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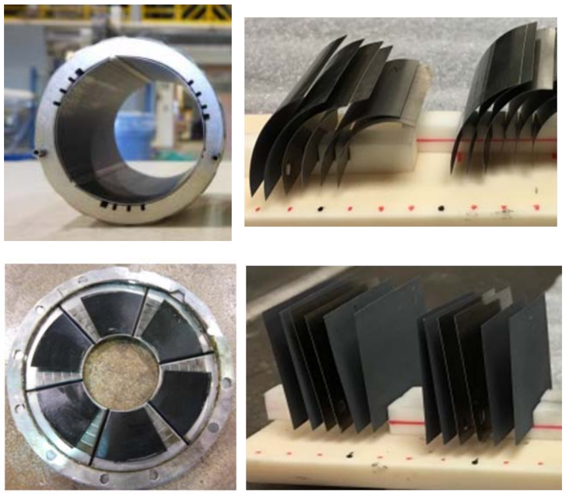

Gas Foil Bearing Coating Behavior in Environments Relevant to sCO2 Power System Turbomachinery

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Energy Innovation [1]; Advanced Nuclear Concepts[2]
Sandia National Laboratories

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6th International Supercritical CO_2 Power Cycles Symposium
Pittsburgh, PA
March 28th 2018

U.S. DEPARTMENT OF ENERGY NNSA

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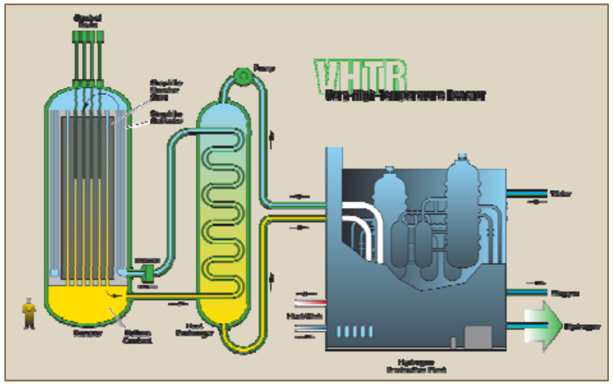
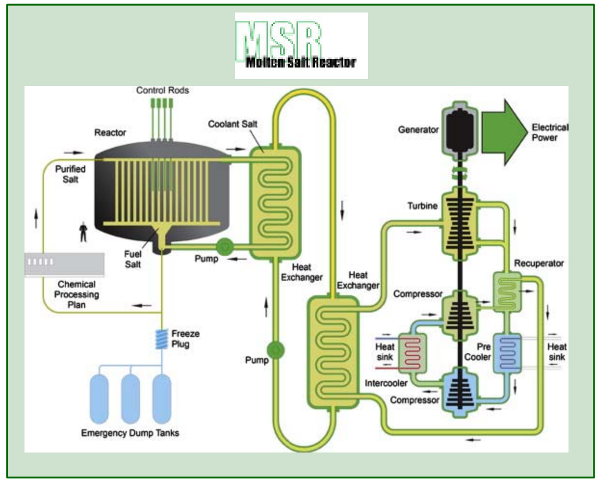
Advanced nuclear reactor concepts aim for advances over existing LWRs

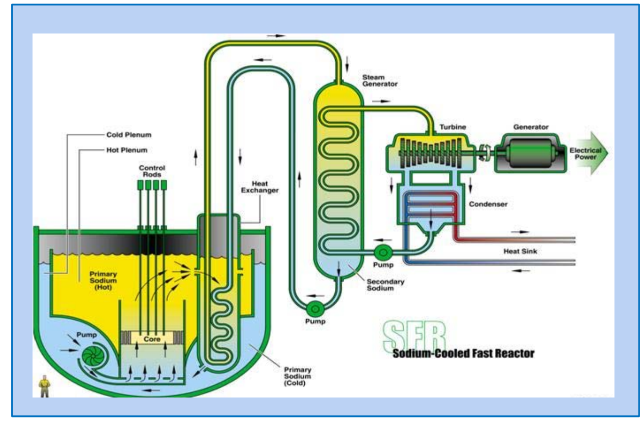
DOE Advanced Nuclear Reactor Program



Program Lead: INL



Program Lead: ORNL



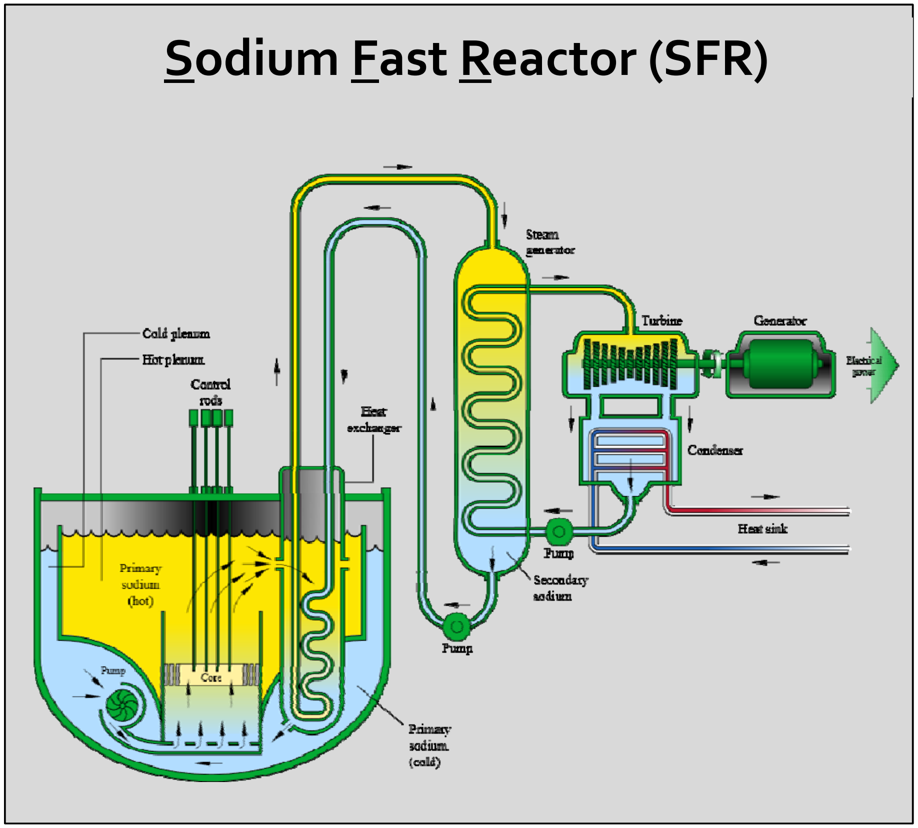
Program Lead: ANL

Advanced reactors are intended to provide advancements in the following areas:

