Gas Bearing Development

For

SCO2 Applications

by

Dr. Christopher DellaCorte (NASA)

Glenn Research Center at Lewis Field

Cleveland, Ohio

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Boston, MA

Background

NASA's goals to Revolutionize Aviation and enhance Access to Space are supported by the development of revolutionary Oil-Free Turbomachinery Propulsion and Energy systems.

Definition

Oil-Free Turbomachinery is defined as "high speed rotating equipment operating without oil lubricated rotor supports…bearings, dampers, seals…"

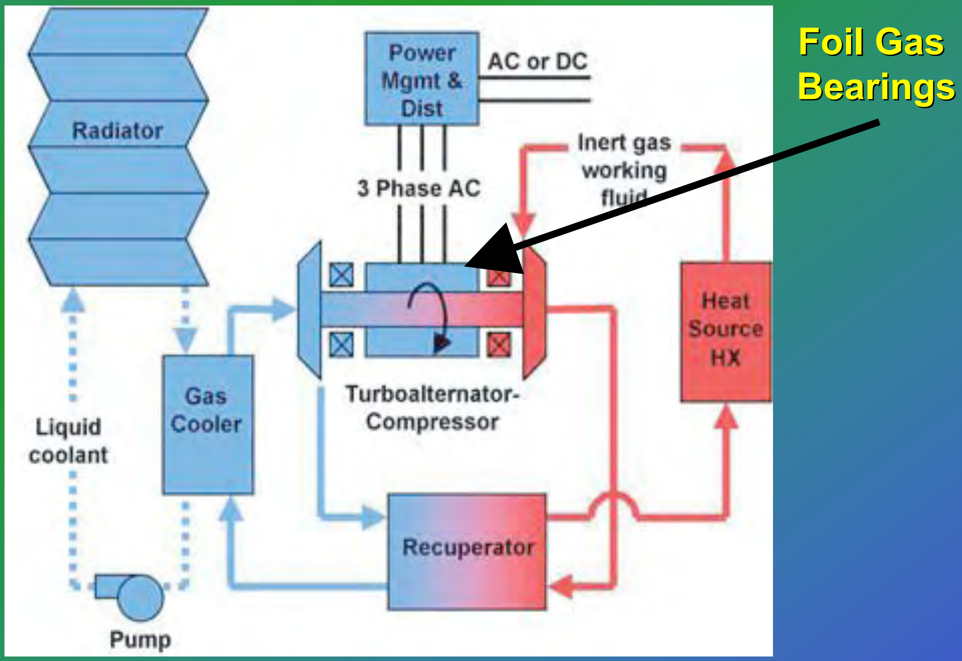
Approach

Capitalize on recent breakthroughs in Foil Air Bearings, Tribological Coatings and Analytical Modeling to enable high speed, high temperature Oil-Free Turbomachinery systems.

Oil-Free Turbomachinery

Nuclear Power for Space Applications

Artist's Conception of JIMO, Jupiter Icy Moon Orbiter



Power system uses foil gas bearings for Oil-Free turbine

Oil-Free Turbomachinery Technology Path

Air Cycle Machines (ACM's) — 1970's
- Clean Oil-Free Cabin Air
- High Reliability
- Maintenance Free

Turbocompressors — 1980's
- No Process Fluid Contamination
- Cryogenic Capability
- Long Life

Turbogenerators — 1999
- Low Emissions
- Lightweight
- Maintenance Free

Turbochargers — 2000
- Mounting Orientation Freedom
- No Particulate Emissions
- High Temperature

Small Gas Turbine Engines — 2005
- High Speed
- Low Cost
- Maintenance Free

Mid-Range & Large Engines — 2010
- High Temperature & High Speed
- Design Architecture Freedom
- Revolutionary Engines

...Starting a Turbomachinery Revolution...

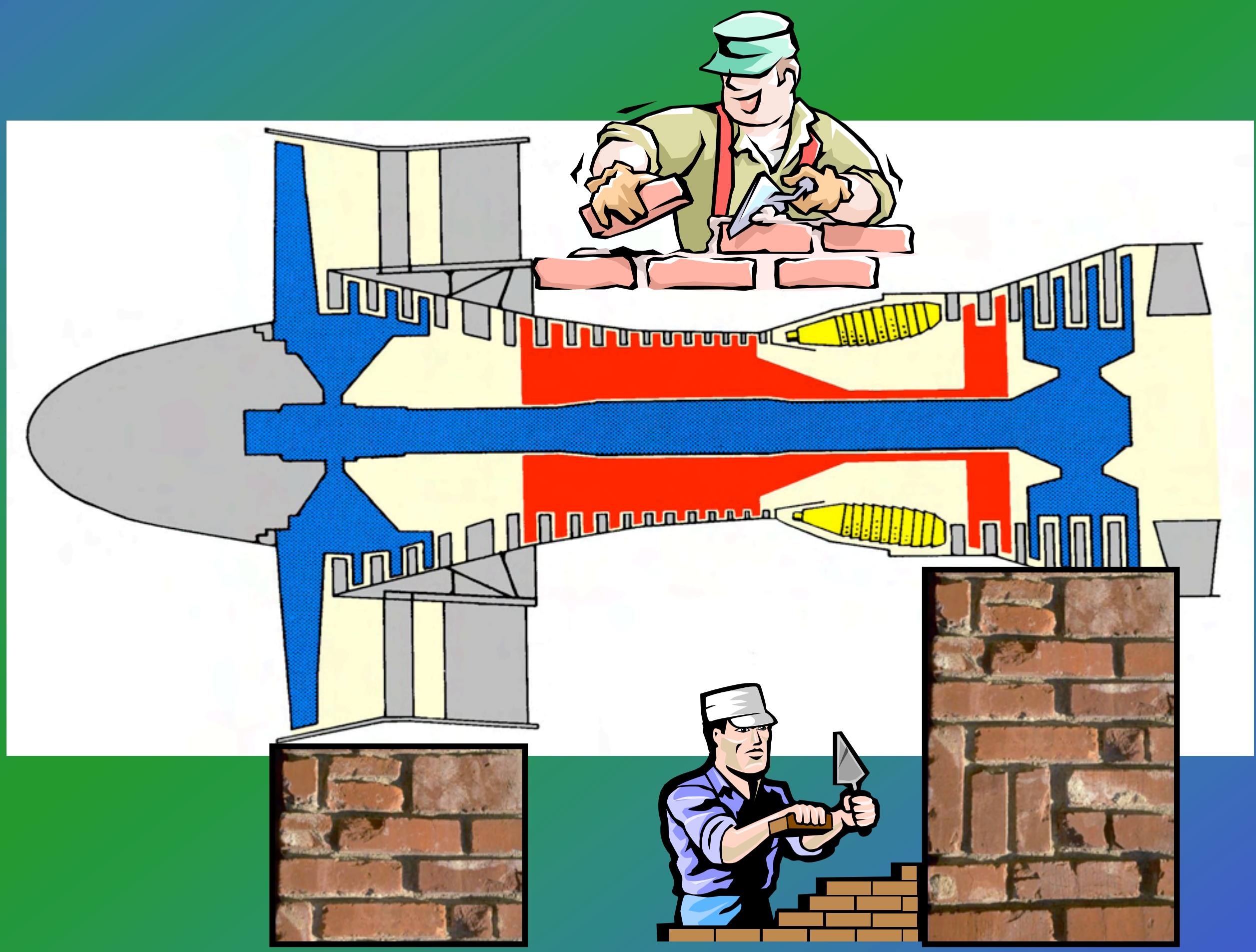
OIL-FREE TURBOMACHINERY PROGRAM

Propulsion for the 21st Century

NASA Glenn Research Center

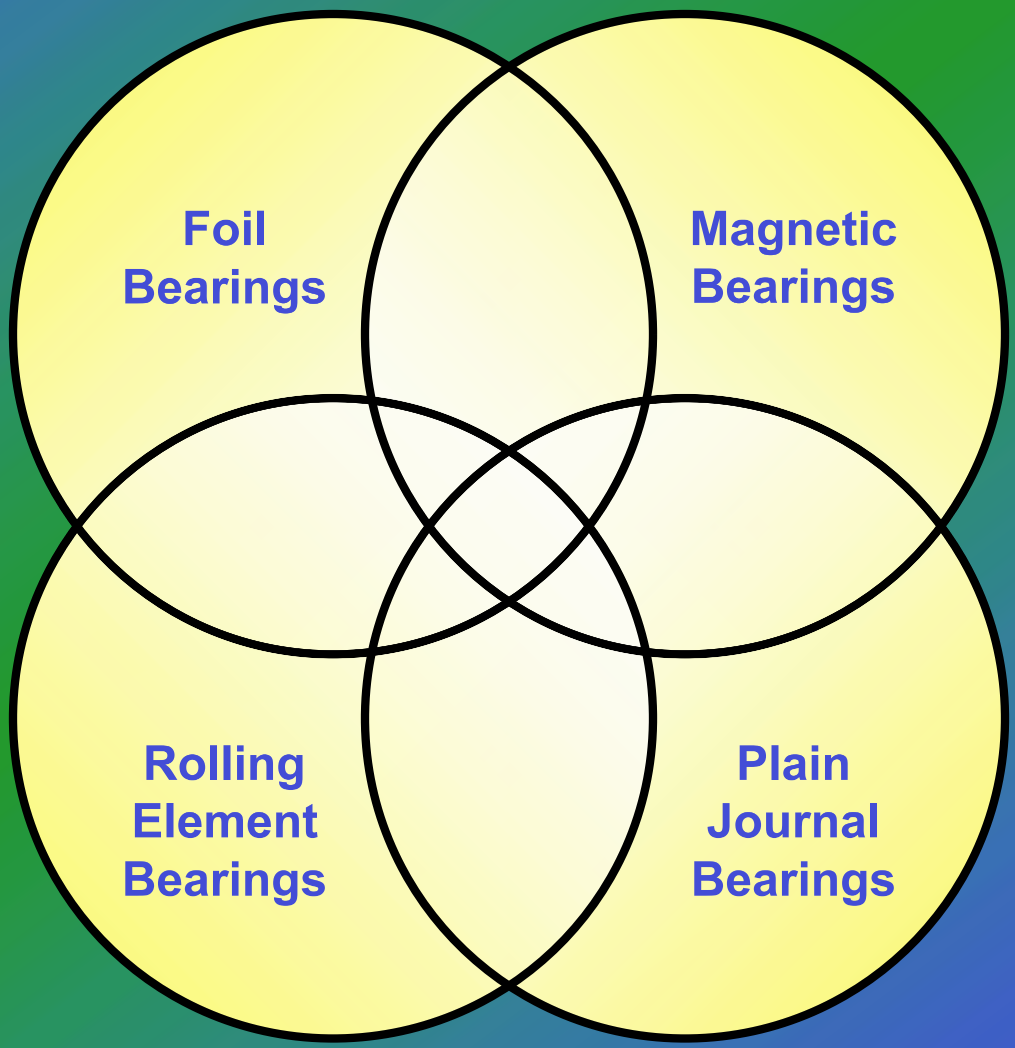
Turbomachinery Rotor Support System

- The rotor support system is the foundation upon which turbomachinery *(compressor, generator, turbine)* is built



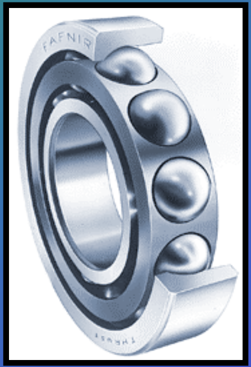
Bearing Characteristics

Commonality & Unique Features



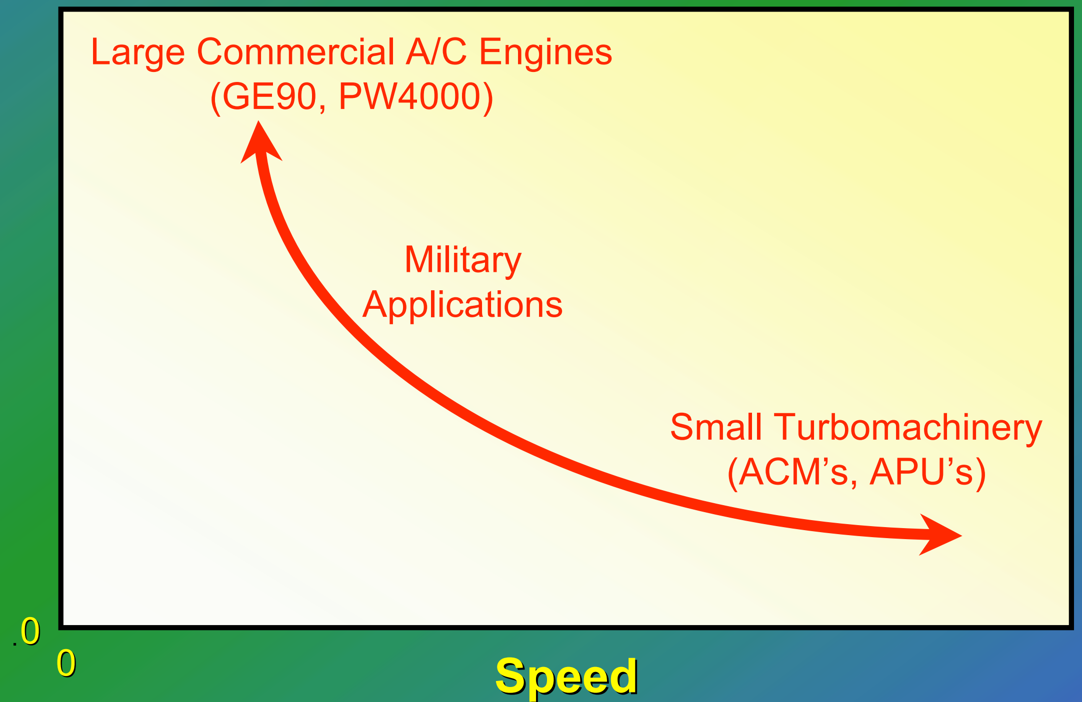
Rolling Element Bearing Speed Ranges

✦ Low Speed	< 10,000 DN
✦ Medium Speed	10,000 DN to 1 MDN
✦ High Speed	1 MDN to 2 MDN
✦ Ultra High Speed	> 2 MDN



