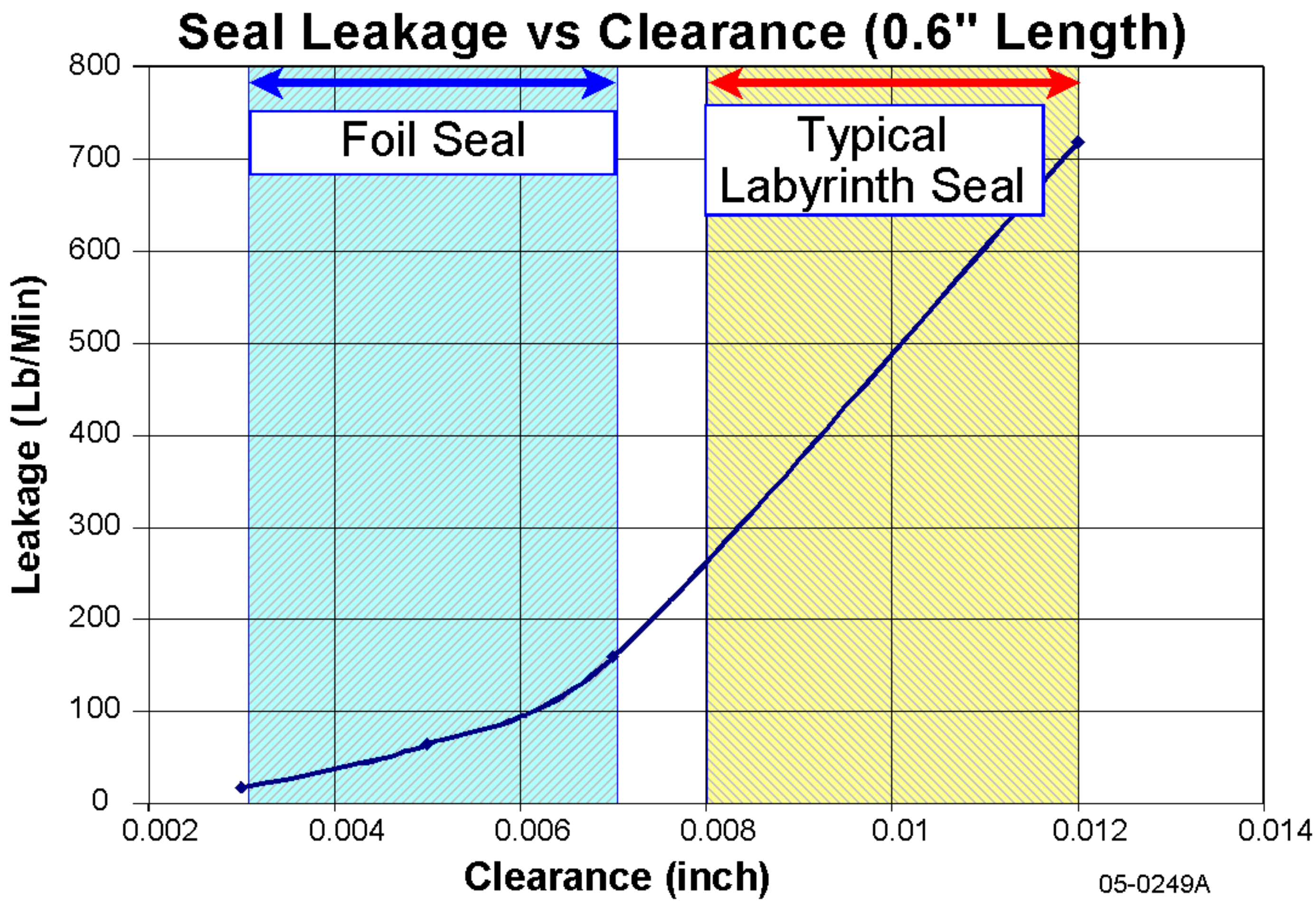




8.5” Foil Seal Developed at MiTi® and Independently Verified at NASA to 30,000 rpm