- Sustainability
- Safety
- Reliability
- Economics
- Non-proliferation

Considering energy conversion systems for Sodium Fast Reactors

Sodium Fast Reactor Concept



Characteristics:

- Sodium coolant
- 550°C outlet temperature
- High thermal efficiency

Fast reactor concepts are important for meeting sustainability goals

- Efficient resource (fissile material) utilization and generation
- Waste minimization (consumption of LWR actinides)

Research program established to develop and integrate a Supercritical CO_2 Energy Conversion System in place of the Conventional Steam Rankine System

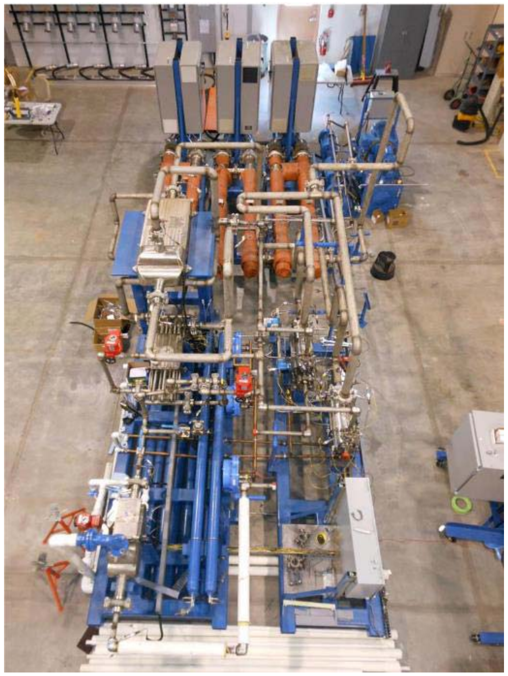
- Sandia is teaming with Argonne to develop this system

Distinct challenges exist with materials for sCO_2 EC Systems

Focus Areas for sCO_2 Materials Development

- Two areas identified where materials contributions are critical to the successful development of this technology :

Sandia National Laboratory
250 kW sCO2 RCBC

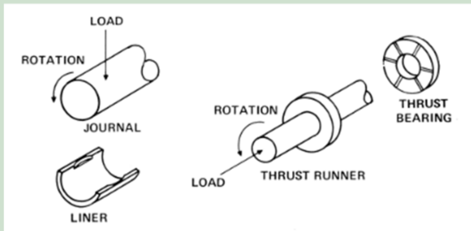


1. **Alloy Selection for sCO_2 EC Systems**
   - T<550°C: SFR
   - T>550°C: HTGR and MSR

2. **Materials Support for sCO_2 System Development**
   - Turbine Degradation
   - Bearing Foil Materials (coatings)
   - Systems for In-situ Measurement of Materials Corrosion
   - sCO_2/Polymer Interactions

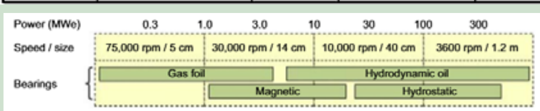
Overview of Gas Foil Bearings for sCO_2 Systems

Radial Bearing **Axial (Thrust) Bearing**

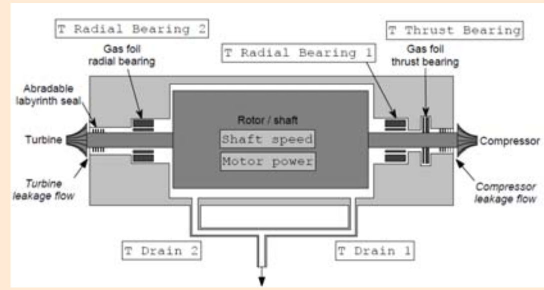


J. McHugh, Proceedings of the 8th Turbomachinery Symposium, Texas A&M Univ., 1979

	Rolling element	Sliding element	Fluid film	Magnetic
Working medium	Gas/oil	Working fluid	Gas/oil	Working fluid
Shaft support	Rolling contact/ hydrodynamic lift	Sliding contact	Hydrodynamic/ Hydrostatic lift	Electromagnetic fields
Stiffness	High	Low	High	Medium
Damping	Low	Low	High	High
Load capacity	Medium	Low	High	Medium
Control	Passive	Passive	Passive	Active
Contacting	At low speed and excursions	Always	At low speed	Never
Cost	Low	Low	Medium	High
Drag torque	Low	Medium	Low-medium	Very low



K. Brun et al., Fundamentals and Applications of SCO2 Based Power Cycles, 2017



Radial (Journal) Bearings

Axial (Thrust) Bearings

Turbine Conditions: 550°C / 300 psi CO2

Compressor Conditions: 315°C / 300 psi CO2

New Bearing Coating Materials are Needed

Motivation

- Bearing coating materials play a very important role in their performance
- Very little is know about the behavior of coating materials in the relevant CO_2 environments (particularly chemical compatibility)
- Available short duration performance data indicates:
  - Poor coating performance for Thrust Bearing
  - Good coating performance for Journal Bearing (material unknown and no longer available)

***Goal:* Evaluate new coating materials for more advanced future bearing rig tests, including cyclical start-stop testing to get at tribological properties**

Evaluating Bearing Coating Materials

Experimental Approach

Bearing Coatings Identified

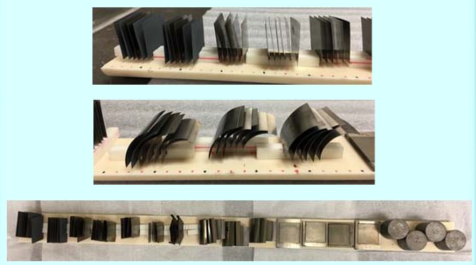
Xdot Engineering and Analysis

Mechanical Solutions, Inc. Engineering Analysis, Test & Technology

Coated Samples Prepared

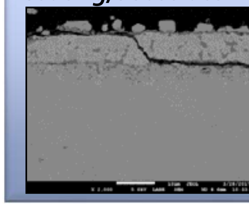
Multiple formats for thrust, journal, shaft

Long Duration CO_2 Exposure Tests



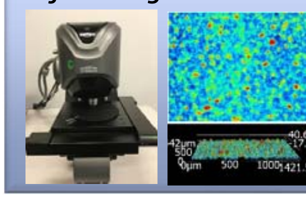
- Two experiments: 550°C and 315°C
- 500 hours exposure
- 300 psi CO_2
- 4 samples of each coating / format