Bearing Characteristics -- Rolling Element Bearings

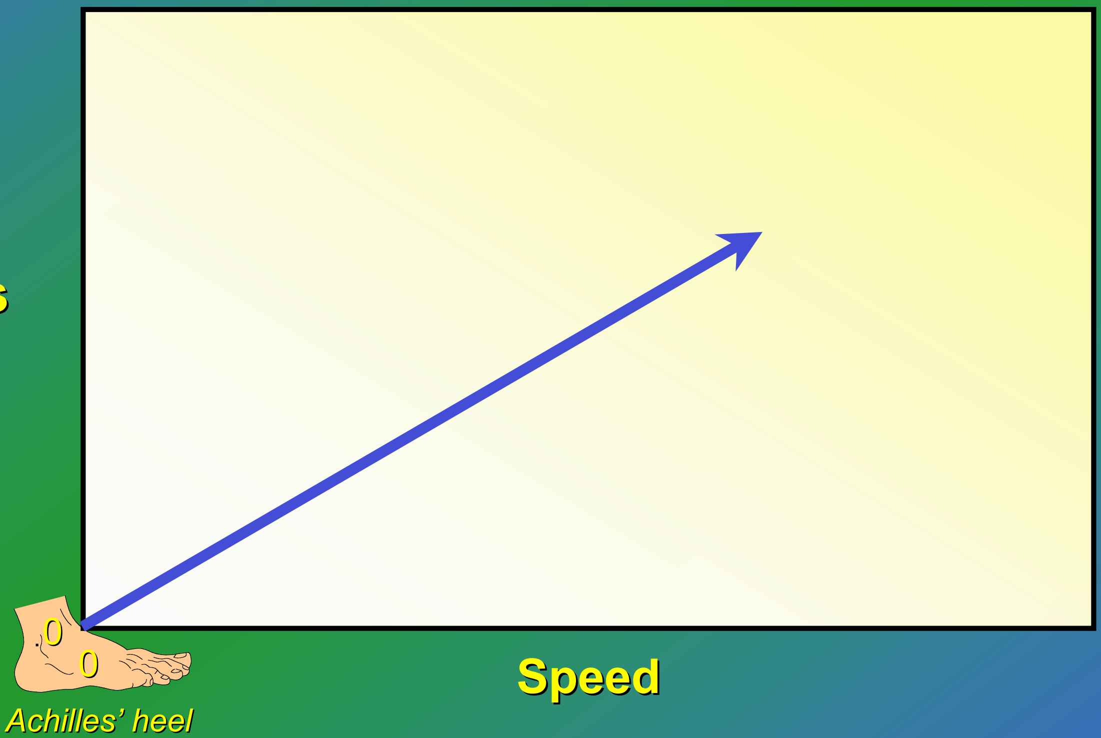
- **Rolling Element Brgs Maximum Load for Long Fatigue Life**



- **Oil-Lubricated Rolling Element Bearings**
- **High loads at low to moderate speeds**
- **Light loads at very high speeds** *(> 2.5 MDN)*
- **Current engines are designed around characteristics of rolling element brgs**

Bearing Characteristics -- Foil Air Bearings

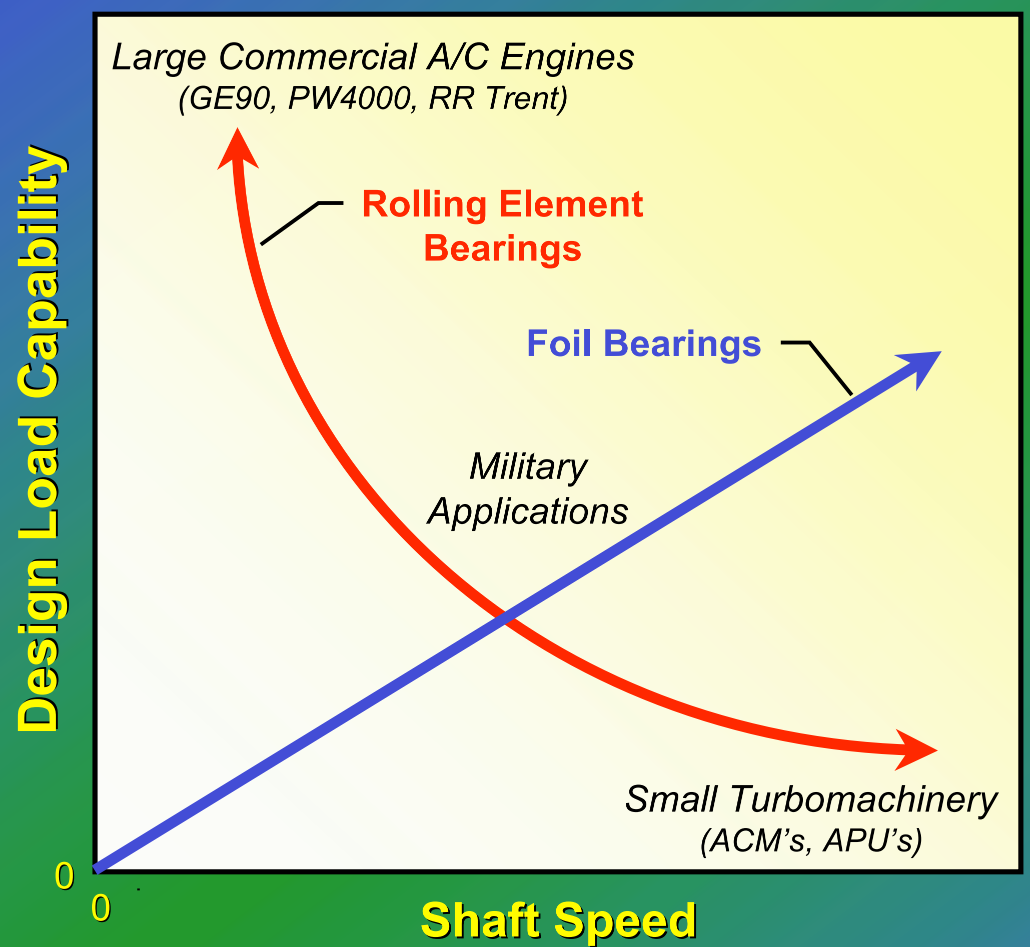
- Foil Air Bearings
  Load Capacity



Foil Bearings

- Load capacity very low at low speeds
- Load capacity increases linearly with speed
- Foil bearings have no practical speed limitations (DN)
- Require no external systems (pressurization)

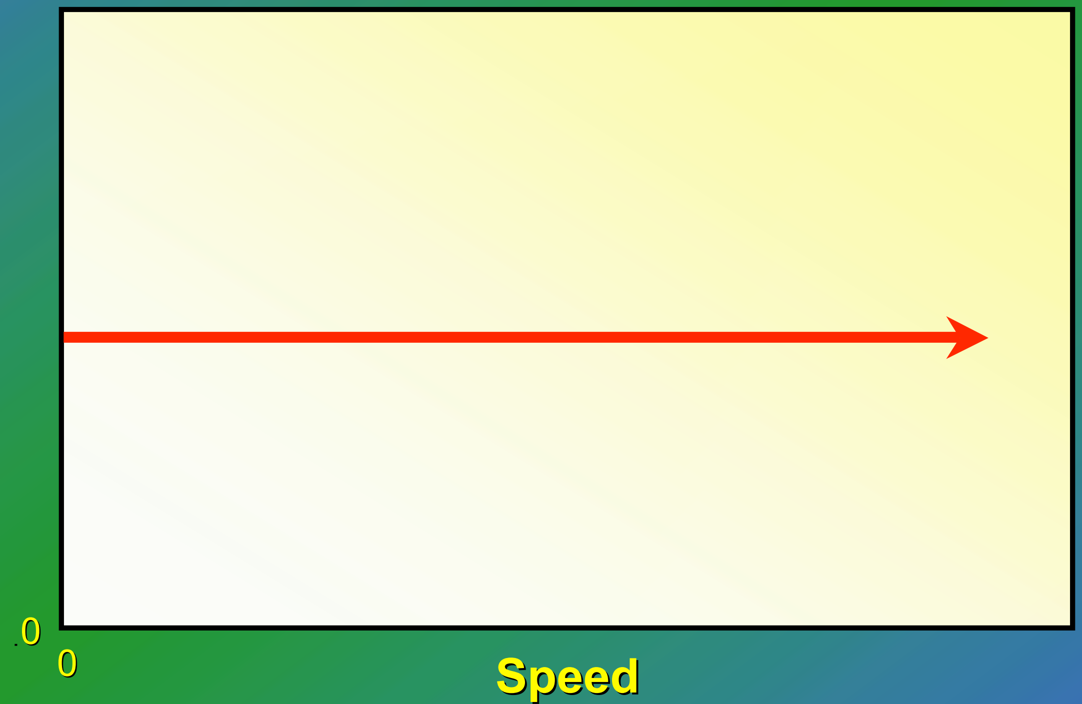
Bearing Characteristics Comparison



- Foil bearings cannot retrofit into large engines – new engine designs needed
- Foil bearings need solid lubricant at startup/shutdown
- Foil bearings outperform rolling element bearings at high speeds

Bearing Characteristics -- Magnetic Bearings

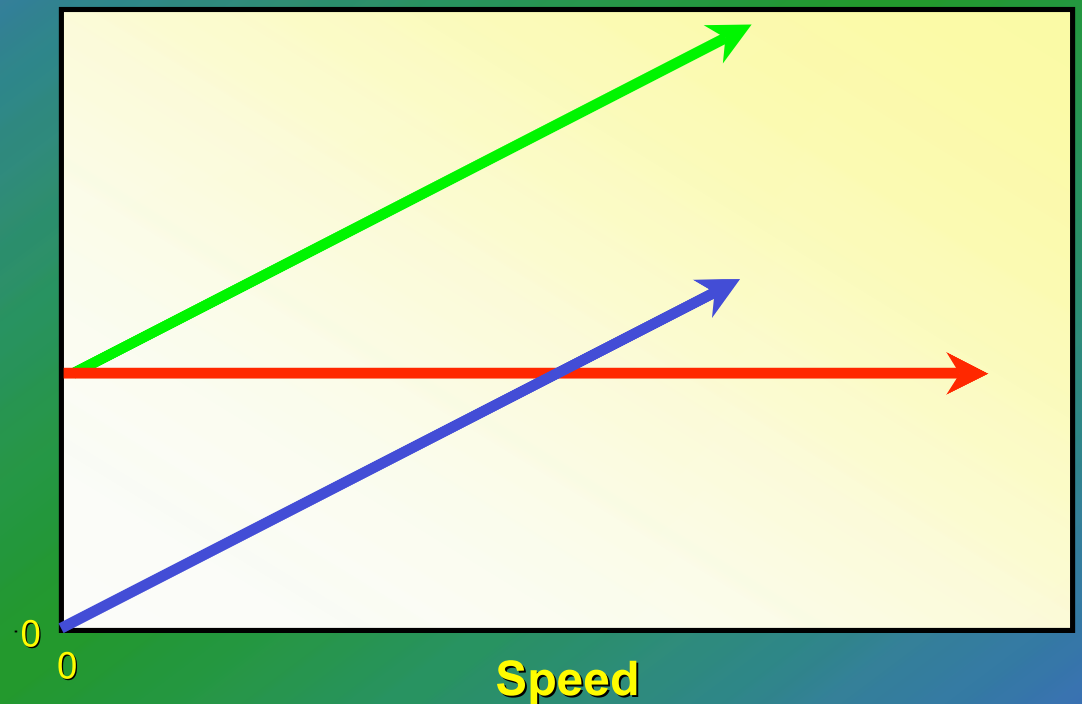
- Magnetic Bearings Load Capacity



- **Magnetic Bearing Load Capacity**
  - Independent of shaft speed
  - Controllable stiffness and damping
  - Susceptible to shock overloads
  - Requires back-up bearing