US Patent: 6505837 Compliant Foil Seal

Foil & Labyrinth Seal Comparisons

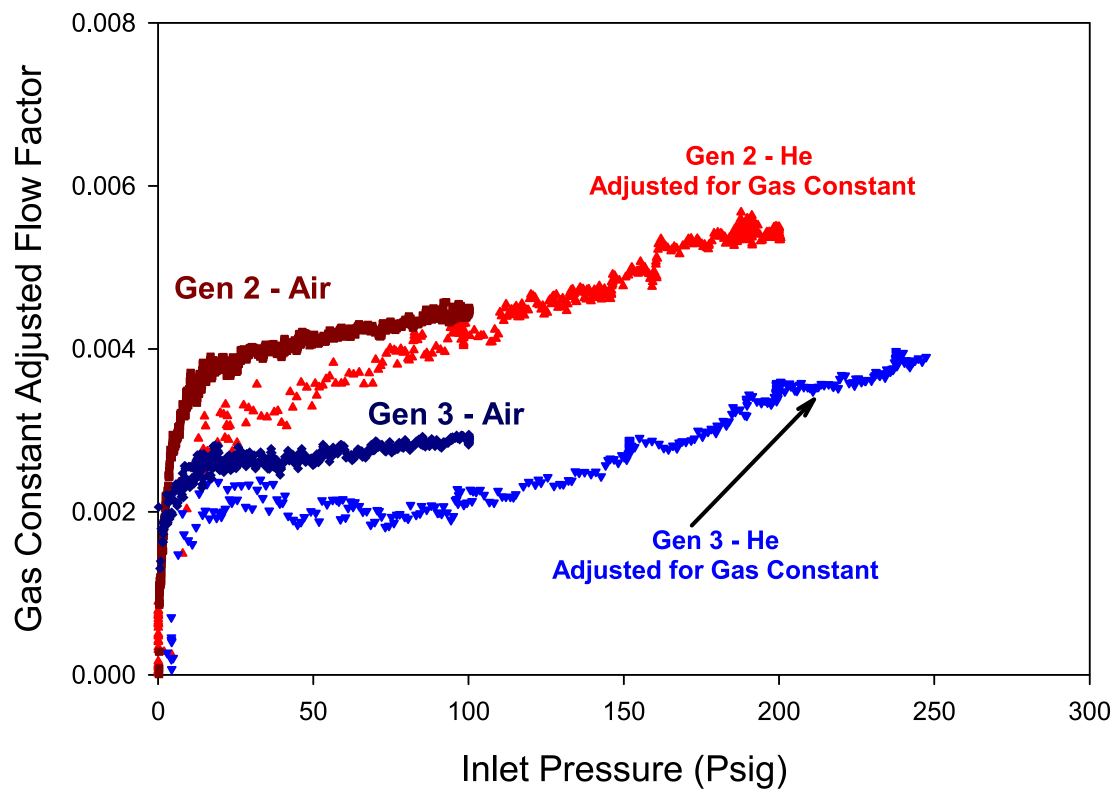


Technical Accomplishments – Related SBIR

Corrected Seal Flow Factor for Helium

$$\psi = \frac{\dot{m}\sqrt{T\left(\Re_{He}/\Re_{Air}\right)}}{P_u D}$$

Flow Factor for Helium is Slightly Less than for Air for Both Seal Designs



Flow Factor Adjustment Was Based on Differences in Gas Constants Between Helium and Air