Coating/Substrate Microstructure



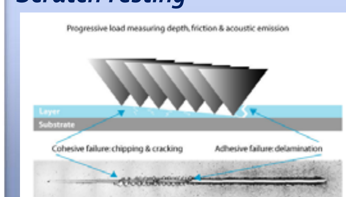
- SEM / EDS
- Pre vs. Post
- 1 Sample

Surface Roughness



- Laser microscope
- Pre vs. Post
- 2 Samples
- 3 areas / sample

Scratch Testing



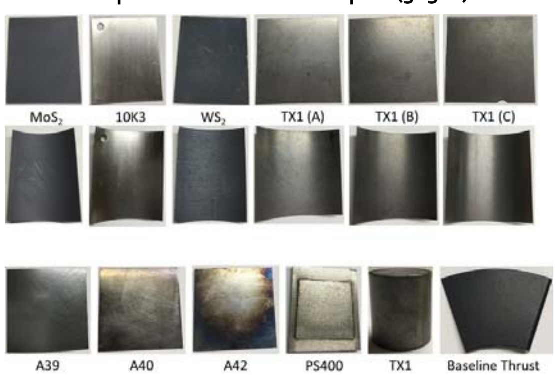
- Cohesive Failure
- Adhesive Failure
- Pre vs. Post
- 1 Sample
- 3 areas / sample

Overview of Coated Foil Samples

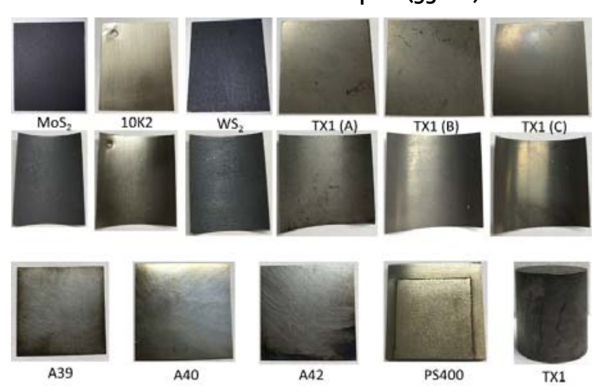
Coating Test Matrix

Sample Name	Bearing Vendor	Coating Vendor	Coating Name	Coating Mtl	Coating Thickness (microns)	Substrate Alloy	Turbine, Compressor, Both
MoS_2	Xdot	Everlube	Perma-slik RMAC	MoS_2	10-16	X750 Inconel	Both
WS_2	Xdot	Everlube	Perma-slik RWAC	WS_2	30	X750 Inconel	Both
10K2	Xdot	General Magnaplate	Nedox 10K2	Ni-P and Si-O	7-8	X750 Inconel	Turbine
10K3	Xdot	General Magnaplate	Nedox 10K3	Ni-P and Si-O	13-23	X750 Inconel	Compressor
TC A	Xdot	TurboCAM	TX1 (Treatment A)	Nitride Surface Treatment	n/a	316 ss	Both
TC B	Xdot	TurboCAM	TX1 (Treatment B)	Nitride Surface Treatment	n/a	316 ss	Both
TC C	Xdot	TurboCAM	TX1 (Treatment C)	Nitride Surface Treatment	n/a	316 ss	Both
PS400	Xdot	Hohman Plating (NASA)	PS400	NiMoAl, Cr-oxide, Ag, Ba-Ca fluorides	380-500	15-5 ss	Both
A39	Mechanical Solutions	Mechanical Solutions	A39	n/a	1.50	X750 Inconel	Both
A40	Mechanical Solutions	Mechanical Solutions	A40	n/a	1.50	X750 Inconel	Both
A42	Mechanical Solutions	Mechanical Solutions	A42	n/a	1.50	X750 Inconel	Both
Baseline-Thrust	SNL	Barber-Nichols Inc.	Unknown	Teflon	20-22	X750 Inconel	Compressor
Baseline-Journal (LT)	SNL	Capstone Turbines	Unknown	Teflon	n/a	X750 Inconel	Compressor
Baseline-Journal (HT)	SNL	Capstone Turbines	Unknown	Unknown	n/a	X750 Inconel	Turbine

Compressor-Side Test Samples (315°C)



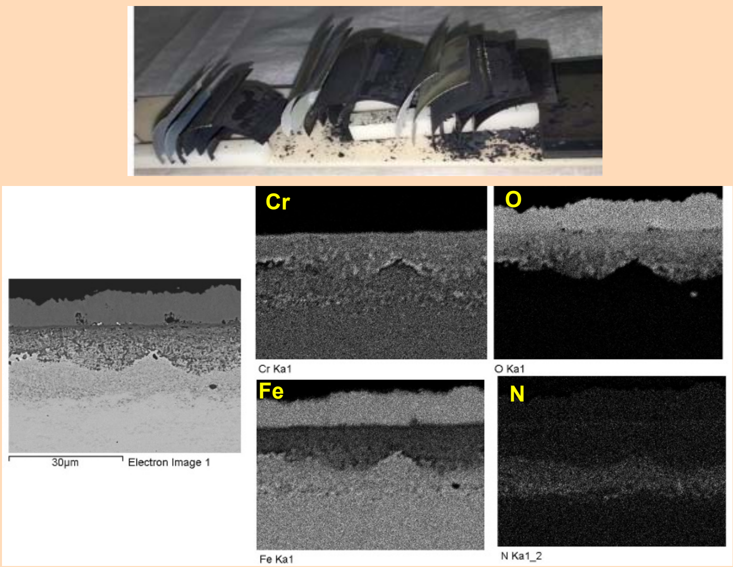
Turbine-Side Test Samples (550°C)