Bearing Characteristics Comparison – Mag & Foil

- Magnetic Bearings Load Capacity
- Foil Air Bearings Load Capacity
- Hybrid Foil/Mag Load Capacity



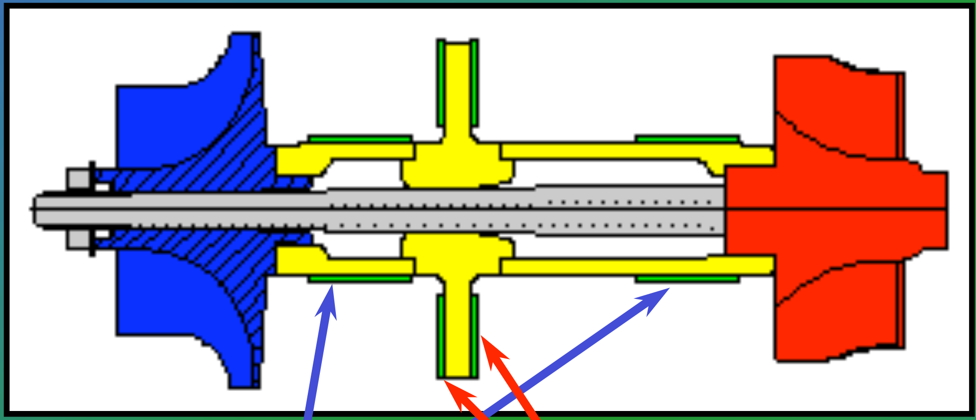
Magnetic Bearing Load Capacity

- Independent of shaft speed
- Controllable stiffness and damping
- Susceptible to shock overloads
- Requires back-up bearing

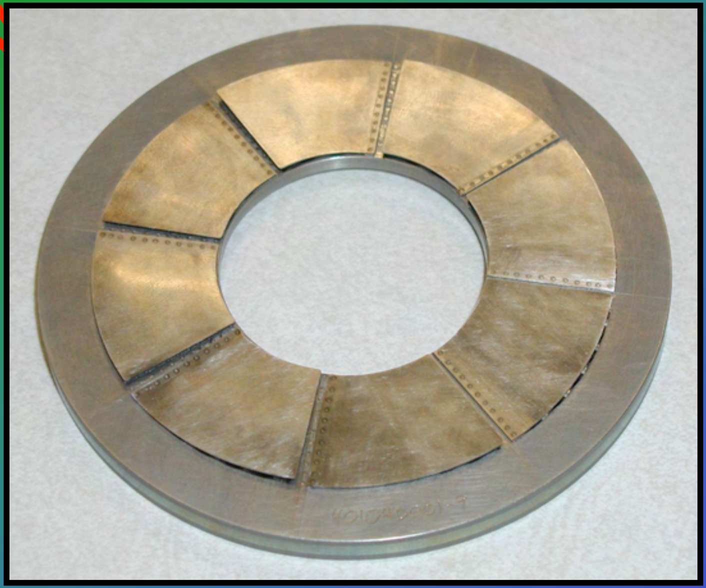
Foil Bearing Load Capacity

- Very low at low speeds
- Increases linearly with speed

Journal & Thrust Foil Bearings



Journal Foil Bearing



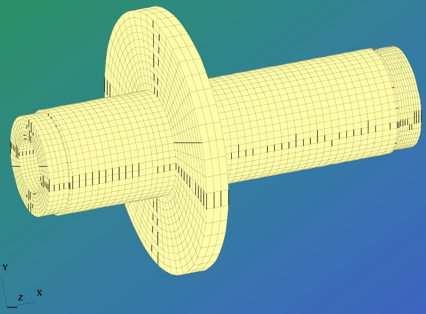
Thrust Foil Bearing

Enabling Technology Breakthroughs

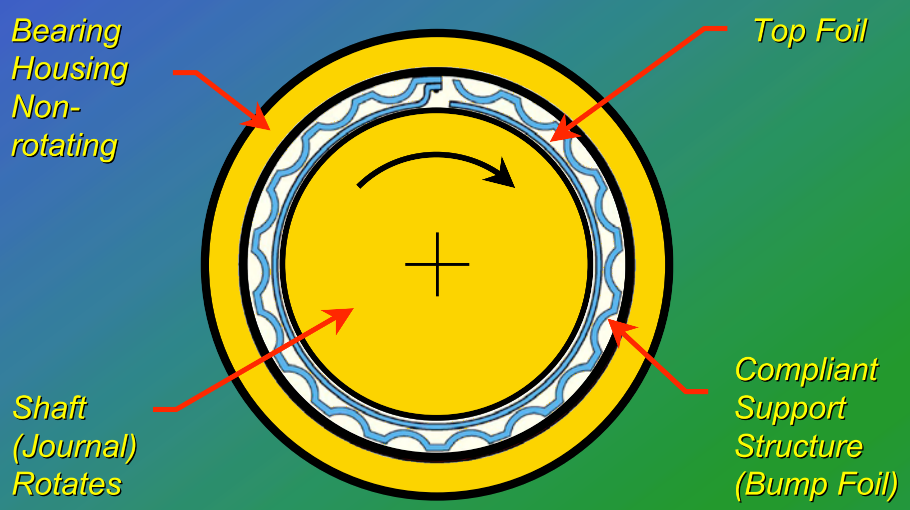
- Advanced Foil Bearings
  - Load capacity has doubled

- High-Temperature Solid Lubricant Coating
  - NASA PS304, 100,000 start/stops, 200 °F to 1200 °F

- Analytical & Rotordynamic Modeling
  - Less time, risk & cost from concept to application



Enabling Technology: Advanced Foil Bearings



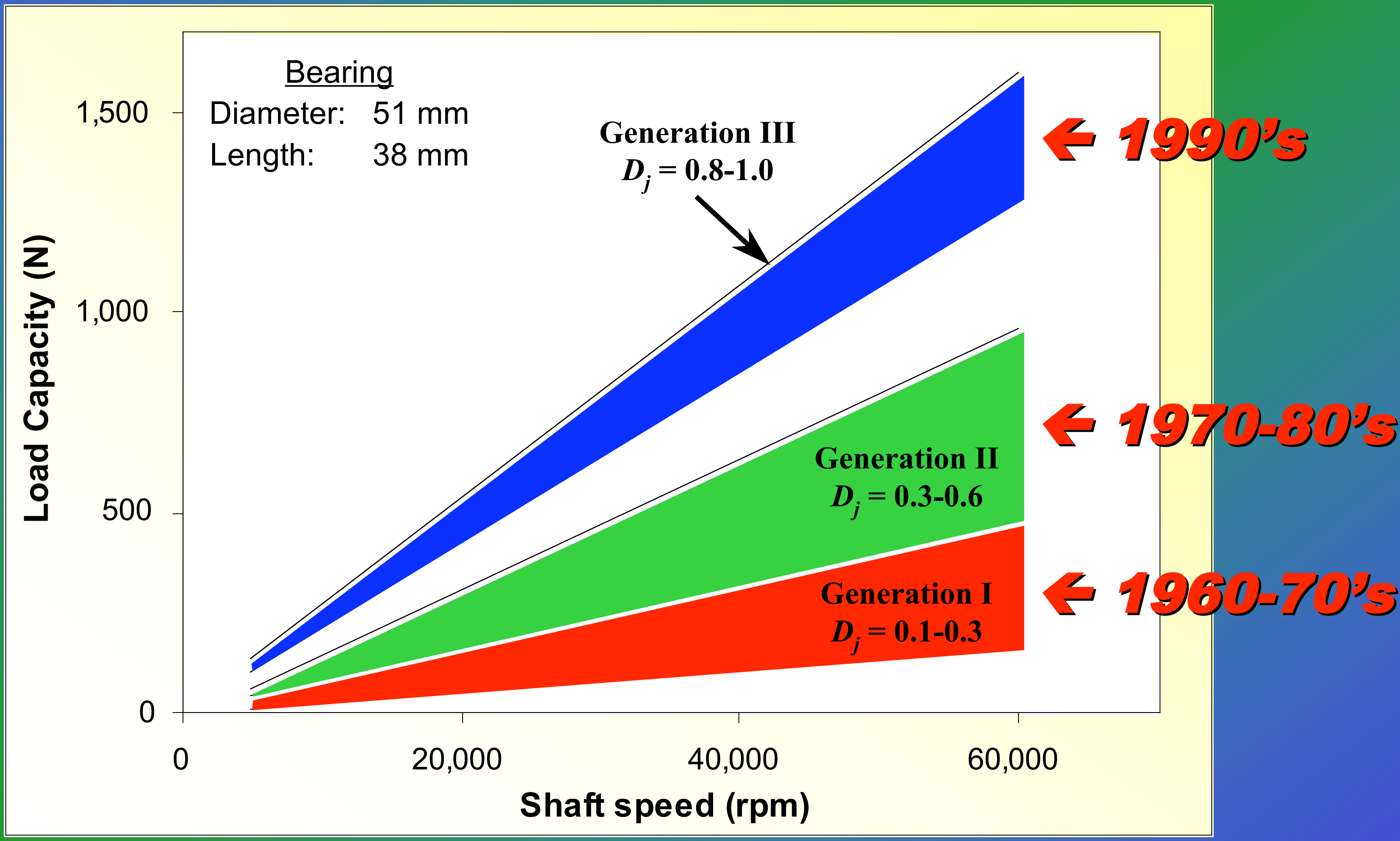
Recent design improvements have doubled load capacity, enabling application to a broad range of Oil-Free turbomachinery

Foil Bearing Benefits:

- ✓ Self-acting hydrodynamic "float on air" ➔ No external pressurization
- ✓ No DN speed limit ➔ Higher power density
- ✓ No lube/tanks/coolers/plumbing/filters ➔ Lower weight
- ✓ Operate to 1200°F ➔ Higher efficiency
- ✓ Compliant "spring" foil support ➔ Accommodate misalignment & distortion
- ✓ No maintenance ➔ Reduce operating costs

Oil-Free Turbomachinery Program

Foil Bearing Load Capacity – Generation I, II, & III



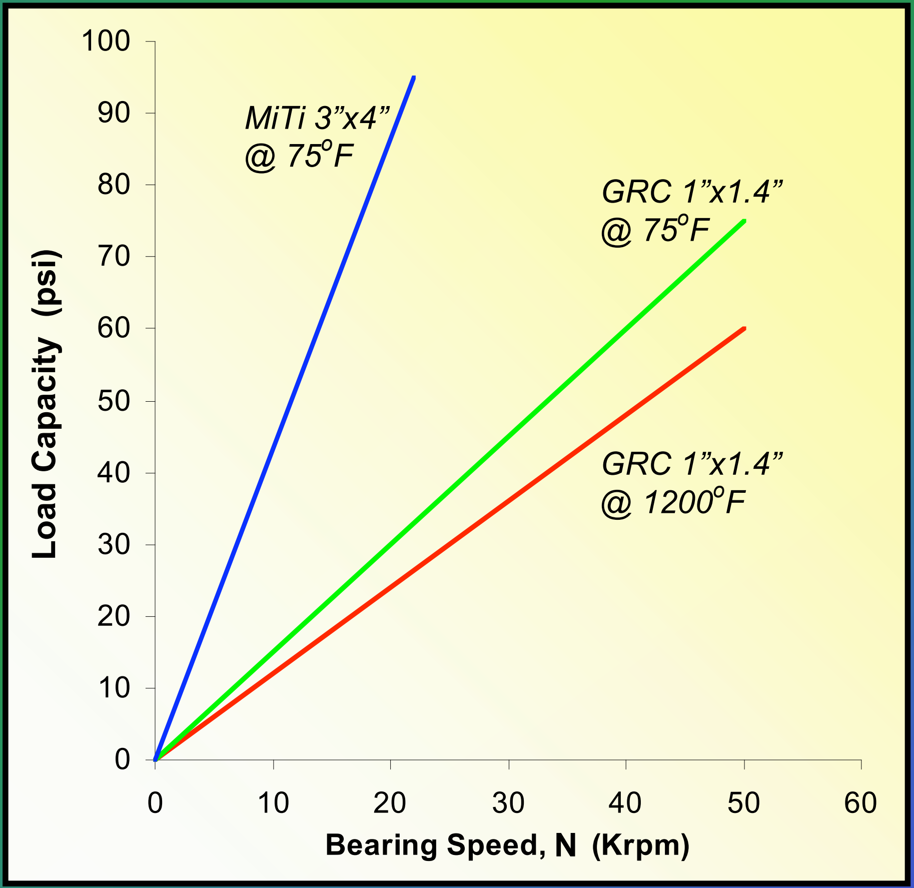
Load Capacity – Foil Air Bearings

Rule of Thumb

. . . a journal foil bearing will support about one pound
per square inch of projected area
per inch of bearing diameter
per thousand rpm

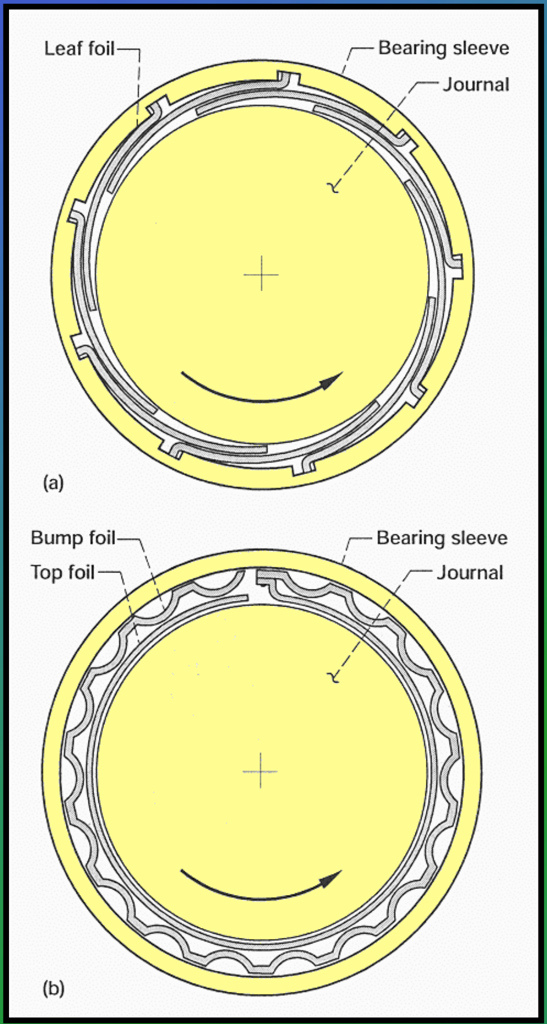
Load = D_j (L×D)×D×N

Data Source	L (in)	D (in)	N (Krpm)	D_j (lb*min/in^3)	Load (lb)
GRC	1.0	1.4	50	1.0	98
MiTi	3.0	4.0	22	1.1	1,140



Current state-of-art foil bearings can support turbine generators From ~10 to 500 kW with unlimited future growth potential.