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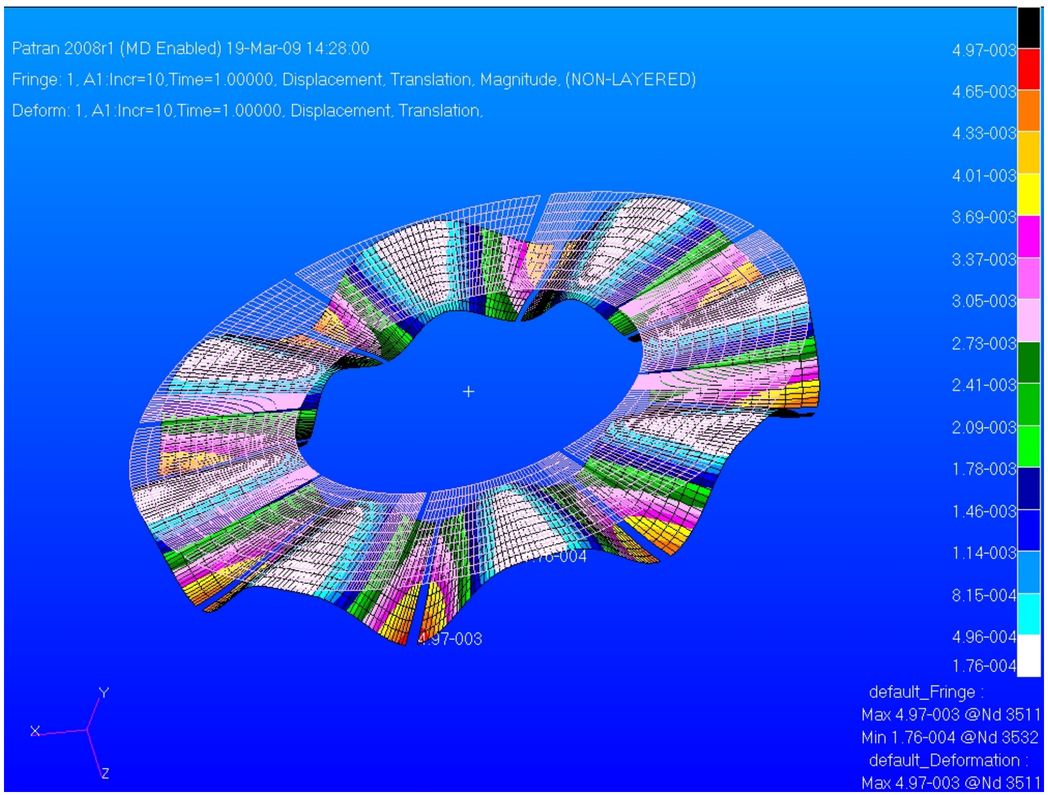
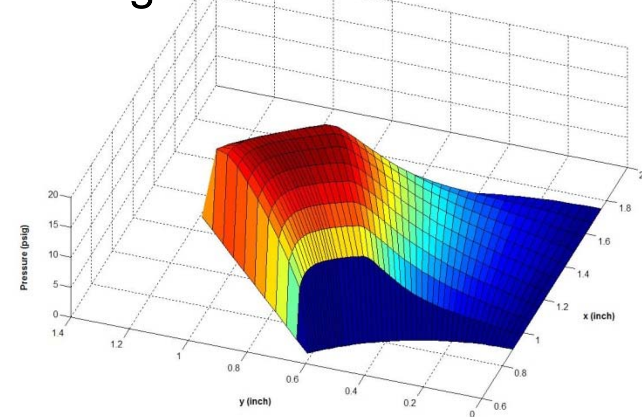
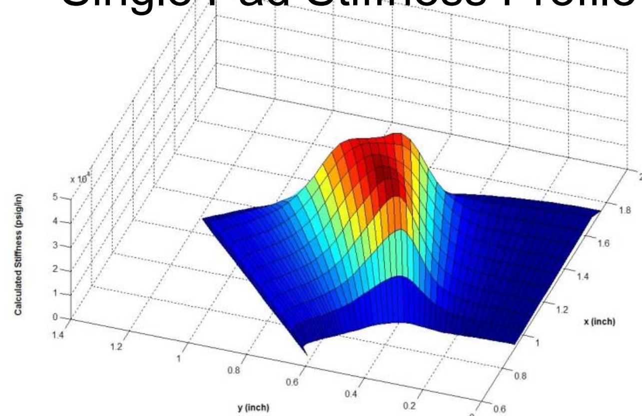
Coupled Elasto-Hydrodynamic Seal Analysis



Single Pad Pressure Profile



Single Pad Stiffness Profile



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Impact of Seal Design For H_2

- Dynamic Compliant Foil Seal
  - Non contact, small clearance and compliant structure
  - Seal Design Parameters:
    - Differential Pressure Across Seal: 80-200 psig
    - Total Leakage = 13 to 30 lb/min
    - Leakage = 2% to 4.5% of Total Compressor Flow

Reduces Required Compressor Power by 3000 HP

Future Work for FY09

- **Complete Rotor-Bearing Dynamic Testing and Final Report**
- **Conduct Seal Dynamic Testing**
  - **High-Pressures (>200 psig)**
  - **Operating Speeds (Suface Velocities > 1000 fps)**
  - **Temperatures to 500°F**
  - **Validate Established Coupled Elasto-Hydrodynamic Design Analysis Methodology**

Project Summary - Seal

- **Coupled Elasto-Hydrodynamic Seal Design Analysis Methodology Developed**
- **Preliminary Static Seal Testing Conducted:**
  - **100 psig in Air**
  - **>200 psig in Helium**
- **Compliant Foil Seal Operation Demonstrated**
  - **Low Flow Factor and Leakage Substantially Less Than Labyrinth Seals**
  - **Close Clearance Film Riding Seal Operation Demonstrated**
  - **Testing at Pressures above 200 psig Successfully Completed**

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