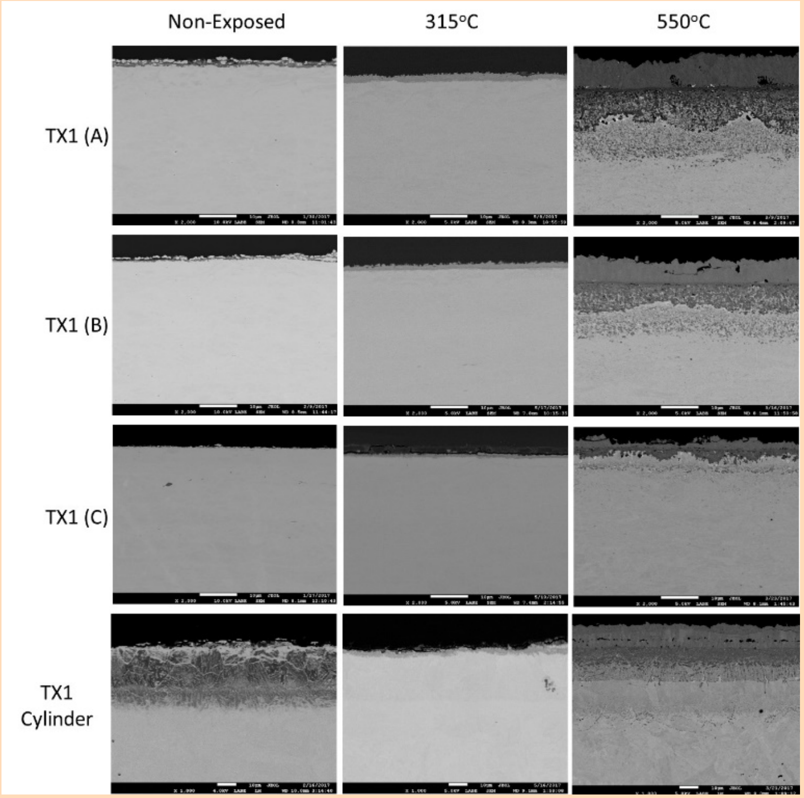


Surface Oxidation is Undesirable

Coating / Substrate Microstructure

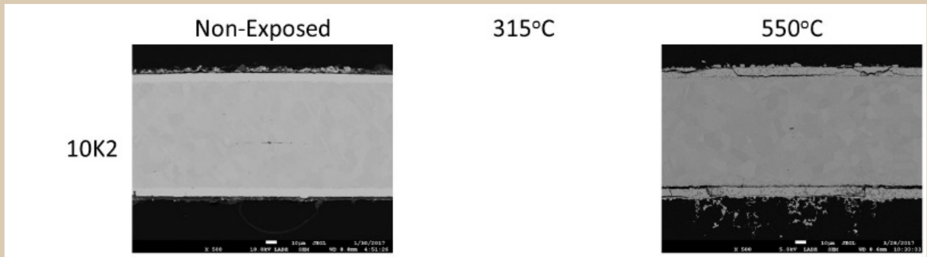
550°C



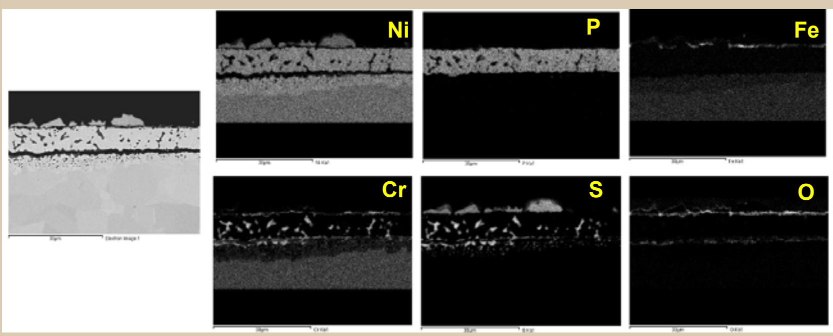


Coating Delamination Observed

Coating / Substrate Microstructure

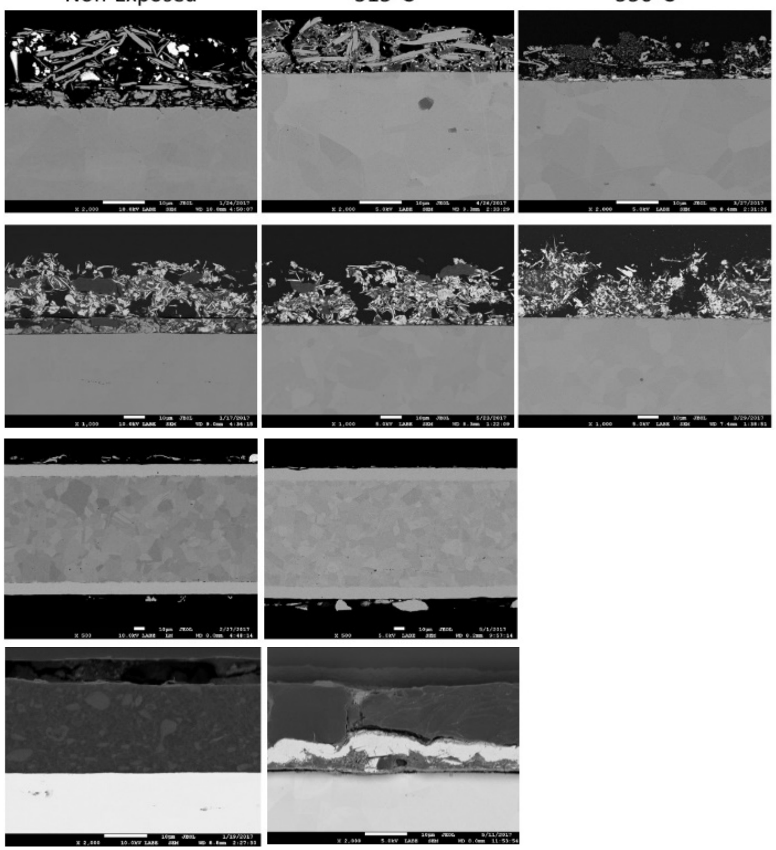


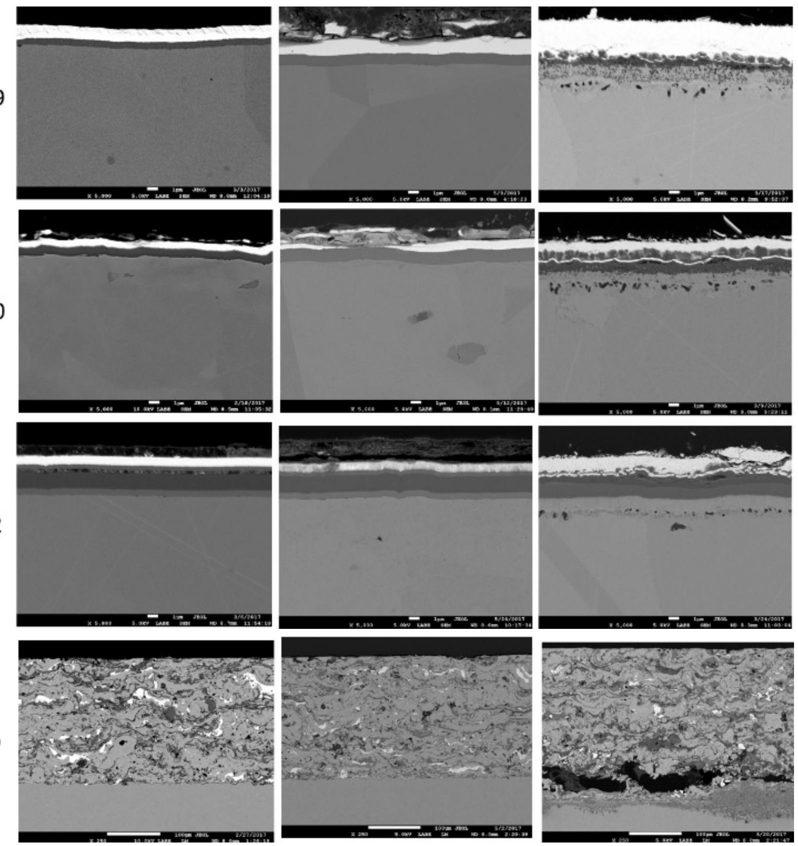
550°C



Other Materials Exhibit Minor Changes

Coating / Substrate Microstructure

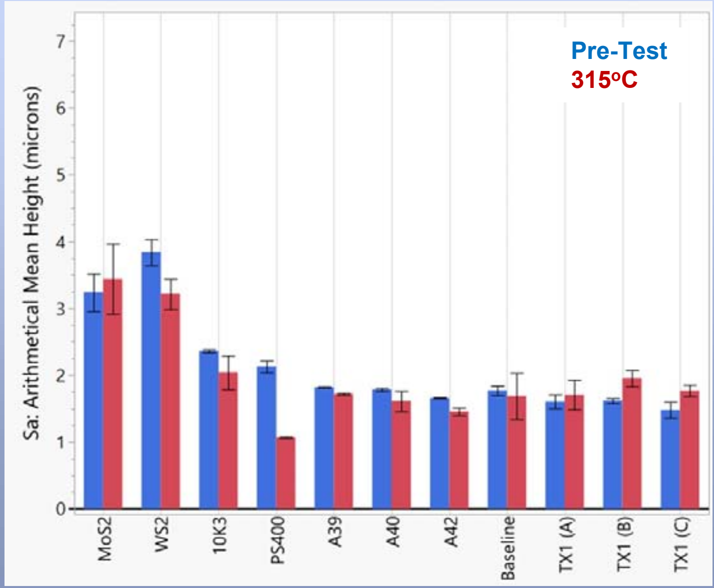




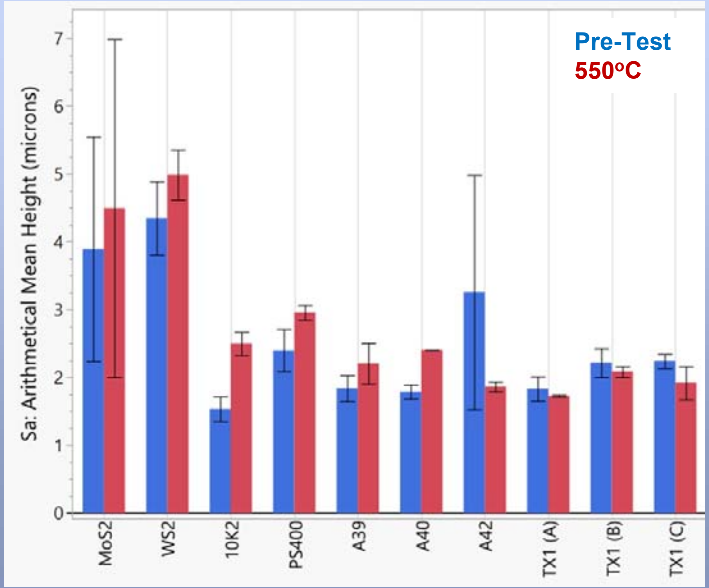
Exposure Temperature has an Impact

Surface Roughness

Compressor-Side Test Samples (315°C)