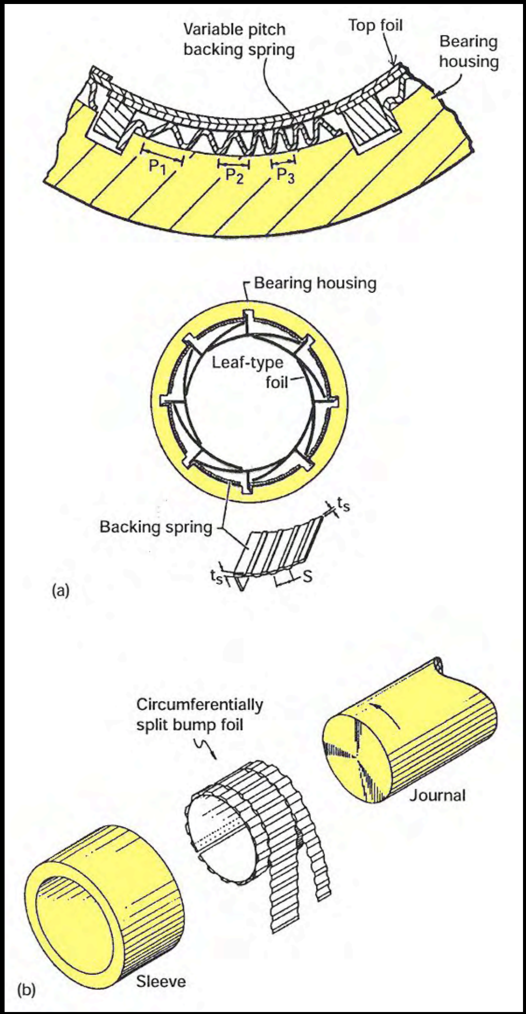
Generation I Foil Bearings *(1960's – 1970's)*



- Load capacity coefficient, D_j's, 0.1 - 0.3
- Foil geometry essentially uniform in both the axial and circumferential directions *(including uniformly periodic circumferential geometry)*
- Stiffness characteristics of the foil structure are more or less uniform
- Foil surface deforms due to the fluid film pressure without support structure specifically accounting for localized effects such as edge leakage, thermal gradients, heat generation and other hydrodynamic phenomena

Source: DellaCorte & Valco, "Load Capacity Estimation of Foil Air Journal Bearings for Oil-Free Turbomachinery Applications, NASA/TM-2000-209782, ARL-TR-2334, Oct 2000

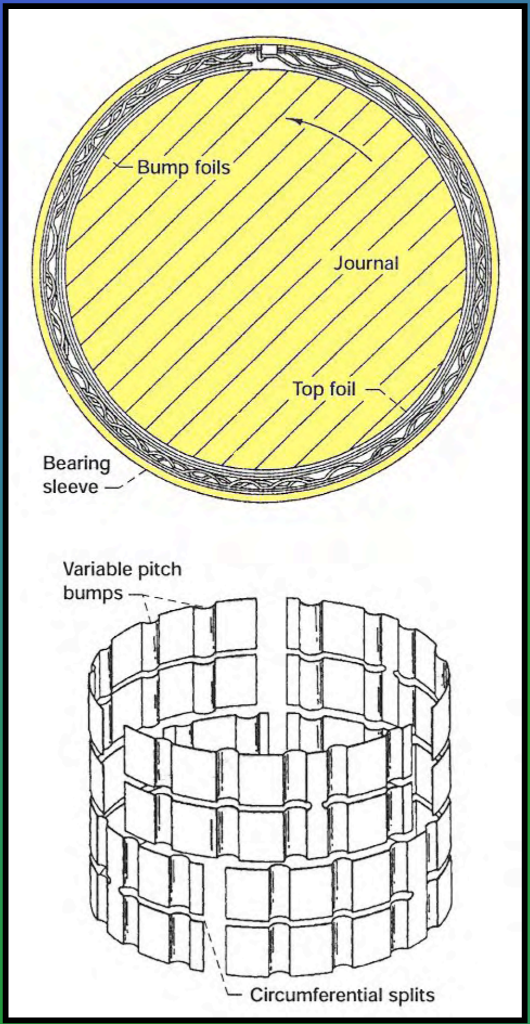
Generation II Foil Bearings *(1970's – 1980's)*



- **Load capacity coefficient, D_j's, 0.3 – 0.6**
- **Stiffness of the foil support structure varies axially along the bearing length or in the circumferential direction, but not both**
- **By controlling stiffness in one dimension** *(axial or circumferential)* **the bearing better accommodates phenomena like edge leakage and, hence, yields improved performance**
- **In leaf foil bearings, use of a "stepped" backing spring**
- **In bump type foil bearings, bump layers are split circumferentially for axial compliance control or the bump pitch is varied for circumferential compliance control**

Source: DellaCorte & Valco, "Load Capacity Estimation of Foil Air Journal Bearings for Oil-Free Turbomachinery Applications, NASA/TM-2000-209782, ARL-TR-2334, Oct 2000

Generation III Foil Bearings *(1990's)*

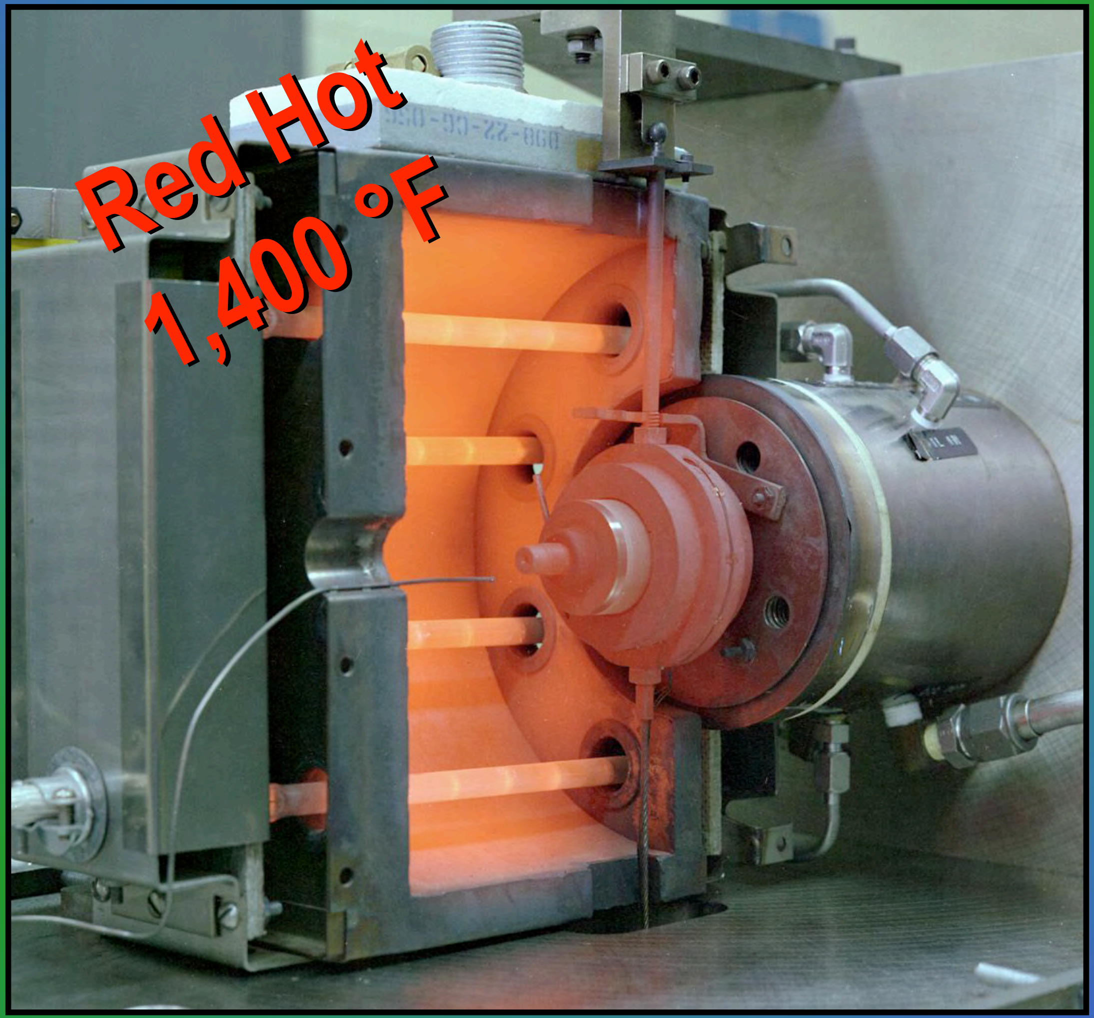


- **Load capacity coefficient, D_j's, 0.8 – 1.0**
- **Tailoring the foil support structure stiffness in**
  - **Axial** (L)
  - **Circumferential** (π)
  - **Radial** (r) *(i.e., displacement sensitive)*

  directions to enhance bearing performance

Source: DellaCorte & Valco, "Load Capacity Estimation of Foil Air Journal Bearings for Oil-Free Turbomachinery Applications, NASA/TM-2000-209782, ARL-TR-2334, Oct 2000

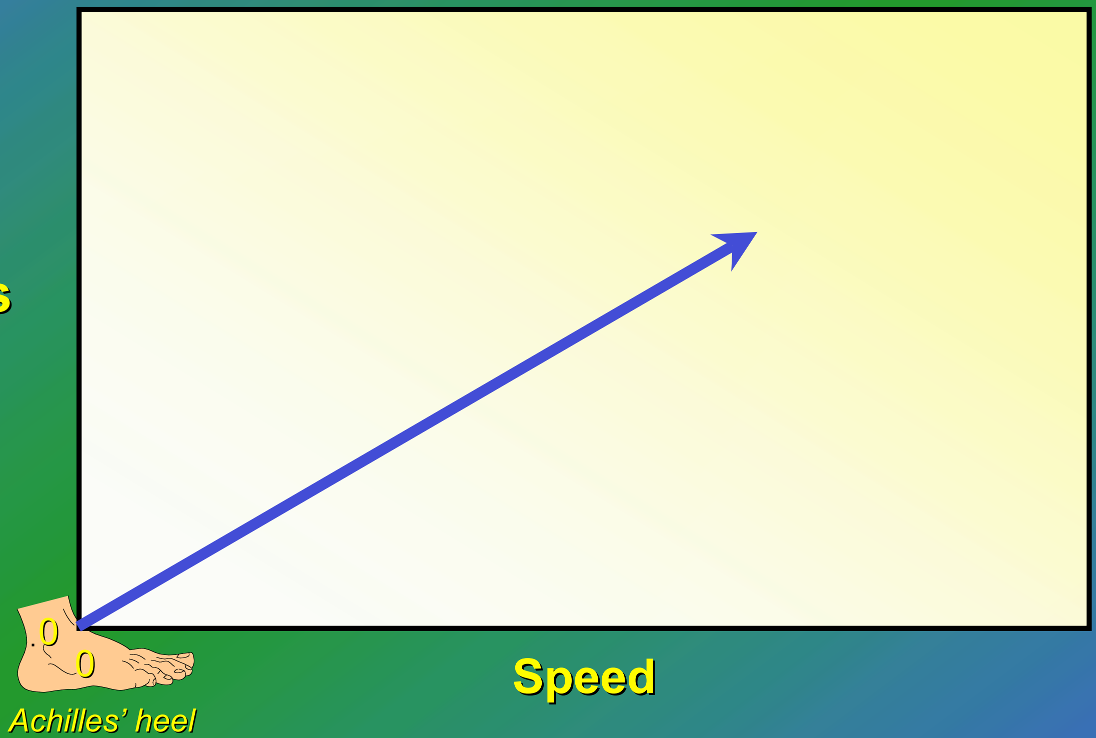
Glenn Research Center Foil Bearing Test Rig