Turbine-Side Test Samples (550°C)

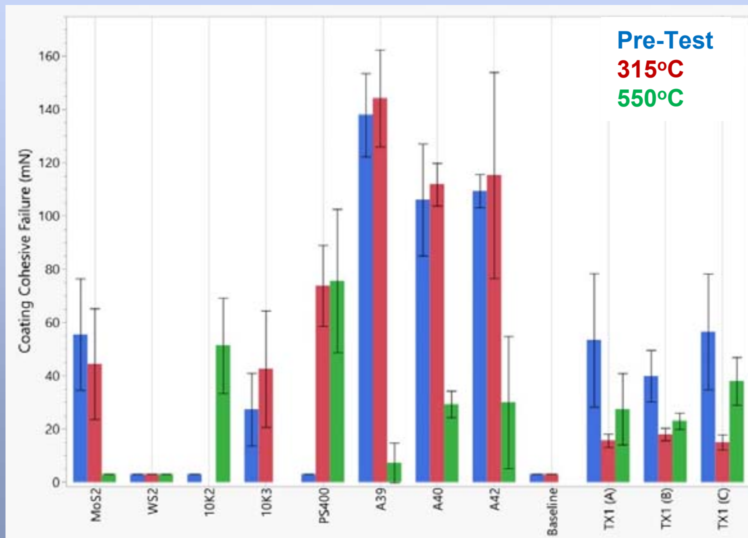


- MoS_2 and WS_2 materials had the highest values at both exposures
- 315°C: Changes were small and generally decreased with exposure
- 550°C: Higher values now that generally increased with exposure

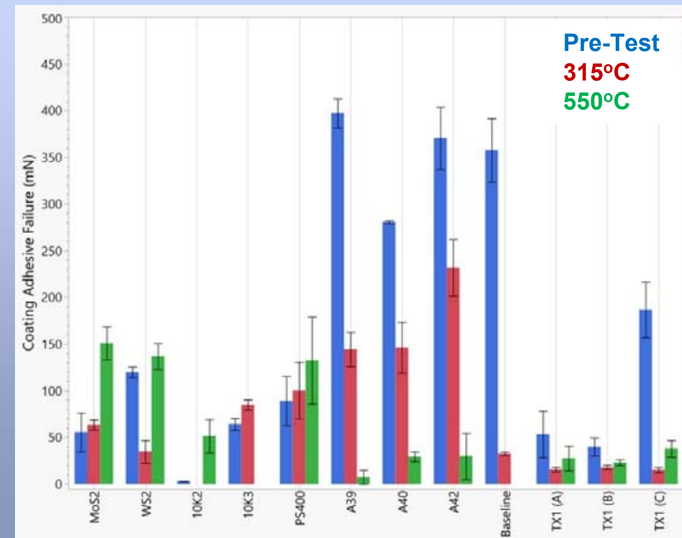
Divergent Trends for Various Coatings

Scratch Testing

Coating Cohesive Failure Measurements



Coating Adhesive Failure Measurements



- Highest pre-test values achieved for Mechanical Solutions coatings
- These also had highest values at 315°C exposure but severely dropped off at 550°C
- Top performing material at 550°C was PS400