(oven cover opened for photograph)

Bearing Characteristics -- Foil Air Bearings

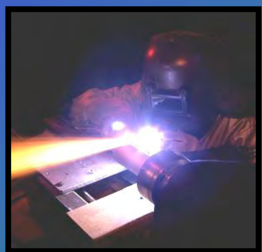
- Foil Air Bearings Load Capacity



Foil Bearings

- Load capacity very low at low speeds
- Load capacity increases linearly with speed
- Foil bearings have no practical speed limitations (DN)
- Require no external systems (pressurization)

Enabling Technology: High-Temperature Solid Lubricant Coating

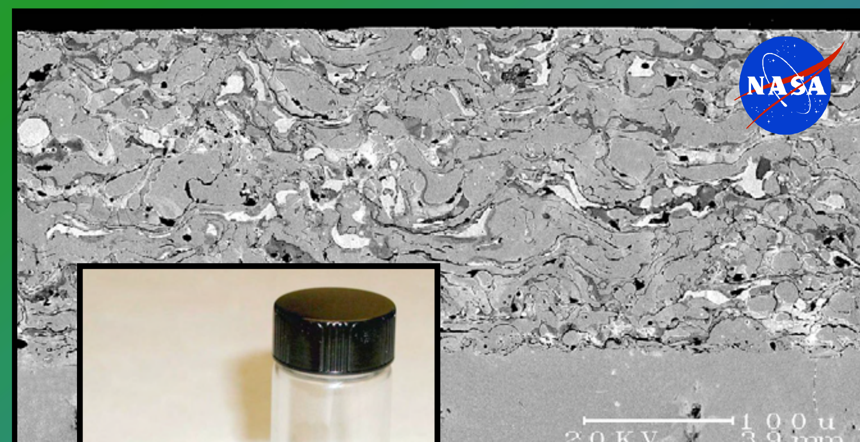


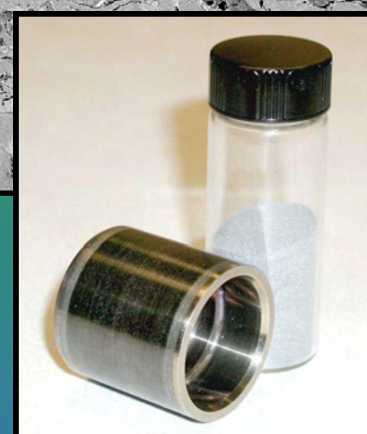
- Provide start/stop wear protection for foil bearings
- Operate from cold start to 850°C
- No vaporization or emissions

NASA PS304 *US Patent No. 5,866,518*

60% NiCr	Binder
20% Cr_2O_3	Hardener
10% BaF_2/CaF_2	Hi-Temp Lube
+ 10% Ag	Low-Temp Lube

= Wide temperature spectrum solid lubricant coating



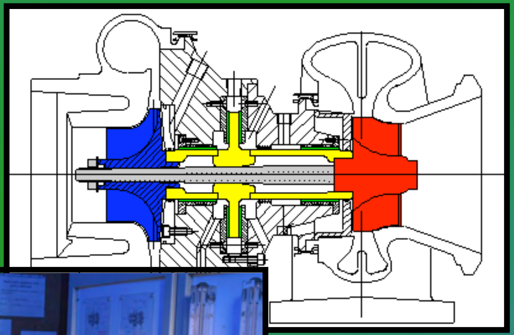


Technology Summary

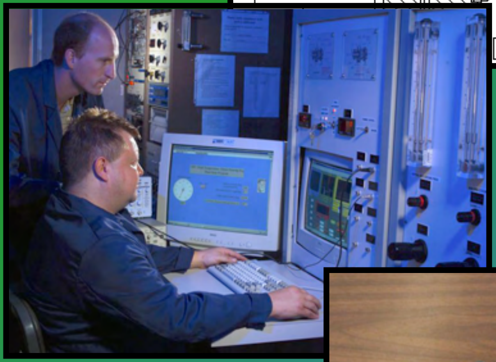
- Foil gas bearings in widespread use as rotor support in ambient air applications. Research needs to be extended to include alternate gases and pressures to successfully apply the technology in CBC turbines
- System level testing and validation are essential elements of a successful application of foil gas bearings for CBC turbines.
- Each new application requires a systematic approach to the deployment of rotor support to minimize risk and enhance the likelihood of success.