Coatings Down Selection Achieved

Summary

- First time evaluation of long duration chemical compatibility of coatings in relevant sCO_2 system environments
- Coating performance evaluated across a range of categories
- Weighted decision matrix used to assist down selection of coating materials for future bearing rig tests
- Three of coatings eliminated from future consideration
- Seven of the coatings will be evaluated in future bearing rig tests

Sample Name	Bearing Vendor	Coating Vendor	Total Score (315°C)	Total Score (550°C)	Ranking (315°C)	Ranking (550°C)
MoS_2	Xdot	Everlube	15	13	6	5
WS_2	Xdot	Everlube	12	13	8	5
10K2	Xdot	General Magnaplate	-	13	-	5
10K3	Xdot	General Magnaplate	16	-	5	-
TX1	Xdot	TurboCAM	16	15	5	4
PS400	Xdot	Hohman Plating (NASA)	18	18	4	2
A39	Mechanical Solutions	Mechanical Solutions	23	17	1	3
A40	Mechanical Solutions	Mechanical Solutions	22	18	2	2
A42	Mechanical Solutions	Mechanical Solutions	21	19	3	1
Baseline-Thrust	SNL	Barber-Nichols Inc.	14	-	7	-

Acknowledgements

Ken Stewart
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Sal Golub (DOE)
Alan Kruizenga (Kairos Power)
Gary Rochau
Amanda Dodd

Questions?

Backup Slides

Sample Name	Bearing Vendor	Coating Vendor	Total Score (315°C)	Total Score (550°C)
MoS_2	Xdot	Everlube	15	13
WS_2	Xdot	Everlube	12	13
10K2	Xdot	General Magnaplate	-	13
10K3	Xdot	General Magnaplate	16	-
TX1	Xdot	TurboCAM	16	15
PS400	Xdot	Hohman Plating (NASA)	18	18
A39	Mechanical Solutions	Mechanical Solutions	23	17
A40	Mechanical Solutions	Mechanical Solutions	22	18
A42	Mechanical Solutions	Mechanical Solutions	21	19
Baseline-Thrust	SNL	Barber-Nichols Inc.	14	-

Sandia is a Leader in sCO_2 System Development

- Component Development with Manufacturers
- Component Testing Platforms
- System Testing and Integration
- System Economics Modelling
- Materials Development

250 kW sCO2 RCBC

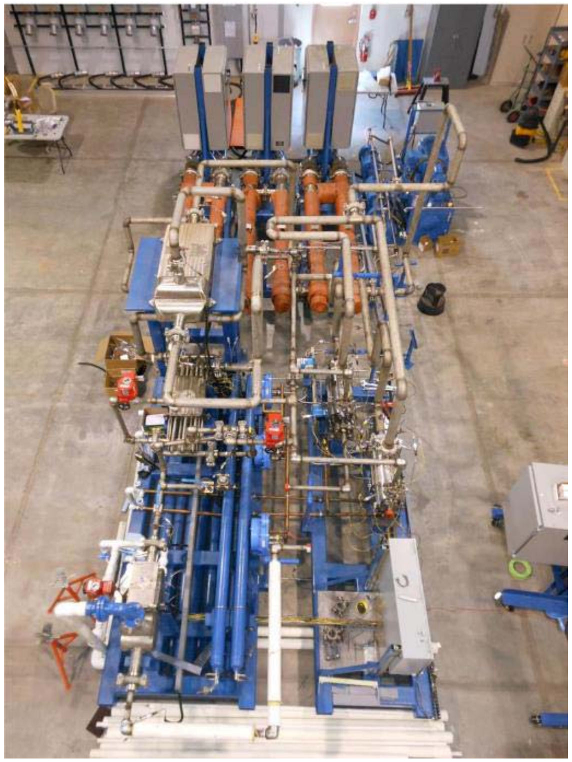


Figure 5: TX1 coating spallation (left) and oxidation (right) for 550°C exposure

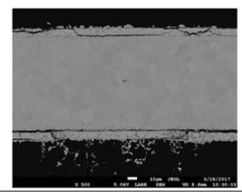


Figure 6: 10K2 coating (550°C) delamination

550°C

315°C

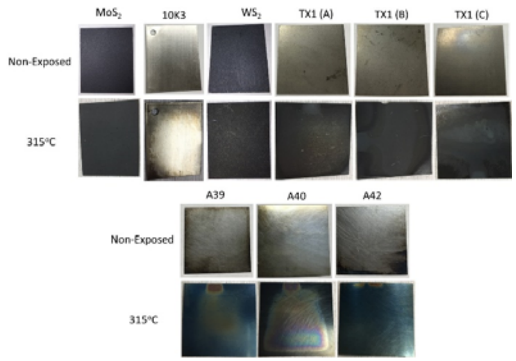


Figure 19. Visual changes for flat foil samples before and after the 315°C exposure test

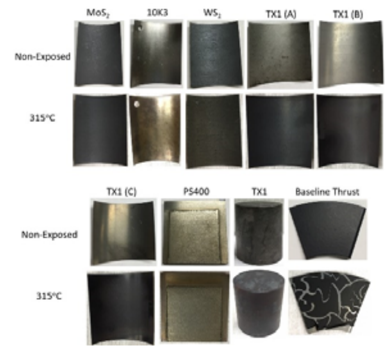


Figure 20. Visual changes for non-flat foil samples before and after the 315°C exposure test

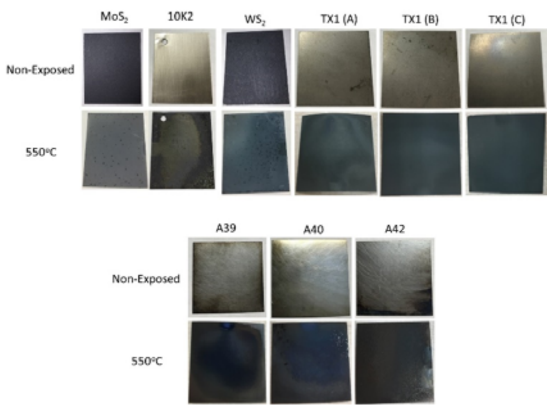


Figure 21. Visual changes for flat foil samples before and after the 550°C exposure test