Oil-Free Technology Integration Approach

1) Rotor System Conceptual Design & Feasibility Study

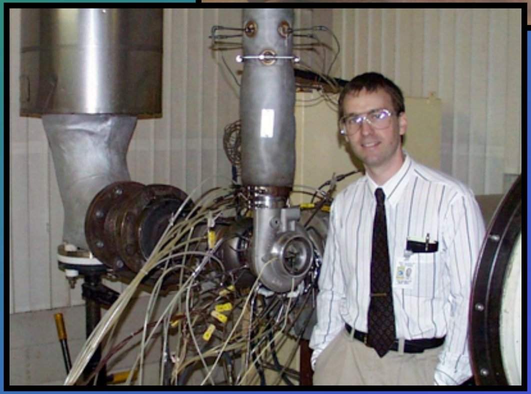


2) Bearing Integration & Testing

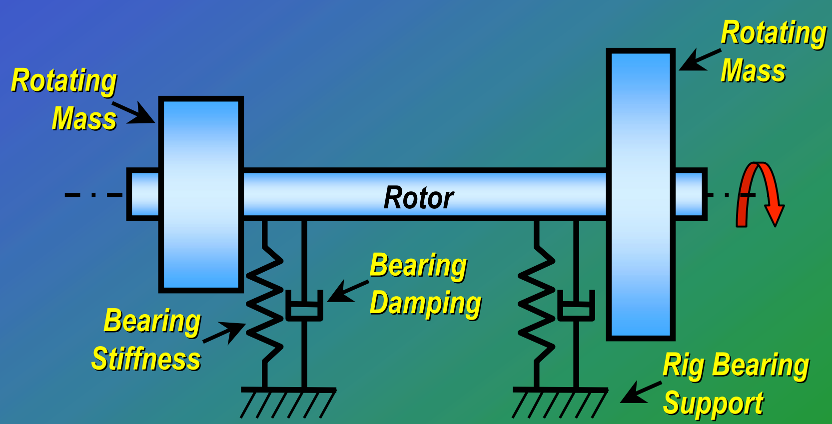


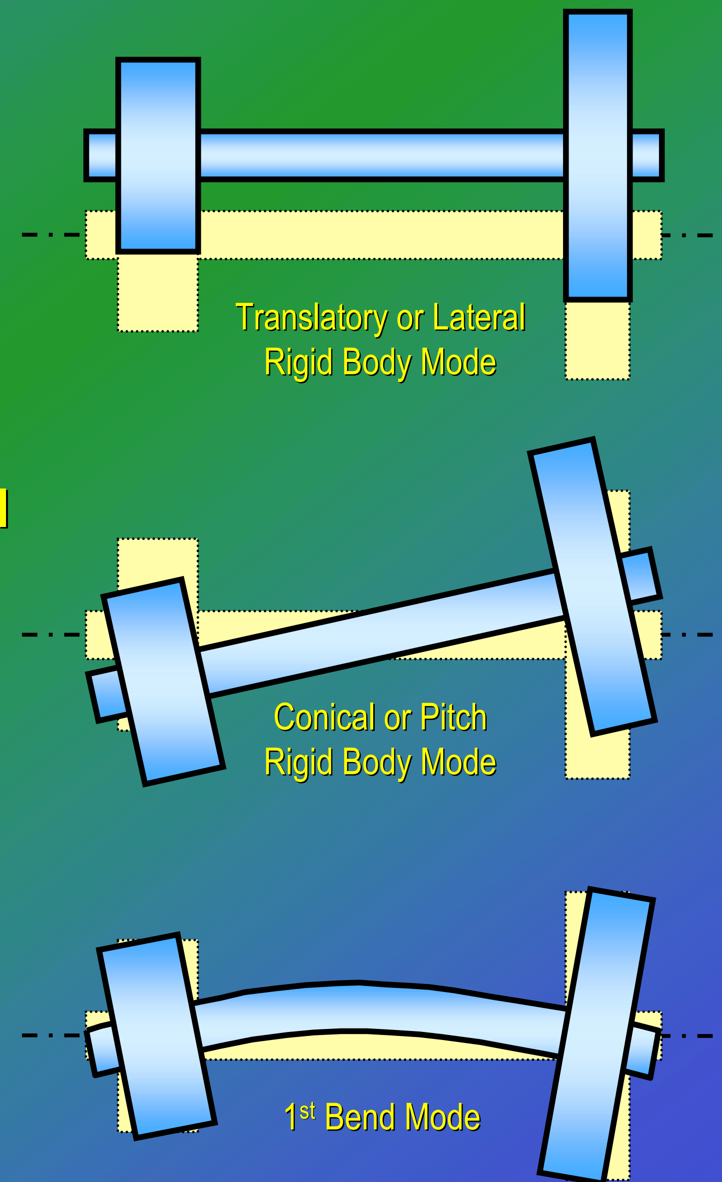
3) Rotordynamic System Simulation

4) Oil-Free Technology Demonstration



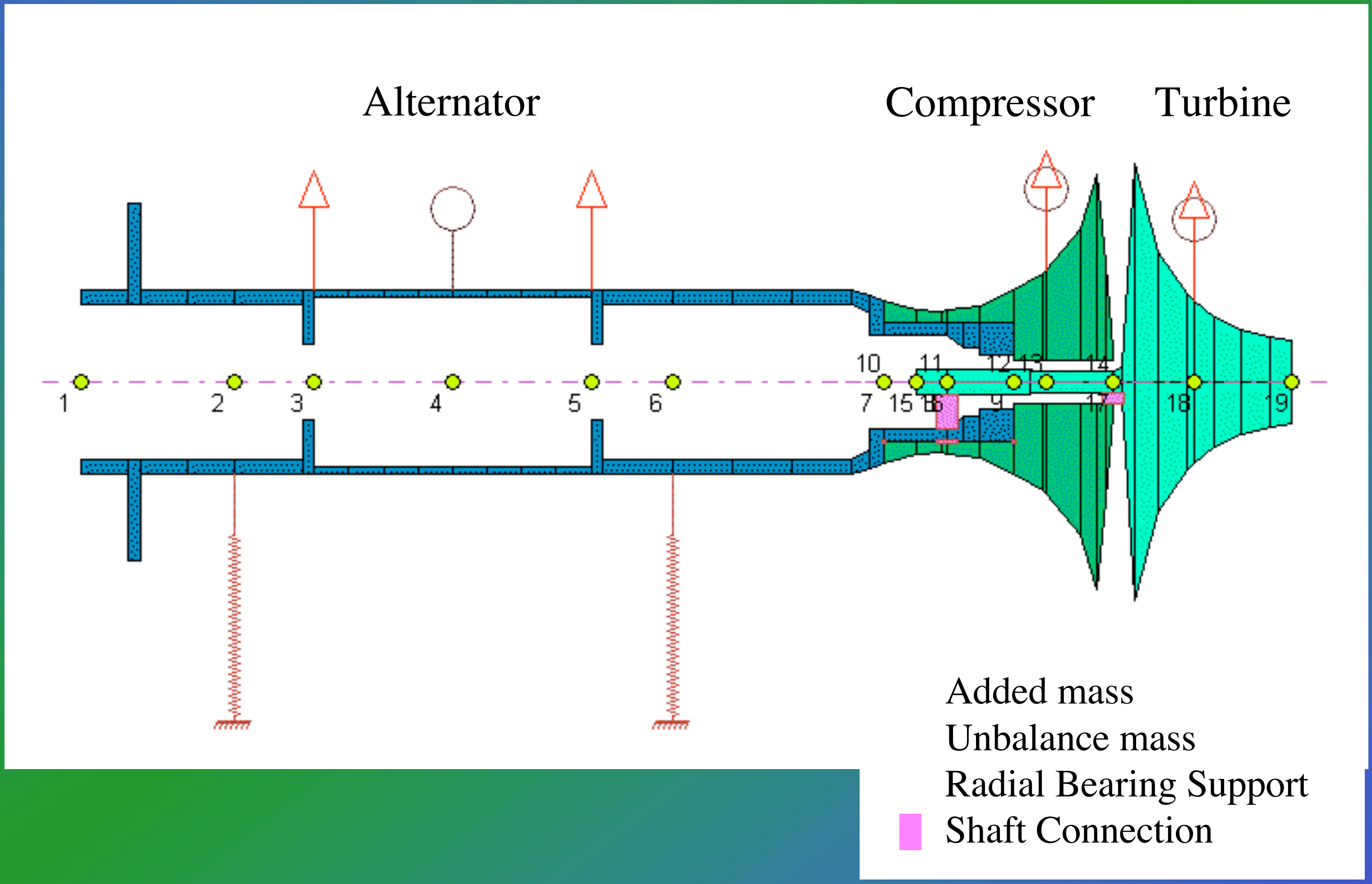
Rotordynamic Analysis





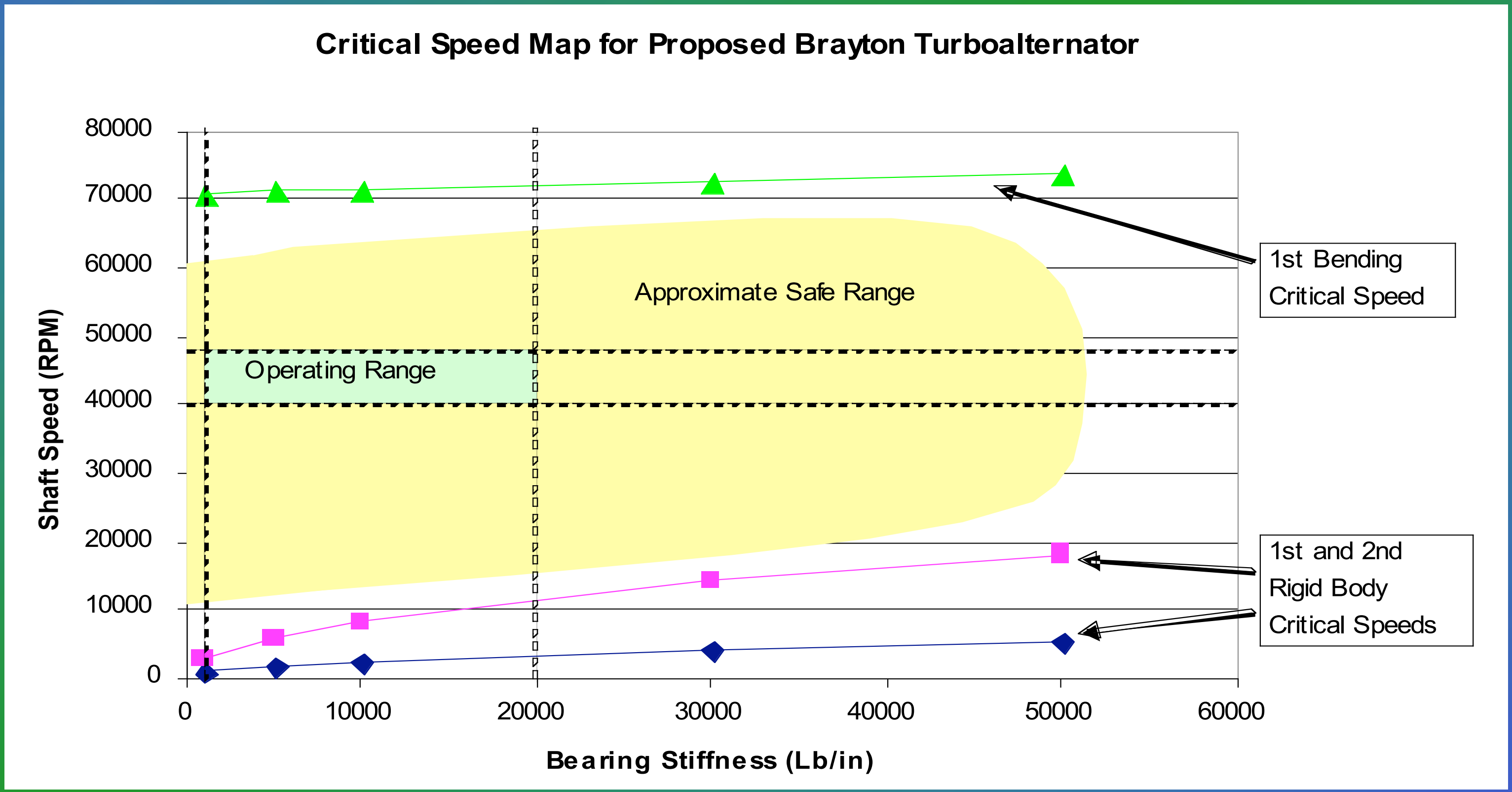
- **Rotor system critical speeds and natural frequencies** *(modes)* **are controlled by:**
  - **Shaft/disk masses and locations**
  - **Shaft geometry and material** *(stiffness)*
  - **Bearing stiffness** *(including rig structural stiffness)*
  - **Bearing damping**
  - **Operating speed**
- **Goal is to design a rotor system** *(shaft & bearings)* **that provides stable operation across the operating range**

Rotor Model

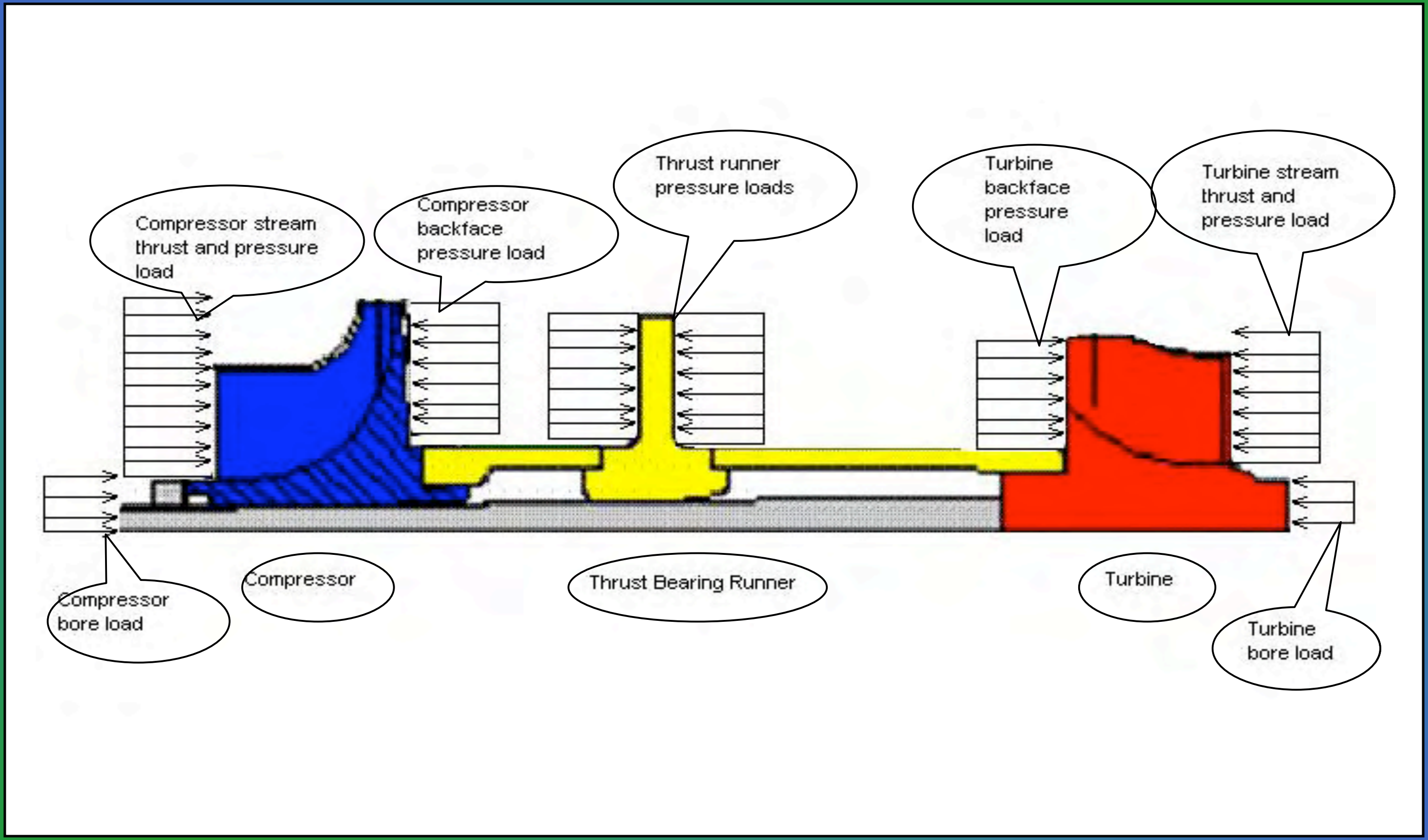

Alternator
Compressor
Turbine
Added mass
Unbalance mass
Radial Bearing Support
Shaft Connection

Analysis

– Critical Speeds (continued)



System Thrust Load Management

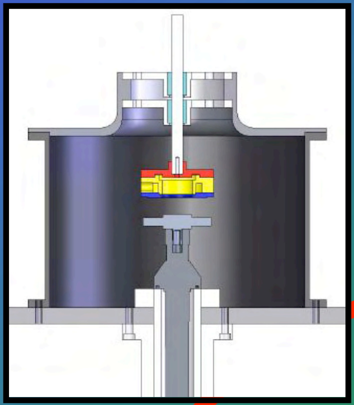


- Use algebraic sum of forces to monitor thrust bearing loads and ensure adequate load capacity margins

System Thrust Load Management

- Aerodynamic forces on various rotating components combine with gas pressures to create axial thrust loads on rotor
- Resulting thrust loads must be carried by foil thrust bearings
- Bearing load capacity must not be exceeded
- Thrust bearing loads result in frictional losses
- System is needed to estimate thrust loads and manage them

Key Facilities & Capabilities

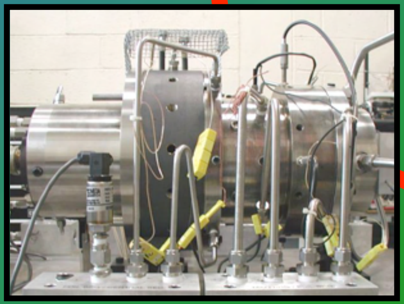


Vertical thrust bearing rig

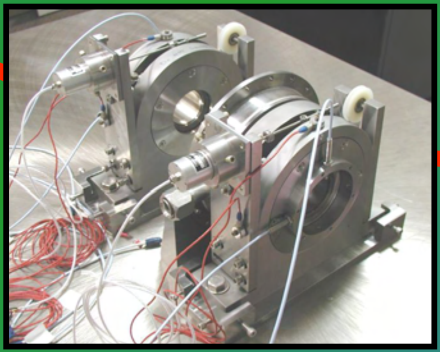
Coating deposition research facility

Hot high-speed journal foil bearing test rig

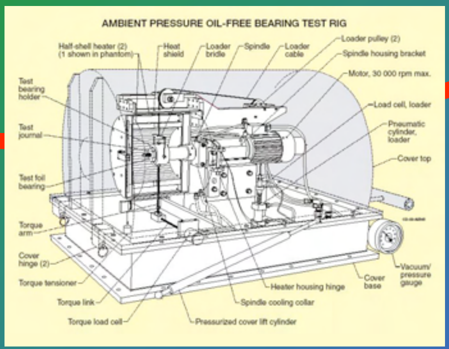
Capstone MicroTurbine proof-of-concept & environmental durability test facility