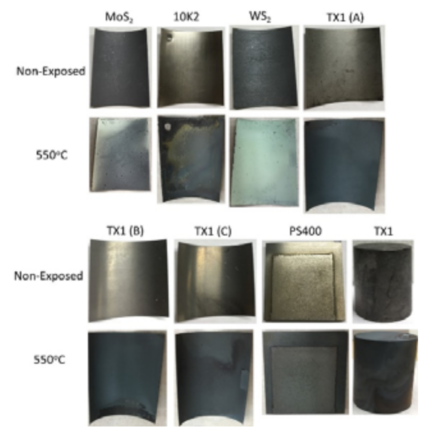
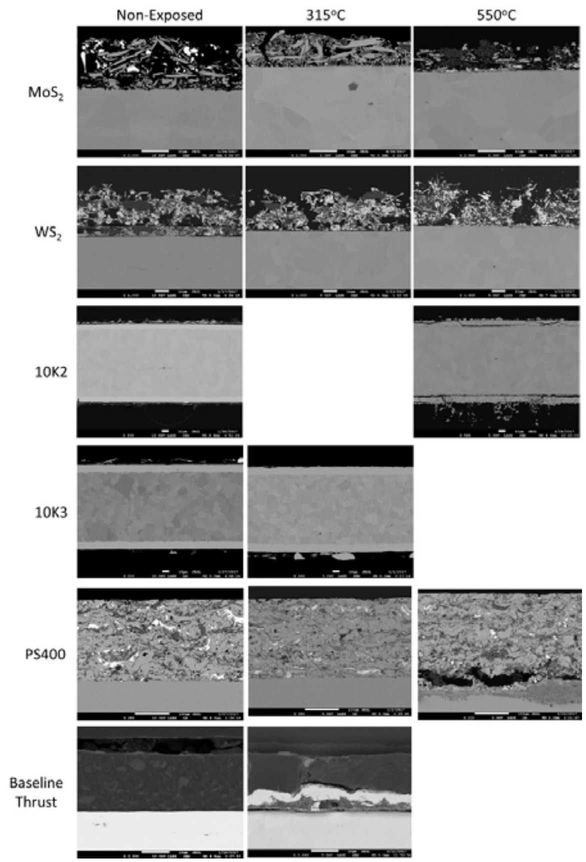
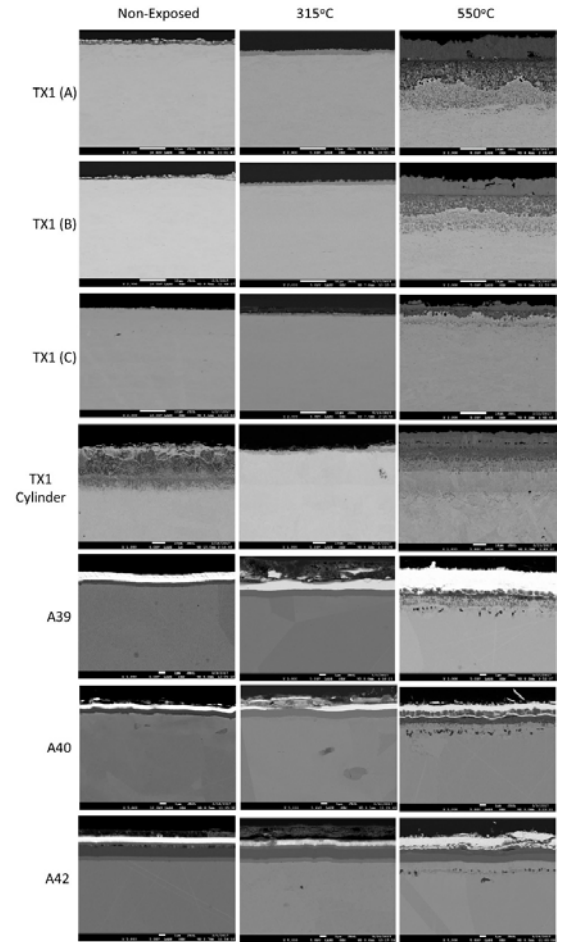
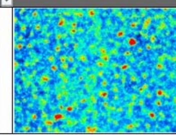
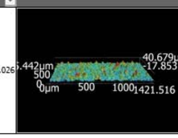


Figure 22. Visual changes for non-flat foil samples before and after the 550°C exposure test

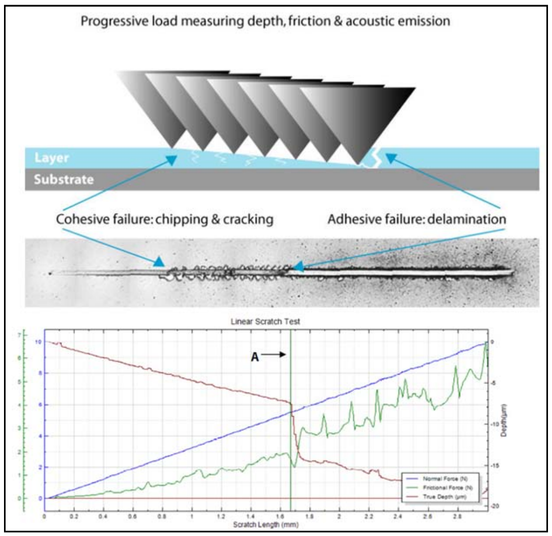
Coating / Substrate Microstructure





File name	Surface roughness / Original surface / Laser +Optical	Main image / Height	Surface roughness / Measured values	Surface roughness Area1 Sa (µm)	Surface roughness Area1 Sz (µm)	Surface roughness Area1 Str	Surface roughness Area1 Spc (1/mm)	Surface roughness Area1 Sdr	3D image
170117_ap-ii-140_WS2_A1	Area1 		see below	3.676	58.532	0.942	2420.362	2.026	

	Sa	Sz	Str	Spc
	µm	µm		1/mm
Max.	3.676	58.532	0.942	2420.
Min.	3.676	58.532	0.942	2420.
Ave.	3.676	58.532	0.942	2420.
Std. DV	0.000	0.000	0.000	0.
Area1	3.676	58.532	0.942	2420.