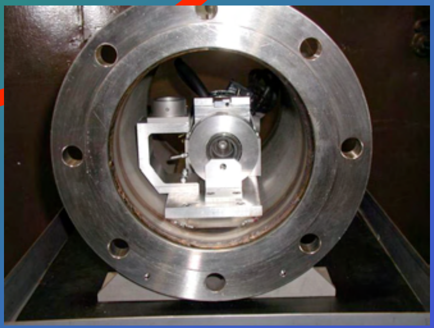
High-speed thrust foil bearing test rig



Shaft rotordynamic simulator test facility



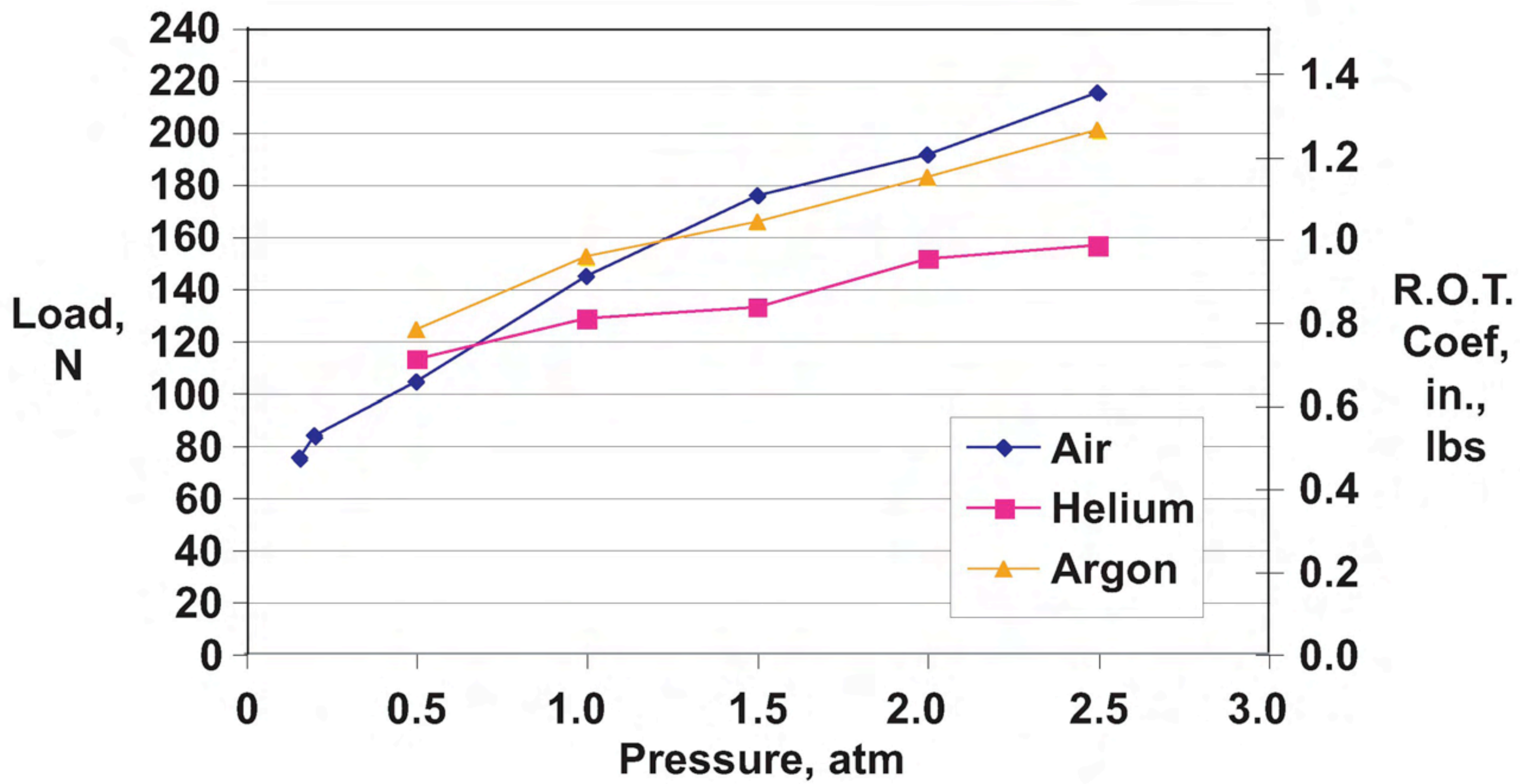
Ambient Pressure journal bearing test rig



High Pressure journal bearing test rig

Foil Bearing Load Capacity

35 mm dia. bearing, 18,000 rpm, 500 °C



- Load capacity increases with ambient pressure
- The exact effect of gas properties is not yet fully understood

Foil Bearing Operating Map

(Physical Limits to operating space)

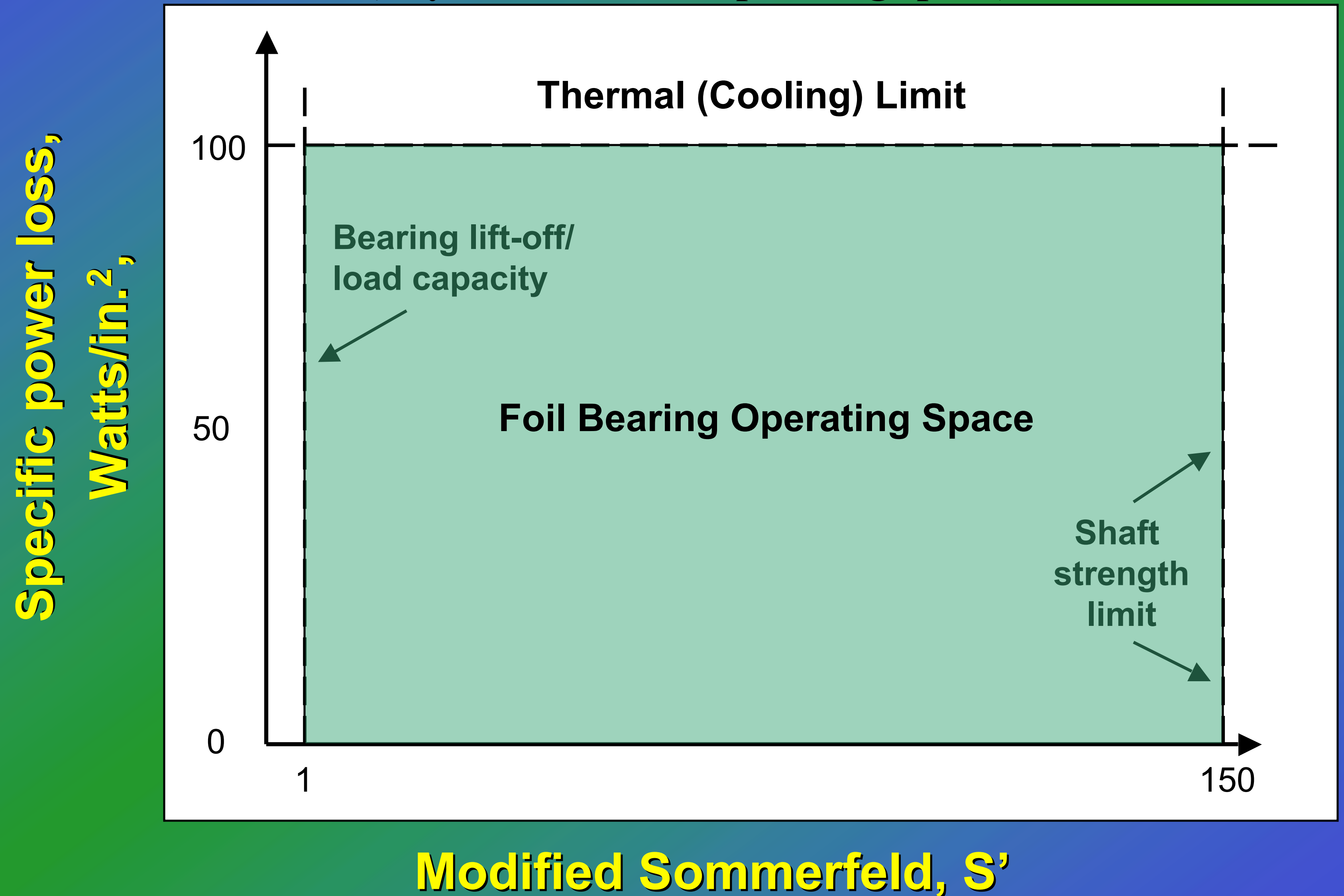
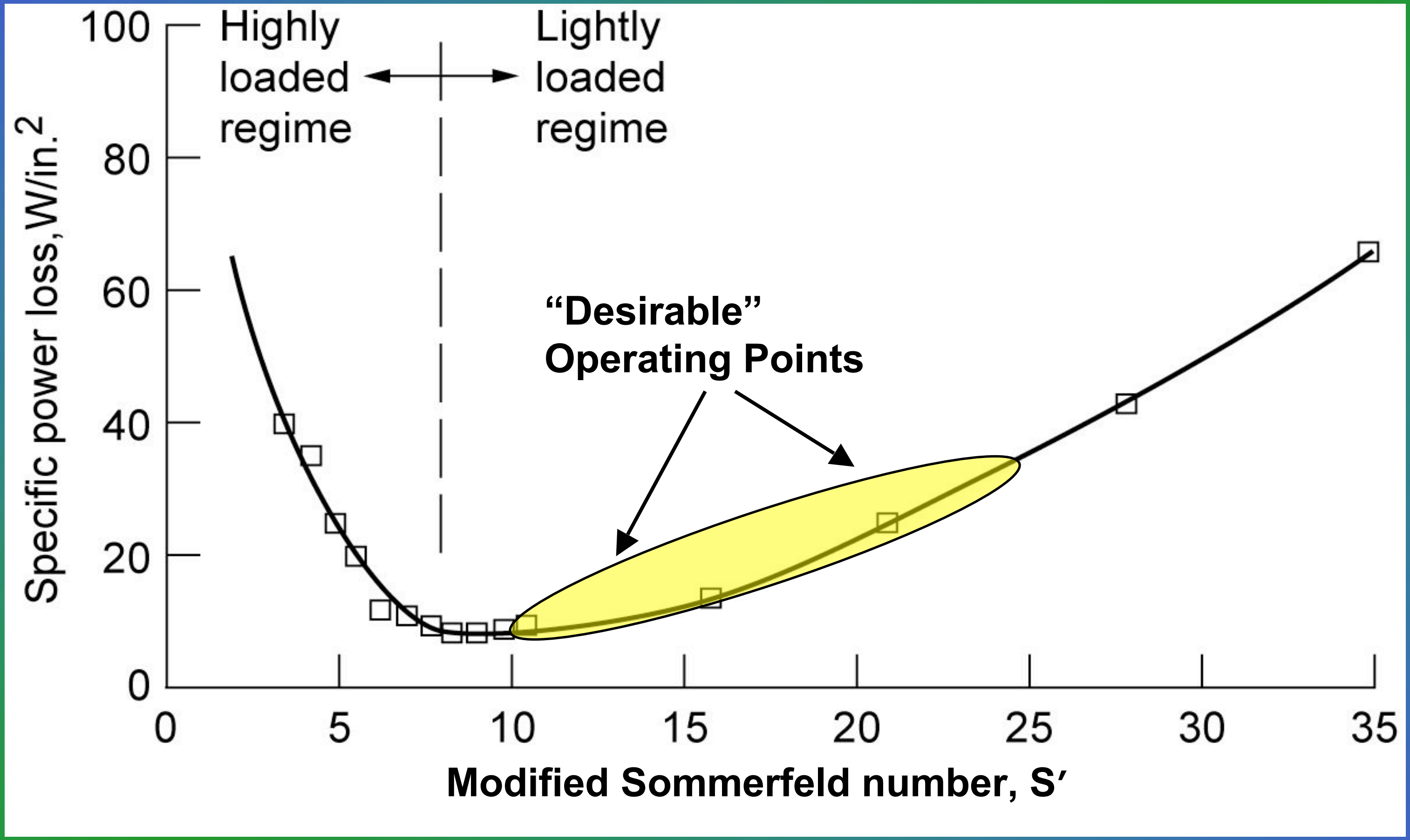


Fig 3

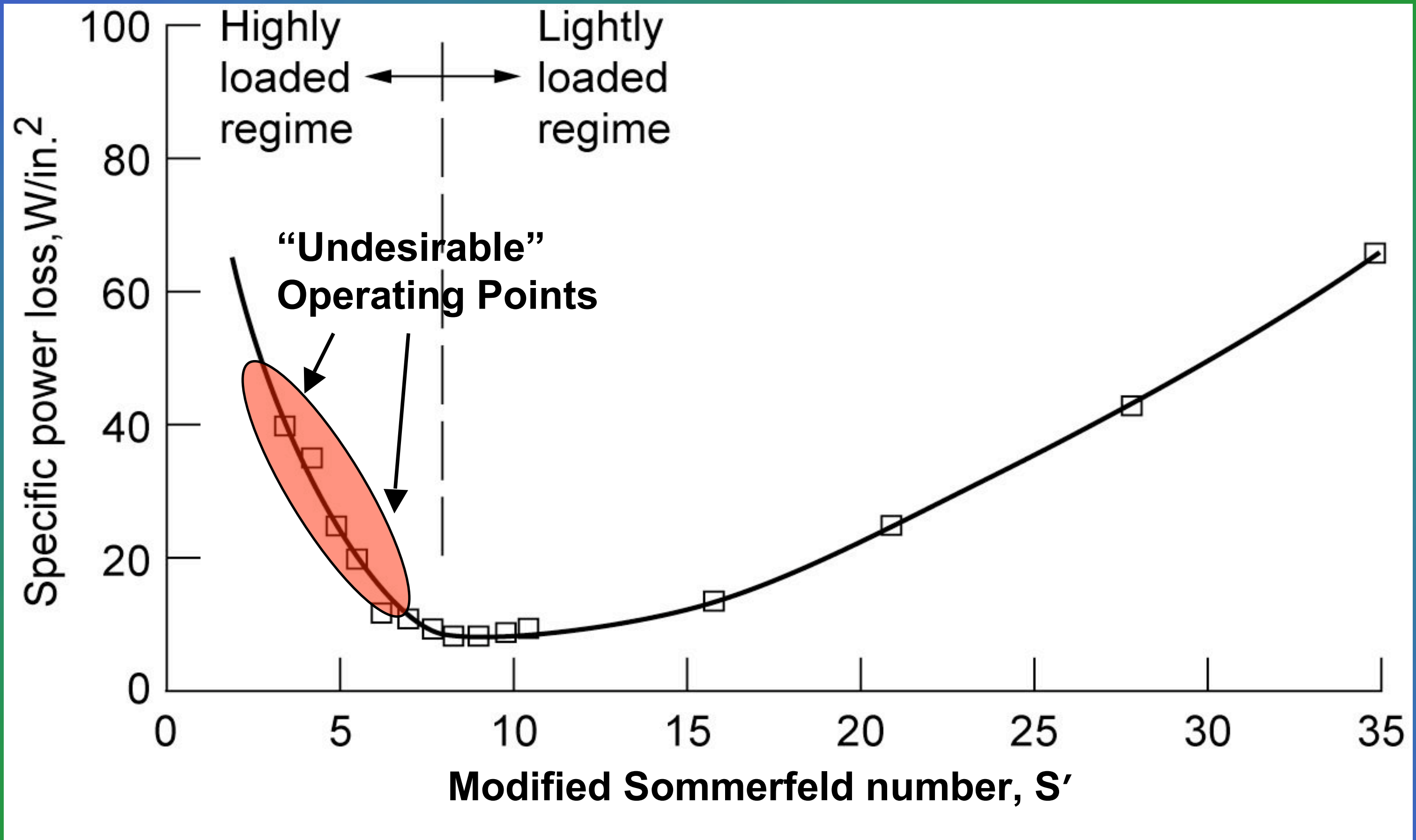
Power Loss versus S'
(Generalized Implications)



Speed increases result in moderate power loss increases
Speed decreases reduce power loss until regime shifts (margin)
Load increases increase power loss slightly (shifts onto a different S' curve)

Power Loss versus S’

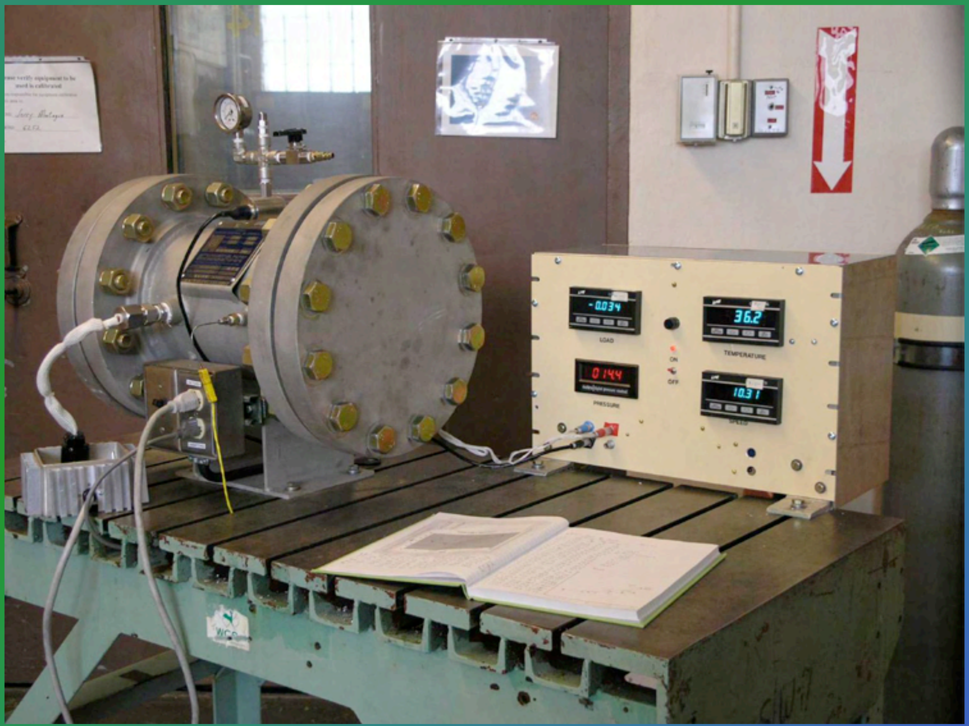
(Generalized Implications)



- Speed decreases result in rapid power loss increases
- Increased power loss increases thermal expansion of shaft into bearing
- Thermal runaway and seizure are likely

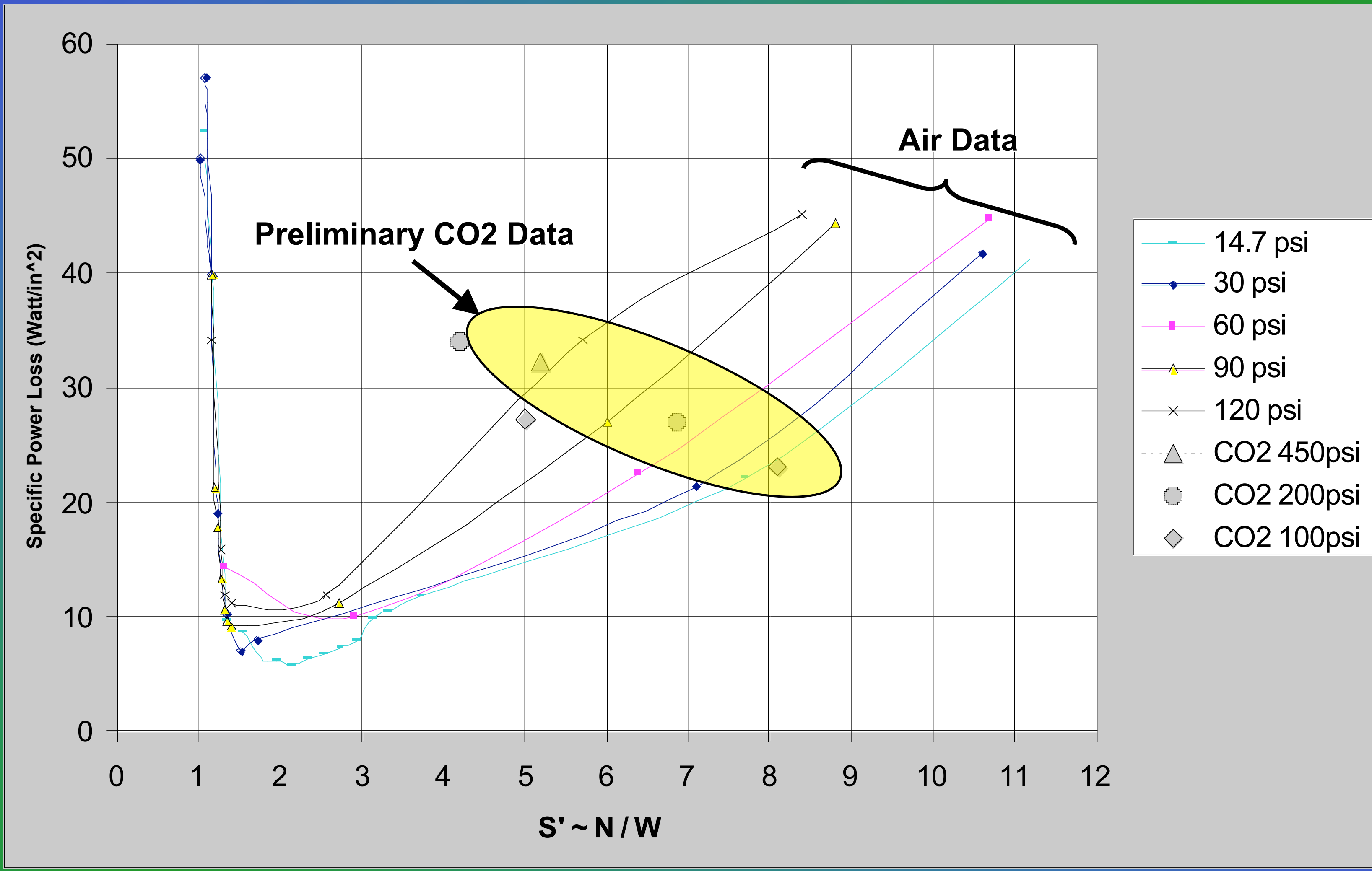
700 PSI Bearing Rig

- 700 psig max. pressure
- ~25 C temperature
- Speeds to 25 krpm (currently)
- Bearing size ~1.4 in.



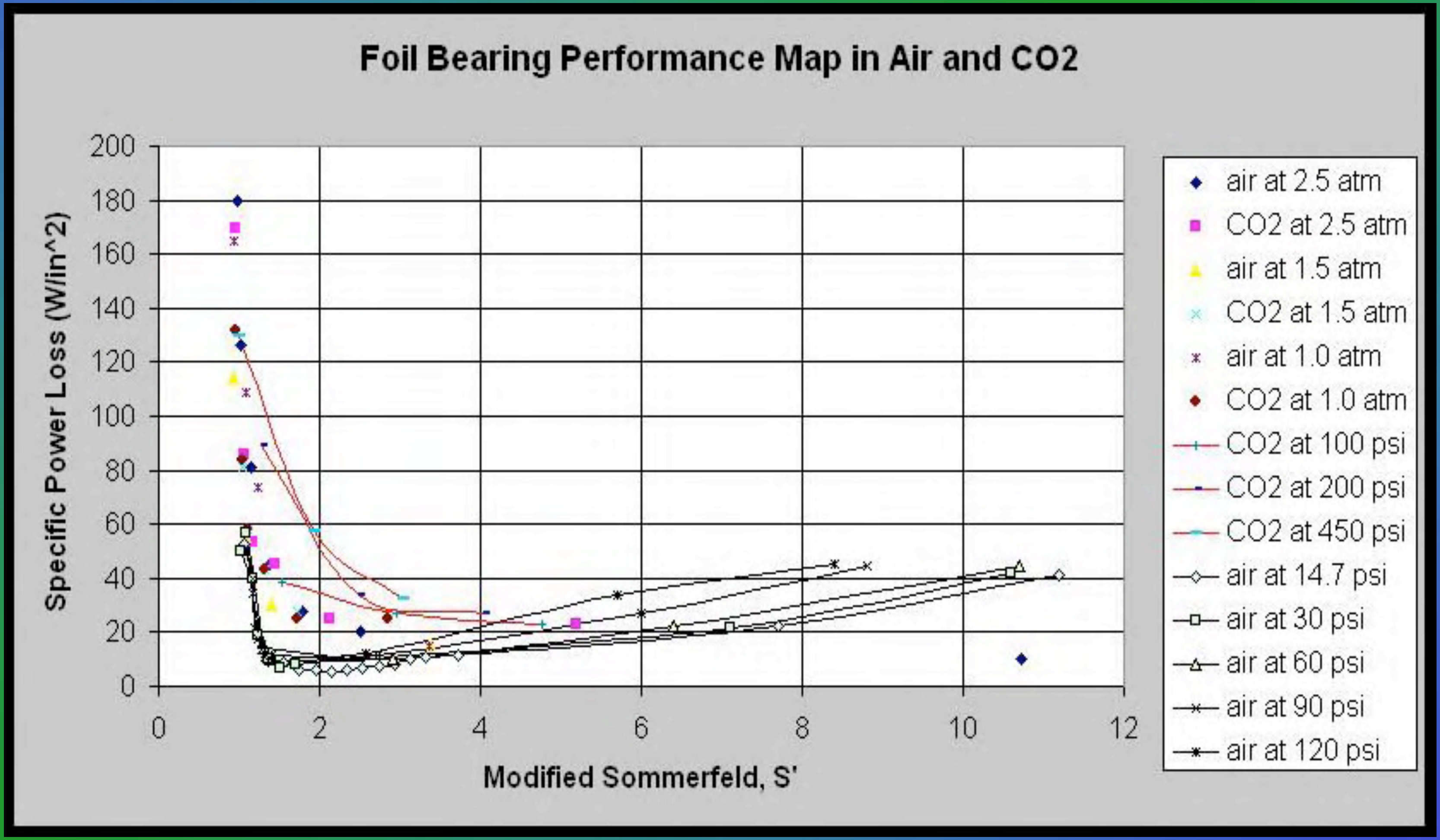
- Provides valuable data to validate models
- Serves as proof-of-concept for future rigs

Preliminary CO_2 Power Loss Behavior



CO_2 power loss similar to air behavior

Preliminary Foil Bearing Performance Data in Air and CO2 at Elevated Pressures



High Pressure Foil Bearing Performance

- Experimental data shows that performance of current state of the art foil bearings in CO_2 and at elevated pressures can be predicted by the foil bearing performance map in the ideal gas range.
- Performance of foil bearings in liquids and supercritical fluid states is not well understood. Experimental and analytic research is necessary to obtain this knowledge.
- Further experimental research is underway to quantify both the extent of high pressure effects in the high speed (S') region and enhanced load capacity.

Summary Remarks

- All turbomachinery systems rely first upon a rotor support system which supports static and dynamic loads and provides a stable foundation.
- The "right" technology for supporting CBC rotors depends upon many factors include size, speed and other constraints.
- Gas foil bearings represent one potentially viable approach to rotor support for advanced CBC system.
- Existing foil bearing models offer guidance for foil bearing integration but need to be extended and validated for new fluids like SCO2.
- We welcome the opportunity to assist in the deployment of these and other Oil-Free CBC turbine systems.

Oil-Free Turbomachinery Program

...Starting a Turbomachinery Revolution...

OIL-FREE TURBOMACHINERY PROGRAM

Propulsion for the 21st Century

NASA Glenn Research Center

www.grc.nasa.gov/WWW/Oilfree