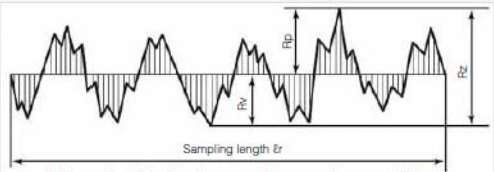
Load Type	Progressive
Initial Load	3 mN
Final Load	500 mN
Scanning Load	3 mN
Loading Rate	500 mN/min
Scratch Length	1 mm
Speed	1 mm/min
Distance between scratches	1 mm
Cantilever	HL-125
Indenter	Rockwell Diamond Radius 10 µm ID: SD-A33/90
Indenter Source	CSM Instruments
Indenter Inspection	Indentation in Copper Before and after testing samples
Temperature	21-23°C
Relative Humidity	45-48%
Conditioning	21-23°C for minimum 24h

Surface Roughness Measurements

Sz (Maximum height)

Sz is defined as the sum of the largest peak height value and the largest pit depth value within the defined area.

$Sz = Sp + Sv$

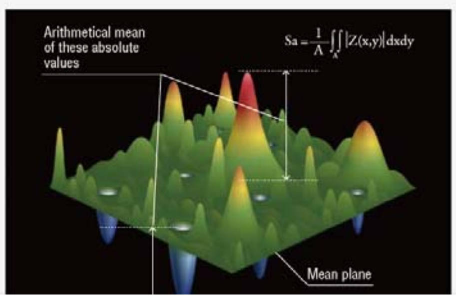


Maximum height of profile curve (for a roughness profile)

The figure is an example of Rz (maximum profile height of a line). Sz is an areal extension of Rz.

Sa (arithmetical mean height)

Sa is the extension of Ra (arithmetical mean height of a line) to a surface. It expresses, as an absolute value, the difference in height of each point compared to the arithmetical mean of the surface. This parameter is used generally to evaluate surface roughness.



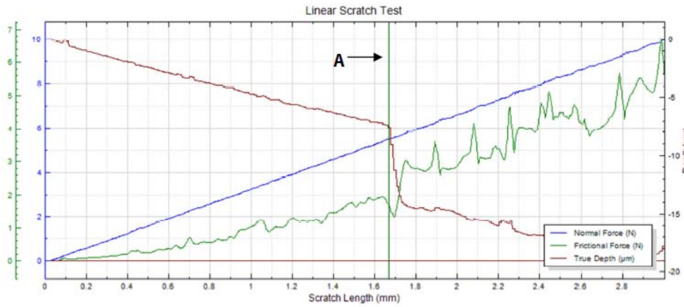


Figure 2: Friction graph showing line of failure (A) Delamination – DLC

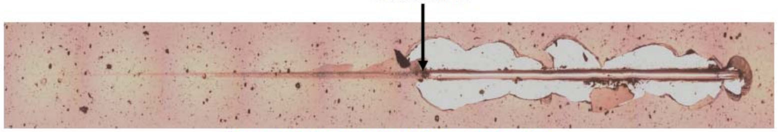


Figure 3: Micrograph of full scratch – DLC

Theory of Scratch Testing

Principle

The scratch testing method is a quantitative test in which critical loads at which failures appear in the samples are used to evaluate the relative cohesive or adhesive properties of a coating or the scratch resistance of a bulk material. During the test, scratches are made on the sample with a sphero-conical stylus which is drawn at a constant speed across the sample, under a constant load, or, more commonly, a progressive load with a fixed loading rate. Sphero-conical styluses are available with different radii (which describes the "sharpness" of the stylus). Common radii are from 20 to 200µm for micro/macro scratch tests, and 1 to 20µm for nano scratch tests.

When performing a progressive load test, the critical load is defined as the smallest load at which a recognizable failure occurs. In the case of a constant load test, the critical load corresponds to the load at which a regular occurrence of such failure along the track is observed.

Comments on the critical load

The scratch test is a quantitative test with high repeatability. The critical load depends on the mechanical strength (adhesion, cohesion) of a combined coating-substrate system but also on several other parameters. Some of them are directly related to the test itself, while others are related to the coating-substrate system.

Test parameters affecting critical load:

- Loading rate
- Scratching speed
- Indenter tip radius
- Indenter material (and also indenter tip wear)

Sample specific parameters affecting critical load:

- Friction coefficient between surface and indenter
- Internal stresses in the material
- Substrate hardness and roughness
- Coating hardness and roughness
- Coating thickness

By keeping the test parameters constant one can obtain very repeatable data to quantifiably compare samples.

Means for critical load determination

Microscopic observation is the most reliable method to detect surface damage. This technique is able to differentiate between cohesive failure within the coating and adhesive failure at the interface of the coating-substrate system.

A.2

The friction force recording enables the force fluctuations along the scratch to be studied and correlated to the failures observed under the microscope. Typically, a failure in the sample will result in a change (a step, or a change in slope) in coefficient of friction. Frictional responses to failures are very specific to the coating-substrate system in study.

The depth sensor recording can also sometimes indicate where a failure occurs. Typically, a significant fall in the depth will indicate that the indenter has broken through one layer of a sample down to the next. The depth recording can also be used to study deformation of a sample surface. Plastic and elastic deformation can be studied by performing pre- and post-scans of the scratch.

Finally, the acoustic emissions recording can also sometimes be used to determine a critical load. Oftentimes a failure will produce cracking noises or other sounds that can be recorded and used to determine the point in the scratch at which the failure occurred.

- Gas foil bearings are a type of hydrodynamic fluid film bearing that has received significant interest in the development of R&D sCO_2 power systems. At high shaft rotational speed these bearings allow the shaft to ride on a cushion of air. Conversely, during startup and shutdown, the shaft rides along the foil bearing surface. To extend the life of the bearings and also to facilitate rotation during these periods, coatings are applied to the foil to minimize friction and wear.

- An experimental program was initiated to elucidate the behavior of coated bearing foils in the harsh environments of these systems. A test configuration was developed enabling long duration exposure tests, followed by a range of analyses relevant to their performance in a bearing. The results obtained provide valuable information in selecting appropriate coatings for more advanced future bearing-rig tests at the newly established Sandia test facility.

- Important requirements for foil surface coatings include chemical compatibility with the fluid environment, surface properties (surface roughness, coefficient of friction, etc.) to minimize abrasive wear and particle debris generation, and good adhesion to the metal substrate. Ten different coating materials were exposed to high pressure CO_2 at two separate temperatures (315^oC and 550^oC) for 500 hours. Sample formats included both flat and curved foils to represent the formats for the 2 types of bearings.